Building Engines for War

A comparative study of British and American production of air-cooled radial aero engines during World War II

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A comparative study of British and American production of air-cooled radial aero engines during World War II

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

King's College London

Department of History

Declaration of originality

This thesis represents my own work. Where the work of others is mentioned, it is duly referenced and acknowledged as such.

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Copyright declaration

Abstract

This dissertation presents, for the first time in the historiography, a critical aspect of British and American wartime production: how British and American aero engine manufacturers shifted from their pre-war practice of low-volume, batch production relying on highly skilled workers using standard machine tools, to large-scale production in wartime using new production methods, semi- and unskilled workers and new types of machine tools in new, larger factories. During World War II, Britain and America built over one million aero engines. The standard narrative of production in World War II is that mass production methods typically associated with the automotive industry were essential to all wartime production. In contrast, this dissertation will argue that aero engine production was not a case of simply adopting these mass production methods, nor was it a simple process of converting what some assume to have been a civilian industry to military production, using civilian factories and existing machine tools to aero engine production. Aero engines were not, and could not, be built on the assembly lines typical of mass production. This dissertation will argue that the key to large-scale production of aero engines was implementing flow production, an argument that has not heretofore appeared in the historiography of production in World War II.

In comparing British and American aero engine production, the dissertation will focus on two leading aero engine manufacturers, Bristol Aeroplane Company in Britain and Wright Aeronautical Corporation in America. The dissertation will, for the first time, give a detailed picture of production of three types of air-cooled radial engines built by Bristol, the nine-cylinder Mercury and Pegasus engines and the fourteen-cylinder Hercules engine, and three types of similar engines built by Wright Aeronautical, the nine-cylinder Cyclone 9, the 14-cylinder Cyclone 14 and the 18-cylinder Cyclone 18. The dissertation will, also for the first time, provide a comparison of automobile engines and aero engines to bring out the extensive differences between them. These differences were not well understood at the time, nor later, but they had profound implications for manufacturing aero engines on a large scale. In describing the transition from low-volume batch production to large scale production the dissertation will describe how Bristol and Wright used production and process engineering to

shift from the pre-war functional layout of machine tools in the factory to a system known as line production, arranging machine tools in the proper sequence of successive operations to achieve flow production, the direct and uninterrupted flow of material through the factory from raw material to finished product.

The dissertation will describe how the British and American Governments organized aero engine production, bringing in the automotive industry through the shadow factory scheme in Britain and licensed production in America. Both governments financed a significant expansion of production capacity. This dissertation will provide the first detailed description and comparative study of the government-financed wartime aero engine factories in Britain and America. The dissertation will argue that aero engine factory design in Britain and America went through four generations of factories, a significant point missing in the historiography. The dissertation will show that many of the American aero engine factories were larger than their British counterparts, including what were, successively, the largest industrial single-story buildings in the world. As the dissertation will also show, American factories were different not only in size but in design and layout.

Aero engine production during World War II provides a unique case in the history of machine tools, a subject not well covered in the historiography. To meet the demand for aero engines in unprecedented quantities, the aero engine manufacturers developed new types of machine tools to cope with the shortage of skilled workers and to facilitate large-scale production. Bristol and Wright replaced many standard machine tools use in their pre-war factories with special-purpose machine tools. Later, Wright developed even more efficient high-production machine tools specifically designed for aero engine production. The dissertation will describe the Greenlee Automatic Transfer machines, the epitome of these high-production machine tools, that Wright developed with the Greenlee Brothers Company.

The dissertation will make clear that while Bristol and Wright were comparable companies in the pre-war years, Wright's wartime aero engine production was on a completely different scale from production in Britain, quantitatively and qualitatively. There were significant differences between Bristol and Wright in output, size of factories, production methods and types of machine tools. The dissertation will, again for the first time in the historiography, look at comparative labour productivity and argue that labour productivity in American aero engine factories was superior to the British factories. The explanation for this difference, it will be argued, is that American aero engine factories were better suited to flow production and used greater numbers of high-production machine tools than British aero engine factories.

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My daughter, Sarah Cooper Young, encouraged me to pursue my dream of obtaining advanced degrees in history. She and her husband, Paul Worthington, were a constant source of encouragement. I am deeply grateful to them both. The dissertation process would have been much harder without them. I cannot fully express how much their love and support has meant to me.

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Introduction

This dissertation will examine a critical aspect of British and American wartime production that has heretofore received little attention: how British and American aero engine manufacturers shifted from their pre-war practice of low-volume, batch production relying on highly skilled workers using standard machine tools, to large-scale production in wartime using new production methods, semi- and unskilled workers and new types of machine tools in new, larger factories. The importance and complexity of this story, involving difficult technological and production challenges, is barely understood.

The dissertation will argue, first, that contrary to the standard narrative on production in World War II, British and American aero engines were not built using the mass production methods and assembly lines common to the automobile industry. Instead, the aero engine manufacturers achieved large-scale production by carefully adapting certain mass production methods to achieve flow production, a different method of production that did use assembly lines. Second, these aero engines were built in new, government-financed wartime factories that were in many cases bigger than the pre-war automobile factories. Third, the factories building these engines used new, specially developed high-production machine tools specifically designed for manufacturing aero engine components that were not used in other industries. Fundamentally, the aero engine manufacturers, and car manufacturers that undertook some production during the war, had to work out how to make large, complex aero engines in ways that had never been attempted before.

The standard narrative of production in World War II is that the mass production methods typically associated with the automobile industry were essential to all wartime production. It is implied that existing factories, especially mass-producing ones, converted from civilian production to armaments, and that the conversion to mass production methods was straightforward. The difficulty with the standard narrative is that it lacks an understanding of the reality of production, using instead a superficial image of mass production centred on the assembly line. This is particularly true regarding American production in World War II, where the 'miracle of mass production' narrative is applied to all forms of production of all types of armaments. In contrast, this dissertation will provide a detailed examination of actual production, focusing on aero engines. The dissertation will argue that aero engine production was not a case of simply adopting these mass production methods, nor was it a simple process of converting what some assume to have been a civilian industry to military production, using civilian factories and converting existing machine tools to aero engine production.

The standard narrative on wartime production in Britain and America has not considered the arguments of Jonathan Zeitlin on mass production and David Edgerton on converting civilian firms to war production. As Zeitlin has argued, for complex weapons like aeroplanes and aero engines, the mass production methods associated with the automobile industry were too rigid to cope with the need for both large-scale production and the flexibility to adjust to rapid changes in design.[1] Instead, the airframe manufacturers, and the aero engine manufacturers, had to develop what Zeitlin calls 'hybrid forms of productive organization' that could carefully adapt selected methods of mass production to reach large-scale production and maintain the precision engineering that aero engines demanded, with the ability to deal with constant design changes and the introduction of new models of engines.[2] As this dissertation will show, these were new processes that were developed during the war specifically for large-scale production.

David Edgerton has argued that the production of aeroplanes and aero engines, and many other armaments, typically did not take place in converted civilian industries, as the standard official narrative tells it, but in new government-funded factories. The new wartime arms industry was primarily an off-shoot of the pre-war arms industry.[3] As Edgerton notes, the British airframe and aero engine industry was 'overwhelmingly an arms industry', and its principle firms, including Bristol and Rolls-Royce, were among the industry leaders world-wide.[4] As Edgerton notes, a huge proportion of this expanded armaments industry operated in government-owned factories using new machine tools financed by the government, operated by both the original designing firms,

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[1] Zeitlin, Jonathan: 'Flexibility and Mass Production at War: Aircraft Manufacture in Britain, the United States, and Germany, 1939-1945', *Technology and Culture*. Vol. 36, No. 1, (January 1995), p. 49.
[2] Zeitlin, 'Flexibility and Mass Production at War', p. 49.
[3] Edgerton, David: *Warfare State: Britain, 1920-1970*, (Cambridge 2006), pp. 79-80.
[4] Edgerton, David: *Britain's War Machine: Weapons, Resources and Experts in the Second World War*, (London, 2011), pp. 28-29.

and by car makers.[5] In other words, the bulk of building and plant used to make aircraft was new, and thus did not involve conversion of existing factories. In this dissertation I go further, making clear that in both the UK and the US, these new factories were very much larger than car plants, and were filled with machine tools which were not used in car making.

Zeitlin and Edgerton focus their analysis and arguments on airframe production, and both argued contrary to an overall national-level picture that labour productivity in the British and American airframe production was comparable overall. This remarkable conclusion was derived from the observation that while the US made aeroplanes in long and efficient production runs, they then had to be retrofitted with modifications. This reduced overall productivity to that achieved by the British, who rather than retrofit, modified production regularly. This dissertation will tell a different story about aero-engine production. Large-scale engine production in America was more flexible than the airframe manufacturing system Zeitlin critiques, and did not result in retrofitting of modifications. This dissertation will show that in the pre-war years, labour productivity at Wright Aeronautical was approximately twice that of Bristol. During World War II American factories were twice, and sometimes three times more productive than their British counterparts. The dissertation will argue that this was due to two factors: first, American factories did not have to incorporate external or internal features designed to limit the potential damage from air attack and could thus be much larger than British factories and better suited to flow production; second, these larger American factories employed more of the later generation advanced high-production machine tools than comparable British factories who relied more on standard machine tools and the second generation of semi- and automatic machine tools. The difference was not due to mass production, but to more advanced flow production.

The dissertation will, for the first time, provide a comparison of automobile engines and aero engines and describe in detail how they were manufactured, to bring out the extensive differences between them. These differences were not well understood at the time, nor later, but they had profound implications for manufacturing aero engines on a large scale. Aero engines were far more complex and stood at the pinnacle of precision engineering: they had far more component parts, required more precision in machining operations, more extensive

[5] Edgerton, *Warfare State*, p. 77.

treatments of materials, far more inspections for quality control and employed different assembly methods than a passenger car engine. The differences between automobile and aero engines made aero engines ill-suited to the methods of mass production.

This dissertation breaks new historiographical ground by arguing that the key to large-scale production of aero engines during World War II was implementing flow production. Flow production does not require large volumes or even standardized products or assembly lines. Where mass production requires mass consumption, flow production requires instead continuity of demand.[6] Instead, the objective is to produce more goods as economically and as quickly as possible by reducing idle time (for men, machines, or product), speeding the flow of materials through the factory, ensuring machines are in continuous use, and reducing the storage of unfinished parts between operations. Flow production is a method of production that can be defined as 'the passage of the part from operation to operation in a direct and uninterrupted sequence.'[7] Flow production incorporates all operations from the beginning to the end of production, from the delivery of raw materials to completion of a product and its preparation for shipment with minimal delays between operations.[8]

Aero engine factories could achieve large-scale production by speeding the flow of material through machining operations by placing machine tools more efficiently, eliminating unnecessary movement of parts through the sequence of operations. The first key element was the shift from the pre-war functional layout of machine tools in the factory, where machine tools were grouped by type, to a system known as line production, sometimes referred to as straight-line production, arranging machine tools in a sequence of successive operations. As will be seen, this transition in the methods of production at the aero engine factories employed the tools of production engineering and process engineering. New types of factories were key to achieving line production.

Flow production does not require nor does it equate to progressive assembly systems common in the automobile industry. The iconic image of mass production is the assembly line,

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[6] Woollard, Frank G.: *Principles of Mass and Flow Production*, 55th Anniversary Special Reprint Edition, (2009), p. 51.

[7] Woollard, Frank G.: *Principles of Mass and Flow Production*, p. 48.

[8] Ryden, A.J.: 'Flow Production', *Work Study*, Vol. 2, Iss. 12, (December 1953), p. 27.

which entailed ‘an orderly prearranged progression of assembly operation’ where the operator adds components as the product moves past.[9] In manufacturing aero engines, assembly was the final stage of the process and not progressive during manufacture. Components came together during final assembly. Final assembly of an aero engine was also far more labour intensive, required more precision and employed a modified method of assembly where a group of workers would assemble the engine at one workstation rather than on a long moving assembly line as in an automobile factory.[10]

This dissertation will argue that the American factories building Wright engines achieved a greater degree of flow production than the British factories building Bristol engines. In the effort to attain large-scale production of the Bristol Mercury and Pegasus engines, the factories involved did so not by moving to flow production, but more through scaling up Bristol’s pre-war manufacturing methods, adding more workers, more machine tools and shifting to a form of line production. Production of the larger and more complex Bristol Hercules involved a step change in production methods, employing bigger factories, more automatic machine tools and a greater effort to achieve flow production. As will be seen, there were limitations on what could be achieved in British wartime factories. American engine production was on a completely different scale, with significantly greater output, in even larger factories and greater use of advanced high production machine tools.

This dissertation will provide, for the first time, a description and a comparative study of the wartime aero engine factories in Britain and America. In both Britain and America there was a shift to larger, rectangular, single-storey factory buildings to allow for better placement of machine tools. In most cases, these factories were considerably larger than the pre-war factories dedicated to mass production in the automobile industry. For a variety of reasons, aero engine factories in America advanced beyond their British counterparts to encompass truly giant factories. These were, predominantly, new buildings built specifically for aero engine production with government financing.

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[9] Immer, John R.: *Layout Planning Techniques*, (New York, NY, 1950), p. 100.
[10] Immer, *Layout Planning Techniques*, p. 100.

Table I-1: Four Generations of Factories Building Bristol and Wright Aero Engines

Factory Generation	Date	Machine Shops Size in Sq. Ft.	Employment	Batch/Flow Production	Transfer Machines
1st: No. 1 Shadow Group Factories (components only)	1936-1937	100,000-175,000 (for components equivalent to 1/5 of an engine)	1,500-5,000	Batch/flow	No
2nd: No. 2 Shadow Group Factories, Wright Plant No. 2	1939-1940	500,000-880,000	5,000-10,700	Flow	No. 2 Shadow Group No/Wright Plant No. 2 Yes
3rd: Wright Lockland, Studebaker, Wright Wood-Ridge	1941-1942	1,000,000-1,800,000	8,300-37,000	Flow	Yes
4th: Pratt & Whitney Kansas City, Dodge Chicago	1942-1943	2,900,000-4,322,000	23,000-33,000	Flow	Yes

The dissertation will argue that aero engine factory design in Britain and America went through four generations of factories, a significant point missing in the historiography. The pre-war Bristol and Wright aero engine factories were built to accommodate low-volume batch production. The first generation of new factories, built under the first shadow factory scheme in Britain, were *smaller* than the pre-war original factories and followed pre-war production methods. The second generation of aero engine factories, built under the second shadow factory scheme and as part of Wright's first expansion in capacity, were substantially bigger and were specifically designed for flow/line production. The third generation built as American rearmament accelerated during 1940-41, were even bigger and were exclusively American. Many were larger than the largest pre-war automobile factories in the USA. The fourth generation, again only in America, were true giants, including the largest single-storey industrial building built up to that time.

The second key element was the progressive deskilling of machining operations to cope with the shortage of skilled workers, breaking down pre-war processes into simpler tasks that semi- and unskilled workers could perform on suitably modified standard machine tools with minimal training. By the middle of the war, roughly 80% of the workers at these factories would be in the semi- or unskilled category, many of whom were women. The third key element of the new system of production was the development of new types of machine tools, first to cope with the shortage of skilled workers and the deskilling of machining operations by transferring the skills of the machinist to the machine tool, and to meet the demands for large-scale production. Significant gains in output could be achieved by cutting machining times, replacing standard machine tools with special-purpose machine tools, and even more efficient high-production machine tools designed for aero engine production.

The dissertation will argue that there were three generations of machine tools each adding more 'automaticity'. The first phase of involved adding specially designed jigs and fixtures to standard machine tools to allow semi- and unskilled workers to operate these machines with a minimum of training. The second phase saw the development of new semi- and fully automatic machine tools that could perform machining operations more quickly than standard machine tools, allowing an automatic machine tool to replace several standard machine tools. These advanced machine tools could perform multiple machining operations on a single machine with little intervention by the machine operator. The third phase, which the American aero engine manufacturers pursued to a greater degree than the British aero engine manufacturers, saw the development of truly high-production machine tools specifically and uniquely for the aero engine industry to manufacture engine components. These machines could replace tens of standard machine tools and machine operators and save hundreds of production hours. The epitome of these machines were the Greenlee and Foote-Burt automatic transfer machines used in many of the factories building Wright and Pratt & Whitney aero engines, the significant consequences of which will be described much more generally and fully than ever before.

The important role British and French orders for aircraft and aero engines and capital assistance played in stimulating the expansion of the American aircraft industry before America's entry into the war is well known. What has not been recognized heretofore is how critical these orders were to stimulating Wright Aeronautical and Pratt & Whitney, the other leading American aero engine manufacturer, to begin working out methods of transitioning from batch to large-scale production. At Wright Aeronautical the British and French orders received during 1940 were five times the number of engines the company had built during 1939. Meeting this demand would require more than just new factories, but new methods of production and new types of machine tools.

Historiography of Mass Production

The standard narrative of wartime production is that the mobilization of British and American industry was straightforward, a matter of applying more money, more labour, and mass production methods to convert what were essentially civilian industries and civilian technologies to the production of war material. As one post-war British report triumphantly described it:

> The private car manufacturers stripped their assembly lines, dumped their special tools in the yard, ripped out the spraying booths, put all the unwanted machines anywhere they could, and so contrived it that within a remarkably short space of time Spitfires were going out of the factory through the same door which a few months previously had seen a procession of family saloons.[11]

Narratives of the American production record in World War II have emphasized the 'miracle' aspect of wartime production. In these narratives there is an emphasis on what David Kennedy has called the American 'distinctive national genius' for mass production.[12] The impression that production was effortless still appears in some histories of the period. Writing on the role of American economists in the war effort, Jim Lacey says that once the American Packard Motor Company had adapted Rolls-Royce's plans for the Merlin engine, which Packard built under license, to American mass production methods, Packard was 'producing engines as easily as roller skates.'[13]

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[11] *The Times*: *British War Production 1939-1945: A Record*, (London 1945), p. 6.
[12] Kennedy, David M.: The Oxford History of the United States, Volume IX: *Freedom from Fear: The American People in Depression and War, 1929-1945*, (Oxford, 1999), p. 629.
[13] Lacey, Jim: *Keep From All Thoughtful Men: How U.S. Economists Won World War II*, (Annapolis, MD, 2011), p. 53.

Much of the literature on the American wartime production effort has focused on industrial mobilization and less on the transformation of methods of production. Mark Wilson has described this literature on industrial mobilization as emphasizing one of two different narratives.[14] The first narrative, which he classes as 'celebratory', emphasizes the 'patriotic' contribution of American business to the war effort.[15] The second narrative is more critical of business, asserting that big business used the war to regain political power and diminish the effects of the New Deal and the power of labour.[16] These studies are less about production and more about the dynamic relationships between business, the government and the military. Wilson's *Creative Destruction: America Business and the Winning of World War II*, provides a more balanced view between the two narratives. Far from being a negligible player as some of the pro-business narratives maintain, the public sector played a vital role in organizing and financing production, developing sources of key materials, managing the priority system and exercising a large degree of control over the economy. Wilson argues that during the war business and government were 'reluctant, contentious, and even bitter partners', but were nevertheless partners.[17]

Recent studies in the more 'celebratory' category are Arthur Herman's *Freedom's Forge: How American Business Produced Victory in World War II* and Maury Klein's *A Call to Arms: Mobilizing America for World War II*.[18] Both books are representative of the recent historiography; they describe the record of American war production, but do not provide much more than general observations on production methods. Herman's book is a paean to American business and to American mass production. He minimizes the role and contribution of the Government in the industrial mobilization effort and argues that what made America so productive was 'the miracle of mass production, which could overcome any obstacle or difficulty'.[19] Herman does make the argument that a key factor in the speed with which the

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[14] Wilson, *Destructive Creation*, p. 2.
[15] Wilson, *Destructive Creation*, p. 2,. 294, fn. 4. Wilson's footnotes to his introduction provide a useful bibliographic essay to the literature.
[16] Wilson, *Destructive Creation*, pp. 3, 294, fn. 5.
[17] Wilson, *Destructive Creation*, p. 286.
[18] Herman, Arthur: *Freedom's Forge: How American Business Produced Victory in World War II*, (New York, 2012); Klein, Maury: *A Call to Arms: Mobilizing America for World War II* (New York, NY, 2013)
[19] Herman, *Freedom's Forge*, p. 337.

American economy did mobilize for war production was the broad network of subcontractors which the larger firms could draw on to supplement their own production.[20]

Unlike Herman, whose coverage of production is superficial, Klein does address production challenges. He recognizes that America needed new production methods in the airframe and aero engine industries. Klein argues that while the principles of mass production were well-known—breaking down a product into many interchangeable parts, manufacturing the parts in quantity with machine tools in the proper sequence and assembling the parts on a moving assembly line—nothing resembling these methods had yet been tried in the aircraft industry.[21] The goal, he argues, in the aircraft industry and all other industries, was to 'devise a system and a plant layout that would produce as much as possible as fast as possible.'[22] The key to successfully adapting these methods was 'the painstaking planning, timing, and direction of the flow of materials and parts through the manufacturing process so that each item arrives at the final assembly line where and when it is needed', though he doesn't refer to this as flow production.[23] Though Klein does not draw any examples from the American aero engine industry, this is a good outline of what the aero engine manufacturers and their licensees from the automobile industry had to accomplish to move from batch to large-scale production.

The common view that all wartime production was based on mass production methods stems in part from the view that mass production was already standard in the USA. Modern production is often defined as mass production, and closely identified with the image of the assembly line. More importantly, the emphasis on mass production reflects a view that Jonathan Zeitlin has described as 'narrative assumptions about the superiority of mass production as a model or paradigm of modern industrial efficiency.'[24]

The origins of mass production are often found in the Ford Motor company. David Hounshell argues that toward the end of the 19th Century the American System of Manufacture had reached its limit in its ability to respond to what was becoming a mass consumption market

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[20] Herman, *Freedom's Forge*, pp. 214-15, 251.
[21] Klein, *A Call to Arms*, pp. 67-68.
[22] Klein, *A Call to Arms*, p. 512.
[23] Klein, *A Call to Arms*, p. 475.
[24] Zeitlin, 'Flexibility and Mass Production at War, p. 47.

in America.[25] What was needed was a new process for manufacturing goods in even greater quantities, or mass production, which Hounshell defines as 'a doctrine, a business philosophy, a large production output, and a technological system; mass production is all these bound together.'[26] Hounshell submits that Henry Ford and his associates adapted the principles of the American System to make this move to mass production at the Ford Highland Park factory between 1910 and 1914.[27] For Hounshell, Ford's key innovation was the moving assembly line, which he argues removed the last production bottleneck–how to assemble the many parts of an automobile– through 'what became the most symbolic mass production operation of all, the final chassis assembly.'[28] The Ford system relied on producing interchangeable parts accurately and in quantity, using large numbers of specialized machine tools that unskilled workers could operate, and installing conveyor systems following the principle of 'bringing the work to the worker'.[29] The logical sequencing of operations and breaking down assembly operations into simple steps capable of being performed by individual workers should be added to this list of key elements in the Ford system.[30] The Ford system of mass production comprised, Hounshell states, a revolution in manufacturing which led to 'the establishment of what could be called the ethos of mass production in America' and profound changes in the world.[31]

Diffusion of mass production to Europe, and particularly to the European automobile industry, has been a subject of debate within the historiography. For this study, what is particularly important in this debate about the diffusion of mass production techniques to the British automobile industry. One theme in the historiography, most closely associated with the work of Wayne Lewchuck and reinforced in the work of Womack, Jones and Roos, is that British automobile firms can be criticized for their 'failure' to invest in 'Fordist', capital-intensive production systems.[32] Womack, Jones, and Roos assert that the Europeans and the British failed

[25] Hounshell, *From the American System to Mass Production*, p. 122.
[26] Hounshell, *From the American System to Mass Production*, p. 122.
[27] Hounshell, *From the American System to Mass Production*, pp. 10, 217, 220-24.
[28] Hounshell, *From the American System to Mass Production*, p. 10.
[29] Hounshell, *From the American System to Mass Production*, pp. 228, 237, 329.
[30] Rubenstein, *Making and Selling Cars: Innovation and Change in the U.S. Automobile Industry*, pp. 14-18.
[31] Hounshell, *From the American System to Mass Production*, pp.11, 218.
[32] Bowden, Sue and David M. Higgins: 'British Industry in the Interwar Years', in *Cambridge Economic History of Modern Britain*, Volume 2: *Economic Maturity 1860-1939*, (Cambridge, 2004), p. 386.

to see the advantages of the new American mass production methods and resisted their adoption. They assert that in Europe 'the poor fit between the requirements of mass production and the craft orientation of both workers and managers insured that adoption of the new technologies was very slow.'[33]

By contrast Tolliday and Bowden and Higgins argue that the 'failure' of these firms to make extensive investments in capital-intensive, high-volume production processes was not due to management's unwillingness to do so, but instead a rational business decision based on the demand characteristics of the British market, a market not at all suited to or requiring high volume production.[34] As Sabel and Zeitlin argue, 'the best indication that the refusal to adopt successful foreign models wholesale was not based on insularity was the concomitant aggressiveness with which firms did incorporate those aspects of foreign experience which served their constantly evolving definition of locally appropriate strategies.'[35] Tolliday argues that British automobile firms in the interwar years successfully undertook 'a process of intelligent and selective applications of elements of Ford methods' demonstrating superior performance for most of the interwar period than Ford achieved with its supposedly superior system.[36], Woltjer shows that certain sectors of British industry, particularly the transportation sector, made substantial investments in capital-intensive production techniques with above average rates of technological change.[37]

Dave Lyddon argues that far from ignoring developments in America, within the British automobile industry there was instead 'a systematic debate on the nature of the production system operating in the car industry.'[38] The large British automobile firms–Morris, Austin, Vauxhall, Rootes, and Standard–all adopted elements of mass production during the 1930s and

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[33] Womack, James, P., Daniel T. Jones, and Daniel Roos: *The Machine that Changed the World*, (New York, 1990), pp. 228, 277.
[34] Tolliday, 'Transferring Fordism: The First Phase of the Overseas Diffusion and Adaptation of Ford Methods, 1911-1939', Actes du GERPISA No. 11. P. 55; 'British Industry in the Interwar Years', p. 386.
[35] Sabel, Charles F. and Jonathan Zeitlin, eds.: *World of Possibilities: Flexibility and Mass Production in Western Industrialization*, (Cambridge, 1997), p. 13.
[36] Tolliday, 'Transferring Fordism', p. 55.
[37] Woltjer, *The Great Escape: Technological Lock-in vs Appropriate Technology in Early Twentieth Century British Manufacturing*, pp. 14-21, 23. Bowden and Higgens also make this point on p. 387.
[38] Lyddon, Dave: 'The Myth of Mass Production and the Mass production of Myth', *Historical Studies in Industrial Relations*, Vol. 1, (March 1996), p. 88.

made substantial investments in production as the volume of automobile sales increased during the decade. The methods these firms chose focused on reorganization of work toward greater flow production, something the Morris Motor Company had pioneered in the 1920s.[39] The changes adopted the techniques of flow production, incorporating moving assembly lines, reconfiguration of work processes and conveyor belts that transferred parts and sub-assemblies to the production lines.[40] And, contrary to Lewchuk's assertion of the strength of labour unions and the preservation of a skilled labour force, in the large automobile factories the work force underwent a steady process of de-skilling.[41] Foreman-Peck, Bowden and McKinlay argue that what they call the 'British System of Mass Production' gave good results for the leading automobile firms, with Britain rising to become the second largest automobile market and industry after America.[42] They, too, note that the higher volumes of production in the 1930s enabled the larger factories to make improvements in factory layout to achieve better continuous flow of parts and components and to ensure that machine tools were employed as continuously as possible.[43]

Many of the studies of mass production focus almost exclusively on what Williams, Haslem and Williams have called a common stereotype of mass production that incorporated three elements– dedicated machine tools, Taylorized semi-skilled workers, and a standardized product —and especially on the assembly line, the symbol of mass production.[44] In contrast to the emphasis on the moving assembly line, their focus is on Ford's development of flow throughout the production process. The real dynamic at Highland Park, they argue, was not the moving assembly line, but 'continuous improvement in workflow via changes in layout' to

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[39] Jolly, Michael: 'Employment Variability and Mass Production Technology in the British Automobile Industry during the Interwar Period', *Journal of European Economic History*, Vol. 25, No. 2, (Fall 1996), pp. 429, 431.
[40] Lyddon, 'The Myth of Mass Production and the Mass production of Myth', pp.91-95; Jolly, 'Employment Variability and Mass Production Technology', pp. 430-32.
[41] Church, Roy: *The Rise and Decline of the British Motor Industry*, (London 1994), pp. 22-26. See also Church, Roy, and Michael Miller: 'The Big Three: Competition, Management and Marketing in the British Motor Industry, 1922-1939' in Supple, Barry ed.: *Essays in British Business History*, (Oxford 1979); Richardson, Keith: *The British Motor Industry*, (London 1977); Overy, Richard: *William Morris, Viscount Nuffield*, (London 1976). For contemporary articles on these changes see Lucato, C.R.: 'At Cowley To-day', *The Morris Owner*, (August 1934), pp. 556-58 and Ware, B.T.: *Production Flow at the Austin Works*, *Machinery*, Vol. 44, (June 7, 1934), pp. 285-88.
[42] Foreman-Peck, James, Sue Bowden and Adam McKinlay: *The British Motor Industry*, (Manchester 1995), p.47
[43] Foreman-Peck, Bowden and McKinlay *The British Motor Industry*, p.49.
[44] See Williams, Karel, Colin Haslem, and John Williams: 'Ford versus 'Fordism': The Beginning of Mass Production?', *Work, Employment & Society*, Vol. 6, No. 4, (December 1992), pp. 517-55.

reduce or eliminate transfer and handling of materials, including placing machine tools in order of use.[45] This is a key link to the idea that flow production does not have to be the same as mass production, a point that is missing in most analyses of mass production.

Alternatives to Mass Production

Whether mass production should be viewed as the optimum mode of production, part of some 'alleged logic of material progress' is another debate within the historiography.[46] Mass production was not suitable to every product and there were alternatives. The most important study of these alternatives is Philip Scranton's *Endless Novelty: Specialty Production and American Industrialization, 1865-1925*.[47] Scranton argues that the 'conventional tale' that Chandler and others have told of the rise of America's industrial growth 'displays the triumph of giant managerialist firms exercising technical ingenuity, organizational refinement, marketing savvy, and the power derived from pursuing efficiency and economies of scale.'[48] The difficulty with the conventional historical approach, in Scranton's view, is that it is not only limited in scope and explanatory power, but also 'seriously incomplete and fundamentally flawed'.[49] The conventional approach 'relegated to a quiet periphery those firms and sectors which did not achieve throughput, sustain mergers, increase minimum effective size, raise public capital, venture internationally, and/or move resolutely to manage markets along with employees and production.'[50] As Scranton points out, the large managerial firms that comprised 'mass production' in America were in fact only a small portion of the total American manufacturing sector that emerged from American industrial development in the 19th Century. There were other sectors, just as successful, who have received little attention or study. Within American manufacturing, there was 'endless novelty' and 'a spectrum of

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[45] Williams, Haslem, and Williams: 'Ford versus "Fordism": The Beginnings of Mass Production?' p. 523.
[46] Sabel and Zeitlin, *World of Possibilities*, p. 6.
[47] Scranton, Philip: *Endless Novelty: Specialty Production and American Industrialization, 1865-1925*, (Princeton, NJ, 1997)
[48] Scranton, *Endless Novelty*, p. 6.
[49] Scranton, *Endless Novelty*, p. 6.
[50] Scranton, *Endless Novelty*, p. 6.

possible approaches to manufacturing'.[51] The compression of history into a single narrative can result in what Stephen Tolliday refers to as 'excessively rigid taxonomies', setting standards for significance which deny the possibility of alternatives, of diversity, and of hybrid forms of manufacturing and industrial organization.[52]

Scranton's most important observation is that mass production is simply one mode of production among several alternatives. He argues that in the evolution of American manufacturing into the 20th Century there were basically four approaches to manufacturing goods:

- Custom production: where a single item was manufactured to a customer's specific requirements.
- Batch production: where goods were manufactured in varied lots based on customer orders.
- Bulk production: where staple goods were manufactured in large quantities using relatively simple technology.
- Mass and flow production: where standardized goods were manufactured in vast quantities using more capital- and technology-intensive methods to meet continuing demand.

Importantly, Scranton points out that these terms refer to <u>approaches</u> to manufacturing products and not to firms or industrial sectors exclusively.[53] Scranton links custom and batch production into what he terms flexible or specialty production and notes that there were numerous cases where a firm would employ various modes of production to manufacture a range of goods, what he terms 'diversity within diversity'.[54] He cites General Electric and

[51] Scranton, *Endless Novelty*, p. 8; Scranton, Philip: 'Diversity in Diversity: Flexible Production and American Industrialization, 1880-1930', *Business History Review*, Vol. 65, (Spring 1991), p. 28.
[52] Tolliday, Steven: *The Rise and Fall of Mass Production*, Volume I, The International Library of Critical Writings in Business History, (Cheltenham, UK, 1998), p. xviii.
[53] Scranton, *Endless Novelty*, p. 11.
[54] Scranton, *Endless Novelty*, p. 19.

Westinghouse as firms whose production ranged from the custom production of specialized electrical machinery to the mass production of consumer electronic goods.[55]

In Scranton's schema of the four approaches, or modes of production, the key variables between the different modes are the nature of the product and the nature of demand. Mass production was not suitable to every product, nor was it the preferred mode of production. The more specialized the product, and the more uncertain and variable the demand, the more likely a firm was to adopt some form of specialty production. Conversely, where products were standardized and where demand was high, the more likely bulk or mass production would be the chosen approach.[56] These distinctions were evident to contemporary and later production engineers, if not to business historians.[57] Scranton categorizes the airframe and aero engine manufactures, for example, as using a combination of 'job-shop' and 'batch' production methods of manufacture, using relationships with smaller specialty firms to provide parts and sub-assemblies.[58] Scranton gives several historical examples of alternatives to mass production. In 'Diversity in Diversity: Flexible Production and American Industrialization, 1880-1930', Scranton looks at the characteristics of batch production noting particularly how some firms 'bridged' modes of production, employing batch and bulk production to produce a range of goods.[59] For Scranton, batch or specialty production was not a failed attempt to reach mass production, but a significant component of American industrialization.[60]

Sabel and Zeitlin have also done extensive studies of alternatives to mass production in the 'historical alternatives' approach to business history, a counterpoint to the mainstream, Chandlerian focus on large hierarchical firms.[61] The historical alternatives approach takes issue

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[55] Scranton, *Endless Novelty*, p. 19.
[56] Scranton, *Endless Novelty*, pp. 17-19.
[57] See, for example, Northcott, Clarence H., Oliver Sheldon, J.W. Wardropper, and L. Urwick: *Factory Organization*, (London 1928); for a more contemporary view see Wild, Ray: *Mass-Production Management: The Design and Operation of Production Flow-Line Systems* (London, 1972)
[58] Scranton, *Endless Novelty*, p. 347.
[59] Scranton, 'Diversity in Diversity', p. 90.
[60] Scranton, 'Diversity in Diversity', p. 90.
[61] Zeitlin, Jonathan: 'The Historical Alternatives Approach', in Jones, Geoffrey G. and Jonathan Zeitlin, eds.: *The Oxford Handbook of Business History*, (Oxford, 2008), p. 120; see also Sabel, Charles F. and Jonathan Zeitlin: 'Historical Alternatives to Mass Production: Politics, Markets, and Technology in Nineteenth Century Industrialization', *Past & Present*, No. 108, (August 1985), pp. 133-76.

with Chandler's emphasis on investment in mass production, mass distribution and professional management as the keys to industrial success and progress.[62]. In his most recent discussion of the historical alternative approach, Zeitlin makes the key point that technology and organization are more malleable than posited in the mainstream Chandlerian approach.[63] For Zeitlin, the key concept is the interaction between actors and contexts. He argues that economic actors are aware of the context in which they are operating and seek out what is to their best advantage. Given the uncertainty of future conditions and the likelihood of change, rather than commit to a fixed choice, economic actors often accept the possibility of change in their technology and form of organization and instead seek to maintain a degree of flexibility. Zeitlin calls this the 'economics of variety', which he defines as 'the capacity to adjust the volume and/or composition of output flexibly and to introduce new products rapidly in response to shifting demand and business strategy.'[64] As with Scranton, Zeitlin would appear to argue that the choices before a manufacturer are not necessarily an 'either/or', but often a choice among 'more than one way to skin a cat.'[65] When the context changes, economic actors adjust their technology, mode of production, or organization in response.

Important supports for the argument for alternatives to mass production are the studies showing the limits on the applicability of mass production. These studies support the assertion that mass production technology was merely one mode of production, suitable for the large-scale production of certain types of products under certain conditions, but not the all-encompassing answer to all aspects of production that some of its proponents have argued. In a study of the automobile repair industry in the early 20th Century, Stephen McIntyer shows how the Ford Motor Company attempted to impose its factory mass production methods upon its network of dealer repair shops.[66] As McIntyer documents, Ford methods were ill-suited to what was a service industry, quite different in its dynamics from manufacturing

[62] Zeitlin, 'The Historical Alternatives Approach', p. 121.
[63] Zeitlin, 'The Historical Alternatives Approach', p. 123.
[64] Zeitlin, 'The Historical Alternatives Approach', p. 122.
[65] Zeitlin, 'The Historical Alternatives Approach', p. 122.
[66] McIntyre, Stephen L.: 'The Failure of Fordism: Reform of the Automobile Repair Industry, 1913-1940', *Technology and Culture*, Vol. 41, No. 2, (April 2000), pp. 269-99.

automobiles. David Hounshell's study of Ford's attempt to mass produce a submarine chaser for the U.S. Navy in World War I shows the difficulties Ford encountered in trying to transfer its mass production methods to a normally custom-built product with its own unique characteristics that was simply not readily adaptable to mass production.[67]

The Limitations of Mass Production in Wartime

Irving Holley's concept of the 'dilemma of mass production' raised questions about the applicability and effectiveness of mass production methods in wartime.[68] As Holley notes, the stability in product design that mass production required in order to produce goods in quantity was in direct conflict with the goal of maintaining qualitative superiority over the enemy. Qualitative superiority required frequent changes in design, the antithesis of mass production.[69] Airframes and aero engines were subject to constant design changes to improve performance. The inability to freeze a design to ensure large-scale production was an equally difficult conundrum for factory managers.

Zeitlin has argued that during the war aircraft production required not just the capacity to build aircraft in large numbers, but also the flexibility to incorporate frequent design changes to keep pace with changes in operational requirements and the constant demand for improved performance.[70] Much as Holley noted in his concept of 'quantity versus quality', Zeitlin argues that 'the central dilemma of wartime aircraft manufacture was the need to balance the qualitative gains obtainable through design modifications against the quantitative losses resulting from interruptions to continuous production runs.'[71] But, as Zeitlin argues, 'established mass-production methods such as those pioneered by the automobile industry, typically proved too rigid for the high level of uncertainty and rapid pace of innovation imposed by the war economy. Successful aircraft manufacturers therefore needed to find new ways of reconciling

[67] Hounshell, David A.: 'Ford Eagle Boats and Mass Production during World War I', in Smith, Merritt Roe: *Military Enterprise and Technological Change: Perspectives on the American Experience*, (Cambridge, MA, 1985).
[68] Holley, Irving B., Jr.: United States Army in World War II: Special Studies: *Buying Aircraft: Materiel Procurement for the Army Air Forces*, (Washington, D.C., 1964), Chapter XX.
[69] Holley, *Buying Aircraft*, p. 512.
[70] Zeitlin, 'Flexibility and Mass Production at War', pp. 48-49.
[71] Zeitlin, 'Flexibility and Mass Production at War', p.53.

the high throughput of mass production with the adaptability of the craft workshop.'[72] What emerged in both Britain and America was what Zeitlin calls 'hybrid forms of productive organization' for building both aircraft and aircraft engines.[73] This was particularly true as in both countries the Governments found that the automobile industry's methods and equipment were "far less appropriate" for aircraft manufacture than had been originally anticipated.[74] 'Automobile Industry practice', as it turned out, 'could not be directly transferred to aircraft manufacture', or, as it turned out, for producing aero engines.[75]

In Britain, he argues the Royal Air Force was committed to a doctrine of quality over quantity, but radical changes in aircraft design could result in long disruptions to production as factories had to convert to new processes and new types of machine tools. Instead, the Air Ministry and the Ministry of Aircraft Production adopted a 'policy of incremental improvements and continuous modifications that could be "spliced in" more quickly and with less disruption to production schedules through careful coordination among airframe, engine, and accessory manufacturers than could a completely new design.'[76] Zeitlin gives as an example of this policy the Supermarine Spitfire, which went through some 20 revisions during the war that saw engine horsepower nearly double, speed increase from 355 mph to 440 mph, and significant improvements in rate of climb, operational altitude and armament.

The American method of dealing with the quantity versus quality dilemma was different it was to temporarily freeze designs to increase large-scale production, with retrospective modifications carried out in specially designated modification centres.[77] This policy enabled the aircraft manufacturers 'to apply line production methods such as progressive assembly, special-purpose machinery, systematic production control and scheduling, and careful balancing of individual operations' to produce aircraft in quantity quickly, but then aircraft would have to spend time at the modification centres before they could be sent to combat units.[78]

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[72] Zeitlin, 'Flexibility and Mass Production at War', p. 49.
[73] Zeitlin, 'Flexibility and Mass Production at War', p. 49.
[74] Zeitlin, 'Flexibility and Mass Production at War', p. 51.
[75] Zeitlin, 'Flexibility and Mass Production at War', p. 51.
[76] Zeitlin, 'Flexibility and Mass Production at War', p. 54.
[77] Zeitlin, 'Flexibility and Mass Production at War', pp. 59-60.
[78] Zeitlin, 'Flexibility and Mass Production at War', p. 58.

The difficulty of transferring automobile industry methods to airframe production is the subject of studies by Robert Ferguson and Irving Holley. Ferguson looks at the Ford Motor Company's effort to build Consolidated B-24 bombers using automobile mass production techniques at the massive Willow Run factory, and contrasts this with the experience of the Eastern Aircraft Division of General Motors and its production of the Grumman F4F Wildcat and TBF Avenger as the FM-2 and TBM-3.[79] Ferguson argues that Ford's effort at Willow Run was 'an aberrant and doctrinaire attempt to treat aircraft like Model Ts' which, though it became a symbol of the myth of the Arsenal of Democracy, was in the end 'an absurd waste'.[80] Supporting Zeitlin's argument, Ferguson shows how the Eastern Aircraft Division was not rigidly wedded to automobile mass production techniques and proved far more successful than Ford using a variety of flexible modes of production and building an extensive network of outside suppliers. Holley gives another example of the difficulty of transferring automobile production techniques in his study of General Motors and the development of the XP-75 fighter plane, an expensive effort to mass produce a fighter plane using automobile mass production methods that ended in complete failure.[81]

Unfortunately, Zeitlin, Holley and Ferguson restrict their analysis to airframe production and say nothing about production of aero engines. The Harvard Business School study is the only source in the historiography to discuss the ways in which the aircraft engine manufacturers increased production, but the study provides little in the way of detail that describes the new systems of production that the aircraft engine firms developed. The existing literature says little about how these firms made the transition from batch to large-scale production.

Although it has become a staple of texts on production engineering, particularly with the advent of the concept of 'lean production', flow production has received little attention in the historical literature, particularly its development in the first half of the 20th Century in the

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[79] Ferguson, Robert G.: 'One Thousand Planes a Day: Ford, Grumman, General Motors and the Arsenal of Democracy', *History and Technology*, Vol. 21, No. 2, (June 2005), pp. 149-75.
[80] Ferguson, 'One Thousand Planes a Day', p. 168.
[81] Holley, I. B., Jr.: 'A Detroit Dream of Mass-Produced Fighter Aircraft: The XP-75 Fiasco', *Technology and Culture*, vol. 28, No. 3, (July 1987), pp. 578-93.

more capital-intensive industries.[82] Michael Nuwer has documented the shift from batch to flow production in the steel industry in America, but only up to 1920.[83] Nuwer provides one of the few detailed descriptions of production, but his focus is more on the changing dynamic in labour relations and less on the development of flow production. With few detailed studies of production methods in the historiography, the best sources of information are the contemporary textbooks of the period that focused on production.

History of Machine Tools

Charles Hyde notes that the history of the wartime development of American machine tools is 'the greatest "untold story" of World War II'.[84] Some key developments can be gleaned from the work of Cristiano Ristuccia and Adam Tooze comparing machine tools in the United States and Germany from 1929 to 1944.[85] Ristuccia and Tooze note that both the United States and Germany made substantial investments in machine tools during the war, with the United States nearly doubling the number of machine tools installed between 1940 and 1944, although by the end of the war the total number of machine tools in each country was nearly equal.[86] In the United States, however, they argue that 'US investment was more targeted' into several classes of advanced machine tools and in particular into more expensive types of machine tools.[87] They point out, for example, that during the war the United States machine tool industry poured resources 'into the expensive and highly sophisticated multiple-spindle automatics' as well as what they call semi- and fully automatic high volume production lathes and centreless grinding machines, categories where the United States maintained a significant advantage over Germany.[88]

[82] A search of *Technology and Culture*, for example, turns up only one article with flow production in the title.
[83] Nuwer, 'From Batch to Flow: Production Technology and Work-Force Skills in the Steel Industry, 1880-1920', *Technology and Culture*, Vol. 29, No. 4, (October 1988), pp. 808-838.
[84] Hyde, *Arsenal of Democracy*, p. 40.
[85] Ristuccia, Cristiano Andrea, and J. Adam Tooze: 'Machine tools and mass production in the armaments boom: Germany and the United States, 1929-44', *The Economic History Review*, Vol. 66, No. 4, (2013), pp. 953-74.
[86] Ristuccia and Tooze, 'Machine tools and mass production', p. 964.
[87] Ristuccia and Tooze, 'Machine tools and mass production', pp. 964, 970.
[88] Ristuccia and Tooze, 'Machine tools and mass production', pp. 961, 964.

Importantly, Ristuccia and Tooze argue that the machine tools the United States added during World War II were six times as productive as machine tools from 1929, while German machine tools were only twice as productive.[89] Given what they call 'the truly remarkable increment to output attributable to each newly installed machine in the United States', they argue that there was a 'within-class' difference between the same type of machine tool in Germany and the United States.[90] As an example, they submit that 'from a basic engineering standpoint a turret lathe in 1940s German and the US may have been the same, but the US version is likely on average to have been larger, faster, more highly powered, and thus more productive.'[91] In an earlier paper, Ristuccia and Tooze make a key argument linking the scale of production with types of machine tools, a point that has direct relevance when comparing the machine tools used in American and British aero engine factories. Since output volumes were substantially larger in the United States, machine tools could be used more productively, and this would have 'warranted the purchase of machines that were larger and more high-powered.'[92]

Philip Scranton has noted several critical improvements in American machine tools in the years leading up to the war and during wartime.[93] During the 1930s, he argues, machine tools improved in 'accuracy, productive capacity, convenience of control' in addition to becoming heavier and more rigid, which made it possible to machine metal to finer tolerances.[94] During the war the key factors in machine tool development were increasing flexibility and automaticity.[95] Scranton argues that 'though the myth would later circulate that "mass production won the war", production directors knew better. Redesigns were continuous, as feedback from problems with weapons in use necessitated manufacturing

[89] Ristuccia and Tooze, 'Machine tools and mass production', p. 967.
[90] Ristuccia and Tooze, 'Machine tools and mass production', p. 970.
[91] Ristuccia and Tooze, 'Machine tools and mass production', p. 970.
[92] Ristuccia, Cristiano Andrea, and J. Adam Tooze: 'The Cutting Edge of Modernity: Machine Tools in the United States and Germany 1930-1945', *Cambridge Working Papers in Economics*, CWPE 0342, (September 2003), p. 32.
[93] Scranton, Philip: 'From Depression to Globalization: Reconfiguring 20th Century American Machinery and Machine Tool Building', Practical Machinist: 06-14-2003.
[94] Scranton, 'From Depression to Globalization', p. 24.
[95] Scranton, 'From Depression to Globalization', p. 29.

changes.'[96] For wartime production, machine tools had to have the capacity to cope with design changes, what Scranton calls 'the flux surrounding manufacturing'.[97]

Scranton argues that automaticity, making more and more functions of a machine tool automatic, was the only means of coping with the shortage of skilled machinists that emerged as the demand for armaments accelerated.[98] The tens of thousands of workers new to metal working, he points out, could not be expected to machine complicated components with just a few weeks of training. Instead, machines had to do the complex machining for them. As a result, during the war there was an increasing move to automatic machines in place of standard machine tools.[99]

The Historiography of Aero Engine Production

A survey of the literature relating to aero engine production during World War II should begin with a review of the official histories. In the British case, there are two volumes in the important *History of the Second World War: United Kingdom Civil Series* that address aspects of aero engine production, beginning with M.M. Postan's *British War Production*.[100] Postan focuses on the organization of engine production, particularly the problem the British Government faced creating war potential during the rearmament period, building the capacity that could be rapidly expanded in wartime.[101] This problem, as Postan notes, led to the creation of the shadow scheme, bringing in selected firms from the automobile industry to build Bristol engines, though he makes no mention of the fact that the original intention of the scheme, to convert the main automobile factories to aero engine production, proved to be impractical. Postan describes how from 1939 to 1942 the airframe industry laboured under the threat of a shortage of engines, due in part to what he calls a chronic under provisioning of engines in the pre-1942 engine

[96] Scranton, 'From Depression to Globalization', p. 29.
[97] Scranton, 'From Depression to Globalization', p. 29.
[98] Scranton, 'From Depression to Globalization', p. 31.
[99] Scranton, 'From Depression to Globalization', p. 31.
[100] Postan, M. M.: *History of the Second World War, United Kingdom Civil Series, War Production Series: British War Production*, (London, 1952)
[101] Postan, *British War Production*, pp. 18-19, 40.

programmes.[102] Postan also brings out the difficulty in utilizing existing production capacity through multiple shifts in the first years of the war, but says little about how this was resolved.[103] Oddly, Postan says little about engine production in later years, and nothing at all about changes in production methods.

William Hornby's study, *Factories and Plant*, covers the expansion of industrial capacity in Britain and the factories the Government set up during World War II for war production.[104] While devoting most of his attention to airframe production, Hornby does include a section on production of aero engines, but says little about methods of production. He makes the key point that the Government's initial expectation that the automobile factories could be rapidly converted to aero engine production proved to be unrealistic. The only mention of production methods is Hornby's observation that the Bristol agency factory at Accrington used machine tools and manufacturing methods 'already well established in the United States for air cooled engines' but doesn't elaborate on what these were.[105] Hornby makes a critical argument about the size and scale of British wartime factories that offers a contrast to Postan's argument on the superiority of the British system of aircraft production. Hornby argues that despite the great expansion in industrial capacity in Britain during the war, '…the industrial effort, extensive and intensive as it was, could not reach the level needed to meet military requirements in full.'[106] This was particularly true, he notes, with regard to aircraft. But meeting these requirements from Britain's existing industrial capacity would have required 'a substantial increase in the efficiency of production, as measured by the relation of labour to output.'[107] Hornby says:

> But in the production of some mechanised equipment, particularly aircraft and motor vehicles, had the efficiency of the United Kingdom equalled that attained in the most efficient factories in the United States, the deficiency in supply could have been substantially reduced without any increase in labour force. A very

[102] Postan, *British War Production*, pp. 166-67.
[103] Postan, *British War Production*, p. 168.
[104] Hornby, William: *History of the Second World War, United Kingdom Civil Series, War Production Series: Factories and Plant*, (London, 1958)
[105] Hornby, *Factories and Plant*, p. 262.
[106] Hornby, *Factories and Plant*, p. 34.
[107] Hornby, *Factories and Plant*, p. 34

important factor in securing this increased efficiency in production would have been an increase in the scale of manufacture. Indeed, it was found that this factor alone accounted for the bulk of the difference in comparative efficiency in aircraft production in the United Kingdom and the United States.[108]

Hornby makes several important points relating to the wartime requirements for machine tools for the British aircraft industry. He notes that the pre-war British automobile industry was heavily reliant on advanced American machine tools and that this dependence continued during the war in the aircraft industry, particularly for what he calls high capacity machine tools and special product machine tools used in building aero engines.[109] He states that the newer factories building Bristol aero engines 'were encouraged to make the fullest use of United States special machines and high capacity production machines', but unfortunately doesn't give examples of the type of machine tools he is referring to.[110] In contrast to Postan's criticism of the Ford Trafford Park factory as needing to replace its machine tools to build a newer mark of the Merlin engine, Hornby argues that the continued demand for machine tools in the aero engine factories was, in fact, 'for the introduction of new types of engines to replace earlier types or for major modification in design of existing types' as well as the need for more spare parts.[111]

He notes Britain's dependence on the United States for imports of machine tools in the first years of the war, but shows how this dependence declined in later years, except for certain types of semi-and fully automatic machine tools for large-scale production.[112] He argues that later in the war, with an increasing shortage of labour in Britain, the Government encouraged industry to make greater use of machine tools that would reduce the need for labour and replace more labour-intensive machines.[113] Unfortunately, Hornby does not provide much information on the types of machine tools in use at the aero engine factories, or the balance between standard and special-purpose machines, nor does he say much about the progressive development of high-production machine tools in either America or Britain.

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[108] Hornby, *Factories and Plant*, pp. 34-35.
[109] Hornby, *Factories and Plant*, p. 311.
[110] Hornby, *Factories and Plant*, p. 311.
[111] Hornby, *Factories and Plant*, p. 311.
[112] Hornby, *Factories and Plant*, pp. 330-31.
[113] Hornby, *Factories and Plant*, p. 344.

The American Government unfortunately did not produce an equivalent to the *History of the Second World War: United Kingdom Civil Series*, but a volume in the series on the history of the American Army Air Force is relevant. The sixth volume in Wesley Frank Craven and James Lea Cate's series, *The Army Air Forces in World War II*, titled *Men and Planes*, contains a long section on the production record for the Army Air Forces.[114] Arguing for the importance of aero engine production during the war, they state that the aircraft's 'power plant and its accompanying propeller were the keys to aircraft performance, for speed, range, altitude, and rate of climb depended in large measure on the power and efficiency of the propulsion unit. The race to increase the power ratings of existing engines and to develop new ones was among the most significant competitions of the war.'[115]

The volume notes the importance of the early British and French orders in stimulating expansion of the American aviation industry prior to America's entry into the war, arguing that 'indeed, it is perhaps not too much to say that the expansion financed by British and French funds in 1939 and 1940 advanced by as much as a year the time within which American aircraft production would reach its peak.'[116] Craven and Cate agree with the Harvard Business School study that the two principal aero engine companies, Wright Aeronautical and Pratt & Whitney, could not have met the full needs for aero engines without bringing in the automobile industry, and note that the enormous increase in manufacturing capacity, amounting to sixteen times the pre-war level in the aero engine firms, came from plants built after 1939 and not conversions of existing civilian factories.[117]

Craven and Cate argue that during the war the American Army Air Force sought to balance quantity with quality, and in their view, the decisions taken 'were sound'.[118] Craven and Cate note how important new production methods were to achieving large-scale production, arguing that 'it is clear enough that new techniques of production played a more important part than did

[114] Craven, Wesley Frank and James Lea Cate, eds.: *The Army Air Forces in World War II,* Volume Six: *Men and Planes*, (Chicago, IL, 1955)
[115] Craven and Cate, *The Army Air Forces in World War II*, Volume Six: *Men and Planes*, p. 195.
[116] Craven and Cate, Volume Six: *Men and Planes*, p. 301.
[117] Craven and Cate, Volume Six: *Men and Planes*, pp. 309, 318.
[118] Craven and Cate, Volume Six: *Men and Planes*, p. 230.

any other factor in making possible the remarkable record achieved.'[119] They focus, however, on the introduction of assembly lines in the airframe factories, which differed considerably from the aero engine factories, and say little about the methods of aero engine production.

Among the more recent studies of wartime production in Britain the most important relating to aero engine production are Sebastian Ritchie's *Industry and Air Power: The Expansion of British Aircraft Production, 1936-1941* and David Thoms' *War, Industry and Society: The Midlands 1939-45*.[120] Ritchie argues that the record of British aircraft and aero engine production in World War II was far from being, as some historians have argued, 'a gloomy catalogue of muddles and missed delivery dates which is compared unfavourably to an idealized (but very misleading) evaluation of German and American aircraft production.'[121] Instead, Ritchie sees the expansion of production in the 1936-1941 period, which saw the Government enlist selected automobile firms to manufacture aero engines through the shadow factory scheme, as an overall success. Government and industry combined to greatly expand production capacity while developing the flexibility to deal with changing operational requirements.

David Thoms covers a broad range of war production in the Midlands but adds more details on the shadow factories building Bristol engines, particularly in the years after 1939 when Ritchie ends his account. Thoms focuses more on the organization of the shadow schemes but provides descriptions of some of the aero engine shadow factories and more data on output than in either Hornby's or Ritchie's studies. Thoms argues that while the contribution of the shadow factories to war production was 'undoubtedly immense', it might have been even more productive but for shortages of labour, machinery, raw materials and had production methods more suitable to large-scale production been developed.[122] While admitting that the 'complex nature of aero engine technology' and the need for frequent design changes 'rendered it difficult to achieve dramatic increases in the speed of assembly', Thoms argues that the production methods that Bristol imposed on the shadow factories left 'little scope for innovation'.[123] Ritchie

[119] Craven and Cate, Volume Six: *Men and Planes*, pp. 330-31.
[120] Ritchie, Sebastian: *Industry and Air Power: The Expansion of British Aircraft Production, 1935-1941*, (London, 1997); Thoms, David: *War, Industry and Society: The Midlands 1939-45*, (London, 1989)
[121] Ritchie, *Industry and Air Power*, p. 264.
[122] Thoms, David: *War, Industry and Society: The Midlands 1939-45*, p. 24.
[123] Thoms, *War, Industry and Society*, p. 56.

and Thoms support David Edgerton's argument that British war production was not a case of a civilian industry producing what were essentially civilian products for the armed forces.[124]

There is still a surprising amount about British aero engine production that remains unknown. There is little on the factories that built these engines. Even the size of the shadow factories is unclear. In his history of British war production Postan laments that 'accurate estimates of floor space or of machining capacity in the aircraft industry as a whole were not to be had at any time, and were not even available for purposes of this study.'[125] There is even less information in the literature on the types and numbers of machine tools used in these factories or much detail on the methods of production, nor on how Bristol and the shadow factories made the transition from batch to large-scale production beyond concepts like flow production or mass production methods which remain ill-defined.

The literature on American aero engine production is similarly limited. While providing some of the essential elements of the story, the recent literature is lacking in essential details, particularly on the transformation in methods of production and machine tool development. There are a few studies that delve more deeply into aero engine production. Charles K. Hyde has studied of the contribution of the American automobile industry to the war effort in his *Arsenal of Democracy: The American Automobile Industry in World War II*.[126] Hyde's book contains a chapter on the automobile companies that built Pratt & Whitney and Wright engines under license. He points out that the history of aero engine production during the war 'is largely unknown, although vital to the aircraft industry', and notes that aero engine production gets little mention in histories of aircraft.[127] Hyde notes that the automobile industry built 56% of all the aero engines for the military. Hyde says that the initial problem was having an industry based on mass production methods confronting an industry based on batch production with parts that required more precision in manufacturing than the automobile companies were used to.[128] He argues that for the automobile companies there

[124] Edgerton, David: *Warfare State: Britain, 1920-1970*, (Cambridge, 2006), p. 75.
[125] *British War Production*, p. 168.
[126] Hyde, Charles K.: *Arsenal of Democracy: The American Automobile Industry in World War II* (Detroit, 2013)
[127] Hyde, *Arsenal of Democracy*, p. 44.
[128] Hyde, *Arsenal of Democracy*, p.47.

was ‘no simple transition from making auto engines to making aircraft engines—much larger and more complex than any engine the auto companies had ever made.’[129] Each automobile company, he argues, ‘faced a unique set of challenges and circumstances.’[130] Hyde says that war production depended on having factories that were the proper size, design and location, and that without the new, large and government-financed factories the automobile companies would not have been able to increase aero engine production as rapidly as they did.[131] In several of the licensee factories, Hyde says, the automobile companies had to modify some of the production methods the aero engine manufacturers used, design new types of machine tools to make interchangeable parts, implement new methods of final assembly and train thousands of new workers. It was not always a smooth process. Hyde states that ‘planning and then managing production of the Wright Cyclone 18 at the Chrysler Dodge Division’s Chicago factory was the most frustrating experience the Chrysler Corporation faced during the war.’[132]

Charles Hyde is one of the few to have described one of the giant factories built in America during the war for aero engine production, one designed by Albert Kahn, the leading industrial architect in America. Kahn, in Hyde’s words, ‘revolutionised American industrial architecture’, yet his wartime work designing factories for the aircraft and aero engine industry is barely known.[133] While there is much written on Kahn, there are few descriptions of his wartime factories. The Dodge Chicago factory that Kahn and his firm designed to build the Wright Cyclone 18, the biggest factory built for the Army Air Force in World War II, receives little mention in the Kahn literature. The literature on Kahn’s designs contains lists of his wartime projects, but few descriptions of these buildings or the innovations that Kahn

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[129] Hyde, *Arsenal of Democracy*, p. 47
[130] Hyde, *Arsenal of Democracy*, pp. 45-46.
[131] Hyde, *Arsenal of Democracy*, pp. 37-38.
[132] Hyde, *Arsenal of Democracy*, p. 69.
[133] Hyde, Charles K.: ‘Assembly-Line Architecture: Albert Kahn and the Evolution of the U.S. Auto Factory, 1905-1940’, *The Journal of the Society for Industrial Archeology*, Vol. 22, No. 2 (1996), pp. 5-24.

introduced in these giant factories.[134] This may be because, as one writer put it, buildings like the Willow Run factory were 'not of sufficient interest to merit individual discussion.'[135]

Jacob Vander Meulen's study of the B-29 programme, *Building the B-29*, covers the origins of the B-29 and the extensive effort to get the airplane into large-scale production at Boeing, Bell and Martin factories across the country.[136] He includes a chapter on the problems with the Wright Cyclone 18 engine for the B-29, looking at the technical difficulties Wright encountered and describing production at the Wright Wood-Ridge, New Jersey, factory and the Dodge Chicago factory which built the engine in quantity. Vander Meulen notes that the Wright Cyclone 18 was a complicated engine that pushed the limits of aero engine technology at the time; well into 1944, there were real questions about whether it would be possible to build the engine in quantity. He argues that successful production of the Cyclone 18, which had to overcome technical delays, shortages of labour and machine tools, among other problems, depended on two principal factors: first, the ability of the production and process engineers at the factories to break down this complex engine into component parts and mechanize production so that the majority of work could be done by semi- and unskilled labour; second, a greatly increased use of special-purpose machine tools so that, he says, the main job of many workers was simply to maintain these machines.[137]

Primary Sources on American Aero Engine Production

The great difficulty in writing a history of aero engine production in Britain and America during World War II is that so much of the most important primary source material—the internal Bristol and Wright corporate correspondence on aero engine production and the correspondence between Bristol and Wright and the automobile firms manufacturing their engines --is missing. The lack of this material may well have contributed to the persistence of the simpler 'miracle of mass production' narrative. In this dissertation I have tried to go beyond this narrative using what

[134] See for example Hildebrand, Grant: *Designing for Industry: The Architecture of Albert Kahn*, (Cambridge, MA, 1974) and Bucci, Frederico: *Albert Kahn: Architect of Ford*, (New York, NY, 1993).
[135] Hildebrand, *Designing for Industry: The Architecture of Albert Kahn*, pp. 205-06.
[136] Vander Meulen, Jacob: *Building the B*-29, (Washington, D.C., 1995), pp.86-98.
[137] Vander Meulen, *Building the B-29,* pp. 92-94.

records are available and by exploring sources that previously may not have been examined in detail.

The government records and company records relating to aero engine production in archives in Britain and America are incomplete, although there is more information in the American archives. In Britain, the National Archives at Kew contain the records of the Air Ministry and the Ministry of Aircraft Production as well as certain Cabinet records, but there are large gaps in the records. While there are records documenting decisions on the quantity of engines to be built, much of the correspondence between Bristol and the shadow factories and the Ministry of Aircraft Production on aero engine production does not appear to have survived. There are two narrative studies relating to aero engine production prepared after the war, but the documents used to prepare these narratives also do not seem to have survived. The Royal Air Force Museum at Hendon holds a critical report that the Bristol Company prepared in early 1945 on production at the shadow factories. At Filton, the Aerospace Bristol Museum has some records of the Bristol Aeroplane Company, particularly the minutes of the Bristol directors' meetings, while the nearby Rolls-Royce Heritage Trust-Bristol Branch contains many records of the Bristol Aero Engine Department. Unfortunately, it appears that much of the internal company correspondence relating to Bristol engines and their production, particularly the correspondence between Bristol and the shadow factories, is missing. Fortunately, the Modern Records Centre at the University of Warwick and the British Motor Museum contain the archives of several of the automobile companies involved in the production of Bristol engines in the shadow factory scheme. There are several books of minutes of directors' meetings, and a daily diary for one of the shadow factories.

In the United States, the National Archives at College Park, Maryland, holds the records of the Army Air Corps and Army Air Force, the U.S. Navy's Bureau of Aeronautics, and the records of the War Production Board and Defence Plant Corporation. These records contain valuable correspondence with Wright Aeronautical on engine production and detailed material on the Government-financed factories that built Wright engines during the war. Several of the Defense Plant Corporation factory files contained lists of machine tools at the factories. But as in Britain, these records, while providing a great deal on the 'what' of aero engine production, say little about the 'how'. The Franklin D. Roosevelt Library at Hyde Park, NY contains the records of the National Defence Advisory Council and the Office of Production Management, predecessors of the War Production Board. These holdings contain the aero engine production programmes, showing changes in production targets and allocations among the different aero engine factories. The records of the Wright Aeronautical Corporation are scattered and incomplete. The Aviation Hall of Fame & Museum of New Jersey holds some corporate records. The Studebaker Museum in South Bend, Indiana has some records of the Studebaker Company that contain references to Studebaker's production of Wright Cyclone engines during the war. The most important source of corporate records are held in the Fiat-Chrysler Corporation North American Archives. These records document on an almost daily basis the work of Chrysler's Dodge Division's giant factory in Chicago which built the Wright Cyclone 18 during the war. In Detroit, the Stillman Branch of the Detroit Public Library holds the records of the Automobile Council for War Production, which has the records of the Council's aircraft engine division.

To understand changes in methods of aero engine production during World War II it is important to look at contemporary descriptions of production methods. Two primary sources that were important to this dissertation were Frank Woolllard's *Principles of Mass and Flow Production* published in 1954, but based on his important paper of 1925, and Richard Muther's 1944 *Production-Line Technique*.[138] Frank Woollard, a pioneering British production engineer, was one of the first to realize that the principles of flow production could be applied to lower volumes of production with beneficial results, and was not restricted to the mass production methods and high volumes that the Ford Motor Company had pioneered.[139] In articulating his principles of flow production, Woollard clearly identified the requirements for mass production and flow production: capital intensive mass production required mass consumption to justify the capital cost; flow production, instead, required not a mass market but continuity of demand.[140] Woollard argued that successful flow production required firms

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[138] Woollard, *Principles of Mass and Flow Production*; Muther, Richard: *Production Line Technique*, (New York, 1944)
[139] Emiliani, M. and P.J. Seymour: 'Frank George Woollard: forgotten pioneer of flow production', *Journal of Management History*, Vol. 17, Issue 1, p. 76.
[140] Woolard, *Principles of Mass and Flow Production,* p. 51.

to specialize in a particular product or related products, that to the extent possible these products should be standardized, and even more importantly, simplified to facilitate repetitive processing, although he believed that production of complex forms and products could be adapted to flow production.[141] The core of flow production, as Woollard defined it, was 'progressive and continuous processing'.[142] The work piece should move progressively from processing stage to processing stage in a continuous flow with no interruptions. Woollard's ideal of flow production was a watershed, with the main river representing the sequence of assembly operations, tributaries feeding in sub-assemblies, as the river moved steadily toward the sea, with 'few bends, no eddies, no dams, no storms' to impede the flow of production and products to the ultimate dealer or consumer.[143]

Although his work was broadly applicable to many industries, Muther's work on line production describes some of the key manufacturing methods that were important to aero engine manufacturing during World War II and the transition from batch to large-scale production. Line production is another term that equates to flow production. Muther contrasts line production with the older method of fabrication by the functional layout of equipment by machining process, whereby all drilling operations were in one department, milling operations in another, etc.[144] In line production, to achieve better flow the product, not the process, governed the placement of machine tools and machining operations. Establishing line production came through production engineering and process engineering. Production engineering refers to the analysis of the product to be manufactured, the determination of most efficient method of production, the machine tools and materials handling equipment to be employed, the layout of machine tools within the factory and line balancing, ensuring that the sequence of operations results in minimal disruptions or downtime between machining operations.[145] Process engineering is a sub-discipline of production engineering, focusing on the manufacturing operations that will be required to manufacture a product and determining the most efficient

[141] Woolard, *Principles of Mass and Flow Production,* pp. 49, 58-66.
[142] Woolard, *Principles of Mass and Flow Production,* p. 77.
[143] Woolard, *Principles of Mass and Flow Production,* p. 48.
[144] Muther, *Production-Line Technique*, p. 7.
[145] Muther, *Production-Line Technique*, pp. 37-38.

methods and equipment to be employed in the manufacturing process, and the specific sequence of operations.[146]

There are three near-primary sources that do delve more deeply into American aero engine production. The most important of these sources, and one that proved crucial to this dissertation, is a study the Harvard Business School conducted at the end of World War II, *Problems of Accelerating Aircraft Production During World War II*, the only study that looked at the problems the airframe and aero engine manufacturers encountered in their effort to increase production.[147] Completed shortly after the end of the war, the Harvard Business School study led by Tom Lilley was based on interviews with the major aircraft and aero engine manufacturers and their licensees. The study is one of the few sources of direct observation of production methods and production problems in the aero engine industry, and the first to define the challenge in accelerating production as the need to shift from batch to large-scale production.[148] The Lilley study is an invaluable resource as it contains sections on production processes used in the manufacture of airframe and aero engines, wartime changes in production processes and the problems encountered during wartime production. The study argues that in June 1940 neither the American Government nor the American aircraft industry were prepared for rapid expansion in production and could not quickly convert from batch to large-scale production.[149] In the pre-war period, the industry had no experience with line production methods as they were unnecessary for the level of demand. The other restraining factor, the study argues, was the limited management capacity of the airframe and aero engine firms, particularly managers with any experience of quantity production. As in Britain, the Government brought in the automobile industry to expand production capacity and to reduce the management load on the primary manufacturers through licensing arrangements.[150]

The most important arguments in the Lilley study relate to changes in production methods. As the study argues, while the airframe and aero engine industries did borrow techniques from other industries, 'the special characteristics of airframes and engines made it

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[146] Muther, *Production-Line Technique*, p. 44.
[147] Lilley, Tom, et al: *Problems of Accelerating Aircraft Production During World War II*, (Cambridge, MA, 1947).
[148] Lilley, *Problems of Accelerating Aircraft Production*, p. 2.
[149] Lilley, *Problems of Accelerating Aircraft Production*, p. 2.
[150] Lilley, *Problems of Accelerating Aircraft Production*, p. 3.

impossible to adopt the established techniques of any other industry without revisions.'[151] As the study notes, the most critical shift in production methods was the adoption of line production, the arrangement of equipment and machining operations in a progressive sequence that was 'the essential prerequisite for the rates of production ultimately required in World War II'.[152] The design and model changes so necessary in wartime were disruptive of line production methods. The mass production industries like the automobile industry had been based on standardization of parts and minimal design changes. The Lilley study argues, contrary to Postan's critique of American factory methods, that 'the fact that the aircraft industry was ultimately able to introduce a high degree of flexibility into production procedures, and thereby make effective use of line production techniques in spite of change, constituted an outstanding contribution in production management.'[153]

The Lilley study argues that regarding aero engine production there were many existing manufacturing processes that could be used, though only with major changes in production and process engineering.[154] More important to achieving large-scale production, however, was the know-how that the aero engine manufacturers could draw from other industries and the development of completely new methods of production, especially the use of new types of high-production machine tools.[155] This was particularly the case in the licensee and branch factories that initially made greater use of special-purpose and high-production machine tools than the parent firms, although by the end of the war these parent factories were also using more and more special-purpose tools.[156] The study does argue, however, that the most important contribution from other industries was the knowledge and experience of production engineering that the automobile licensee factories brought to the challenge of shifting to large-scale production.[157]

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[151] Lilley, *Problems of Accelerating Aircraft Production*, p. 41.
[152] Lilley, *Problems of Accelerating Aircraft Production*, p. 40, 57.
[153] Lilley, *Problems of Accelerating Aircraft Production*, p. 41.
[154] Lilley, *Problems of Accelerating Aircraft Production*, p. 53.
[155] Lilley, *Problems of Accelerating Aircraft Production*, pp. 53-54.
[156] Lilley, *Problems of Accelerating Aircraft Production*, p. 54.
[157] Lilley, *Problems of Accelerating Aircraft Production*, p. 55.

Another source is *Great Engines and Great Planes*, a book the Chrysler Corporation commissioned just after the war to document its record building the Wright Cyclone 18 engine at the giant Dodge Chicago factory and parts Chrysler built for Army Air Force airplanes.[158] This is perhaps the only book to document engine production at a specific factory. The book describes the many challenges Dodge had to overcome getting the Cyclone 18 into production, not least the 6,274 design changes the factory received during the engine's production run, evidence of the need for a system of flexible production.[159] The book also provides an example of how disruptive design changes could be. When Wright shifted to a new system for adding cooling fins to the barrel of the Cyclone 18 cylinders, the Dodge factory had to rip out countless machine tools, develop new types of machine tools and disrupt the production line to accommodate the changes.[160]

A popular work published ten years after the end of the war that is still an important source of information on production is Francis Walton's *Miracle of World War II: How American Industry Made Victory Possible*.[161] Walton's book is an example of Mark Wilson's celebratory story of American production in World War II that focuses on 'tales of patriotic American business leaders and their companies'.[162] Although his work follows the myth that America's production record in World War II was somehow a miracle, instead of a focused application of America's enormous resources on arms production, Walton's book contains a useful chapter on aero engine production and is one of the very few works to describe in some detail the wartime factories built with Government financing and the development of new types of machine tools.

Walton characterizes American industry's achievement during the war as 'the greatest single manufacturing job in the history of the world' with big business playing 'the lion's share of the miracle'.[163] He places great weight on methods of mass production as the key to America's record, arguing that America's production record in World War II was the 'climactic and historic

[158] Stout, Wesley W.: *Great Engines and Great Planes*, (Detroit, MI, 1947).
[159] Stout, *Great Engines and Great Planes*, p. 23.
[160] Stout, *Great Engines and Great Planes*, p. 27.
[161] Walton, Francis: *Miracle of World War II: How American Industry Made Victory Possible*, (New York, NY, 1956)
[162] Wilson, Mark R.: *Destructive Creation: American Business and the Winning of World War II*, (Philadelphia, PA, 2016), pp. 2, 294, fn.4.
[163] Walton, *Miracle of World War II*, pp. vii, 550.

justification of American mass manufacturing', but also notes the range of individual initiatives to improve machine tools and production methods. [164] The singular importance of mass production is a theme that continues in the historiography to the present day. He sees the 'secret' of American industrial activity during the war as the result of first, the remarkable interchangeability of factories and their ease of conversion to war production (although this was certainly not the case in the aircraft industry); second, the mastery of a variety of manufacturing processes; and third, the standardization of parts which greatly eased subcontracting.[165]

Walton argues that the design of the wartime factories was based on the principle of flow production, creating a structure that would allow a continuous and uninterrupted flow from the delivery of raw materials to the finished product.[166] 'No structural idea was accepted', he says, 'that would in any way interfere with the ideal of war products moving uninterruptedly toward "shipping".'[167] The result, he argues, was an architectural revolution where factories were built around the manufacturing process, resulting in large single-storey buildings with all manufacturing under one roof. He describes the early interaction between the aero engine firms and the automobile companies the Government brought into aero engine production as a 'collision of two inimical worlds', with the automakers being surprised at the lack of single-purpose tools in the aero engine factories and the lack of standardization due to frequent design changes.[168] He argues, however, that the two industries overcame these differences to achieve a 'vast technological transfusion', through a continuous exchange of information, as the Lilley study observed.[169]

There are two contemporary films that provide an important visual depiction of the main arguments of this dissertation. The first, *Wright Builds for Air Supremacy*, shows production of the Wright Cyclone 14 14-cylinder engine at the Wright Aeronautical Corporation factories in Paterson, New Jersey during 1941.[170] The film confirms that to meet wartime demand Wright

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[164] Walton, *Miracle of World War II*, p. 547.
[165] Walton, *Miracle of World War II*, p. 544.
[166] Walton, *Miracle of World War II*, p. 210.
[167] Walton, *Miracle of World War II*, p. 210
[168] Walton, *Miracle of World War II*, p. 280-81.
[169] Walton, *Miracle of World War II*, p. 287.
[170] Wright Aeronautical Corporation, *Wright Builds for Air Supremacy* (1942), available on YouTube at https://www.youtube.com/watch?v=sBfFpcdyd5Q&t=1260s, accessed 27 July 2020.

shifted to line production in its factories, laying out machine tools for maximum efficiency so that parts moved progressively along machining operations. As the camera pans over lines of machine tools, the narrator comments, as the dissertation will argue, that most of them had been designed especially for use in the Wright factories, and many had never been used before for making aero engine parts. Most importantly, the film clearly shows the differences between aero engine production and automobile production, demonstrating why the mass production methods of the automobile industry could not have been adopted for aero engine production.[171] The film describes the attention to precision machining, the multiple inspections of every one of the more than 8,000 parts in a Cyclone 14 engine and the careful and time-consuming assembly process, completely different from an automobile assembly line. The second film, *Engines for Superbombers*, describes the Chrysler Corporation's Dodge Division factory in Chicago that built the big Wright Cyclone 18 18-cylinder engine for the Boeing B-29 bomber.[172] Made after the end of the war, the film shows little actual production, but one gets a sense of the vast size of this factory, at the time the largest single-storey industrial building in the world, and the extensive conveyor systems used to speed parts through machining operations, a key feature of the American aero engine factories. Here, too, one can see the care and precision necessary in assembling the engine from the numerous component parts. In a key difference with automobile engine manufacture, the film shows how each and every engine went through a lengthy testing process, at the end of which the engine was completely disassembled and every part inspected before being re-assembled and shipped out.

The most important source for this dissertation were the many articles in contemporary industry magazines and the journals of professional engineering associations, a resource that is not always explored in depth. These contained a surprising wealth of articles on production processes used in the manufacture of aero engines during the interwar period and in World War II. A number went into considerable detail, describing methods on specific machine tools. These articles helped make up, to some extent, for the lack of inter-company

[171] Compare *Wright Builds for Air Supremacy* with *Master Hands-Chevrolet Manufacturing* (1936), available on YouTube at https://www.youtube.com/watch?v=8bT6txm4RpA, accessed 27 July 2020.
[172] Chrysler Corporation, *Engines for Superbombers* (1945), available on YouTube at https://www.youtube.com/watch?v=_t3akMEm9bI accessed 27 July 2020.

correspondence on production methods. Comparing articles from early in the war with articles from the late war period was particularly useful in documenting changes in production methods and the introduction of new types of machine tools. These magazines include such titles as *Aircraft Engineering, Aircraft Production, American Machinist, Automobile and Aviation Industries, Factory Management and Maintenance, Iron Age, Machinery (Lon), Machinery (NY), Mechanical Engineering, Mill and Factory, Steel, Tool Engineer, Journal of the Society of Automobile Engineers, Proceedings of the Institution of Mechanical Engineers* and several others. The company magazine for the Bristol Aeroplane Company, *The Bristol Engine Review*, has articles on engine development and advances in engine production, but ends in 1939. The similar magazine for Wright Aeronautical, *Trade Winds*, has extensive coverage of Wright engines and engine production leading up to America's declaration of war and after.

Still photographs and contemporary documentaries will be valuable in identifying and confirming changes in production processes. There is no one source for photographs of production, and not every factory has photographic coverage. These were collected wherever and whenever possible.

The Structure of the Dissertation

To appreciate the central argument of this dissertation that the key to large-scale production was shifting to flow production, Chapter One will provide an overview of aero engine production methods during the interwar period. The chapter will compare automobile and aero engine production to demonstrate the qualitative differences in manufacturing processes, which were considerable but not clearly understood. This Chapter will also provide an overview of the aero engine industry in the interwar period and some background on both Bristol and Wright Aeronautical. Chapters Two and Three will cover the shift to large-scale production of Bristol's major wartime air-cooled radial engines. Chapter Two will look at the Mercury and Pegasus engines and argue that while production of the engines was successful, the methods employed at the first set of shadow factories building these engines had their limitations. Chapter Three covers production of the larger Hercules engine and will argue that with the Hercules there was a step change in production methods, shifting toward flow production in new, bigger factories and employing more automatic machine tools. Chapters Four and Five will cover production of Wright engines in America, documenting how production was on a completely different scale from Britain. Chapter Four will look at production of the Wright Cyclone 9 and examine how Wright used production and process engineering to successfully develop methods of large-scale production. Chapter Five will cover production of the Wright Cyclone 14 and Cyclone 18 at two of the largest aero engine factories in America, and document how Wright worked with the major American machine tool companies to develop advanced high production machine tools uniquely for aero engine production. Chapter Six will look at comparable productivity among the different American engine factories and between factories in Britain and America. This chapter will argue that the American factories were more productive than their British counterparts and were better able to take advantage of the benefits of flow production and will offer some hypotheses as to why.

Chapter One: Building Aero Engines 1929-1939

Introduction

The literature on the aero engine industry between the wars is limited as we have seen, and the literature on production even more so. Using contemporary textbooks on automobile and aero engine technology and articles in contemporary industry magazines, this chapter will, for the first time, describe the methods of building aero engines in detail and provide a comparative analysis of automobile engine production and aero engine production during the period. This chapter will provide an overview of aero engine production in the pre-war period. It examines the nature of the engines, and how these characteristics influenced the methods of production. The chapter will go on to demonstrate that while in the pre-war period the Bristol Aeroplane Company and the Wright Aeronautical Corporation were comparable in size, product and production methods, they would take radically different approaches to large-scale production during the war and build engines on vastly different scales. Finally, the chapter will, for the first time in the historiography, explain the connection between the transformation of aero engine power during the 1930s, the shift to larger, more powerful double-row air-cooled radial engines toward the end of the decade and the implications this development had for quantity production during World War II.

Contrary to what many in industry, government and the public thought at the time, aero engines could not be manufactured in automobile factories using the same methods and machine tools used for building automobiles. The large air-cooled radial engines that Bristol and Wright built were far more complex machines than automobile engines and stood at the pinnacle of precision engineering. A critical difference was that aero engines were not built on long, continuous moving assembly lines, as were automobiles, and unlike automobiles, were assembled, disassembled and assembled again before shipment. These and many other differences made building large aero engines in quantity challenging. Quantity production would require new, larger factories, considerably more machine tools, and to preserve the requirements for precision and quality some means of coping with the probable shortage of skilled workers in wartime.

Building Automobile Engines

To understand the complexity of an aero engine, one must start with its closest relative, the automobile engine. In his textbook on aero engines, D.R. Pye noted that in its essentials the aero engine was the same as any high-speed internal combustion engine.[1] Pye went on to assert, however, that there were critical qualitative differences between the two. In his view the aero engine was 'the aristocrat, or rather, perhaps, the athlete of the species, with no superfluous tissue and every part fine-drawn to put forth its maximum effort and to endure for long periods under those severe conditions'[2] The large high-performance aero engine was, as Sir Harry Ricardo claimed, at the pinnacle of precision engineering. As Ricardo said, 'The modern piston aero-engine…represents probably the finest achievement ever reached in any sphere of mechanical engineering.'[3] There are five key areas of differentiation between aero engines and automobile engines that need to be explored: requirements for the engine and its characteristics, the impact on design, materials used in construction, the manufacturing processes and quality control and testing.

The basic requirements and characteristics of an automobile engine were its performance, smoothness of operation, fuel consumption, weight and low initial cost of manufacture and installation.[4] During the 1930s, the average passenger car came with a water-cooled engine of four, six, or eight cylinders producing from 10 horsepower (hp) to 85 hp. The typical automobile engine usually ran at 22% power and only rarely above this level.[7] Thus the engine was rarely subjected to abnormal stress. The required level of reliability was a level 'deemed adequate for that particular application'.[5] What was deemed adequate reliability could vary with operating conditions, but under normal operations engine failure in an automobile did not necessarily have to be life-threatening. While weight was an important consideration, as a

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[1] Pye, D.R.: *The Internal Combustion Engine*, Volume II: *the Aero-Engine*, (London, 1934), p. 1.
[2] *The Internal Combustion Engine*, p.1.
[3] Ricardo, Sir Harry R.: *The High-Speed Internal Combustion Engine*, 4th Ed., (London, 1953), p. 301.
[4] Fenton, John, ed.: *Gasoline Engine Analysis for Computer Aided Design*, (London, 1986), p. 1.; Heldt, P.M.: *High-Speed Combustion Engines: Design: Production: Tests*, 13th Ed., (New York, 1946), p. 62; Heywood, John B.: *Internal Combustion Engine Fundamentals*, (New York, 1988), pp. 42-43.
[5] Heldt, *High-Speed Combustion Engines*, p.62.

lighter engine improved performance or allowed the weight savings to go toward other features, the power output to the weight of the engine was not a critical consideration for the average automobile engine. The automobile engines of the 1930s were straightforward machines.

The Ford Flathead V-8 engine, introduced in 1932, is a typical example. The Ford V-8 had two banks of four cylinders, set in a V form, forming the cylinder block with the upper half of the crankcase.[6] This monobloc design, with the cylinders cast integrally, provided a rigid supporting structure for each individual cylinder. The initial model of the Ford V-8 produced 65 hp, later increased to 75 HP and then 95 hp by the end of the decade.[7] During this period the Ford V-8 had only minor modifications as the horsepower increased. A complete Ford V-8 engine contained over 2,000 individual parts.[8] It did not use special high strength steels or alloys. The cylinders and the upper half of the crankcase were cast in a single bloc from Gray cast iron with a small amount of steel added.[9] Gray cast iron was typically used in automobile engines at the time because it was inexpensive, easy to machine, and had excellent compressive strength and vibration dampening characteristics.[10] The cylinder head attached to the top of the crankcase and the pistons were cast from aluminium alloys, while the crankshaft and camshafts were cast or forged from carbon manganese steel and then heat treated before machining.[11]Ford used carbon manganese steel and a drop-forging process to make the connecting rods that were heat treated after forging and a chromium and nickel alloy for the engine valves.[12] The lower half of the crankcase was a steel stamping. At 585 lbs in weight, the 85 hp Ford V-8 had a weight to power ratio of 6.88 lbs per hp.

By the late 1930s, Ford had mastered the mass production of its V-8 engines. In 1939, Ford was producing 3,600 V-8 engines a day at its River Rouge plant; a complete engine could be

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[6] Pagé, Victor W.: *The Ford Models V8, B and A Cars: Construction-Operation-Repair*, (New York, 1933), pp. 529, 534-35.
[7] Judge, Arthur W.: *Motor Manuals: Volume I: Automobile Engines in Theory, Design, Construction, Operation, Testing & Maintenance*, (London, 1942), pp. 196-97.
[8] This information courtesy Patrick Collins at the National Motor Museum Trust.
[9] 'Machining Ford 8-h.p. Cylinder Blocks', *Machinery (London)*, vol. 41, No. 1045, (October 20, 1932), p. 67.
[10] DeGarmo, Paul, J.T. Black, Ronald A. Kosher, and Barney E. Klamecki: *Materials and Processes in Manufacturing*, 9th Ed., (Hoboken, NJ, 2003), p. 77.
[11] 'Machining Cast Crankshafts and Camshafts', *Machinery (London)*, vol. 47, No. 1208, (December 5, 1935); 'The Manufacture of Motor-car Engine Components', *Machinery (London)*, vol. 47, No. 1215, (January 23, 1936)
[12] Pagé, *The Ford Models V8, B and A Cars*, p. 529.

built in 3 ¼ hours.[13] The V-8 cylinder blocks were cast in a single mould at the foundry and after cooling went into an acid bath to remove sand and scale and then washed before machining. Almost all machining operations took place on specialized machine tools, with parts moving between machines on rolling conveyors.[14] In some of the drilling, reaming, boring and grinding operations the machines could complete 30 to 70 cylinder blocks per hour, completing the required operation in seconds.[15] The cylinder block went through a large number of operations in this short space of time. As an example, a Plymouth six-cylinder cylinder block required 106 operations, including multiple cleanings, painting and inspection.[16] At the Morris Motors factory in Coventry, a cylinder block for the Morris Eight or Ten engine could be machined in approximately an hour and 53 minutes, with the longest machining operation requiring only twelve minutes to complete.[17]

After casting or forging and heat treating, the crankshaft, camshaft, pistons, connecting rods and valves all went through similar but fewer machining operations on specialized machines. At the Morris Motors factory a crankshaft went through 16 machining operations in one hour and 44 minutes.[18] Once completed, conveyor systems fed the finished parts to the assembly lines where workers assembled the complete engine. While British automobile manufacturers did not approach Ford's level of production, they still built substantial numbers of automobile engines. By 1935, using more specialized machines, moving conveyors and line production on multiple assembly lines, the Austin Motor Company could turn out 2,000 engines a week, while Morris Motors had the capacity of producing 3,000 engines a week using similar methods.[19]

Automobile manufacturing was based on the moving assembly line, a system where workers progressively added parts along the line, building up a complete automobile along the way. The line usually began with the chassis, the section that forms the base of the automobile

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[13] Bryan, Ford R.: *Rouge Pictured in its Prime*, (Dearborn, MI, 2003), p. 119.
[14] 'Manufacturing the Ford V-Eight', *The Automobile Engineer*, Vol. XXVI, No. 343, (March 1936), p. 96.
[15] 'Manufacturing the Ford V-Eight', pp. 98-99.
[16] Ricardo, *High-Speed Internal Combustion Engines*, pp. 158-61.
[17] 'Producing Morris Eight Engines; The Foundry and Machine Methods at the Coventry Works', *The Automobile Engineer*, Vol. XXV, No. 335, (August 1935), pp. 291-296.
[18] 'Producing Morris Eight Engines', pp. 291-296.
[19] 'Austin Production Methods: An Improved Layout of the Engine Shop', *The Automobile Engineer*, Vol. XXV, No. 329, (February 1935), pp. 43-47; 'Producing Morris Eight Engines', pp. 291-296.

and to which all components and the body are added. Separate assembly lines built up sub-assemblies, like engines, transmissions, axles or radiators. When finished these would be added to the chassis at the correct point along the line. At the final stage, the auto body, built on its own assembly line, would be joined to the chassis. Assembly was thus continuous until the finished automobile rolled off the line.

Quality control, inspection and testing practices varied by company, but followed certain basic practices. In the production of cylinder blocks, for example, Morris Motors would cast a test bar with each pouring of molten metal from the cupolas but did not apparently test each cylinder block individually.[20] After cooling each cylinder block would be inspected for cracks prior to machining. Partway through the machining process and again at the end, the cylinder block would undergo a water test for tightness of the water jacket inside the cylinder block to reveal any cracks in the block.[21] If the cylinder block passed the water test, it went on to final assembly. After machining a piston would be weighed to a standard with a limit of plus or minus two grams, and its dimensions checked on a special measuring device.[22] Connecting rods were inspected to check that the bolt holes connecting the big end of the rod to the crankshaft were parallel, and then weighed to ensure they were within limits, if not exactly equal.[23] Crankshafts went through an inspection for dimensional accuracy and balance.[24] In American passenger automobile practice, the key measurement was the 'production tolerance', the difference between the minimum and maximum dimension of the parts that an inspector would pass, usually measured in thousandths of an inch and specified in standard tables.[25]

Once assembled, an engine went to the test department to measure its performance against specifications. At the Austin Motor Company a test machine would drive the engine at low speeds to break it in, then with water, gasoline and oil connections attached the engine's own ignition would be engaged to run the engine on its own power for up to two hours, including

[20] 'Producing Morris Eight Engines', p. 293.
[21] Ricardo, *High-Speed Internal Combustion Engines*, pp. 154-55.
[22] 'The Manufacture of Motor-car Engine Components', p. 491.
[23] Ricardo, *High-Speed Internal Combustion Engines*, p.239.
[24] Ricardo, *High-Speed Internal Combustion Engines*, p. 272.
[25] Ricardo, *High-Speed Internal Combustion Engines*, p.746.

fifteen minutes at full power.[26] This two hour engine test seems to have been common across the industry. Engines that successfully passed the tests went directly to the chassis assembly for installation in an automobile. At Vauxhall Motors in the mid-1930's, one engine in every ten was stripped down to its component parts for a more detailed inspection.[27]

The technology behind the design and construction of automobile engines did not undergo significant change during the 1930s, nor were there demands for radical increases in horsepower. The quality and reliability of these standard engines was more than adequate for the normal operations of passenger vehicles. Aero engines, however, were vastly different in their requirements, characteristics and manufacturing methods.

Aero Engines

In February 1942, the American magazine *Automobile and Aviation Industries*, the leading journal for the American automobile industry, had this to say about the differences between aero engines and automobile engines:

> The fact of the matter is that the resemblance between an airplane engine and a passenger car engine is one of name only; from a manufacturing standpoint there is little resemblance. True, the component parts bear the same names— because of standardization of nomenclature —but they are made of different materials, have different form, are subject to more intensive loading, and demand an entirely different set of specifications as to tolerances and finish.[28]

Compared to automobile engines, aero engines were far more powerful, more complex, more expensive, had more demanding requirements and were more difficult to build.

Aero engines were very much more powerful than car engines. The Ford V-8 engine of the late 1930s produced 95 hp. In contrast, the Wright Cyclone 9 and the Bristol Pegasus

[26] 'Austin Production Methods', p. 47; 'Engine-Testing Equipment: New Electrical Installation at Longbridge Works', *The Automobile Engineer*, Vol. XXV, No. 332, (May 1935), pp. 177-78.
[27] 'Drilling Operations on the Vauxhall Cylinder Block', *Machinery (London)*, Vol. 43, No. 1120, (March 29, 1934), p. 771.
[28] 'Keeping the Record Straight', *Automobile and Aviation Industries*, Vol. 86, No. 4, (February 15, 1942), p. 19.

produced 1,000 hp. To produce greater power, aero engines had far greater capacity. The Ford V-8 had eight cylinders with a capacity of 239 cubic inches. The Cyclone 9 and the Pegasus had nine cylinders with a displacement of 1,823 cubic inches in the Cyclone and 1,753 cubic inches in the Pegasus. The Cyclone 9 and the Pegasus were radial air-cooled engines, with the cylinders arranged in a circle around the crankshaft and individually attached to the crankcase. Air flowing past the cylinders provided the cooling medium, with each cylinder having fins in the cylinder head and barrel to dissipate the heat from combustion. As well as more cylinders, engines like the Cyclone and the Pegasus also required more accessories than the typical automobile engine, particularly a series of gears to transfer power from the crankshaft to the propeller and a supercharger to provide more air for the air/fuel mixture at altitude. Not surprisingly, the large radial engine had more parts than an automobile engine. The Wright Cyclone 9 of the mid-1930s, for example, had 2,946 parts, and the larger Cyclone 14 with 14 cylinders had over 8,000 parts.

Aero and automobile engines differed greatly in price. In 1936, a standard Ford V-8 Tudor Sedan, Ford's most popular passenger car, sold for £130 ($520).[29] Using a rough estimate that the V-8 engine represented 40% of the value of the automobile, the 1936 Ford V-8 would have cost around £51 ($204), or roughly £.60 ($2.40) per horsepower for an 85 hp engine. In contrast, Bristol Aeroplane Company sold its Pegasus engine of 965 hp to the Air Ministry for £1,795 ($8,921), or 17 times the price of the Ford Tudor (the cost to Imperial Airways was £1,876 ($9,324) per engine, while sales to the more lucrative foreign markets were £1,976 ($9,820) per engine).[30] Using the cost to the Air Ministry as the basis, the Pegasus cost an estimated £2.24 ($8.95) per horsepower. This was another indication of the greater complexity and cost of manufacture of aero engines compared to automobile engines.

The requirements for aero engines were qualitatively far more demanding. The primary requirements for an aero engine were performance, weight and reliability.[31] To a far greater extent than in the design of an automobile engine, these requirements were often conflicting objectives. Maximum performance was the primary objective. The airplane designer could

[29] http://www.american-automobiles.com/Ford/1936-Ford.html, accessed 19/10/2017.
[30] Bristol Aeroplane Company Limited Financial Report for 1936, Aero Engine Sales for the year ending 31 December 1936, copy in the archives of the Bristol Aero Collection Trust, Filton.
[31] Liston, Joseph: *Aero Engine Design*, (New York, 1942), p. 1.

calculate, based on estimated weight and drag of the airframe, the amount of horsepower required to achieve the airplane's desired performance with a given payload. The goal of the aero engine designer was to meet or exceed this requirement. The engine designer first chose the number of cylinders needed to generate the required horsepower and then decided on their arrangement and method of cooling. To complicate the design task engine weight becomes a critical issue, far more critical for aero engines than for automobile engines.

The weight of an aero engine had to be kept to a minimum to increase the airplane's useful load or performance. Assuming a constant structural weight, every ounce saved in engine weight could go to payload or improved performance. The engine designer's goal was to achieve maximum horsepower for minimum weight, as measured by pounds per hp. The 85 hp Ford V-8 engine had a weight to power of 6.88 lbs per hp, while the 1,000 hp Wright 9 engine had a weight to power of 1.18 lbs per horsepower. If the Wright Cyclone 9 had had the same weight to power of the Ford V-8, the two Cyclones that powered a Douglas DC-3 would have weighed almost as much as the empty weight of the entire airplane, reducing the payload to next to nothing. There are numerous ways of increasing engine performance, but these often involved increases in the maximum pressures and temperatures in the cylinder requiring stronger and heavier parts to cope with the higher heat and additional stress. This leads to possibly unacceptable increases in weight. The engine designer had to strike a delicate balance between strength and weight in every part of the engine. In the early 1930s, the design of aero engines involved '…striking a judicious and well-balanced compromise between conflicting demands.'[32] To compound the problem, the engine designer had also to reduce the frontal area of the engine to improve drag in flight, thereby limiting the number and placement of cylinders and compressing the space available for every other part in the engine.

Achieving maximum performance at minimum weight was challenging, but even more fundamental was engine reliability.[33] An airplane engine could have outstanding performance but would be useless if it not dependable. Unlike its automobile counterpart, failure of an aero engine could and did lead to loss of life. All parts of the engine– valves, pistons, connecting rods,

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[32] Liston, *Aero Engine Design*, pp. 2-3.
[33] Frass, Arthur P.: *Aircraft Power Plants*, (New York, 1943), p. 4.

crankshaft, gears and propeller – had to work in near perfect harmony across the speed range of the engine. A failure of one part could cascade to a failure of the entire engine. Though difficult to achieve, the standard for reliability had to be perfection.[34] As aero engines increased in performance and complexity finding a compromise between strength, weight and reliability became more challenging. An important aspect of the pursuit of reliability was meticulous attention to detail, hence the 'thousand and one steps' necessary to improving engine performance and reliability.[35]

The requirement that aero engines have high performance, minimum weight and complete reliability, under all operating conditions, had important implications for their construction and manufacture.[36] To an extent not seen in most other engineering operations, the aero engine manufacturer had to exercise a far greater degree of control over the quality of materials and finished parts used in engine construction.[37] This could only be achieved through rigorous testing and inspection. In the design of engine components the engine designer had to consider not only the properties of the material used in the component part, but also the need to impart a uniform distribution of stress through all the parts in the engine.[38] This often entailed placing a priority on refining the design of the part over its ease of production.[39] In designing component parts for the engine the engine designer also had to consider whether existing manufacturing or machining processes were adequate to produce the component part to the desired standard of strength, weight and finish. This involved close coordination between the engine designer and the production engineer. Cost was an additional consideration, as the skilled labour that might be required to finish a part to specifications was expensive.[40]

Because engine components had to fit together with a high degree of precision and exacting tolerances, their manufacture required an extremely high degree of accuracy.[41] This could only be assured through stringent inspection of the accuracy of parts at each stage of

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[34] Pye, D.R.: *The Internal Combustion Engine*, Volume II: *the Aero-Engine*, (London, 1934), p. 2.
[35] Ricardo, *The High-Speed Internal Combustion Engine*, p. 283.
[36] Fairbrother, E.: 'Aero-Engine Production', *Aero engineering*, Vol. 16, Issue 7, (July 1944), p. 209.
[37] Fairbrother, 'Aero-Engine Production', p. 209.
[38] Nixon, Frank: 'Design of Aero-Engines for Production', *Aero engineering*, Vol. 11, issue 3, (March 1939), p. 127.
[39] Nixon, 'Design of Aero-Engines for Production', p. 127.
[40] Liston, *Aero Engine Design*, p. 145.
[41] Molloy, E.: The 'Complete Engineer' Series, Volume 2: *Aircraft Production*, (London, 1941), p. 87.

production.[42] These exacting standards of quality control over materials and component parts had to be part of the manufacturing process from start to finish. While there was some standardization of aero engine components, designs were not always permanently fixed. Manufacturing an engine had to incorporate a degree of flexibility as well. The relentless effort to improve performance and reliability through constant testing of materials and components, introducing new production methods and changing requirements from customers led to frequent changes in design that had to be incorporated into the manufacturing process. It was not uncommon for an engine manufacturer to put through as many as 1,400 design changes during a year.[43]

Ensuring aero engine reliability was more challenging because these engines were subject to greater stress and a wider range of operating conditions than the standard automobile engine. Like all internal combustion engines, mechanical stress in an aero engine came through the rapid increase in pressure and heat within the cylinder during combustion and the movement of the valves, pistons, connecting rods and crankshaft as combustion transformed heat energy into mechanical energy. At take-off and during climb, the engine will often be run at maximum power, while at cruising speed the engine operates at 50%-60% of maximum power, compared to the typical automobile engine which runs at 22% power and only rarely above this level.[44] Moreover, unlike other internal combustion engines, the aero engine must cope with a far greater range of air pressures and temperatures as it operates at different altitudes. Given the heat and mechanical stresses an engine was subject to, it was not surprising that for many years aero engines were subject to a long catalogue of failures such as fractures in the crankshaft, broken exhaust valves, piston failures, bearing failures, and many more.[45]

The requirement for maximum power output with minimum weight and great reliability placed severe constraints, to a far greater extent than for automobile engines, on the materials that could be used in aero engine construction. For greater reliability, component parts had to

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[42] Fairbrother, 'Aero-Engine Production', p. 209.
[43] Leak, A.H.: 'Problems Co-coordinating Engine Design and Production', (Wright Aeronautical Corporation, 1940), p. 9.
[44] Frass, *Aircraft Power Plants*, p. 4; Gunston, Bill: *The Development of Piston Aero Engines*, Reprinted, (Sparkford, Somerset, UK, 1994), p. 30.
[45] Pye, *The Aero Engine*, Vol. II, p. 21.

be exceptionally strong to withstand the stresses of operation, but at the same time exceptionally light to minimize weight, a contradiction seemingly impossible to resolve. In addition, the engine designer had to use materials that could both withstand the heat generated in combustion and contribute to the dissipation of heat to ensure engine cooling. In designing an engine, the designer had to carefully consider the competing demands of strength, weight and operating temperatures. Based on the required strength, the engine designer had to select appropriate materials that would meet this requirement with minimum weight, but that would also be readily adaptable to the manufacturing process.[46] As an example, the Gray cast iron used in the Ford V-8 cylinder block was inexpensive, easy to cast and easy to machine, but was heavy and had poor thermal conductivity, making it unsuitable for aero engines.[47] The air-cooled aero engine cylinder needed lightness, rigidity and good thermal conductivity.[48] Steel could combine rigidity with light weight, but did not have adequate thermal conductivity. For this, engine designers had to construct the cylinder head, where temperatures from combustion were greatest, from aluminium alloy, which had far greater thermal conductivity than steel.[49]

Aero engine designers made extensive use of high tensile strength steel alloys, particularly nickel-chromium-molybdenum steel alloys that could be put through a nitriding process for additional hardening.[50] For its excellent thermal conductivity, cylinder heads and pistons were made of Y-alloy aluminium, while aluminium's light weight made it suitable for radial engine crankcases. In time, stronger and lighter manganese replaced aluminium in crankcases. For valves and valve seats, especially exhaust valves that were subject to the highest temperatures during combustion, a special cobalt-chromium alloy called Stellite came into use during the 1930s. The high-performance air-cooled radial engine of the 1930s, unlike the comparable automobile engine, consisted of a variety of metals with different characteristics and manufacturing requirements. As aero engine power steadily increased during the 1930s, there

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[46] Price, Brian: 'Developments of Aero-Engine in War 1915 to 1950: Impacts of Knowledge Management and Heuristics in the Configuration of Aero-Engine Architecture', in Starr, Fred, Ed Marshall, and Bryan Lawton, eds.: *The Piston Engine Revolution: Papers from a Conference on the History of Reciprocating Internal Combustion Engines held at the Museum of Science and Industry, Manchester, 14-17 April 2011*, (London, 2012), p. 403.
[47] Pye, *The Aero-Engine*, pp. 6-7.
[48] Pye, *The Aero-Engine*, p. 7.
[49] Pye, *The Aero-Engine*, p. 7.
[50] Pye, *The Aero-Engine*, pp. 228, 247, 255.

was a constant effort to improve the quality of materials used in engine components.[51] The science of metallurgy was arguably far more important to aero engine development than to automobile engines.

The precision required for aero engine components and the materials used in construction posed manufacturing problems of a different magnitude to those used in automobile manufacturing. The high-strength steel alloys employed in aero engines were more difficult to machine than the cast iron and medium-strength steels used in automobile engines.[52] These steel alloys required more powerful machine tools and sharper and more expensive cutting tools, like the new tungsten-carbide tools coming into use, than automobile steels. Machining these stronger steels was critical because of the need for even closer tolerances and finer finishes in the manufacture of aero engine components compared to automobile engine components.[53] Where automobile tolerances were measured in thousandths of an inch, for fine work in aero engines the tolerances were often measured in ten thousandths of an inch.[54] With space at a premium to reduce frontal area, the dimensions of aero engine components had to be compressed to the minimum possible. Because parts had to fit together with such precision, they had to be machined to a much finer finish on all sides compared to automobile parts that did not require the same level of finish.[55] An exceptionally fine finish to all surfaces was also important for the reliability of components, as even small scratches or surface imperfections could result in fatigue stress on the component and potentially, failure.[56]

The complexity of manufacturing a high-performance aero engine compared to the manufacture of an automobile engine is neither understood nor appreciated. The differences are not simply those of the time involved, but entirely different magnitudes of complexity, operations and processes. It was not a case of pushing a chunk of metal through a set of

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[51] Ricardo, *The High-Speed Internal Combustion Engine*, p. 283.
[52] 'Machining a Gear Bank', *Aircraft Production*, Vol. III, No. 27, (January 1941), p. 5.
[53] 'Machining a Gear Bank', p. 5.
[54] See 'Aero Engine Manufacture-VII', *Machinery (London)*, Vol 29, No. 730, (October 7, 1926), p. 3; 'The Manufacture of High Performance Aero Engines', *Machinery* (London), Vol. 48, No. 1249, (September 17, 1936), p. 756.
[55] This observation is from Robert Hercock, Rolls-Royce Heritage Trust-Bristol Branch.
[56] 'Some Machining Operations in the Manufacture of Bristol Air-cooled Aero Engines', *The Machine Tool Review*, Vol. 22, No. 139, (March-April 1934), p. 37.

machining operations. Unlike the manufacture of automobile engines, a significant amount of time and effort went into hardening components. Given the high and continuous mechanical stresses an aero engine was subject to, the need for engine reliability meant that engine components, even when made from high-strength steel alloys, had to go through additional hardening processes after machining. Cylinder barrels, connecting rods, crankshafts and valves went through the nitriding process involving heating these components for a long period in an atmosphere of ammonia, in some cases for up to 72 hours, which would result in nitrogen– a component of ammonia –reacting with the steel to form a very hard compound known as nitride on the surface of the steel.[57] Smaller engine parts needing exceptional surface hardness went through a carburizing process where the components were heated to 900° C together with a carbon-containing material so that the steels could absorb the extra carbon after quenching in oil.[58] Hardening aero engine components through nitriding and heat treatment was more comprehensive and more time consuming than similar processes in the automobile industry.

Machining operations for aero engine components were more extensive than for automobile engine parts. A Wright Aeronautical study of production of the Cyclone 9 engine determined that producing the engine's 2,946 parts required 36,857 machining operations, including 568 operations in the Wright foundry.[59] Producing one nine-cylinder Wright Cyclone 9 aero engine required 40 operations on each of the nine cylinder heads and 42 operations on each cylinder barrel, 57 operations on the master connecting rod, 44 operations on each articulated connecting rod, 65 operations on the front section of the crankshaft and 50 operations on the rear section, 87 operations on the supercharger housing and 47 operations on the propeller reduction gear; this does not include machining operations on the valves, crankshaft or the pistons.[60]

In another contrast with automobile practice, machining operations on some aero engine components removed substantial amounts of metal. Many components started out as heavy

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[57] 'New Heat-treatment Department at Bristol Aeroplane Co., Ltd.', *Machinery (London)*, Vol. 52, No. 1350, (August 25, 1938), p. 638; 'The Manufacture of High Performance Aero Engines', p. 744.

[58] 'The Manufacture of High Performance Aero Engines', p. 637.

[59] 'Wright Aero Will Expend $1,350,000 for Extensions to Factory and New Equipment', *Trade Winds*, Vol. 3, No. 7, (May 1937), p. 2.

[60] 'Wright Aero Will Expend $1,350,000 for Extensions to Factory and New Equipment', p. 2.

steel or aluminium forgings. Finished components often weighed just 25 to 30 per cent of the original heavy metal forging.[61] At the Bristol Aero Engine Department, as an example, a forged aluminium cylinder head would arrive at the factory weighing 49 lbs; 80 machining operations would reduce this to 15 lbs.[62] Similarly, the master connecting rod for the Bristol Pegasus engine went from 42 lbs to nine lbs 5 oz. during numerous machining operations involving successive work on a lathe, drilling machines, vertical and horizontal milling machines and grinding machines.[63] This amount of metal had to be removed slowly and carefully, requiring more time setting up machines than in manufacturing automobile engines.[64] Automobile parts, in contrast, could be machined at higher cutting speeds and with fewer cuts.[65] Making a connecting rod for an American Cadillac automobile involved 20 machining operations taking .2 man-hours, compared to 97 operations taking 11 man-hours to make a connecting rod for the liquid-cooled Allison engine.[66] Weight reduction through machining that was common in the aero engine industry, had never been tried in mass production.[67]

This example is indicative of another contrast with automobile practice. The machining operations in the manufacture of aero engine components in this period often involved operations on standard machine tools as opposed to the more specialized machine tools used in automobile engine production, but these machine tools were significantly different from the machine tools used in automobile factories. Removing the amount of metal typical in making aero engine components required machine tools that were larger and heavier than similar machine tools in the automobile industry.[68] The heavier weight provided the rigidity necessary for the finer tolerances and greater precision needed for aero engine components.[69]

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[61] Geschelin, Joseph: 'Conversion Almost Complete', *Automobile and Aviation Industries*, Vol. 87, No. 7, (October 1, 1942), p. 266.
[62] 'The Manufacture of High Performance Aero Engines', pp. 746-49.
[63] 'Machining Master Connecting Rods for Radial Aero Engines', *Machinery* (London), Vol. 49, No. 1253, (October 15, 1936), p. 61.
[64] 'Keeping the Record Straight', p. 19.
[65] 'Keeping the Record Straight', p. 19.
[66] 'Keeping the Record Straight', p. 19.
[67] Geschelin, 'Conversion Almost Complete', p. 226.
[68] 'Keeping the Record Straight', p. 19.
[69] 'Keeping the Record Straight', p. 19.

The greatest difference between automobile and aero engine practice was the far more rigorous system of quality control and inspection. With engine reliability not just a customer requirement but a vital marketing tool and potential source of reputational risk, it is not surprising that the aero engine manufacturers devoted far more effort to quality control than their automobile counterparts. Testing and inspection were continuous throughout the production process. Every engine component had to be made with extreme accuracy to exceptionally fine tolerances and finishes to ensure minimum weight with unquestioned reliability.[70] To this end the Bristol Engine Department and Wright Aeronautical maintained extensive engine inspection departments responsible for testing the quality of materials and the accuracy and condition of every part as it made its way through production. At the Bristol Engine Department in the mid-1930s, each engine and its component parts received over 30,000 separate inspections.[71] As an example, manufacturing a connecting rod for one type of large aero engine required 90 machining operations but 100 inspections, while manufacturing a connecting rod for an automobile engine required only 25 operations and 30 inspections.[72]

Quality control began with the arrival of raw materials and parts at the factory. Instead of taking a sample of molten metal from a cupola as in the automobile world, the Bristol Engine Department inspected and performed tests on every bar and ingot that came into the factory to ensure that all materials met with official Air Ministry standards. In the Production Section inspectors checked the first component from every operation, and in some cases every component, checking for dimensional accuracy with gauges that could measure to the ten thousandths of an inch and the quality of the finish. At the end of machining operations, every part received a final inspection before being passed, with inspectors checking for hardness and, for highly stressed components, using a Magna-Flux test machine to search for flaws in the material. The Engine Department maintained a detailed set of inspection instructions for every component, every assembly operation and the final assembled engine. As workers combined component parts into sub-assemblies, inspectors examined each sub-assembly for tolerances

[70] 'The "Bristol" Engine Inspection Department', *The "Bristol" Review*, Engine Issue No. 11, (November 1936), p. 30.
[71] 'The "Bristol" Engine Inspection Department', p. 30.
[72] Lilley, *Problems of Accelerating Aircraft Production in World War II*, p. 39.

and working order. Final assembly of the complete engine went through further inspections at every stage.[73]

Unlike automobile factories, aero engine factories did not use continuous moving assembly lines to progressively assemble engines. Assembly came, not during, but at the very end of machining operations, a completely different way of organizing production and the layout of the factory. The main activities in the aero engine factories were machining and finishing components. The Bristol Aeroplane Engine Department's operations in 1938 provides an example.[74] Final assembly of a Bristol aero engine was the responsibility of the Engine Building Department, which had three sections: Fitting, Sub-assembly and Erecting. Finished components arrived at the Fitting Section where they were test fitted, inspected, and then passed to the Sub-assembly Section which assembled the separate components into sub-assemblies such as the crankshaft and connecting rods, the complete cylinder and complete crankcase. To speed the process, Bristol had divided the staff in the Fitting and Sub-assembly Sections by component, so that there were teams who dealt only with the crankshaft, the crankcase, the cylinder, the supercharger and so on. The Sub-assembly Section passed the sub-assemblies to the Erecting Section for final assembly into a finished engine. Here the sub-assemblies were allocated to individual specialist assemblers who, working with one junior, would together assemble a complete engine. Neither the sub-assemblies, or the final engine assembly was done on a line, but on individual benches or stations with the engines mounted on erecting stands.

Every single aero engine went through a more rigorous testing procedure than that used for automobile engines. After thorough inspection following assembly an engine went to a test stand where it underwent an endurance test, running for two hours or more at normal power after which every engine, as opposed to one in ten, was completely stripped down to its individual parts and every part inspected for any defects. The engine was reassembled and put through a final test run for half an hour at full throttle. Additional tests determined the fuel and oil consumption and made sure that the power output conformed to standards for the specified

[73] 'The "Bristol" Engine Inspection Department', pp. 31-33; 'Inspection: Routine Employed by the Bristol Aeroplane Co., Ltd., to Ensure Quality and Accuracy', *The Automobile Engineer*, Vol. XXIII, No. 306, (May 1933), pp. 169-70.
[74] See 'New Engine Building Department', *Bristol Review* Engine Issue No. 13, (June 1938), pp. 35-37

type of engine.[75] Once all tests had been completed, there was one last full inspection and then the engine was ready for shipment. This was not a process that could be easily converted to automobile assembly line practice.

The differences between manufacturing automobile and aero engines and the greater complexity of aero engine production, outlined in this chapter for the first time, had significant implications for shifting to building aero engines in quantity. In the first place, the idea that the automobile industry and its existing factories and machine tools could be easily converted to aero engine production, a not uncommon view in the pre-war years, proved to be an illusion.[76] As an example, the Studebaker Corporation, which built the Wright Cyclone 9 engine under license during the war, found that only 414 of the more than 3,000 machine tools in its automobile factory could be adapted to build aero engines.[77] The second point is that the mass production, assembly-line oriented methods of automobile production were ill-suited to aero engine production. The third point is that replicating the existing methods of aero engine production to increase output would have required an enormous number of standard machine tools and, more importantly, thousands more skilled operators. If neither machine tools nor skilled operators were available, what were the alternatives? This would be the challenge the aero engine manufacturers would confront when faced with demands for undreamed of numbers of engines in wartime.

The Aero Engine Manufacturing Industry in the Interwar Period

Who built high-performance aero engines in the interwar years? A surprisingly small number of companies, nationally and internationally. The industry was highly capital-intensive and required a level of specialized engineering and production knowledge that was difficult to replicate. The financial risks facing an aero engine manufacturer were daunting. This was due to 'the enormous cost of developing an engine, the almost catastrophic consequences if the engine fails to be

[75] 'The "Bristol" Engine Inspection Department', pp. 30-35; Swan, Andrew: *Handbook of Aeronautics*, Volume II: *Aero-engine Design and Practice*, (London, 1938), pp. 462-68.
[76] Hornby, *Factories and Plant*, p. 253.
[77] Klein, *Call to Arms*, p. 388.

accepted, and the relatively small production orders in peace time, if the engine is successful.'[78] Given the high costs of entry into the industry, the huge financial risks from failure to secure orders, and the low level of demand for high performance engines in peace time, it is not surprising that there were few aero engine firms manufacturing high-performance engines and that the industry structure was something of a natural oligopoly, although highly competitive. Airframe designers typically chose a specific model of aero engine to power an airplane and because engines were not interchangeable, once the airframe designer had chosen the specific engine model the aero engine manufacture received an effective monopoly on providing engines for that airplane.[79] The winning aero engine manufacturer would receive what amounted to a guaranteed revenue stream for as long as that airplane was in service, hence the intensity of competition.

It is important to realize just how small this industry was prior to the beginning of rearmament. In 1936, the entire British aero engine sector had 14,291 employees, and the entire British aircraft industry had just 36,000 employees.[80] In contrast, the Austin Motor Company had over 19,000 employees in 1935.[81] During 1936 the British aero engine manufacturers delivered 2,248 engines to the Royal Air Force.[82] The following year, with rearmament underway, the sector delivered 3,440 engines to the RAF and employed 16,936 people.[83] In comparison, that same year the British automobile industry produced 379,310 passenger cars and 113,946 commercial vehicles.[84] The American aviation industry was similarly miniscule in size. In 1937, the entire industry-- airframe, engine and parts manufacturers --employed 30,384 people, well below 1% of total American manufacturing employment.[85] Employment in the aero engine sector did not go over 16,000 until February 1940.[86] During 1937, the American aero engine companies delivered 1,366 aero engines of greater than 500 hp to the military and produced an additional

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[78] Banks, F.R.: 'The Art of the Aviation Engine', *Journal of the Royal Aeronautical Society*, Vol. 52, Issue 453, (September 1948), p. 531.
[79] Eltscher and Young, *Curtiss-Wright: Greatness and Decline*, p. 70.
[80] Ritchie, *Industry and Air Power*, pp. 90, 138.
[81] 'Austin Production Methods', *The Automobile Engineer*, Vol. XXV, No.329, (February 1935), p. 43.
[82] Ritchie, *Industry and Air Power*, p. 138.
[83] Ritchie, *Industry and Air Power*, p. 138.
[84] https://en.wikipedia.org/wiki/Automobile_industry_in_the_United_Kingdom, accessed 18/10/2017.
[85] Modley, Rudolf, ed.: *Aviation Facts and Figures 1945*, (New York, 1945), p. 18.
[86] *Aviation Facts and Figures 1945*, p. 20.

2,161 in the same class for the commercial market.[87] That year the Ford Motor Company built 942,005 vehicles.[88]

Despite fluctuations in sales to its military and commercial airline customers, during the interwar years the aero engine manufacturing industry was decidedly military, not civilian, in its orientation.[89] All major piston engines in use in civilian airliners during the interwar period began as military engines.[90] In the absence of a vibrant commercial airline market during the interwar period, few aero engine manufacturers could take on the financial risk of developing an engine purely for the commercial market. It could take as long as four or five years to bring an engine from a prototype to full production.[91] Governments were willing to support the technical development of aero engines through research and development funds and military orders.[92] As a result, nearly every high performance aero engine 'in its prototype form and in the early production "Marks", generally owes its existence to the military requirements of the particular country in which it is built.'[93] The military provided the funding for aero engine development and military orders gave the aero engine manufacturers the opportunity to gain experience and obtain greater reliability with their engines that would make them suitable for the commercial airline market.[94]

With large capital requirements, the need for specialist knowledge, the heavy financial risks involved, and the limited demand for aero engines, there were never as many aero engine manufacturers as there were airframe companies. In Britain during the interwar years, the Air Ministry supported fourteen airframe manufacturers but only four aero engine firms: Armstrong Siddeley Motors, Napier, Rolls-Royce and the Bristol Aeroplane Company, but relied mostly on Bristol and Rolls-Royce for military aero engines.[95] Bristol was the dominant firm in the production of air-cooled radial engines, while Rolls-Royce's expertise was in the production of

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[87] *Aircraft Yearbook for 1938*, (New York, NY, 1938), p. 446.
[88] https://en.wikipedia.org/wiki/U.S._Automobile_Production_Figures, accessed 18/10/2017.
[89] Edgerton, *England and the Aeroplane*, pp. 32-33; Vander Meulen, *The Politics of Aircraft*, pp. 3-4.
[90] Banks, 'The Art of the Aviation Engine', p.532; Schlaifer, Robert: *Development of Aero engines*, (Cambridge, MA, 1950), p.12.
[91] Banks, 'The Art of the Aviation Engine', p. 534.
[92] Banks, 'The Art of the Aviation Engine', p. 532.
[93] Banks, 'The Art of the Aviation Engine', p. 531.
[94] Banks, 'The Art of the Aviation Engine', p. 532.
[95] Ritchie, *Industry and Air Power,* pp. 7, 18-20.

liquid-cooled inline engines. Similarly, the American Army Air Corps and U.S. Navy used around sixteen airframe manufacturers and three aero engine firms, none of which was particularly large.[96] Two companies, the Pratt & Whitney Company and Wright Aeronautical Corporation, dominated the manufacture of high-performance aero engines. As the American military and the commercial airlines had, by the 1930s, adopted the air-cooled radial engine as their preferred engine type, Pratt & Whitney and Wright Aeronautical both concentrated their efforts in radial engine technology and production.

France had four firms building engines in the greater than 500 hp class, Italy also had four firms, while Germany had three and Japan two.[97] Only a handful of aero engine manufacturers could be considered real leaders in the field, based on the widespread sale of their engines to many airframe manufacturers and to their granting licenses for production to countries who lacked the resources to develop their own indigenous industry. In the mid-1930's, this list would have included Rolls-Royce and Bristol Aeroplane in Britain, Pratt & Whitney and Wright Aeronautical in America and Gnôme-Rhône and Hispano-Suiza in France.

Bristol and Wright

In this study I am therefore examining two of the most important engine firms in the world, the Bristol Aeroplane Company and Wright Aeronautical. Both firms could trace their origins to the early years of flight.

Founded in 1910, the Bristol Aeroplane Company built small numbers of airplanes and ran flying schools in the years before World War I.[98] During the war the Company built several thousand Bristol F.2B two-seat fighters for the Royal Flying Corps and the Royal Air Force. During the interwar years Bristol built a range of aircraft for the Royal Air Force and for export markets.[99] Bristol entered the aero engine field in 1920 when, with encouragement from the Air Ministry, it purchased the Cosmos Engineering Company, gaining the services of Roy Fedden, who would become Bristol's chief engine designer, and the design for the Jupiter nine-cylinder air-cooled

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[96] This list is taken from Mingos, Howard: *Aircraft Yearbook for 1938*, (New York, 1938)
[97] Gray, C.G: *Jane's All the World's Aircraft for 1936*, (London, 1936)
[98] Barnes, C.H.: *Bristol Aircraft Since 1910*, 3rd Edition, (London, 1988), pp. 13-24.
[99] Barnes, *Bristol Aircraft Since 1910*, pp. 28-34.

engine.[100] This became the Bristol Aero Engine Department. The Jupiter was an outstanding success and saw wide service in military and commercial aircraft around the world, with several European countries building the Jupiter under license. In the late 1920s, Bristol introduced the nine-cylinder Mercury engine, which by 1935 could offer 825 hp. The larger nine-cylinder Bristol Pegasus, came out in the early 1930s, and by 1936 had reached 980 hp. These two engines were the backbone of Bristol's engine business during the 1930s and, like the Jupiter saw widespread service with the Royal Air Force and other military services in Europe and the commercial airlines.[101]

The Wright Aeronautical Corporation could trace its lineage back to the company Wilbur and Orville Wright founded in 1909.[102] Merged with the Glenn L. Martin Company in 1916, during World War I the Wright-Martin Company built small numbers of Martin aircraft but thousands of Hispano-Suiza liquid-cooled engines for the U.S. Army Air Service and the Allies.[103] Reorganized as the Wright Aeronautical Corporation in 1919, the Company began working on air-cooled radial engines at the U.S. Navy's request. In 1925 Wright introduced the J-5 Whirlwind of 220 hp. This engine gained fame powering Charles Lindbergh's 'Spirit of St. Louis' on his historic New York to Paris flight. In the late 1920s, Wright began developing a more powerful nine-cylinder, air-cooled radial engine, the Wright Cyclone. Starting at 575 hp, by 1939 Wright had taken the power rating of the Cyclone 9 to 1,200 hp.[104] The Whirlwind and the Cyclone 9 were Wright's mainstays during the 1930s as it competed fiercely with Pratt & Whitney for military and commercial orders. Following the merger of the Curtiss and Wright groups in 1929, Wright built engines for many of the aircraft of its sister company, the Curtiss Aeroplane and Motor Company.[105] As the world's military air services began to rearm in the mid-1930's, and with the growth of commercial airlines, Wright aero engines saw widespread service around the world.[106]

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[100] Lumsden, Alec: *British Piston Aero-Engines and Their Aircraft*, reprint of 1994 edition, (Ramsbury, Marlborough, UK, 2003), p. 93.
[101] Lumsden, pp. 103-11. For more background on the Bristol and Wright engines built during the war, see Appendix II in this dissertation, on p. 311.
[102] Eltscher and Young, *Curtiss-Wright: Greatness and Decline*, p. 43.
[103] Eltscher and Young, *Curtiss-Wright: Greatness and Decline*, pp. 44-47.
[104] Eltscher and Young, *Curtiss-Wright: Greatness and Decline*, pp. 47-52.
[105] Eltscher and Young, *Curtiss-Wright: Greatness and Decline*, pp. 69-74.
[106] Eltscher and Young, *Curtiss-Wright: Greatness and Decline*, pp. 71-79, 85-88.

In many ways, in the interwar years Bristol and Wright were comparable companies. They both concentrated on building air-cooled, radial aero engines and their primary customers were military, not commercial. Their main products in the pre-war period were nine-cylinder aero engines, the Mercury and Pegasus at Bristol and the Cyclone 9 at Wright, all in the 850-1,200 HP class. They had a work force of several thousand employees, small factories and built small lots of engines to specific orders using standard, universal machine tools and highly skilled machine operators. Neither firm produced more than a hundred engines a month nor had any experience with large-scale production. For example, during 1935, the Bristol Aeroplane Company's Engine Department produced 725 complete engines and the equivalent of 230 engines in the form of spare parts.[107] This works out to an average production of 18 engines per week. In comparison, during the U.S. Government's Fiscal Year 1935 (July 1, 1934 to June 30, 1935), Wright delivered 175 Cyclone 9 engines to the Army Air Corps and 84 Cyclone 9 engines to the U.S. Navy.[108] During Fiscal Year 1936 (July 1, 1935 to June 30, 1936) Wright received contracts or delivered 737 engines to the Army Air Corps and the Navy.[109] Engine production in the period prior to rearmament and war conforms to what Philip Scranton has classified as batch production, at a rate of 2-3 per day.

Neither Bristol nor Wright Aeronautical built engines for inventory but only to specific orders from military and civil customers. They also built many more models of engines to cater for the different requirements of their military and commercial customers. Whereas the Ford Motor Company effectively produced only two models of the Ford V-8 from 1932 to 1939, there were over a dozen different models of the Bristol Mercury and Pegasus engines and the Wright Cyclone during the same period. Engine orders depended on the airframe manufacturer selecting an engine with the required horsepower, so that the aero engine manufacturers had to provide a range of horsepower in their engine models to meet a wider range of need. Customers ordered specific models of the main Bristol and Wright aero engines, for example a Wright Cyclone 9-F-

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[107] Bristol Engine Department Engine Delivery Chart for 1935, Rolls-Royce Heritage Trust Collection.
[108] *The Aircraft Yearbook for 1936*, (New York, 1936), pp. 469-470
[109] *The Aircraft Yearbook for 1936*, (New York, 1936), pp. 469-470; *The Aircraft Yearbook for 1937*, (New York, 1937), pp. 456-57.

53 or -G-2 or a Bristol Pegasus Mk.III, which meant that it was difficult for the companies to standardize on one engine model.

At this level of differentiated demand, there was no need, and no financial incentive, to make the heavy investment in the specialized equipment, conveyor systems and assembly lines necessary for mass production. When in 1936 Bristol wanted to expand production of its Mercury and Pegasus engines, the company built a new single-storey factory building alongside its existing works at Filton and increased the number of employees, adding 200,000 square feet of space and taking total employment to 2,800.[110] In total, the Bristol Aero Engine Department occupied around 460,000 square feet.[111] In the new factory building the Engine Department appears to have made some adjustments to its production methods, grouping machine tools by type of operation and organizing a modified form of line production for certain engine components.[112] In contrast to the automobile industry's methods of mass production, Bristol's Engine Department did not use specialized machine tools, purchasing instead standardized universal models that could be used to perform several different operations without the need for elaborate jigs and fixtures.[113] This flexibility was necessary when producing small batches of different models of engines at the same time. With the goal of maximizing quality and reliability, however, the Engine Department had an aim similar to the automobile industry to achieve the highest level of accuracy possible in order to have truly interchangeable parts and to reduce the need and cost of hand labour involved in 'fitting' parts– making adjustments by hand to ensure a proper fit – once completed.[114]

The layout of Wright Aeronautical's factory in Paterson, New Jersey, where Wright built all its engines for most of the 1930s, was adequate for batch production.[115] Wright's factory was a four-story reinforced concrete building built in 1916, with separate departments on three floors, each department building different engine components. The assembly building stood next door to the main building, but the Wright foundry for casting aluminium and steel components

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[110] 'The Manufacture of High Performance Aero Engines', p. 739.
[111] NA, AVIA 10/267, See undated note 'Engine Factory Floorspace'.
[112] 'The Manufacture of High Performance Aero Engines', p. 742.
[113] 'The Manufacture of High Performance Aero Engines', p. 742.
[114] 'The Manufacture of "Bristol" Aero Engine Components', p. 23.
[115] Faurote, Fay Leone: 'Layout of a Manufacturing Plant', *The Iron Age*, (December 26, 1929), p. 1730.

was located nearby, and not next to the main factory. The main factory had no conveyor arrangements to move parts to the engine assembly building for final assembly or completed engines to the production test building next door for endurance tests. Like Bristol, Wright preferred standard universal machine tools over specialized tools to give greater flexibility as designs and models changed over time.[116] In 1937 the Wright factory had a capacity of producing around 200 engines a month, though actual production was well below this level.[117] By 1936, the Wright factory complex and foundry occupied some 675,000 square feet of floor space.[118] In 1937, to accommodate an expected increase in production of Cyclone engines, Wright announced a $1,350,000 expansion keeping to its practice of using four-story buildings with a new wing adding another 125,000 square feet of space.[119]

During the interwar years, the Bristol Engine Department and Wright Aeronautical relied heavily on skilled labour. Maintaining the highest level of dimensional accuracy and finish required a high level of skill and experience not only in machining operations, but also in inspection, testing and final assembly of aero engines. Contemporary articles featuring aero engine production at Bristol and Wright describe a labour-intensive process using skilled machinists operating a variety of standard universal machine tools. Photographs from the period typically show individual machinists conducting a specific operation on a single machine tool and relatively few photographs of machines carrying out the same operation on multiple work pieces at the same time. The Harvard Business School study of aircraft production during World War II characterized the pre-war aero engine factories as 'job shops', 'geared to intermittent production in lots which, together with the equipment arrangement, caused the flow of production to be sluggish.'[120] While length of service does not necessarily correlate to skill level, at the end of 1935 43% of Wright Aeronautical's 2,100 employees had been with the company for five years or

[116] 'Wright Aero Will Expend $1,350,000 for Extensions to Factory and New Equipment', *Trade Winds*, Vol. Three, No. Seven, (May 1937), p. 2.
[117] 'Visit of Messrs. Evans & Mansell to U.S.A. in May-June 1937', Section B (3), p. 9,
[118] 'Over 900 Wright Employees Are Cited For Long Service; 52 Receive 15-year Awards', *Trade Winds*, Vol. Two, No. Seven, (October-November 1935), p. 2.
[119] 'Wright Aero Will Expend $1,350,000 for Extensions to Factory and New Equipment', *Trade Winds*, Vol. Three, No. Seven, (May 1937), p. 2.
[120] Lilley, *Problems of Accelerating Aircraft Production During World War II*, p. 40.

more, including 239 employees with more than ten years of service.[121] While precise numbers are difficult to find, it is likely that Wright Aeronautical, and the Bristol Engine Department as well, had only small numbers of managers and engineers running the day to day operations in the factories and working in the experimental departments developing and testing new models of engines. While direct comparisons of pre-war labour productivity at Bristol and Wright are difficult, looking at the total number of workers per engine built per month shows that Wright was roughly twice as productive as Bristol, requiring 16 total workers per engine as opposed to 35 total workers per engine at Bristol.[122] Labour productivity at Wright may actually have been even greater as Wright was less reliant on sub-contracting than Bristol.

The Bristol Aeroplane Company had extensive experience in licensed production, Wright Aeronautical less so. During the 1920s and 1930s, Bristol had as many as fourteen licensees across Europe and in Japan building the Bristol Jupiter, Mercury and Pegasus engines. Bristol maintained a small department, the Foreign License Office, to manage its relations with its licensees. The office's functions including providing information on manufacturing methods and machine tools, complete drawings and specifications, and experienced Bristol staff to help set up production.[123] This gave the Bristol Engine Department considerable experience in helping other factories master the methods of Bristol engine production.

The two companies differed in their reliance on sub-contractors. The Bristol Engine Department appears to have relied on several smaller British engineering firms for forged and cast engine components, while Wright Aeronautical chose to build 90% of its engine within its own factory as it preferred to exercise rigid control over quality.[124] Both companies, however, purchased accessories like carburettors, magnetos, valves, piston rings and other small

[121] 'Over 900 Wright Employees Are Cited For Long Service; 52 Receive 15-year Awards', *Trade Winds*, Vol. Two, No. Seven, (October-November 1935), p. 2.
[122] Lilley, *Problems of Accelerating Aircraft Production During World War II*, p. 12; Manpower Office, Management Control, Air Technical Service Command, Army Air Forces: *Labor Statistics for the Aircraft Industry*, November 1944-July 1945, File 218.6-7 Labor Statistics, AFHRA; Mr. Haag to Secretary Morgenthau, 'Employment in the Aviation Manufacturing Industry', January 14, 1941, Diaries of Henry Morgenthau, Vol. 347- January 13-14, 1941, FDR Library Digital Collections;; Bristol Aeroplane Company, Summary of All Employees for 1937 and 1938, copy in the archives of Aerospace Bristol Museum.
[123] Heaven, John: *Bristol Piston Engines Since 1914*, copy in the possession of the Rolls-Royce Heritage Trust, Filton.
[124] 'Over 36,500 Operations are Required in the Production of the Wright Cyclone', *Trade Winds*, Vol. Two, No. Six, (September 1935), p. 2.

components from outside vendors. During World War II, arranging successful license production and building a reliable chain of sub-contractors would become critical factors in expanding aero engine production.

This, then, was the character of the aero engine industry for much of the interwar period, an industry that was highly concentrated, fiercely competitive, heavily reliant on government support and government contracts, building comparatively small numbers of aero engines with a very small number of skilled workers using universal machine tools and working to exceptionally precise standards. It was not, at first glance, an industry that seemed capable of rapid expansion into quantity production. Factory size and plant layout, work processes and types of machine tools and skill levels of employees were all suited to batch production as this fitted the characteristics of aero engines and level of demand, building small batches of engines to orders from military and commercial airline customers. When demand increased rapidly with government orders as rearmament gathered pace, Bristol and Wright Aeronautical had to adapt all these factors– factory size and layout, work processes and machine tools, worker skill levels – to build production to unprecedented levels. During the war, the British and American aero engine manufacturers had to undertake major changes in process and production techniques.[125]

What compounded these challenges was the dramatic transformation in engine power that took place during the 1930s. The incessant demand for quality– improvements in performance and reliability –from commercial and military customers had, by the end of the decade, led to the development of aero engines with significantly greater power. The methods used to increase aero engine power, however, put even greater demands on aero engine designers and production engineers in their struggle to obtain maximum power output for minimum weight. As aero engines became more complicated, with more parts and using stronger materials, their production became more challenging just as demand for greater quantities began to accelerate.

[125] Lilley, *Problems of Accelerating Aircraft Production During World War II*, p. 53.

The State of the Art in 1939: The Transformation in Engine Power

The linkage between the transformation of aero engine power during the 1930s, the large more powerful double-row aero engines that entered service at the end of the decade and the implications this had for building these engines in quantity has not been described before in the literature on World War II production. During the 1930s, the aero engine manufacturers nearly quadrupled the power output of the air-cooled radial aero engine, an astonishing technical achievement that has received little notice. Continued development had pushed the power output of the nine-cylinder radial air-cooled airplane engine from around 575 hp. at the beginning of the 1930s to 1,000 hp. or greater by the end of the decade. At the same time new engines appeared which produced 2000 hp. By 1939, airplane engine designers and manufacturers had addressed many of the technical problems limiting the power output, if not completely solving them. Piston aero engine technology had reached something of a plateau by the end of the decade.[126] Engine design, construction, and manufacturing processes had kept pace with the new high octane aviation fuels and superchargers but increased power required stronger engine components to cope with the greater pressures and higher temperatures in the cylinder and increased stress on the moving components of the engine. As Harry Ricardo observed, 'it is probably safe to say that within a period of ten years of intensive development, almost every single stressed part of every aero-engine in service has been revised, not once but many times.'[127] The quality of materials in other aero engine components steadily improved as well, with the introduction of new steel alloys for crankcases and connecting rods with elements of nickel, chromium and molybdenum and hardening through the nitriding process resulting in a doubling of tensile strength.[128] The most important development regarding materials was improvement in precision engineering. Roy Fedden, who ran the Bristol Engine Department

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[126] Schlaifer, *The Development of Piston Aero Engines*, p. 150.

[127] Ricardo, *The High-Speed Internal Combustion Engine*, 4th Ed., p. 303.

[128] Gough, H.J.: 'Materials of Aircraft Construction', Twenty-Sixth Wilbur Wright Memorial Lecture, *Royal Aeronautical Society Journal*, Vol. XLII, (October 1938), p. 941; Fedden, A.H. Roy: 'Aircraft Power Plant Past and Future', Thirty-Second Wilbur Wright Memorial Lecture, *Royal Aeronautical Society Journal*, Vol. XLVIII, (1944), pp. 419-29.

during the 1930s and into World War II, commented that 'the most important factor of all, however, in connection with aero engine materials has been, and still is, the improvement in technique of fabrication by the introduction of high precision methods.'[129]

One straightforward method of increasing engine power that came into use in the mid-1930s was to increase the number of cylinders in the engine. With the knowledge that a large number of small cylinders was more efficient than a small number of large cylinders, the aero engine manufacturers began moving to the double-row air-cooled radial engine, initially with two rows of seven cylinders and later two rows of nine cylinders.[130] These double-row air-cooled radial aero engines produced around 1,500 hp, with 2,000 hp. air-cooled radial engines on the horizon. Bristol and Wright were in the forefront of this development. By the late 1930s, both companies had 14-cylinder engines nearing production—the Hercules for Bristol and the Cyclone 14 for Wright—with the early marks of the Hercules offering 1,375 hp and the Cyclone 14 beginning at 1,600 hp. Both had even larger 18-cylinder engines in development targeting the 2,000 hp range, the Bristol Centaurus and the Wright Cyclone 18.

Beginning in the early 1930s, however, Bristol had chosen a different technological path from Wright, shifting from the standard poppet-valves to the sleeve-valve. Instead of using poppet-valves to introduce the fuel-air mixture into the cylinder and expel the exhaust from combustion, a sleeve-valve aero engine used a cylindrical sleeve in the cylinder, placed between the side of the cylinder barrel and the piston, with ports cut in the sides of the sleeve. The sleeve-valve surrounded the piston and moved up and down within the cylinder barrel in an elliptical, circular motion to enable the ports in the sleeve to line up with ports cut out of the cylinder barrel to allow the intake of the fuel-air mixture and expel the exhaust.[131] With no hot exhaust valve to trigger detonation, the premature combustion of the fuel-air mixture, a sleeve-valve engine could run at a higher compression ratio giving more power.[132] By doing away with the poppet-valves and their associated parts, the sleeve-valve engine reduced the risk of failure of any of these parts

[129] Fedden, 'Aircraft Power Plant Past and Future', p. 420.
[130] Fedden, 'Aircraft Powerplant Trends', p. 457; Taylor, C. Fayette: 'Engine Design in 1936', *Aviation*, Vol. 36, No. 1, (January 1937), p. 21.
[131] Pye, *The Aero-Engine*, pp. 95-96.
[132] Pye, *The Aero-Engine*, p. 96.

and, in theory, simplified manufacturing.[133] Having proved the concept in the earlier Perseus nine-cylinder sleeve-valve engine, Bristol chose the sleeve-valve for the Hercules, Bristol's first large double-row, fourteen-cylinder air-cooled radial engine, and the 18-cylinder Centaurus. This was a major change, but one not followed by US manufacturers, who stuck, as did generally Rolls-Royce, to poppet valves.

These large high-power, double-row radial engines were far more complex machines than the older nine-cylinder engines. Doubling the number of cylinders, adding single and two-speed superchargers and reduction gears of various settings had all added to this complexity. The Cyclone 14, for example, contained 8,500 parts compared to the 2,946 parts in the Cyclone 9. Building the larger Cyclone 14 engine required more than 80,000 machining operations and 50,000 inspections to ensure quality.[134] The even larger 18-cylinder engines had upwards of 13,000 parts.

Moving from around 3,000 parts in a nine-cylinder engine to 8,000 parts in a 14-cylinder engine required far more machining operations, more time in heat treatment, many more machine tools, many more machine operators and more factory floor space to build. Similarly, the need to inspect and test every part, put 8,000 components together into a finished engine and dis-assemble the engine after final testing placed heavy demands on the inspection and engine assembly departments.

During 1939, Wright built only 163 Cyclone 14 engines and three of the larger Cyclone 18 engines while production of the Bristol Hercules was also still in its relative infancy.[135] Soon the two companies would face Irving Holley's 'quantity versus quality' dilemma of mass production.[136] With the onset of war, the British Royal Air Force and the American Army Air Force would insist on quantity production of all these aero engines in numbers undreamed of.

It was unlikely that the pre-war production methods employed at Bristol and Wright could have been replicated on a scale that would have produced the quantity of aero engines needed in the time required, although both companies would initially employ these methods to ramp up

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[133] Pye, *The Aero-Engine*, p. 98.
[134] '30,000 Workers in 6 Wright Plants to Build 3,780,000 HP Monthly', *Trade Winds*, (April 1941), p.4.
[135] Lilley, *Problems of Accelerating Aircraft Production*, Table 18, p.105.
[136] Holley, *Buying Aircraft,* p. 512.

production in the first years of the war. With the start of the war competition for machine tools and skilled workers from other armament industries and the military services made it extremely unlikely that the aero engine manufacturers could have obtained the machine tools and workers they would have needed to greatly expand batch production methods. New production methods had to be devised that would meet the need for increasing quantity but with the flexibility to respond to the design changes that would come from the drive for improving quality, what the Harvard Business School study termed 'a revolutionary approach to the basic methods of production.'[137] How Bristol and Wright responded to this challenge and made the transition from batch to quantity production is the subject of the following chapters. The next chapter is devoted to Bristol's nine-cylinder Pegasus and Mercury, and the following one to the 14-cylinder Hercules.

[137] Lilley, *Problems of Accelerating Aircraft Production During World War II*, p. 39.

Chapter Two: Building the Bristol Mercury and Pegasus

Introduction

This chapter offers the first comprehensive account of how the Bristol Aeroplane Company and a select group of British automobile firms operating the shadow factories rapidly shifted to large-scale production of the Bristol Mercury and Pegasus engines. As we shall see, the shadow factories achieved a three-fold increase in monthly output. The factories were equipped on the model of the Bristol parent, but they doubled the number of workers and employed them in two shifts per day, while adding, at most factories, only a small number of standard machine tools. The factories may also have shifted to some form of flow production. Between the summer of 1939 and the summer of 1940 there was a doubling in labour productivity despite a decline in the percentage of skilled workers at the factories.

This chapter will show that the shadow factories were intended to supplement Bristol's own output at a level that was not significantly greater than Bristol's relatively low pre-war production rate. These first shadow factories were small in size and located close to their parent firms for easier access to labour and management. The factories operated with an all-male labour force in a single shift, using the production methods Bristol employed for batch production and British-made, standard machine tools. As originally conceived, the shadow factory scheme was set up to meet the requirements of the Government's rearmament program and to provide additional production capacity in time of emergency. The underlying premise was that in the event of war the automobile firms could rapidly convert their main automobile factories to aero engine production.

This chapter will provide a detailed description of the methods used to build Mercury and Pegasus and evidence that the transition to building these engines in greater quantities at the shadow factories came through scaling up these methods. The central argument of this chapter is that to meet wartime demand, there were no feasible alternatives except adding more workers and more machine tools. Contrary to initial hopes, the works of the automobile firms themselves could not be rapidly converted to aero engine production and were never used for this. By 1939 the Air Ministry had learnt that aero-engines could only be made in specialized plants.

There are large gaps in the documentation relating to the first shadow factories. There are archival records on the formation of the shadow scheme, the allocation of components among Bristol and the five participating automobile firms and information on the decision to adopt Bristol's pre-war production methods. These areas have been well-covered in the literature, although only Hornby notes the implications of the inability to convert the automobile factories to aero engine production. There is far less information available about the process of shifting from batch production rates to large-scale production during 1939-1940. The minutes of meetings of the Air Ministry's Air Council Committee on Supply, and later the Air Supply Board, do provide a record of decisions to increase Mercury and Pegasus production and provide information on allocations for new machine tools and building expansions to support increases in production, but say nothing about how this was to be achieved.

Three key sources are the Bristol Aeroplane Company's study 'History of the Production of Bristol Aero Engines by the Shadow Industry' which documents Bristol's assistance to the shadow factories, and two post-war narratives on British piston engine production, 'Aero Engine Production Expansion of Capacity 1935-1945' and 'Reciprocating Aero Engine & Engine Accessories Production Programmes'. Bristol's history does provide details of the technical support Bristol provided but does not make clear how production methods changed, if at all. The post-war narratives provide information on output and expenditures but also say little about production methods. Following the outbreak of the war, contemporary industry journals do not describe production at the first shadow factories, perhaps a confirmation that production methods remained unchanged from previous pre-war descriptions.

Organizing Production

The decision to create a shadow industry for aero engines came from the realization that the aero-engine manufacturers alone could not build the quantity of engines needed for the

Government's planned aircraft rearmament programme within the required time frame.[1] In particular there was insufficient capacity to produce the number of Mercury and Pegasus engines the Royal Air Force needed.[2] The solution was to enlist Britain's automobile firms to obtain additional productive capacity to build these engines. The first aero engine shadow scheme was thus set up to build Bristol engines exclusively. The Air Ministry created a structure to transfer production knowledge from Bristol to participating automobile firms who would collectively manufacture selected Bristol engines and, ideally, build the experience necessary to convert their parent automobile factories to full aero engine production in time of war. The potential to convert the parent factories to airframe and aero engine production, 'thus providing increased productive capacity, rapidly available, over and above that obtainable from the regular aircraft and engine manufacturers', was a critical aspect of the shadow factory scheme.[3]

The scheme was launched in 1936, with the goal of providing the Royal Air Force with 4,000 Bristol Mercury engines by April 1939.[4] Construction of six shadow factories for aero engines began in October 1936. Most were completed a year later.

The Air Ministry invited the Austin Motor Company, the Daimler Motor Company, Rootes Securities, the Rover Company and the Standard Motor Company to participate. Bristol and the automobile firms proposed that each company's factory build separate components and sub-assemblies, but not complete engines, as the most economic and efficient means of achieving the Air Ministry's target on time.[5] Final assembly would be done at one factory in the group and at Bristol's own aero engine works. This created a sole source supply chain, with each factory acting as the only source of the particular engine component or sub-assembly. While this form of supply chain was vulnerable to disruption from production delays or air attack at any one of the factories in the system, the Air Ministry reluctantly agreed to this structure.[6] As a result, the first shadow factories became specialized makers of aero engine components.

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[1] Ritchie, *Industry and Air Power*, p. 57.
[2] Hornby, *Factories and Plant*, p. 255.
[3] "The Government Aircraft "Shadow" Scheme', *Machinery (London)*, vol. 51, No. 1308, (November 4, 1937), p. 133.
[4] Ritchie, *Industry and Air Power*, p. 59.
[5] Ritchie, *Industry and Air Power*, p. 59.
[6] Thoms, *War, Industry and Society*, p. 4.

Bristol divided production roughly equally between the automobile firms, based on total machining hours per component,. The original production assignments were as follows:

Austin Motors-Birmingham		
Crankshaft and reduction gear	426 hours	
Engine assembly and test	250 hours	
		Total: 676 hours
Daimler-Coventry		
Crankcase front cover and oil sump	299 hours	
Rocker Gear	430 hours	
		Total: 729 hours
Rootes-Coventry		
Blower, crankcase rear cover	620 hours	
Petrol pump	80 hours	
		Total: 700 hours
Rover-Birmingham		
Connecting rods, pistons	632 hours	
Cam and tappet gear	83 hours	
		Total: 715 hours
Standard Motors-Coventry		
Cylinders and sub-assembly		Total: 676 hours
Bristol Aeroplane-Filton		
Engine assembly and testing		Total: 250 hours[7]

The Air Ministry wanted the firms involved to plan the floor space in their factories on the basis of making 50 sets of components per week on a single day shift, to produce a total of 50 complete engines per week.[8] Although this required more machine tools and thus more floor space than double-shifting, this was acceptable to the Air Ministry. However, the Ministry limited the size of the factories to meeting the existing aircraft programmes, assuming that room for

[7] NA, AIR 2/2577, Notes on a meeting of the Aero Engine Committee at the offices of the Standard Motor Company, 8th October 1936.
[8] NA, AIR 2/17 38, H.A.P. Disney, Director of Aeronautical Production, to Sir Hubert Austin, 3 July 1936.

expansion would not be necessary as the plan was to convert the parent automobile factories in an emergency.[9]

The Factories

There are three key elements that characterize the first shadow factories: their location, size, and design.

In locating the new factories, the Air Ministry had to strike a balance between risk and practicality. In 1934 the Air Council, the Royal Air Force's governing body, divided the country into areas deemed relatively safe from air attack, west of a line drawn from Weston-Super-Mare in Somerset to Haltwhistle in Northumberland, and dangerous areas in the southeast, south and eastern areas of Britain.[10] Birmingham and Coventry, centres of the motor industry in Britain and the planned location for the five factories the automobile firms would manage, fell in between, but were deemed 'unsafe' areas.[11] Nevertheless, the need for the factories to have ready access to management and labour from their parent firms was the paramount concern. The Air Ministry also recognized that in time of war converting the parent factories to aero-engine production would require the closest possible coordination with their shadow factories, an additional reason to have the factories close by.[12] Thus it was that the automobile shadow factories were located in Birmingham and Coventry, with the Bristol shadow factory added to the Bristol Company's existing factory at Filton outside of Bristol. With the exception of the Rover factory, the factories were adjacent to their parent works. Because of limited space at Rover's Tyseley works in Birmingham, the Air Ministry selected a site at Acocks Green, a little over a mile away. Countering the argument that a bomber aiming at one factory could hardly miss hitting another, a journalist reported that the authorities 'are satisfied that the propinquity of the factories to each other is

[9] H.A.P. Disney, Director of Aeronautical Production, to Sir Hubert Austin, 3 July 1936.
[10] Hornby, *Factories and Plant*, p.286.
[11] Hornby, *Factories and Plant*, p.286.
[12] NA, AIR 19/5, See minute from the A.M.S.O to the Secretary of State for AIR, 20 April 1936.

not dangerous, and indeed argues that the factories are extremely difficult to identify amid the sprawling factories of the Midlands.'[13]

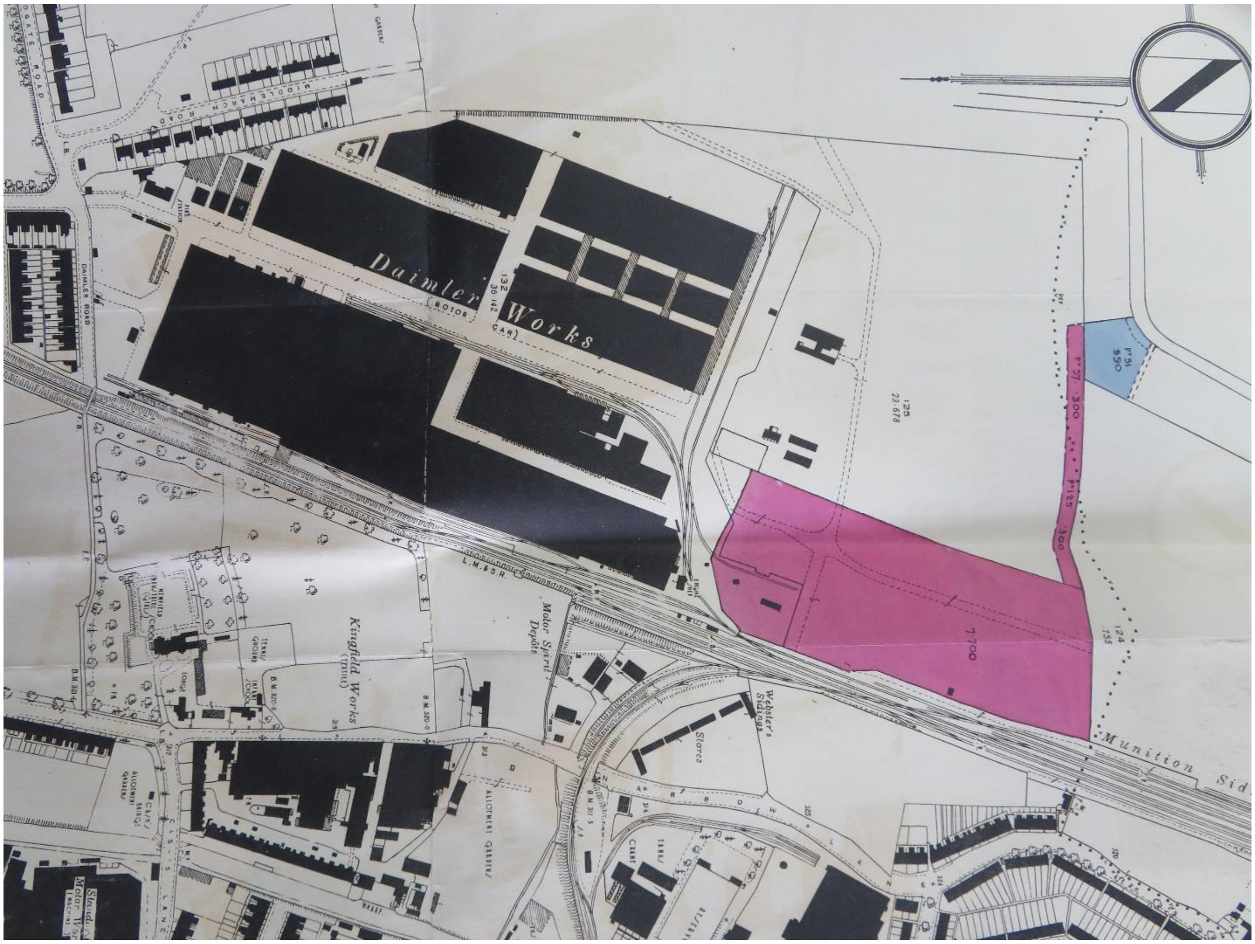

Illustration 2-1: A contemporary map showing the plot of land next to the Daimler Radford automobile works in Coventry that the Air Ministry purchased from Daimler to build the first Daimler shadow factory in 1937. Source: National Archives (NA), AIR 2/2324: Aircraft Production: Shadow Factories (Code B, 6/2): Daimler Coventry: purchase site for shadow factory.

Bristol's head of production had estimated that with a floor area of approximately 100,000 sq. ft. each of the factories could produce enough components for around 20 complete Mercury engines per week, with space for plant, storage of materials and finished components, heat treatment and nitriding facilities, inspection and assembly as required.[14] In fact, to meet

[13] James, Thurstan: 'Getting Going At the Shadow factories', *The Aeroplane*, Vol. LIII, No. 1350, (3 November 1937), p. 532.
[14] NA, AIR 19/4, Notes on the Visit to the Works of the Bristol Aeroplane Company 10 April 1936, p. 4.

the Air Ministry's requirement for 50 Mercury engine sets a week the shadow factories turned out to be a bit bigger than Bristol's initial estimate. The machine shops at each factory varied slightly in size based on the number and type of machine tools required for manufacturing the allocated Mercury engine component. A contemporary document gives the following data on floor space at the new factories[15]:

Bristol	116,000 sq. ft.
Austin	94,000 sq. ft.
Daimler	130,000 sq. ft.[16]
Rootes	177,000 sq. ft.
Rover	128,000 sq. ft.
Standard Motors	165,000 sq. ft.

In contrast to the dedicated buildings of the other factories, Austin Motors placed its aero engine manufacturing and assembly operations in the same 670,300 sq. ft shadow factory where it was building airframes, allocating a portion of the factory for the plant required for engine component production and space for the assembly of completed engines.[17]

The shadow factories followed new principles of industrial factory design. After World War I, British industrial architecture adopted the American preference for larger, single-storey, steel-framed factory structures instead of the previous multi-story brick and reinforced concrete designs. The ideal factory building was seen as allowing 'a smooth and unhampered flow' of production from raw materials to finished product.[18] This new factory design was present in the British automobile industry where several firms had adopted forms of line production, arranging machine tools in a sequence of operations rather than by type, requiring wider, more open

[15] NA, AVIA 10/267, See undated note 'Engine Factories-Floor Space'.
[16] An article in *The Aeroplane* suggests that the Daimler factory was 172,800 sq. ft., which is close to dimensions taken from the 1948 Ordnance Survey Map. See *The Aeroplane*, (November 3, 1937), p. 534.
[17] 'Shadow factories in Being', p. 499.
[18] Holme, C.G., Ed.: *Industrial Architecture*, (London 1935), p. 16.

spaces than the vertical mill factories of the past.[19] These steel-framed buildings had steel roof trusses with steel supporting columns with bays 25 feet wide, adequate for two rows of machine tools, with walls of brick.[20] The buildings typically had a saw-toothed, north-lit roof, with the north-facing slope having some clear material to let in daylight while the south-facing slope was covered with wood, asbestos or corrugated iron.[21]

These first shadow factories were 'planned to a lavishness which contrasts with the stringency that was to be the rule later', and were built using 'normal peacetime standards and requirements of the managing firms.'[22] The factories followed 'the best practice in large-scale engineering production' where the layout conformed 'to straight directional work flow from the material receiving end, through the material view into the approved stores, thence to the shops and, finally, back to the finished stores and despatch', in other words, flow production.[23] All the factories were rectangular single-storey buildings built to this new factory pattern, divided into separate bays, with a 6'' steel-reinforced concrete floor to take the weight of the machine tools.[24] After a visit to the completed factories, a contemporary observer remarked, 'the shops themselves are of the most modern design, air conditioned, and having high roofs and a minimum of overhead cables and roof members. Wide concrete gangways separate the lines of machines, each of which has its separate power supply. These conditions combine to give exceptionally light, airy shops and pleasant working conditions.'[25]

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[19] Winter, John: *Industrial Architecture: A Survey of Factory Building*, (London, 1970), p. 89; Collins, Paul, and Michael Stratton: *British Car Factories from 1896: A Complete Historical, Geographic, Architectural & Technological Survey*, (Goodmanstone, Dorset, 1993), p. 48.
[20] Collins and Stratton, *British Car Factories from 1896*, p. 47.
[21] Collins and Stratton, *British Car Factories from 1896*, p. 48.
[22] Koham, C.M.: *Works and Buildings*, History of the Second World War, Civil Series, (London, 1952), p. 311.
[23] "The Government Aircraft "Shadow" Scheme', p. 134.
[24] NA, AIR 2/1842, Daimler Motor Company Limited, Supplementary Details of Proposed Engine Factory at Radford, Coventry, 4 November 1936.
[25] 'Shadow factories in Being', *Flight*, (4 November 1937), p. 446.

Table 2-1: Expenditures on Shadow factories 1936-39

	Original Sanctions	Revised Sanctions	Actual Expenditure to 30.11.1939
Austin Motors	£720,920	£701,000	£668,227
Bristol Shadow No.2	389,786	390,873	384,023
Daimler Motor	579,841	764,244	696,939
Rootes Securities	542,700	936,959	752,250
Rover Motor	708,221	842,424	796,945
Standard Motor	610,000	889,804	627,908
Totals	£3,551,468	£4,525,304	£3,926,292

Source: NA, AIR 19/9, Statistics Relating to the Twelve Air Ministry 'Shadow' Factories in Production, Memo of December 1939, 'Shadow' Factories: Renumeration of Managing Firms.

While construction of the new factories was getting underway, Bristol Aeroplane Company's Aero Engine Department had, at its own expense, been expanding its facilities at Filton to increase production capacity. In early 1936, the Department completed a new factory of 200,000 sq. ft., adding a second building during the first half of 1937.[26] This second building accommodated the engine fitting, sub-assembly, and erection sections, as well as sections for manufacturing sleeve-valves. Bristol financed these additions, which need to be distinguished from the Government-financed Bristol Shadow Factory No.2, built at Filton to assemble aero engines from the components produced at the other factories, next to the main aero-engine works at the Bristol factory.[27] In June 1938, the Air Ministry approved £924,200 for additional

[26] 'A new "Bristol" Engine Factory', *Bristol Review (Engine Issue)*, No. 11, November 1936, pp.44-46; 'Further Extensions to the "Bristol" Engine Factory', *Bristol Review (Engine Issue)*, No. 12, June 1937, pp.42-43.
[27] NA, AIR 2/2366, Air Ministry Memorandum No. 42, Treasury Inter-Service Committee, Bristol Engine Assembly Factory-Shadow Industry.

buildings and machine tools at the Bristol factory to increase monthly production of all Bristol aero engines, outside the Shadow scheme (see Table 2-1).[28]

Maintaining balanced production among all the factories proved to be a challenge. Disruptions did happen during the initial years of production at the factories, as will be explained below, and following the German air raid on Coventry during the night of 14 November 1940.[29] German bombs hit the Daimler Radford works, severely damaging the nearby Daimler shadow factory.[30] Fortunately the factory's production was ahead of schedule, so that although it took five weeks to restore production, the total loss in output for all the shadow factories only amounted to two weeks production.[31] Following the November raid on Coventry and the Government's push to disperse production, the automobile shadow factories acquired smaller buildings in the surrounding areas, including a carpet factory, a laundry, a mill and several garages to use as dispersal factories.[32] As it turned out, these designated Dispersal Points did not have to be used for aero engine production, but later in the war became an important sources of spare parts.[33]

The Production Record

By September 1937, the shadow factories were ready. They were preparing to manufacture the Mercury Mark VIII under an initial contract for 1,500 engines and an additional 500 engines in the form of spare parts.[34] By August 1938 the factories had reached their production target of 50 engines per week.[35] That same month the automobile firms agreed to an Air Ministry proposal to build 1,000 Bristol Pegasus XVIII engines concurrently with the Mercury. Although similar in construction to the Mercury, initiating Pegasus production involved extensive preparations and

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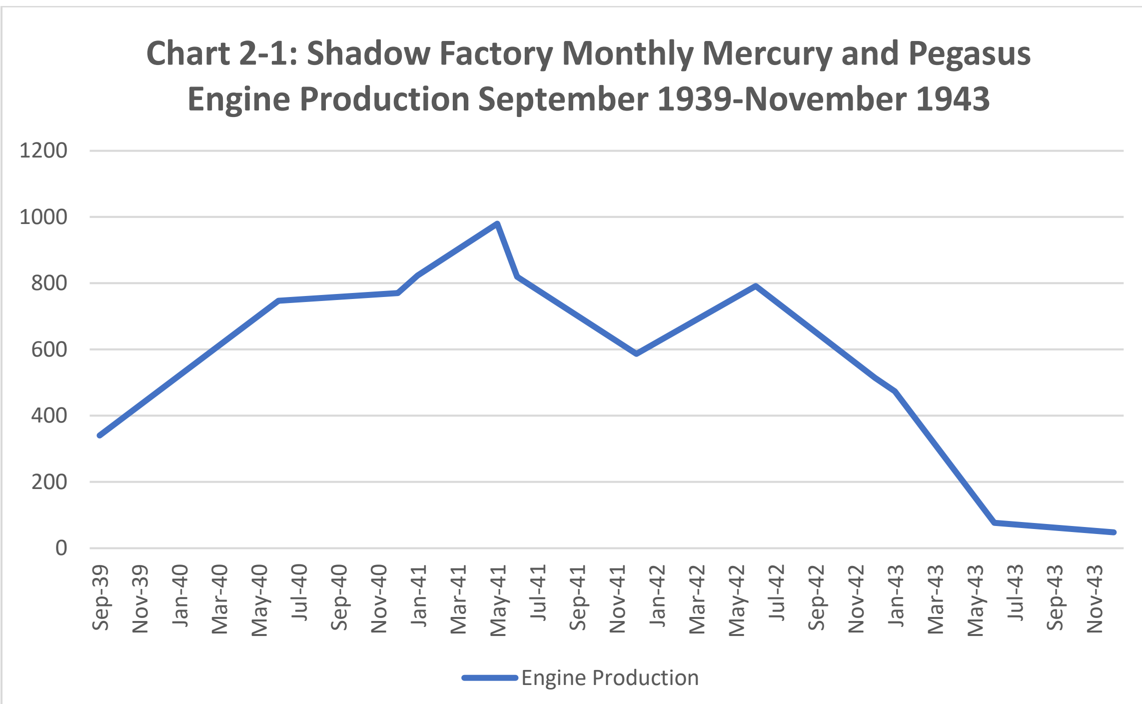
[28] NA, AVIA 46/261, *Narrative-Aero Engine Production Expansion of Capacity 1935-1945, Capacity for Production of Bristol Aero Engines 1938-1945*, A).
[29] Thoms, *War, Industry and Society*, pp. 104-112.
[30] Thoms, *War, Industry and Society*, P.108*; History of Production of Bristol Aero Engines by the Shadow Industry Operating Under the Joint Aero Engine Committee in Conjunction with the Bristol Aeroplane Company Limited*, XC03-8876/066, Royal Air Force Museum, p. 65.
[31] *History of Production of Bristol Aero Engines by the Shadow Industry*, pp. 65-66.
[32] *History of Production of Bristol Aero Engines by the Shadow Industry*, pp. 65, 119.
[33] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 66.
[34] Ritchie, *Industry and Air Power*, P. 126.
[35] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 8.

the first 39 Pegasus engines were not completed until June 1939.[36] The Air Ministry planned to gradually phase out Mercury and Pegasus production at Bristol and transfer production entirely to the shadow factories, with the expectation that by June 1939 production of these engines at Bristol would cease.[37] This would allow Bristol to concentrate its development and production efforts on the new 14-cylinder Hercules and 18-cylinder Centaurus. However, the approach of war created demands for more Mercury and Pegasus-powered aircraft. The Air Ministry postponed ending production of the Mercury and Pegasus at Bristol. The company stopped manufacturing the Mercury during 1940, continuing with the Pegasus until 1942.[38]



Source: Abridged Record of Engines, Spares and Accessory Output from Shadow Industry for 1938-44, *History of Production of Bristol Aero Engines by the Shadow Industry Operating Under the Joint Aero Engine Committee in Conjunction with the Bristol Aeroplane Company Limited*', XC03-8876/066, Royal Air Force Museum.

As war approached production of the Mercury and Pegasus accelerated (see Chart 2-1). By the summer of 1939, production had reached 80 engines a week. Once war began the Air

[36] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 8.
[37] Notes of a Meeting Held at the Austin Shadow Factory at Birmingham on the 10th June 1938, Appendix I (b) Programme of Production Engines.
[38] Chart of New Engines Delivered 1924-1948, copy in the Rolls-Royce Heritage Trust.

Ministry requested the factories to boost production to 100 engines a week and to plan for increasing output to 120 engines a week.[39] In October the Air Ministry approached the factories about increasing production to 150 engines a week and in early November formally requested the factories to reach this level by March 1940.[40] However, production declined during the first few months of the war as a result of black out restrictions, problems with transporting materials and the call-up of workers for the services.[41] During the first half of 1940, there were production delays at the Austin and Rootes factories but Bristol and the shadow factories attained the Air Ministry's new target of 150 engine sets per week in June 1940 and reached 761 engines completed during August.[42] The new Ministry of Aircraft Production still deemed this insufficient for the number of Blenheim, Hampden and Wellington bombers on order that called for an output of 950 Mercury XV and Pegasus XVIII engines per month.[43] That same month the Ministry approved a new production target for the factories of 200 complete engine sets per week, with an additional 20 sets as spares.[44]

Production peaked during 1941 when the factories produced 9,611 complete Mercury and Pegasus engines, achieving their highest monthly output in May when they built 980 engines, nearly 250 engines a week. Production of the two engines continued at a high rate during 1942, totalling 8,499 engines, but dropped off sharply during 1943 to 1,711 engines as the shadow factories cut production and Bristol stopped building the Pegasus.[45] Production of the Pegasus at the shadow factories ended in September 1943 while Mercury production came to a close in September 1944.[46] From June 1939 until February 1945, Bristol and the shadow factories built 16,041 Mercury engines and 15,713 Pegasus engines, with the majority completed at the shadow

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[39] Minutes of Management Committee Meeting 20 September 1939, Rover Company Limited (Aero Engines), Rover Company Directors Minute Book 1937-1939.
[40] Minutes of Management Committee Meeting 31 October and 27 November 1939, Rover Company Limited (Aero Engines), Rover Company Directors Minute Book 1937-1939.
[41] *Narrative-Aero Engine Production Expansion of Capacity 1935-1945, Capacity for Production of Bristol Aero Engines 1938-1945*, September 1938-December 1941.
[42] *History of the Production of Bristol Aero Engines by the Shadow Industry*, Abridged Record of Engines, Spares and Accessory Output from Shadow Industry for 1940.
[43] NA, AVIA 46/35, Air Supply Board, No. 1 Shadow Group- Production of Mercury XV and Pegasus XVIII engines, 16 August 1940.
[44] NA, AVIA 46/35, Air Supply Board, No. 1 Shadow Group- Production of Mercury XV and Pegasus XVIII engines, 16 August 1940.
[45] Abridged Record of Engines, Spares and Accessory Output from Shadow Industry for 1941-1944.
[46] Ministry of Aircraft Production: *Statistical Review 1939-1945,* p. 32.

factories.[47] The factories benefited from the fact that they were producing well-established models of these engines, which required few modifications that affected production. There were only a few changes in engine model when the factories shifted from the Mercury VIII to production of the Mercury XV, Mercury XX, Mercury 25, and Mercury 30, later versions with minor changes, while Pegasus production remained on the Pegasus XVIII.[48] Stabilizing the engine model enabled higher volume production.

How it Was Done: Building a Mercury Engine

To understand how Bristol and the shadow factories moved from building 50 engines a week to building 250 engines per week, we need to understand Bristol's production methods. Drawing on series of articles that appeared in the journal *Machinery* on Bristol's methods of production, articles in Bristol's company magazine *The Bristol Review*, and contemporary text books on aero engine production, we can get a good picture of how Bristol built Mercury engines.[49]

During 1937-1938, the Bristol Aero Engine works was manufacturing Mercury and Pegasus engines at a rate of around 30 complete engines a week, building to small production orders from the Air Ministry, Imperial Airways, and foreign air forces and airlines.[50] The emphasis was on precision, quality and reliability, not the rate of production and Bristol organized its engine works accordingly. This level of production can be characterized as batch production.

The Mercury and Pegasus were both nine-cylinder, air-cooled radial engines. The Pegasus was slightly larger having a stroke that was two inches longer requiring a longer master connecting rod and articulated rods, but these and other parts were similar. The Pegasus engine

[47] *Statistical Review 1939-1945,* p. 26.
[48] Lumsden, Alec: *British Piston Aero-Engines and Their Aircraft*, reprint of 1994 edition, (Ramsbury, Marlborough, UK, 2003), p. 108.
[49] 'The Manufacture of High Performance Aero Engines', *Machinery* (London), Vol. 48, No. 1249, (September 17, 1936), pp. 737-56; 'The Production of Aero-engine Crankcases and Superchargers', *Machinery* (London), Vol. 48, No. 1250, (September 24, 1936), pp. 774-78; 'Machining Aero-Engine Crankshafts and Airscrew Shafts', *Machinery* (London), Vol. 49, No. 1252, (October 8, 1936), pp. 33-38; 'Machining Master Connecting Rods for Radial Aero Engines', *Machinery* (London), Vol. 49, No. 1253, (October 15, 1936), pp. 61-65; Clinton, Arnold C.: 'Machining Operations on the Bristol "Mercury" Engine', in Nelson, W/C H.: *Aero Engineering*, Vol. II, Part 1: Production, (London, 1939), pp. 342-90.
[50] Scranton, *Endless Novelty*, p. 12; Bristol Aeroplane Company Minutes of Directors' Meeting in Committee, 11 June 1936, BAC Directors' Committees Minutes, Vol. 5., Aerospace Bristol Museum Archives.

had a two-stage blower (supercharger) which needed different machining than the single-stage blower on the Mercury. The metal alloys used were the same. There was sufficient commonality between the two engines that the shadow factories could build both engine types concurrently, although building components for the Pegasus did require some different types of machine tools, jigs, and fixtures.[51]

The manufacture of an air-cooled radial engine required the following steps:

- Material control: inspection of raw materials and bought out finished parts.
- Manufacture of component parts: machining, hardening, finishing.
- Preparation of sub-assemblies.
- First assembly of complete engines from components and sub-assemblies.
- Engine testing.
- Stripping and inspection after endurance testing.
- Final test.
- Final inspection.[52]

The component parts and sub-assemblies were:

- Cylinder assembly, including the cylinder barrel, cylinder head, valves and rocker mechanism and pistons.
- Crankshaft, master connecting rod and articulated connecting rods.
- Crankcase front and rear covers.
- Blower/supercharger.
- Propeller shaft and reduction gear.[53]

From beginning to end it took approximately 3,870 man-hours to build a Mercury VIII or Pegasus XVIII, with 2,470 man-hours of machining, 560 man-hours of polishing and detail fitting, 420 man-hours in assembly, 150 man-hours for testing and 250 man-hours for stripping, inspection and rebuilding each engine.[54]

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[51] *History of the Production of Bristol Aero Engines by the Shadow Industry*, p. 8.
[52] *History of the Production of Bristol Aero Engines by the Shadow Industry* p. 306; Fairbrother, E.: 'Aero-Engine Production', *Aircraft Engineering*, Vol. 16, Issue 7, (July 1944) pp. 209-10.
[53] 'The New Engine Building Department', *The "Bristol" Review*, Engine Issue No. 13, (June 1938), p. 35.
[54] NA, AIR 19/5, Notes on the Visit to the Works of the Bristol Aeroplane Company, 10 April 1936.

The manufacturing process began with a thorough inspection of all raw materials and all components purchased from outside specialist suppliers. Bristol maintained a Raw Material Inspection Department and a Rough View Department to carry out these inspections, checking all materials to ensure they met Air Ministry specifications, following inspection procedures laid down in the Government publication *Airworthiness Handbook for Civil Aircraft*.[55] Companies supplying materials to the aero-engine manufacturers had to use manufacturing methods that the Government's Aeronautical Inspection Department had approved, and had to provide the engine companies a release certifying that the material or part met the standards of quality.[56] A first visual inspection searched for any obvious flaws or defects in the material. Raw materials, such as steel bars or the wire used in valve springs, went through tests to determine hardness, the presence of any internal flaws or cracks not visible and tensile strength. Forgings for crankshafts, connecting rods, pistons and crankcases and other components came with a test piece that could be broken off and tested to check grain flow and the orientation of metal crystals, to ensure that the flow matched the shape of the component to provide greater strength in addition to tests for hardness, tensile and impact strength.[57]

Building the cylinders began with the cylinder barrel. The barrels arrived as rough hollow forgings of nickel-chrome-molybdenum steel, a special alloy developed to provide an extremely hard internal surface, which received the most wear, and the strength to resist distortion at the much higher power levels of large air-cooled radial engines.[58] The first operation was to bore out the inside of the rough cylinder on a turret lathe to a diameter of 5.720 inches, leaving .03 inches to be removed during a later operation to obtain the correct bore of 5.75 inches for the cylinder.[59] After more work on both ends, cylinders went for heat treatment to improve strength and hardness, being placed in an oven for eight hours at a temperature of 500° C. When cool,

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[55] 'The "Bristol" Engine Inspection Department', *The "Bristol" Review*, Engine Issue No. 11, (November 1936), p. 31; Clinton, Arnold C.: 'Short Survey of Aero-engine Production', in Nelson, W/C H.: *Aero Engineering*, Vol. II, Part 1: Production, (London, 1939), p. 307.
[56] Clinton, 'Short Survey of Aero-engine Production', p. 307.
[57] 'The "Bristol" Engine Inspection Department', *The "Bristol" Review*, Engine Issue No. 11, (November, 1936), p. 31; 'Short Survey of Aero-engine Production', p. 309; 'The Manufacture of High Performance Aero Engines', *Machinery* (London), Vol. 48, No. 1249, (September 17, 1936), p. 741.
[58] 'Modern Aircraft Engine Materials', *The "Bristol" Review*, Engine Issue No. 13, (June 1938), p. 28.
[59] 'The Manufacture of High Performance Aero Engines', pp. 743-44.

cylinders went through a nitriding process to harden the internal surfaces and make them more resistant to wear. This entailed placing the cylinders in an oven at 485° C where they were bathed in ammonia gas for 72 hours, the ammonia reacting with the heated steel to leave a deposit of nitrogen on the internal surface of the cylinder.[60]

The next procedure was to machine the cooling fins on the side of the cylinder barrel. To improve the flow of air around the cooling fins, each fin was tapered to have a thickness of .062 inches at the base of the fin and .015 inch at the tip.[61] This needed a complex two-stage machining operation, the first stage to cut the fin shape out of the bulged side of the forged cylinder, and the second stage to taper the fins with a special type of lathe using 38 cutting tools to cut one side of the fins and another 39 tools to cut the other side. With the fins cut to the correct depth, an internal centreless grinder ground the internal surfaces of the cylinder barrel to within .002 inches of its final diameter.[62]

The cylinder head was a drop forging, made from forcing heated metal onto a specially shaped die, and then fully heat-treated. These were made from Y-alloy, an aluminium alloy containing copper, nickel and magnesium that combined strength with resistance to high temperatures during combustion. Arriving at the engine works as a rough forging, cylinder heads went through 80 operations to remove metal and machine the work into the required size and shape, reducing the weight from 49 lb. to 15 lb. in the process.[63] Machining cylinder heads was complex due to the number of irregularly shaped cooling fins on the top and sides, the shape of the combustion chamber and the requirement for flat spaces on either side for the two inlet and two exhaust ports. This involved careful milling to machine the correct surfaces using several different types of milling machines. Once the surfaces were prepared, additional milling machines cut out the cooling fins and then tapered them in 26 separate operations.[64] The ports for inlet and exhaust valves— two inlet and two exhaust ports on each cylinder head — were machined from the inside of the cylinder head, then valve seats where the valves rest when

[60] 'The Manufacture of High Performance Aero Engines', p. 744.
[61] 'The Manufacture of High Performance Aero Engines', p. 745.
[62] 'The Manufacture of High Performance Aero Engines', p. 745.
[63] 'The Manufacture of High Performance Aero Engines', p. 746.
[64] 'The Manufacture of High Performance Aero Engines', p. 749.

closed were carefully ground as well as holes drilled for the sparking plugs.[65] Thread milling machines cut threads on the inside of the cylinder head and on the top of the cylinder barrel. The cylinder head went into an oven for an hour's heat treatment at 400° C and then had the valve seats, sparking plug adapters and valve guides inserted while still hot, after which the cylinder head was screwed onto the cylinder barrel.[66] The final operation of this stage was to hone the inside of the cylinder barrel for an even smoother finish.

Pistons were made from R.R. 59 alloy, also known as Hinduminium, a development of the earlier Y-alloy of aluminium specifically for aero-engine pistons that Bristol obtained from High Duty Alloys Co. Ltd. The pistons were made by stamping, where metal at room temperature as opposed to heated went under a forge or press and was forced over one or more dies to make the rough shape of the piston.[67] This 9 ¾ lb. rough stamping went through 44 machining operations, removing 6 lbs. of metal.[68] The first stages of machining worked on the outside skirt of the piston to bring it close to the required dimensions, and to rough out the inside of the piston. A drilling machine drilled a hole through the piston for the gudgeon pin that held the connecting rod to the piston, which was then bored to a finer finish. The outside of the piston was machined to create two recesses with flat plates for the gudgeon pin, after which a lathe cut grooves on the sides of the piston for the piston rings. As a measure of the accuracy required, the diameter of the gudgeon-pin hole was bored and finished to 1.154 inches, with a tolerance of +.0007 inches.[69] At the end of the machining process, the piston crown and skirt underwent further surface finishing.

Inlet and exhaust valves were the final parts of the cylinder assembly. Valves had to be exceptionally strong to resist the constant hammering they received as the valve ports opened and closed and high pressures and temperatures within the combustion chamber. The valves were made from hardened steel forgings and put through a nitriding process for further

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[65] 'The Manufacture of High Performance Aero Engines', p. 750; 'Machining Operations on the Bristol "Mercury" Engine', pp. 347, 352, 357.
[66] 'Machining Operations on the Bristol "Mercury" Engine', pp. 342,352, 354; Hesse, Herman C.: *Engineering Tools and Processes: A Study of Production Technique*, (New York, 1941), p. 487.
[67] *Engineering Tools and Processes: A Study of Production Technique*, pp. 400-06, 411-15.
[68] 'The Manufacture of High Performance Aero Engines', p. 754; 'Machining Operations on the Bristol "Mercury" Engine', P. 354.
[69] 'The Manufacture of High Performance Aero Engines', p. 755.

hardening. Exhaust valves, which had to cope with higher temperatures, had a cavity drilled out of the stem that was filled with sodium.[70] At high temperatures the sodium melted and moved back and forth within the cavity, helping to transfer heat down the stem of the valve. For additional protection, the valve seat at the back of the face of the valve had Stellite, a special hardening substance that resisted corrosion from the exhaust gases of higher octane fuels, welded on while the face of the valve was covered with Brightray, another type of hardening agent.[71] The valve springs that held the valves closed were made from steel wire that was coiled to a set length then tempered in an oven at 340° C. for an hour and afterwards plated with cadmium, a corrosion-resistant coating for steel.

The crankshaft and connecting rods are described next. The crankshaft transfers the mechanical energy transmitted from the pistons, through the connecting rods, to the propeller through a shaft at the front of the crankshaft. Bristol used a two-piece crankshaft with counterweights, the front half containing the crankpin which holds the master connecting rod and a front shaft connecting to the propeller reduction gear, while the rear half contained a shaft to drive the impellor for the blower, the two halves being clamped together with a maneton joint and maneton bolt.[72] Both parts of the crankshaft were forged from nickel-chromium-molybdenum alloy steels with high tensile strength and received additional strengthening through nitriding. Front and rear halves of the crankshaft went through a series of similar machining operations to drill and ream holes through the crankpin and the front and rear shafts to reduce weight, drill a hole for the connecting maneton joint, shape the counterweights and progressive grinding to ensure a smooth surface overall. [73]

Master connecting rods and the articulated connecting rods were also made from nickel-chromium-molybdenum alloy steels to better withstand torsional stresses.[74] Bristol received master connecting rods as a steel stampings roughly in the correct form weighing 42 lbs. After

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[70] 'The Manufacture of High Performance Aero Engines', p. 751.

[71] 'The Manufacture of High Performance Aero Engines', p. 751; 'Machining Operations on the Bristol "Mercury" Engine', pp. 376-83.

[72] 'Machining Aero-Engine Crankshafts and Airscrew Shafts', *Machinery* (London), Vol. 49, No. 1252, (October 8, 1936), p. 33; 'Machining Operations on the Bristol "Mercury" Engine', p. 364.

[73] 'Machining Aero-Engine Crankshafts and Airscrew Shafts', pp. 33-36.

[74] 'Machining Master Connecting Rods for Radial Aero Engines', *Machinery* (London), Vol. 49, No. 1253, (October 15, 1936), pp. 61-65.

machining all surfaces in different milling machines to obtain the correct form the finished master rod weighed 9 lbs. and 5 ½ oz.[75] Drilling machines drilled a hole at the top of the master rod for the gudgeon pin to connect with the piston, and eight holes around the base to hold the articulated rods. Once drilled these holes were bored and ground to a fine smooth finish. The articulated rods went through similar machining and drilling processes to achieve the correct form and form holes for connecting pins. After machining, both the master connecting rod and the articulated rods went through a polishing process to remove any marks that might result in fatigue fractures.[76] Since the Pegasus engine had a longer stroke than the Mercury, the Pegasus' master connecting rod and articulated rods were slightly longer, though the machining operations were basically similar to the Mercury's components.

Since they were subject to less stress, crankcases could be made from R.R. 56 aluminium alloy, another in the Hinduminum range. After stamping to obtain the rough form of the front and rear halves of the crankcase, the parts went through a heat treatment process to increase the tensile strength.[77] Once again, machining removed considerable amounts of metal, the front half being reduced from 84 lbs. to 41 lbs. while the rear half went from 75 lbs to 42 lbs. The two halves went through repeated machining operations, sometimes separately and sometimes temporarily bolted together. The centre of each half was drilled out to take the front and rear shafts of the crankcase and nine holes cut out around the circumference of the crankcase to hold the cylinder barrels, while numerous holes were drilled on each half to bolt the halves together and to attach the cylinders and other components. After inspection and a final treatment of all surfaces by hand, the crankcase was sandblasted, and then un-protected parts received a coating of protective enamel. [78]

The final sections to be described are the blower (supercharger) unit, the propeller shaft and reduction gear. Mercury and Pegasus engines used gear-driven centrifugal superchargers, with the Pegasus using a two-speed unit containing more parts and gears than the unit in the

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[75] 'The Manufacture of "Bristol" Aero Engine Components', *The "Bristol" Review*, Engine Issue No. 8, (November 1934), p. 23.

[76] 'The Manufacture of "Bristol" Aero Engine Components', p. 24; 'The Production of Aero-engine Crankcases and Superchargers', *Machinery* (London), Vol. 48, No. 1250, (September 24, 1936), pp. 774-78.

[77] 'The Manufacture of "Bristol" Aero Engine Components', p. 25.

[78] 'The Manufacture of "Bristol" Aero Engine Components', p. 26.

Mercury engine.[79] The casings for the blower unit were made of lighter weight magnesium alloy machined on both sides with holes bored in the centre for the rear shaft of the crankshaft which drove the impeller within the blower.[80] The impeller was made of much stronger nickel steel and arrived as a rough stamping. A hole was bored in the centre of the stamping to connect with the crankshaft while the individual blades of the impeller were cut out and tapered. After heat treatment to strengthen the blades, they underwent several grinding operations to obtain the correct angles. The propeller shaft and reduction gear transferred the movement of the crankshaft to the propeller but reduced the speed between the crankshaft and the propeller. The propeller shaft with the trunnions that held the reduction gear was a steel forging. Machining the propeller shaft was straightforward and could be done on a standard lathe, but the attached trunnions required special fixtures.[81] Gear shapers cut the teeth for the bevel-shaped reduction gear which were then ground to the correct size and shape.[82]

Assembly and engine testing were the final stages of the production process.[83] At Bristol, engine components underwent over 30,000 separate inspections over the course of construction.[84] Components parts went through a cleaning process to remove any traces of metal filings before going to the Sub-Assembly Section where they underwent further testing to ensure they met specified standards. At this stage sub-assemblies included the crankshaft and connecting rods, the cylinder unit, the complete blower unit, the propeller shaft and reduction gear and the crankcase, with smaller components such as the pistons, rocker gear and push rods and other engine accessories prepared in other sections. Skilled staff assembled the complete engine on special stands that allowed the engine to be rotated to progressively accept the sub-assemblies and other parts to build up a complete engine, checking for the alignment of all components and adjusting mechanisms prior to engine testing. There were no assembly lines.

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[79] The Bristol Aeroplane Co. Ltd.: *The "Bristol" Pegasus Aircooled Radial Engines*, Vol. III, Types XVII and XVIII, (Filton, UK, March 1940), p. 10.
[80] 'The Production of Aero-engine Crankcases and Superchargers', p. 777.
[81] 'Machining Operations on the Bristol "Mercury" Engine', p. 366.
[82] Herb, Charles O.: *Machine Tools at Work*, (New York, 1942), pp. 448-55; *Aircraft Engines*, Vol. Two, p. 275.
[83] 'The Engine Fitting, Stripping and Re-Building Department', *The "Bristol" Review*, Engine Issue No. 10, (June 1936), p. 35.
[84] 'The "Bristol" Engine Inspection Department', *The "Bristol" Review*, Engine Issue No. 11, (November 1936), p. 30.

Testing the assembled engine began with several hours of running-in, during which an electric motor ran the engine to check that all moving components were working correctly.[85] Next the engine went to a dynamometer for endurance testing. With fuel and oil supplied, the engine ran for half an hour at low revolutions per minute (RPM), and then ran at progressively higher RPM and horsepower settings for another two hours when the engine was stopped, the oil replaced, and the engine run for an additional hour. When the endurance test was over, the engine went back to the inspection department where it was completely disassembled, and every component closely inspected. After re-assembling the engine, a final running test checked oil and fuel consumption and power output to meet Air Ministry specifications.[86]

Production at the Shadow Factories

Production at the shadow factories, at least until the outbreak of the war in September 1939, involved the exact replication of Bristol's pre-war production methods. At the inaugural meeting between Bristol and the representatives of the shadow factories in June 1936, the automobile firms decided they would 'slavishly follow Bristol Aeroplane Company production practice, and improve on this if and when experience justified any changes.'[87] Fortunately Bristol had extensive experience in providing technical advice and support for manufacturing Bristol engines. For nearly a decade, Bristol had been cooperating with European firms building the Bristol Jupiter, Mercury, and Pegasus engines under license. To assist the licensees, Bristol had prepared a compilation of drawings, specifications, and schedules documenting production in exhaustive detail known as the 'Bristol Engine Bible'.[88] This compilation, and Bristol's extensive experience, proved invaluable in setting up production at the shadow factories.

Soon after the inauguration of the shadow scheme Bristol set up a special Shadow Industry Office to coordinate the supply of technical information and assistance to the factories. Over the next two years the Office supplied more than 68 folders of detailed information and

[85] *Aircraft Engines*, vol. Two, p. 420.
[86] 'The "Bristol" Engine Inspection Department', p. 34.
[87] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 11.
[88] Neale, M.C., ed.: *An Account of Partnership-Industry, Government and the Aero Engine: The Memoirs of George Purvis Bulman*, Rolls-Royce Heritage Trust Historical Series No. 31, (Derby, UK, 2001), p. 223.

precise instructions on engine production, specifying in exacting detail the types and number of machine tools to be used in each machining operation, machining times, specifications of materials and schedules of equipment for engine testing and assembly, among others.[89] Bristol based these specifications on its own experience in its aero-engine works.[90] The factories set up a managers' committee which met frequently during this initial phase to work out common problems in cooperation with Bristol and the Air Ministry, while senior executives of the motor firms formed the Aero Engine Committee (Shadow Industry) to provide overall direction.[91]

The plant required for the factories cost three to four times more than the factory buildings, though the investment varied by factory and the number of machine tools each factory required. The number ranged from 439 machine tools at the Rootes factory to 729 at the Rover factory.[92] After providing information on machine tools, Bristol prepared schedules and detailed information on the jigs, fixtures, tools and gauges that the factories would need.[93] Each of the factories had a special standards room where the jigs and tools could be checked for accuracy with measuring instruments accurate to the ten-thousands of an inch required on many parts of an aero-engine.[94]

Line production would become a critical factor in expanding aero engine output during the war. Line production is defined as a system where the machine tools and work areas are set up 'in the order of operations required to fabricate the part or to effect the assembly.'[95] This creates 'a controlled flow of the product through work areas in which balanced operations have been laid out in progressive sequence', thereby minimizing time between operations, reducing handling of components, improving labour efficiency and raising output.[96] The extent to which the shadow factories fully adopted a system of line production in the pre-war period, however, is difficult to judge, though there is evidence that it was used.

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[89] *History of Production of Bristol Aero Engines by the Shadow Industry*, pp. 11-14, 28-29.
[90] *History of the Production of Bristol Aero Engines by the Shadow Industry*, p. 74.
[91] Ritchie, *Industry and Air Power*, p. 125.
[92] See note Rootes Securities Ltd., Aircraft Division, Engine Factory, Coventry, AIR 19/7, NA; and Minutes of Management Committee Meeting 29th September 1937, Rover Company Limited (Aero Engines), Rover Company Directors Minute Book 1937-1939, 80/148/4/67-RCO, British Motor Industry Trust.
[93] Muther, *Production Line Technique*, p. 6.
[94] 'Shadow factories in Being', p. 446.
[95] Muther, *Production Line Technique*, p. 7.
[96] Lilley, *Problems of Accelerating Aircraft Production*, P. 40; Muther, *Production Line Technique*, pp. 21-23.

At the time Bristol was advising the shadow factories on setting up production, the company itself was still grouping machine tools by type and function and only using line production to a limited extent.[97] This arrangement was perfectly adequate for batch production. When Bristol provided the factories with suggested layouts for machine tools, based on manufacturing processes at each factory and projected output, it provided several alternatives.[98] Bristol did offer a plan that incorporated the possibility of employing line production, if the quantities of components required this method of quantity production at some later date.[99] Bristol decided, however, that the initial output of 50 complete engine sets per week did not justify setting up an extensive line production system.[100]

While following Bristol's recommendations, the automobile companies did have some leeway in choosing different approaches to production methods and laying out machine tools at their respective shadow factories. Despite Bristol's recommendation that a line production system was not necessary, it appears that the Rootes, Rover and Standard Motor factories adopted some form of line production. A report on the Rootes factory noted that 'the main machine shop runs in parallel lines the full length of the factory' and that the factory had taken care to 'minimize the delay caused by interruption of the straight flow of machining sequences brought about by the necessity of secondary processes such as heat treatment', a good description of line production.[101] The Standard Motor shadow factory was described as 'quite definitely a show place'.[102] The Standard factory had 'the simplest and yet at the same time the most difficult manufacturing programme.'[103] The Standard factory built the cylinder head and cylinder barrel, and while machining these components was complex, it allowed the factory to adopt line production, with one line for the cylinder head and one line for the cylinder barrel, and facilitated using conveyors to move parts between machining operations.[104] How production was organized at the Austin, Daimler and Bristol shadow factories is uncertain.

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[97] 'The Manufacture of High Performance Aero Engines', p. 742.
[98] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 74.
[99] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 74
[100] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 74.
[101] 'Getting Going at the Shadow Factories', p. 530.
[102] 'Getting Going at the Shadow Factories', p. 534.
[103] 'The Shadow Factories: A Preliminary Survey of the Plant and Methods', p. 446.
[104] 'The Shadow Factories: A Preliminary Survey of the Plant and Methods', p. 446.

Inevitably, despite the best efforts of Bristol and the automobile firms, there were delays and disruptions in output. Before the beginning of the war, the most serious delays occurred at the Rootes Humber factory manufacturing the blower (supercharger) units for the Mercury. Apparently Bristol had specified that the Rootes factory should use the Swiss Maag gear grinder for the blower gear wheels, but William Rootes insisted on using the British Orcutt grinding machine, only to find later that the Mercury engines equipped with the Orcutt-ground gears failed their engine test, forcing a change in the gear-grinding machine tools.[105] By July 1938 Rootes was 774 units behind schedule which 'caused a considerable amount of discontent amongst the other members as bonus payments would be delayed.'[106] During July-August 1938 the shadow factories failed to produce a single complete engine. While monthly output improved during 1939, there continued to be problems with the Austin and Rootes shadow factories meeting their production targets.[107] This became an even greater problem after the war began as the Air Ministry pushed the shadow factories to rapidly expand production. In March 1940, the Air Council Committee on Supply reported that due to difficulties in arranging supply of materials to the Austin and Rootes shadow factories, both factories were seriously behind schedule, with Austin short 2,000 crankshafts and Rootes short 1,000 blower gear stampings.[108] This was due in part to a lack of forging capacity in Britain for forging crankshafts, forcing Bristol to develop alternative sources of supply in America.[109] This lesson was not lost on the Air Ministry.

The Tools

Bristol's choice of machine tools to build the Mercury and Pegasus stressed flexibility. The Bristol machine shops did not use special-purpose machine tools that were common in the automobile industry. Instead, the company purchased standard machine tools that did not require special

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[105] Neale, M.C., ed.: *An Account of Partnership-Industry, Government and the Aero Engine: The Memoirs of George Purvis Bulman*, Rolls-Royce Heritage Trust Historical Series No. 31, (Darby, UK, 2002), pp. 227-28.
[106] Aero Engine Shadow Committee Meeting Held at the Standard Aero Works 10/7/1938.
[107] Minutes of Management Committee Meeting 14th November 1939, Rover Company Limited (Aero Engines), Rover Company Directors Minute Book.
[108] NA, AVIA 10/169, Air Council Committee on Supply, Mercury Engines (Note by D.D.G.P.I), 1 March 1940.
[109] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 40.

jigs or fixtures, and that could perform several operations on the same machine tool.[110] Contemporary articles describe labour-intensive machining operations on sequences of separate and different types of machine tools, with few mentions of machine tools that could perform multiple operations on the same machine. At the time, Bristol classed over 40% of the work force in the Aero Engine Department as skilled workers.[111] This was the operation that Sir Herbert Austin, the first chairman of the shadow factory group, observed on his visit to the Bristol engine works in June 1936, concluding that 'it would certainly not be an easy matter to improve on their present practice, unless special machinery was installed and a large number of engines produced.'[112]

The majority of the machine tools for the first shadow factories came from British machine tool makers, apart from small numbers of automatic machine tools and milling machines imported from America.[113] While there were delays in delivery due to the growing demand for machine tools, by October 1937 the shadow factories had most of the plant they needed. The Daimler shadow factory had 82% of its machine tools, Rootes had 90% and the Standard Motor Company factory had 92%.[114] As *Flight* magazine commented after a visit to the shadow factories that same month, 'to have designed, built and equipped in twelve months five factories with new machine tools embodying the latest practice, and this during a period of increased demand from other industries, is a feat bordering on the miraculous.'[115]

How it Was Done: The Transition to Large-scale Production

It took a little over a year for the shadow factories to make the transition to large-scale production. From early 1939 to late 1940, the factories expanded their weekly capacity from 50 to 200 complete engine sets a week, a four-fold increase. Few primary documents are available

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[110] Bristol Aeroplane Company Minutes of Directors' Meeting in Committee, 11 June 1936, BAC Directors' Committees Minutes, Vol. 5.
[111] See Minutes of Directors Meetings in Committee for June-September 1936, The Bristol Aeroplane Company Ltd., Minutes of Directors Committees, Vol. 5,
[112] Notes on the Visit to the Works of the Bristol Aeroplane Company 10th April 1936, p. 3.
[113] 'The Shadow Factories: A Preliminary Survey of the Plant and Methods', p. 444.
[114] 'At the Shadow factories', p. 529.
[115] Shadow factories in Being', pp. 445-46.

describing how the factories shifted to building engines in greater quantities. The Bristol history of the shadow industry refers to the 'copious correspondence between the Bristol Shadow Office and the individual factories' dealing with all manner of production issues, but this correspondence does not seem to have survived.[116] However it is possible to show that to expand production the factories greatly increased machine utilization by moving to double shifts, nearly doubling the number of workers at the factories with a doubling of labour productivity.

The transition to larger scale production began before the start of the war in September 1939. The factories reached their initial target of 50 engines per week in August 1938. During the first half of 1939, the factories used overtime to build up to 80 engines per week, achieving this target in July.[117] This effort was part of a three-fold increase in aero engine production at all the British aero engine factories— at Bristol, the shadow factories, Rolls-Royce, Armstrong Siddeley Motors, and De Havilland —between July 1938 and July 1939.[118] A July 1939 memorandum for the Air Council from the Air Ministry's Director General of Production on the progress of production for re-armament documented how the aero engine factories had achieved this increase.[119] The memorandum stated that the increase was due to:

a) Increased machine utilization.
b) Increased working hours.
c) Increased production equipment.
d) Increased labour strength.
e) Increased area at Main Factories
f) New area at shadow factories
g) Increased sub-contracting.[120]

[116] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 57.
[117] NA, AIR 6/58, 177th Progress Meeting, The Progress of Production for Air Re-armament, Memorandum by D.G.P., 12th July 1939, p. 16.
[118] 177th Progress Meeting, The Progress of Production for Air Re-armament, Memorandum by D.G.P., 12th July 1939, p. 14.
[119] 177th Progress Meeting, The Progress of Production for Air Re-armament, Memorandum by D.G.P., 12th July 1939, pp. 14-15.
[120] 177th Progress Meeting, The Progress of Production for Air Re-armament, pp. 14-15.

Table 2-2: 1940 Expenditures on Shadow factories

	Number of Machine Tools	Estimated Cost of Machine tools	Estimated Cost of Equipment
Austin Co.	72	£81,400	--------
Daimler Co.	12	£11,450	--------
Rootes Securities	287	£341,000	--------
Rover Co.	45	£77,000	£25,428
Standard Motor Co.	31	£27,040	£1,612
Total	497	£537,890	£27,040

Source: NA, AVIA 46/35, Air Supply Board, No. 1 Shadow Group- Production of Mercury XV and Pegasus XVIII engines, 16 August 1940, Ministry of Supply: Establishment, Registered Files (Series 1). Narratives on supply of Aircraft parts, especially aero engines: source papers

Additions of new machine tools to the factories were modest (see Table 2-2). To achieve the target of 150 engines per week, in December 1939 the Air Ministry approved expenditures of £407,765 for more machine tools and equipment for the shadow factories and £158,746 for building work to provide more storage space for parts and space to assemble the increased number of engines.[121] This represented an increase of approximately 14% over the amount spent on machine tools at the factories up to November 1939.[122] The Rootes factory received half of this allocation for machine tools, representing a 40% increase over the original expenditure for the factory.[123] This was probably an effort to improve production of blowers at the Rootes factory, which still lagged. In August 1940, a review of production determined that with more machine tools production could in fact be boosted to 200 engines a week.[124] This was done through an additional expenditure of £537,890 with £27,040 on other equipment, an amount

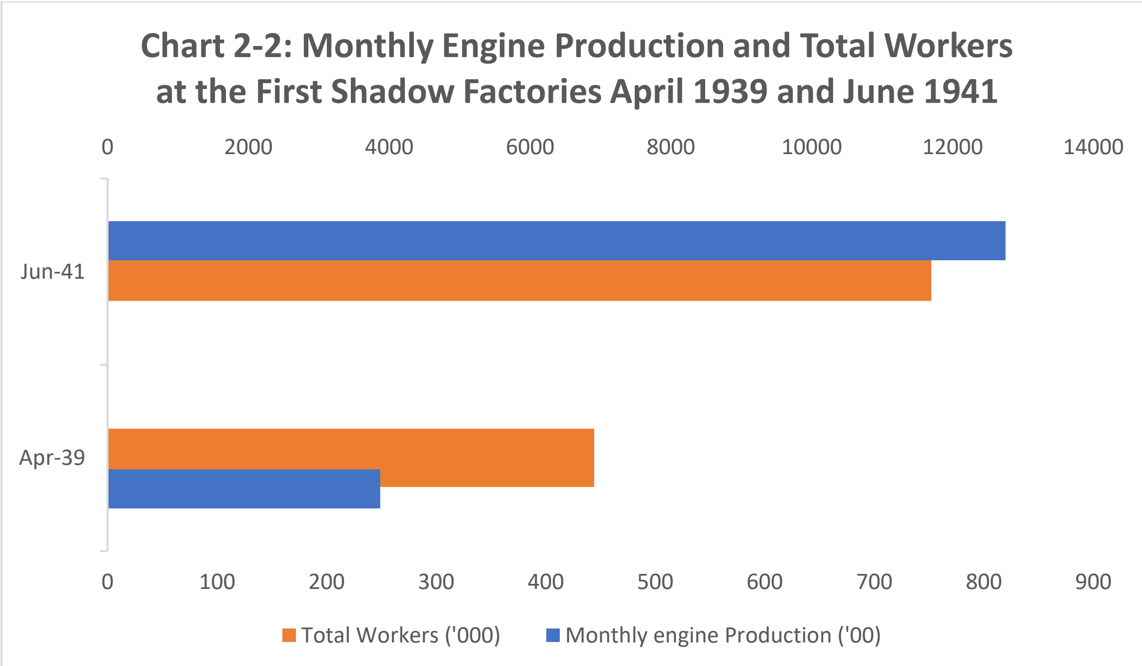
[121] NA, AVIA 10/166, Air Council Committee on Supply Meetings December 1939-January 1940, No. 1 Shadow Engine Production Memorandum by D.E.P.
[122] NA, AIR 19/9, Statistics Relating to the Twelve Air Ministry 'Shadow' Factories in Production, Memo of December 1939, 'Shadow' Factories: Renumeration of Managing Firms. Based on Hornby's estimate of the percentages spent on buildings and plant at the aero engine factories. See *Factories and Plant*, p. 253.
[123] No. 1 Shadow Engine Production Memorandum by D.E.P.
[124] *Narrative-Aero Engine Production Expansion of Capacity 1935-1945*, Capacity for Production of Bristol Aero Engines 1938-1945, B) By Shadow Schemes.

roughly equal to around 20% of the original expenditure.[125] Once again Rootes received the major portion of the allocation for machine tools. These two allocations for the Rootes shadow factory nearly doubled the number of machine tools, which rose from 606 in 1939 to 1,035 at the end of 1941.[126] While the expenditure at the Rover factory represented approximately one-third of the original expenditure for the factory, the amounts allocated to the Austin, Daimler and Standard Motor factories were less. There is no evidence that these new machine tools were different in any way from the standard machine tools already in the factories. It is highly likely, but not certain, that during this period those factories that had not already done so shifted to line production to increase output. The directors' minutes of the Rover Company shadow factory, for example, speak of changing the layout of machine tools within the factory to increase production to 150 engine sets per week.[127]

[125] *Narrative-Aero Engine Production Expansion of Capacity 1935-1945*, Capacity for Production of Bristol Aero Engines 1938-1945, B) By Shadow Schemes.

[126] Thoms, David, and Tom Donnelly: *The Motor Car Industry in Coventry Since the 1890's*, (Abingdon, Oxon., 2018), p. 128.

[127] Minutes of Management Committee Meeting 17th January 1940, Rover Company Limited (Aero Engines), Rover Company Directors Minute Book.



Source: Abridged Record of Engines, Spares and Accessory Output from Shadow Industry for 1938-44, *History of Production of Bristol Aero Engines by the Shadow Industry Operating Under the Joint Aero Engine Committee in Conjunction with the Bristol Aeroplane Company Limited,* XC03-8876/066, Royal Air Force Museum; Ministry of Aircraft Production, *Statistical Review 1939-1945*.

The most important factors in increasing production were, however, increasing the number of workers at the factories, moving to double shifts and improved labour productivity (see Chart 2-2 and Table 2-3). Between April 1939 and June 1941, the number of workers at each of the factories nearly doubled. More workers, enough to accommodate working double or triple shifts, allowed much greater machine tool utilization and increased component production. There is insufficient data to determine when the individual factories reached this level of employment, but it is probable that this occurred toward the end of 1940 when during October weekly production reached 200 engines per week for the first time.[128] The move to double shifts apparently took place shortly before the start of the war.[129] It is likely that as the labour force expanded, so too did the number of workers assigned to each shift.

[128] Abridged Record of Engines, Spares and Accessory Output from Shadow Industry for 1940, 'History of Production of Bristol Aero Engines by the Shadow Industry'.
[129] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 15.

Table 2-3: Employment at the Shadow Factories 1938-42

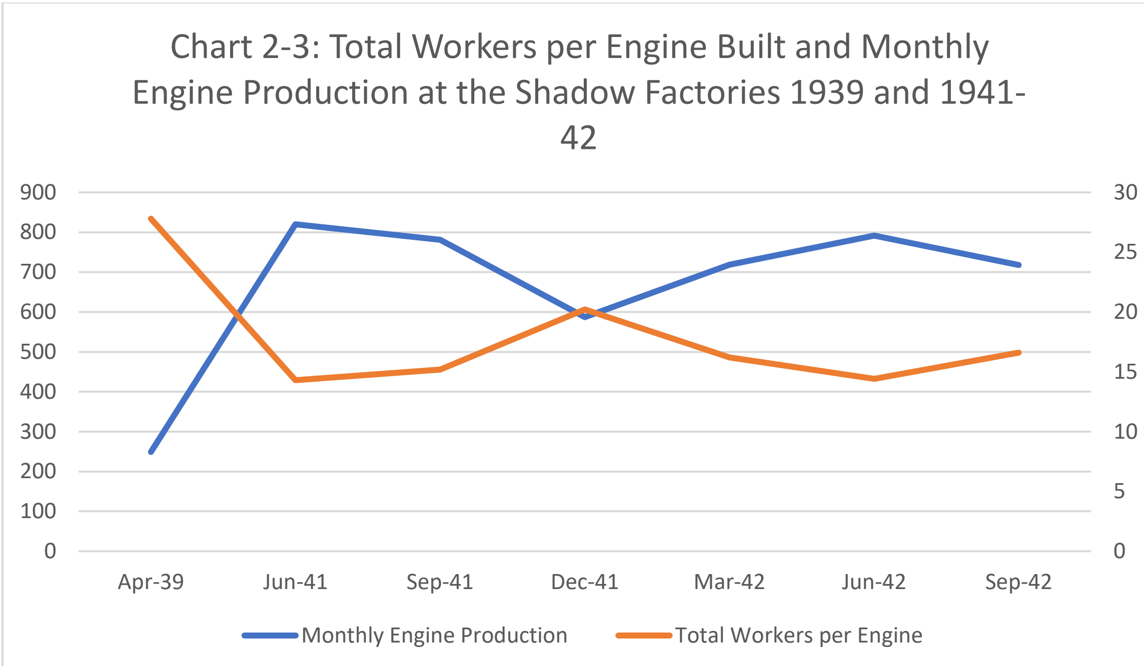
	August 1938	April 1939	June 1941	March 1942
Austin	1,112	1,327	2,211	2,211 est.
Daimler	1,243	1,351	2,481	2,713
Rootes	1,306	1,542	2,873	3,413
Rover	1,320	1,425	2,891	3,429
Standard Motor	801	1,266	1,952	2,576
Total	5,782	6,911	12,408	14,342 est.

Source: NA, AIR 6/58, 177th Progress Meeting, The Progress of Production for Air Re-armament, Appendix VI, Memorandum by D.G.P., 12th July 1939, AIR 6/58; NA, AVIA 10/383, Table Showing strength of wage earners at certain dates of total labour force at 7 March 1942.

Labour Productivity at the Shadow Factories

While determining how labour productivity changed at the shadow factories over time is difficult due to the lack of data, there is evidence that labour productivity nearly doubled as the factories shifted to large-scale production. Unfortunately, data on man-hours per engine or cost per engine at the factories during the war does not seem to have survived if it was calculated at all at the time. Some idea of labour productivity can still be obtained by measuring the total number of workers required to build one engine per month.[130] The number of total workers per engine built dropped from 27.8 total workers per engine in April 1939, as the factories entered their second year of production, to 14.3 per engine by June of 1941. More to the point, in June 1941, the factories built 229% more engines than they had built in April 1939, but with only 80% more total workers.

[130] Bitran and Chang: 'Productivity Measurement at the Firm Level', p. 35.



Source: Abridged Record of Engines, Spares and Accessory Output from Shadow Industry for 1938-44, *History of Production of Bristol Aero Engines by the Shadow Industry Operating Under the Joint Aero Engine Committee in Conjunction with the Bristol Aeroplane Company Limited,* XC03-8876/066, Royal Air Force Museum; Ministry of Aircraft Production, *Statistical Review 1939-1945*.

How did labour productivity improve at the factories? The shift to line production after the start of the war may well have had some effect as would more machine tools, but the factories do not appear to have acquired more special-purpose or advanced high-production machine tools that would have greatly improved worker productivity. This suggests that improvement came through the learning curve effect (see Chart 2-3). The concept of the learning curve, discussed in more detail in Chapter Seven, is that as workers and management gain experience in production of a product, they become more productive over time and the man-hours required to manufacture the product decline.[131] The factories were fortunate in that in the years from the start of the shadow factory scheme to the outbreak of the war they recruited a large number of personnel from the automobile and engineering industries around Birmingham and Coventry who, with the management of the factories, gained considerable experience in

[131] See Wright, T.P.: 'Factors Affecting the Cost of Airplanes', *Journal of Aeronautical Sciences*, Vol. 3, No. 4, (February 1936), pp. 122-128; Alchian, Armen: 'Reliability and Progress Curves in Airframe Production', *Econometrica*, Col. 31, No. 4, (October 1963), pp. 679-693; Rapping, Leonard: 'Learning and World War II Production Functions', *The Review of Economics and Statistics*, Vol. 47, No. 1, (February 1965), pp. 81-86.

building the Mercury and Pegasus before the shift to large-scale production after the start of the war.[132] By the summer of 1940, when output neared 200 engines a week, the factories had accumulated some three years of experience building Mercury and Pegasus engines. By this time, the factory managers, supervisors and skilled machine operators knew how to build these engines.

Despite the fact that the first shadow scheme for aero engine production did not evolve as the Government had originally intended, the scheme was, as Hornby notes, 'an outstanding venture into group organization for shadow industry development.'[133] The belief that the parent automobile factories could rapidly convert to aero engine production was a central feature of the shadow factory scheme. As late as September 1938, just after the Munich crisis, the Air Ministry's Air Council Committee on Supply was discussing plans for providing the parent automobile factories with machine tools for aero engine production.[134] That autumn a review of the possibility of conversion showed that only a small percentage of the machine tools in the automobile factories could be converted to aero engine production and that re-equipping the factories would be time consuming and result in severe delays in aero engine production as the automobile factories would not be available until after the outbreak of war.[135] The central premise of the shadow factory scheme for building Bristol engines proved to be flawed. The Air Council Committee on Supply also concluded that the existing factories should not be greatly expanded as this would make their principal drawback, the sole source supply chain system, even more vulnerable.[136] The Air Ministry had no feasible alternative to increasing the numbers of engines that could be built in the existing factories.

Fortunately, this effort proved successful. The transition to building the Mercury and Pegasus in greater quantities after the start of the war provided Bristol, the shadow factory managements and the Air Ministry and Ministry of Aircraft Production with invaluable experience. Production of the larger and more complex Bristol Hercules would, however, be

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[132] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 19.
[133] Hornby, *Factories and Plant*, p. 255.
[134] NA, AVIA 10/155, Notes of Meeting of the Air Council Committee on Supply, 30 September 1938.
[135] NA, AVIA 10/230, Air Ministry Memorandum No. 432, Treasury Inter-Service Committee, Bristol Type Engines-Provision of further capacity to provide war potential and to meet the present programme, 28 March 1939, p.2.
[136] Air Ministry Memorandum No. 432, p. 4.

entrusted to a new shadow factory group, set up on a completely different basis and on a completely different scale of factory size, production methods, machine tools and output.

Chapter Three: Building the Bristol Hercules

Introduction

This chapter will cover production of the Bristol Hercules engine, the second most-produced British wartime aero-engine after the Rolls-Royce Merlin. The 14-cylinder Hercules was larger, more powerful, and more complicated than the Bristol Mercury and Pegasus, and had a sleeve valve system. It represented a new generation of British aero engines, with more power than the early marks of the Merlin. Yet while the Merlin is famous, the Hercules is barely known despite the enormous scale in which it was made, and indeed the size and importance of the new factories which built it. This chapter for the first time tells the story of that production, making the crucial point that the factories and the methods and tools used were very different from those used to make the earlier generation of Bristol engines. We move here into the second type of wartime engine production, which was characterised by large plants, flow production, and the use of new automatic machine tools, mainly imported from the United States.

Hercules production was on a completely different scale from building the Mercury and Pegasus. To build the Hercules, the Government set up a completely new shadow factory scheme, using factories with four to five times the total floor area of the first shadow factories to build complete aero engines, not components. The new shadow factories were built on greenfield sites, well away from their parent automobile factories. They employed new flow production methods derived from the American aero engine manufacturers, not from Bristol, and new types of machine tools that semi- and unskilled workers, including a higher percentage of women, could use with minimum training. The new Bristol shadow factory at Accrington would become the model for these new methods, though the Accrington factory receives only a cursory mention in the literature. Yet, this chapter will also argue that the Hercules factories fell short of the goal of full flow production, due to constraints imposed on the design and location of the factories to minimise the risk of disruption from air attack.

The chapter will argue that large-scale production came from advances in production engineering, specifically the effort to achieve flow production through careful attention to plant layout, placing machine tools in the proper sequence of operations referred to as line production. The new shadow factories also benefited from greater attention to process engineering, reconfiguring manufacturing operations for greater efficiency and higher output. The new shadow factories succeeded in moving down the learning curve to improve productivity, even after the amalgamation of the first shadow factories into Hercules production.

Despite the importance of Hercules engines during the war, there is even less documentation than for production of the Mercury and Pegasus. The greatest gap is the loss of the correspondence between Bristol and the shadow factories documenting changes in production methods, though the Bristol history of Bristol's work with the shadow factories does provide some insights. The minutes of the Air Supply Board meetings cover changes in programme targets and expenditures for new machine tools and other equipment but say little about production. The most important source of information on Hercules production is the series of articles that appeared in industry magazines at the time. When compared to similar articles on Mercury and Pegasus production, the changes in manufacturing methods become apparent, particularly the differences in types of machine tools employed. There is even less information available about the factories that built the Hercules, even though these were some of the largest industrial buildings built in Britain during the war.

Organizing Production

Having determined that automobile factories could not be speedily converted to aero engine production, and reluctant to expand the first shadow factories because of their inherent vulnerability to disruption, the Air Ministry was left with no alternative but to arrange for production of the Bristol Hercules in a new set of factories. The war potential of the automobile firms was now seen as providing labour and management for the new shadow factories, rather than factory space or plant.[1]

The Air Ministry's new scheme, initiated in early 1939, had three elements: first, to build at Government expense a new shadow factory under Bristol management to be located away

[1] 160th Progress Meeting, War Potential-Aero Engines (Memorandum by A.M.D.P.).

from Bristol's Aero Engine Department at Filton; second, to expand Bristol's existing factory and plant at Filton; and third, to create a completely new shadow factory scheme with the automobile firms operating the existing shadow factories.[2] The Air Ministry now proposed that four firms—Standard, Daimler, Rootes and Rover (Austin having declined to participate in the new scheme)—be grouped in pairs, Standard with Daimler and Rootes with Rover, and that each pair would build complete Hercules engines.[3] Each firm in the pairings would build a factory, and each factory would manufacture 50% of the Hercules engine's components. One factory in the pairing—the Standard factory in the Standard-Daimler pairing and the Rover factory in the Rootes-Rover pairing—would take on responsibility for final assembly and testing. All these new factories were built on greenfield sites, away from the main works of the companies.

Each pair of factories was designed for an initial output of 100 complete engines per month on a day shift.[4] This was soon raised to 125 complete engines a month from each pairing, or 250 per month from the four factories.[5] The Bristol shadow, designated Bristol No. 3 Shadow Factory, would build complete engines and was to have an initial capacity of 260 Hercules engines a month, providing a combined capacity of over 500 Hercules engines a month from all five factories.[6] This was 125 engines per week, less than the Mercury and Pegasus production programme, but the Hercules was a more complicated engine to build.

The new No. 2 Shadow Group factories (the four large factories run by the motor firms) received substantial help from the factories in No. 1 Shadow Group (as the older shadow factories were now known). These were running down Mercury and Pegasus production as the now-obsolete Blenheim, Hampden and early marks of the Wellington went out of production.[7] At the

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[2] Postan, *British War Production*, p. 68.

[3] NA, AIR 46/159, *Narrative: Reciprocating Aero Engines and Engine Accessories Production & Programmes*, Paragraph 39; NA, AVIA 10/230, For Lord Austin's refusal, see memorandum of A.H. Self, Air Ministry, to Private Secretary, Secretary of State for Air, 12 May 1939.

[4] NA, AVIA 10/230, For Lord Austin's refusal, see memorandum of A.H. Self, Air Ministry, to Private Secretary, Secretary of State for Air, 12 May 1939.

[5] *Narrative: Aero-Engine Production Expansion of Capacity 1935-1945,* Capacity for Production of Bristol Engines, B) Shadow Schemes, p. 4.

[6] *Narrative: Aero-Engine Production Expansion of Capacity 1935-1945,* Capacity for Production of Bristol Engines, B) Shadow Schemes, p. 5.

[7] Capacity for Production of Bristol Aero Engines 1938-1945, p.7, *Narrative-Aero Engine Production Expansion of Capacity 1935-1945*; Adjustments of Aircraft Orders, Air Supply Board Meeting, S.B.M. 207/41, 22 March 1941, AVIA 10/181, NA.

end of December 1941 the Minister of Aircraft Production decided that No. 1 Shadow Group should convert to producing Hercules engines in cooperation with No. 2 Shadow Group, while continuing to manufacture the older engines and spare parts in diminishing quantities.[8] During 1942, the factories in No. 1 Shadow Group started producing component parts for the Bristol Hercules to support their No. 2 Shadow Group sister factories. In effect, the two groups were combined into one large production group for the Hercules.[9]

The Factories

As with the factories in the first shadow scheme, the key variables for factories built under the new scheme were location, size and design based on required monthly output. With the contribution of the parent automobile factories now seen as providing labour and management instead of factory space and plant for aero engine production, the Air Ministry wanted the new shadow factories to have access to this pool of workers and managers from their parent firms.[10] But because these new factories would be substantially bigger than the No.1 Shadow Group factories, they needed more space than was available near the automobile factories. The Air Ministry therefore decided that the new factories would be located in open country around Birmingham and Coventry, but not more than three to four miles from their parent automobile factories to ease problems of transportation and to avoid the need to provide housing.[11] Although they would work in pairs, the factories remained some distance apart and component parts and sub-assemblies had to be transported from one factory to the other for final assembly, adding time to the production process.

Daimler found a site three miles northwest of the centre of Coventry, and had received instructions to locate its new factory no more than five miles from the factory of its partner, Standard Motor, which was located three and a half miles to the west of the city.[12] For some

[8] Bristol No. 1 Shadow Group- Change over from Napier Sabre planning to Bristol Hercules VI production, Air Supply Board Meeting, S.B.M. 1058/41, 21 December 1941.
[9] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 23.
[10] 160th Progress Meeting, War Potential-Aero Engines (Memorandum by A.M.D.P.), 16 March 1939.
[11] *Narrative: Aero Engine Production Expansion of Capacity 1935-1945,* Capacity for Production of Bristol Aero Engines 1938-1945, P. 5.
[12] Richardson, Kenneth: *Twentieth-Century Coventry*, (Coventry, UK, 1972), pp. 66-67.

reason the same logic did not apply to the Rootes-Rover combination, as Rootes located its No. 2 Factory seventeen miles away from Rover. The Rootes plant was four and a half miles southeast of Coventry at Ryton-on-Dunsmoor, while Rover's No. 2 Factory was located at Solihull, eight miles from the centre of Birmingham. For the new Bristol No. 3 Shadow Factory, the Air Ministry chose a site near the town of Accrington, northeast of Manchester, west of the line demarcating the danger zone for air attack.[13] The Ministry believed that the Accrington factory could draw labour from the area around Manchester, although this would prove difficult to do.

The factories in No. 2 Shadow Group were substantially larger than the factories in No. 1 Shadow Group. The machine shops at each of the No. 2 Shadow Group factories covered around 660,000 sq. ft., with some of the assembly buildings almost as large.[14] In total area, with machine shops, assembly buildings, offices, canteen, test houses and other ancillary buildings included, each of the four shadow factories covered an area of close to 1,000,000 sq. ft. and in some cases more, more than five times larger than the average factory in No. 1 Shadow Group.[15]

The Standard No. 2 Shadow Factory at Banner Lane was the largest of the four factories. The complex consisted of three large parallel buildings, two for machining and one final assembly building, ancillary buildings and engine test stands that were separated from the final assembly building.[16] The total floor space was approximately 1,141,000 sq. ft..[17] At some 925,000 sq. ft. the Rover No. 2 Shadow Factory at Solihulll southeast of Birmingham was three times bigger than its No. 1 Shadow Factory, and comprised one large machine shop and a separate assembly building, plus engine test stands, separate from the assembly building, and ancillary buildings.[18] Daimler and Rootes, who did not assemble, each had one large machine shop and a separate building for putting sub-assemblies together. If each of the pairings is considered as a single factory unit, then the total area they occupied was probably close to 2,000,000 sq. ft. in total

[13] NA, AIR 2/3683, A.H. Self, Air Ministry, to the Bristol Aeroplane Company, 24 September 1939.
[14] This figure is derived from measuring post-war plans for the Daimler, Rover and Standard Motor No. 2 Shadow Factories.
[15] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 119.
[16] Richardson, *Twentieth-Century Coventry*, p. 68.
[17] NA, CAB 102/274, 'Government Owned Factories Operated by Contractors on Agency Terms' lists the size of this factory as 1,181,000 square feet.
[18] Richardson, *Twentieth-Century Coventry*, p. 67.

floor space, comparable to the new shadow factory Rolls-Royce was building at Hillington, near Glasgow, which had an initial floor area of 1,508,000 sq. ft.[19]

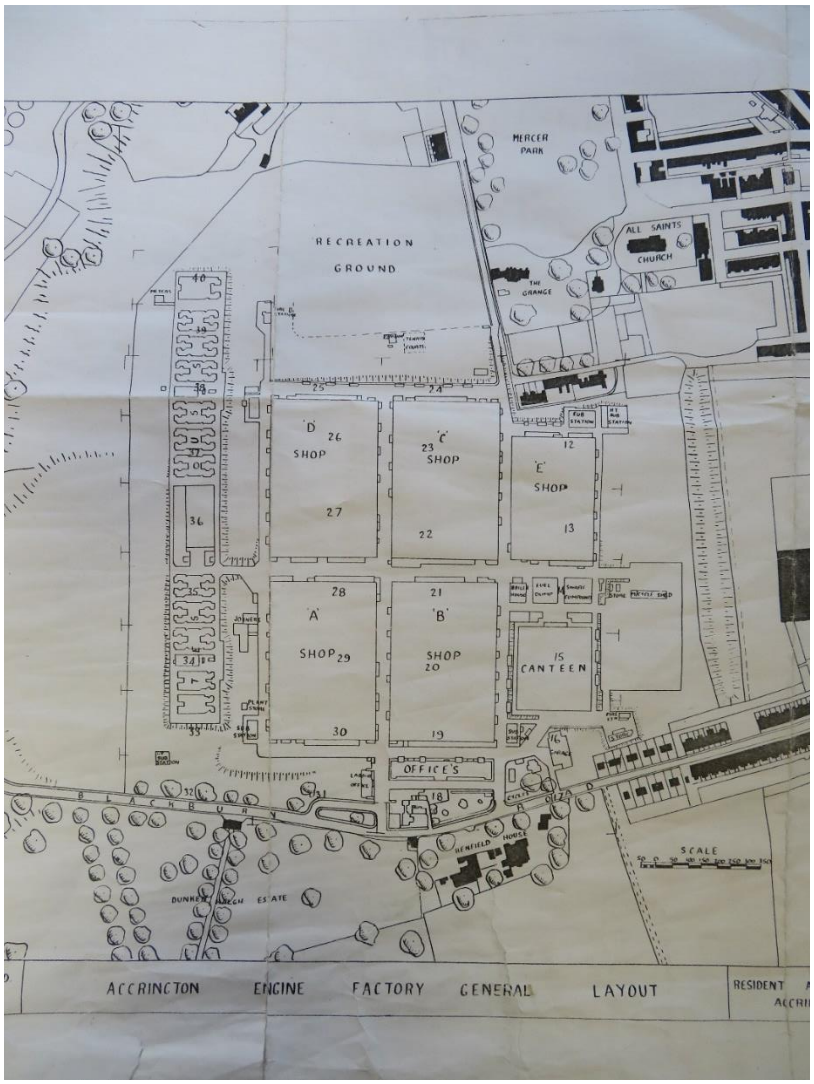

Illustration 3-1: A plan of Bristol No. 3 Shadow Factory at Accrington. Note how the factory was divided into five separate machine shops, A to E, instead of being built as one large single building. The engine test cells were to the left of the machine shops, separated by a large earthen berm and several hundred yards from Shop 'A', the engine assembly building. (This original factory plan provided courtesy of Mick Donnelly, Junction 7 Business Park, Accrington.)

[19] NA, AVIA 46/23, Capital Commitments as of December 1942, Schemes of Value over £800,000; *History of Production of Bristol Aero Engines by the Shadow Industry,* p. 119.

Bristol's No. 3 Shadow Factory at Accrington was a bit larger in total area as it was charged with building complete engines on one site, like the Rolls-Royce shadow factory at Hillington. The Accrington works comprised four large square buildings, comprising three separate machine shops to manufacture components and a fourth shop for engine assembly, each 200,000 sq. ft. in area (see Illustration 3-1).[20] Within the machine shop buildings, an average of 130,000 sq. ft. was devoted to machining operations. In the machine shops, for which accurate plans still exist, the bays appear to have been 30 ft. wide, allowing ample room for machine tools, with 18 bays per shop building. Special departments for heat treating or other processes were located alongside the machining areas. Bristol added a slightly smaller building of approximately 120,000 sq. ft. close by to build exhaust rings, cowlings, flame dampers and other external parts for the Hercules. There were 24 engine test stands occupying 260,000 sq. ft., placed several hundred yards from the final assembly building and protected with earthen berms, with only one entrance into the engine test stand area. Completed engines had to move from the engine assembly building by truck to the test cells and back again, which took time. With offices, canteen, and other ancillary buildings the Accrington factory had over 1,300,000 sq. ft. in total floor space.

The new factory buildings were typical of the period, large steel sheds with steel columns, placed on a thick concrete slab, supporting strong steel beams with steel trusses attached to the beams to support the roof structure.[21] Most of the buildings had a north-lit, saw-tooth roof to allow in daylight, with some additional artificial lighting, although in some factories the daylight glazing may have been blacked out at all times. Walls were of brick and were not intended to provide structural support but to keep out the weather and provide some protection from bomb fragments.[22] The need to incorporate measures for air raid protection was the principal difference between the new and the older shadow factories.

The need for the factories in No. 2 Shadow Group and Bristol's No. 3 Shadow Factory at Accrington to take precautions externally and internally against damage from air attack had a significant impact on the design and layout of these factories. The British Government's concern

[20] NA, AIR 2/3683, See Bristol Brochure of 11 September 1939, Air 2/3683 and diagrams of Accrington works in Air 2/3684.
[21] Collins and Stratton, *British Car Factories from 1896*, p. 50.
[22] 'Single Storey Wartime Factory Design', p. 76.

with air raid protection focused on dispersal of factory buildings and production lines 'to reduce to a minimum any interference with production by bomb hits.'[23] The goal was to avoid disrupting production and a key to this was to move away from the trend toward very large industrial buildings.[24] To limit damage, it was deemed preferable to have several smaller buildings rather than a single large structure. A direct hit on a single large building could destroy the entire roof removing protection for the machine tools inside, but smaller buildings could contain an explosion, to some extent, thereby preventing damage to adjacent buildings.[25]

The Government recommended that factory buildings should be spaced widely apart, with a minimum of 50 ft. between buildings and should not be in parallel nor in a regular or symmetrical form, although the factories in No. 2 Shadow Group did not follow this prescription. This need, in turn, had a significant effect on the ability of these factories to maximize the potential for flow production. Furthermore, to protect machine tools in the factories the Government recommended that blast walls be built laterally within the factory buildings.[26] The Bristol Accrington factory and the Rootes Ryton factory both incorporated internal blast walls and it is likely that the other shadow factories did as well (see Illustration 3-2). The blast walls at the Rootes factory were '…fourteen inches thick and constructed at different heights according to the configuration of the equipment being protected.'[27] Up until late 1943, the machine shops at the Bristol Accrington factory had extensive blast walls within the machining area for air raid protection (see Illustration 4-2 below). These were 1 ft. 2 in. wide and 4 ft. 6 in. high.

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[23] Section XI, 'Standard Designs for Single Storey Factories for War Industries, With Notes on Siting and Layout', *Wartime Building Construction*, First American Edition, (New York, 1942), p. 118.
[24] Ministry of Home Security, Research and Experiments Department: Bulletin C 12, 'Single Storey Wartime Factory Design', *Journal of the Institution of Civil Engineers*, Vol. 16, No. 5, (March 1941), p. 73.
[25] Ministry of Home Security, 'Single Storey Wartime Factory Design', p. 73.
[26] 'Standard Designs for Single Storey Factories for War Industries, With Notes on Siting and Layout', pp. 117-18.
[27] Thoms, *War, Industry and Society*, p. 111.

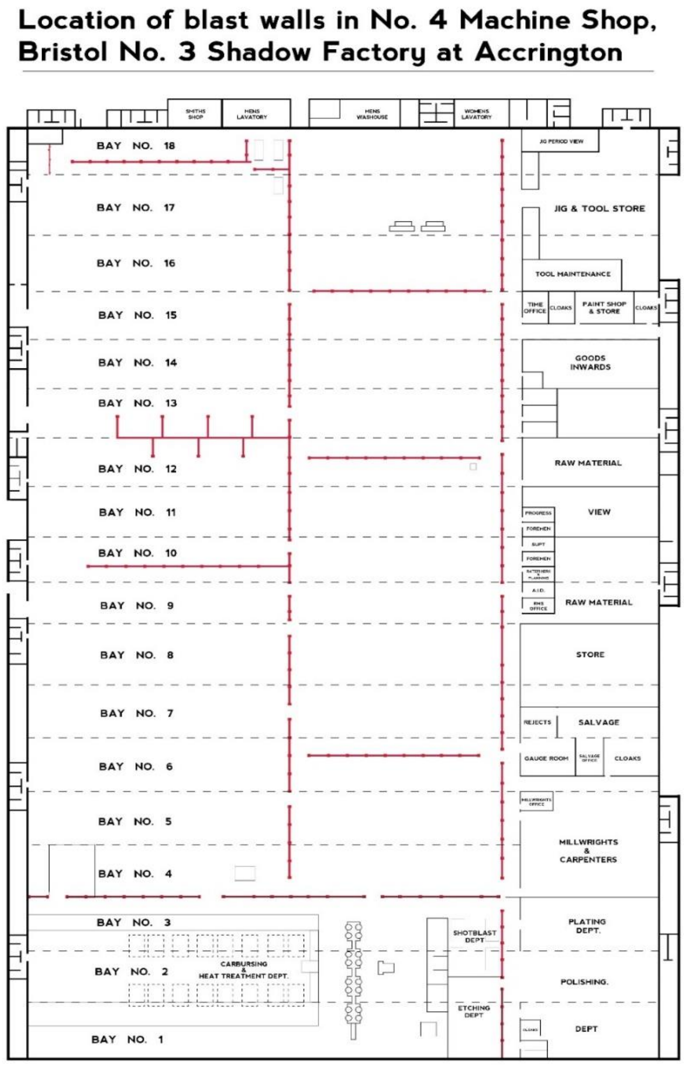

Illustration 3-2: This illustration shows the layout of the blast walls in the No. 4 Machine Shop at the Bristol No. 3 Shadow Factory at Accrington, taken from the original factory plans. The blast walls were apparently removed in late 1943 or possibly later. The factory management told the Ministry of Aircraft Production that the walls had '…always caused great inconvenience.'[28]

Although the factories of No. 2 Shadow Group would adopt elements of line production, the restrictions air raid precautions imposed on the factories were not ideal for this method. In the ideal case, line production contributes to an improved flow and thus speed of work. In line

[28] NA, AVIA 200, Bristol Aeroplane Co. Ltd., Accrington-Engine Factory- Proposal to remove protective walls in machine shop, 21 September 1943, Air Supply Board Meeting No. 269, 30 September 1943. The Board deferred a decision out of concern that demands from other factories would require considerable construction labour, and a concern that workers would think their safety was being compromised.

production ‘the material moves *continuously* and at a *uniform rate* through a sequence of balanced operations which permit of *simultaneous performance* throughout, the work progressing toward completion along a *reasonably direct path*.’[29] At these factories, the flow of work was not continuous nor was the path direct. The location of blast walls within the machine shops would have interfered with the placement of machine tools and the flow of work and would have restricted mechanical conveyor systems. Finished parts had to move between buildings at most of the factories, from the machine shops to final assembly in separate buildings. Completed engines had to be taken from the assembly building to the engine test sheds and brought back to the assembly building for final inspection. All these steps added time to the production process, invariably slowing production from what might have been achieved in a larger, single purpose machine and assembly building. This was not true flow production.

The Production Record

The first complete Hercules engines emerged from No. 2 Group factories in January 1941, eighteen months after receiving approval to begin factory construction, although this was behind original estimates. Within nine months of completing the first engines, the factories had exceeded their initial targeted output of 250 complete engines per month. By May 1942, the factories were building over 500 Hercules engines a month and by the end of the year production had reached over 800 engines a month (see Chart 3-1).[30] When the Air Ministry shifted No. 1 Shadow Group to Hercules production in 1942, the Ministry set a target for No. 1 Shadow Group to produce Hercules components equivalent to 500 engines a month, giving a combined shadow factory production of 1,350 complete Hercules engines a month to be reached by August 1943. In the event, the combined shadow factories reached this goal in November 1943, two months late.[31] In August 1943, the Ministry of Aircraft Production instructed No. 1 and No. 2 Shadow Groups to plan for a production rate of 1,500 Hercules engines a month with an additional 300

[29] Muther, *Production-Line Technique*, (New York, 1944), p. 10.
[30] *History of Production of Bristol Aero Engines by the Shadow Industry*, Abridged Record of Engines, Spares and Accessory Output from Shadow Industry for 1942.
[31] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 23.

engine sets in the form of spare parts, and to achieve this rate by July 1944.[32] The factories attained this level of production in March 1944, which turned out to be the peak level of output from the two shadow groups.[33] This was eight times the production rate of 1939.

The Bristol No 3 Accrington factory took longer to get into production. The factory did not meet its initial target of 260 Hercules engines a month until some 15 months from the start of production in early 1941, and only achieved its later planned production rate of 400 engines a month in January 1944, and then only for a few months before the Ministry of Aircraft Production began to scale back Hercules production later in the year.[34] The factory suffered from two persistent drawbacks, as well as occasional shortages of machine tools which caused a reduction of 530 engines in the factory's 1943 production programme.[35] The original plan for the factory was based in part on the expectation that the factory could draw on a wide range of sub-contractors, but this proved not to be the case, leading to shortfalls in production.[36] Labour proved to be a persistent problem. The many munitions plants in Manchester and the Coventry area absorbed workers that might otherwise have gone up to Accrington.[37]

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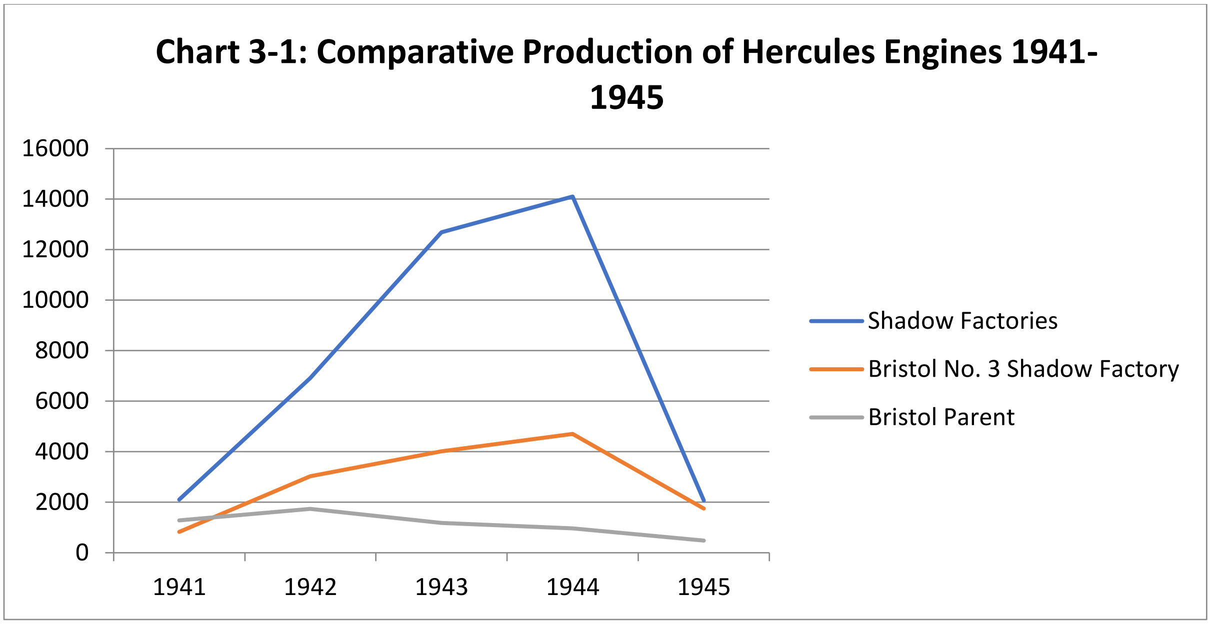
[32] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 23.
[33] *History of Production of Bristol Aero Engines by the Shadow Industry*, pp. 23-24.
[34] *Narrative: Aero-Engine Production Expansion of Capacity 1935-1945*, Capacity for Production of Bristol Engines, P.4; NA, AVIA 15/414, Minute of D.P. Welman, DDGEP, Ministry of Aircraft Production, 11 May 1944.
[35] *Narrative: Reciprocating Aero Engines and Engine Accessories Production & Programmes'*, Paragraph 222.
[36] Minute of D.P. Welman, DDGEP, Ministry of Aircraft Production, 11 May 1944.
[37] *Narrative: Reciprocating Aero Engines and Engine Accessories Production & Programmes'*, Paragraph 225.



Source: Ministry of Aircraft Production Statistical Review 1939-1945; *History of Production of Bristol Aero Engines by the Shadow Industry*, Abridged Record of Engines, Spares and Accessory Output from Shadow Industry 1941-1945; New Engines Delivered-Piston Engines, Rolls-Royce Heritage Trust**.**

Just after reaching the peak Hercules production in March 1944, a labour shortage forced the Ministry of Aircraft Production to cut its aircraft programme and cancel the shadow factory target of 1,500 Hercules engines a month.[38] The Ministry ordered the factories to cut back to 1,350 Hercules engines a month and they remained at this level until August 1944.[39] By October 1944 production had dropped below 1,000 engines a month and continued to decline until production ceased in the summer of 1945. Of the 60,672 Hercules engines built during the war, the No. 1 and No. 2 Group contributed 37,884 or 62%.[40] Bristol's No. 3 Shadow Factory built 14,379 Hercules engines, making the total for the combined shadow factories 52,243 engines, equal to 86% of the total Hercules production.[41] As the new factories ramped up Hercules production, the Bristol parent factory concentrated more on engine development, coming out with improved models of the Hercules and the more powerful 18-cylinder Centaurus so that its contribution to Hercules production declined after 1942.

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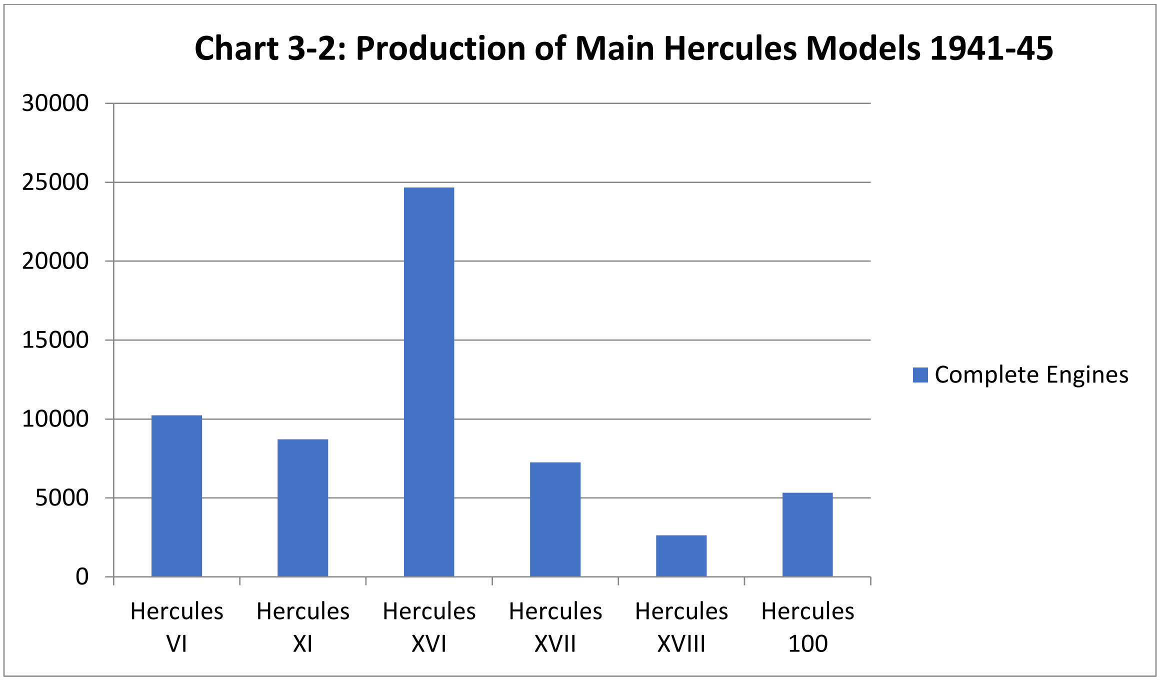
[38] Cairncross, Sir Alec: *Planning in Wartime: Aircraft Production in Britain, Germany and the USA*, (London 1991), p. 88.
[39] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 24.
[40] Ministry of Aircraft Production *Statistical Review 1939-1945*, pp. 31-32.
[41] *Statistical Review 1939-1945*, p. 28.



Source: Ministry of Aircraft Production Statistical Review 1939-1945; *History of Production of Bristol Aero Engines by the Shadow Industry,* Abridged Record of Engines, Spares and Accessory Output from Shadow Industry 1941-1945; New Engines Delivered-Piston Engines, Rolls-Royce Heritage Trust**.**

Bristol and the shadow factories achieved a good balance between quantity and quality, Holley's 'dilemma of mass production'. What is particularly important about this record is the ability of Bristol and the shadow factories to respond to the unforeseen increase in demand for Hercules engines that came out of the 1941 Heavy Bomber Programme, which led to increased production of the Hercules-powered Wellington bomber and the decision to re-engine the Halifax bomber with the Hercules. During 1942 Bristol and the shadow factories nearly tripled Hercules production, boosting production by over 50% again during 1943, and sustaining a high level of production through most of 1944 (see Chart 3-1).[42] Furthermore, between 1941 and 1945, the shadow factories built six different models of the Hercules, while the Accrington factory built five models (see Chart 4-2).[43] Transitioning from one engine model to another was not, as might be assumed, a simple matter as often the change-over required substantial re-tooling. The

[42] Ministry of Aircraft Production, *Statistical Review 1939-1945*, II. Engines, Table 9, p. 26.
[43] Ministry of Aircraft Production, *Statistical Review 1939-1945*, II. Engines, Table 12, pp. 30-31.

Hercules 100, the last model built during the war, had a completely new type of carburettor to install and a redesigned supercharger.[44] In the case of production of the Hercules 100 at the Rover No. 2 Shadow Factory, the new model had seven completely new components and seven existing components that required radical modifications to their manufacture, the combination of new and modified components requiring 44 new machine tools.[45] This combination of quantity and quality production took place in the face of continued dilution of the skill levels in the work force and progressive 'deskilling' of the manufacturing process.

The factories regularly brought a new model of the Hercules into production while simultaneously phasing out an older model, at times producing multiple models concurrently. The two models of the Hercules built in greatest numbers were the Hercules VI and the Hercules XVI. During the war, No. 1 and No. 2 Group factories and the Accrington factory built 9,106 Hercules VI engines, but even more of the Hercules XVI, completing 24,381 by the end of the war.[46] In general, Bristol and the shadow factories managed this process well, sustaining production while converting to a new engine model with few disruptions.[47] The Rover and Rootes No. 2 Shadow Factories, for example, began manufacturing the Hercules XI in 1941, ending production in 1942 and shifting to the Hercules VI, ending production of the Hercules VI in early 1943 and shifting to the Hercules XVI, which the factories continued to produce until the end of the war (see Chart 3-3). The factories started producing the Hercules XVII and XVIII at the end of 1943 and continued to produce these models until the beginning of 1945, but in April 1944 shifted their main effort to the Hercules 100.[48]

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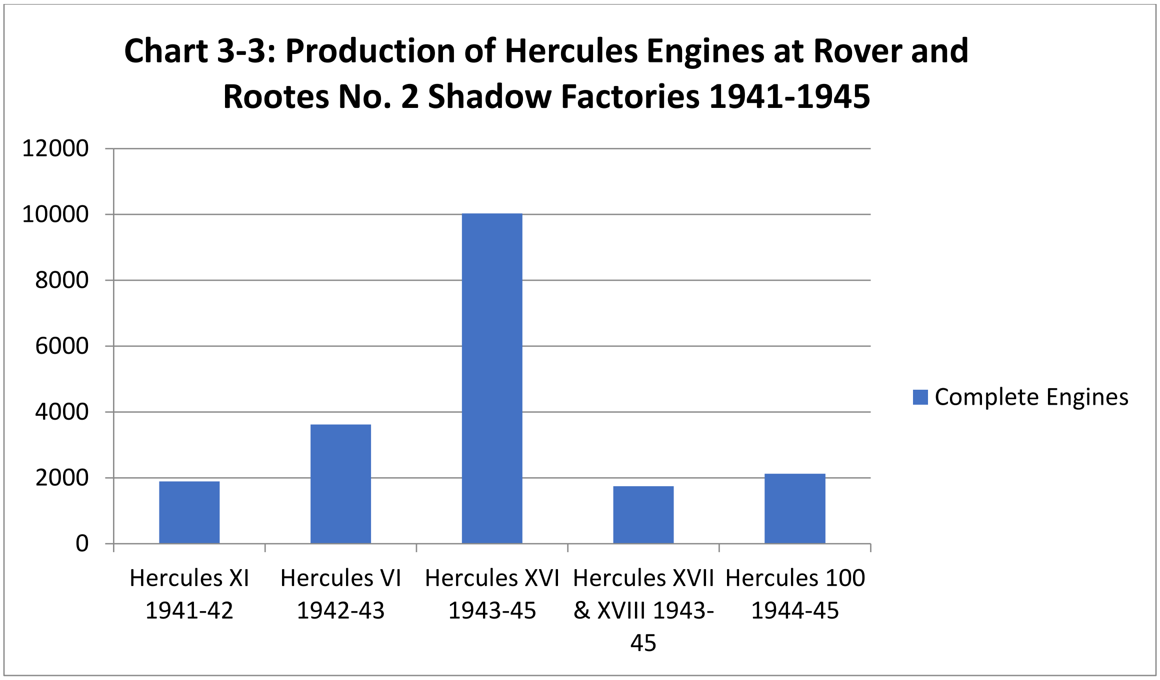
[44] *Narrative: Reciprocating Aero Engines and Engine Accessories Production & Programmes*, Paragraph 228.
[45] *Narrative: Reciprocating Aero Engines and Engine Accessories Production & Programmes*, Paragraphs 228.
[46] Ministry of Aircraft Production, *Statistical Review 1939-1945*, II. Engines, Table 12, pp. 31-32.
[47] Cairncross, *Planning in Wartime*, p. 87.
[48] Chart of Hercules engine production, The Rover Company Limited (Aero Engines) No. 2 Factory, Lode Lane, Solihull, Diary 1939-1945.



Source: The Rover Company Limited (Aero Engines) No. 2 Factory, Lode Lane, Solihull, Diary 1939-1945, L-RCO-103, British Motor Industry Heritage Archives, British Motor Museum

How it Was Done: Building the Hercules Engine

The Hercules was a complex piece of precision engineering with over 7,000 parts, more than double the number of parts in either the Mercury or Pegasus, and took 4,457 man-hours to build compared to 3,662 man-hours for the Pegasus XVIII.[49] The Hercules had fourteen cylinders arranged in two rows of seven and a two-speed blower.[50] The crankcase, made from forged aluminium alloy, was in four sections, a front cover, front section, centre and rear sections. The operating mechanism for the sleeve-valves in each of the fourteen cylinders was attached to the front section of the crankcase, with a series of gears driven by the crankshaft that drove fourteen cranks that operated the sleeve in each cylinder. The blower assembly and other accessories attached to the rear section of the crankcase. As a double-row engine, the Hercules had two main journals for the two connecting rod assemblies, one for each bank of cylinders, each assembly

[49] Bristol Aeroplane Co. Ltd.: *The Power Behind Their Wings: An account of the part played by the Bristol Aeroplane Company in the development of the air-cooled radial aero engine in Great Britain*, (No Date), p. 35; Table of man-hours for aircraft and aero engines, CAB 102/274, National Archives.
[50] Bristol Aeroplane Co. Ltd.: *"Bristol" Hercules VI-XI-XVI-XVII-XVIII Operator's Handbook*, (August 1945), p. 12.

having a master rod and six connecting rods made from forged steel alloy. The crankshaft was made of nickel-chrome Nitralloy steel, stamped to rough form, and then machined. The crankshaft drove the propeller through a series of reduction gears at the front of the crankcase and the impeller blades of the blower through gears attached to the rear section of the crankcase. Though there were more of them to manufacture, these components of the Hercules were basically the same as those in the Mercury and Pegasus and did not require more complex machining.[51] The Hercules cylinder and sleeve-valve were not so straight-forward.

The sleeve-valve cylinder barrel for the Hercules presented '…many machining difficulties, particularly for line production.'[52] The top and bottom thirds of the Hercules cylinder had concentric fins to aid cooling, but the middle third, termed the induction belt, had two exhaust ports and three inlet ports, with eccentric fins (i.e. not completely circular) in between.[53] The ports had a difficult profile that had to be cut to precise limits, while the cooling fins on the outside of the cylinder varied in depth adding to the difficulty of machining the cylinder barrel. Manufacturing the sleeve itself was even more challenging and resulted in '…possibly more manufacturing problems than any other component.'[54] To fit between the wall of the cylinder barrel and the piston, the sleeve had to be exceptionally thin, a little over 1/10 of an inch thick, machined to a tolerance of .0012 of an inch.[55] The thinness and hardness of the sleeve meant that distortions could occur after every machining operation.[56] These distortions could lead to seizure of the piston. Bristol spent considerable effort to find the correct material for the sleeve, finally determining that a sleeve made from austenitic nickel-chrome-tungsten steel, with nitriding, would work best.[57] In the fall of 1939, as No. 2 Shadow Group's new shadow factories

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[51] See 'The Production of the Bristol Hercules Engine: Methods and Plant Employed in one of the Recently Built Government "Shadow" Factories', *Machinery (London)*, Vol. 60, No. 1528, (January 22, 1942); 'The Production of Aero engine Crankshafts: Methods Employed at a Government "Shadow" Factory in the Manufacture of the Bristol Hercules Engine', *Machinery (London)*, Vol. 60, No. 1534, (March 5, 1942).
[52] Oates, J. A.: 'The Bristol Hercules: Part I. Sleeve Valve Design and Operation: Manufacturing the Cylinder and Sleeve', *Aircraft Production*, Vol. IV, No. 40, (February 1942), p. 178.
[53] Oates, 'The Bristol Hercules: Part I', p. 178.
[54] Oates, 'The Bristol Hercules: Part I', p. 183.
[55] Bristol Co., *The Power Behind Their Wings,* p. 32.
[56] Oates, 'The Bristol Hercules: Part I', p. 183.
[57] Bristol Co., *The Power Behind Their* Wings, p. 31.

were under construction, Bristol was still having problems manufacturing the Hercules.[58] It took Bristol several years to overcome the sleeve-valve's production problems and establish true interchangeability.[59]

A description of manufacturing the Hercules engine begins with the cylinder. Manufacturing the cylinder barrel alone required over 100 separate machining operations.[60] The cylinder barrel was made from an aluminium alloy forging that weighed 54 lb. at the start of machining and 22 lb. at the end. One of the more difficult operations on the cylinder barrel was to machine the cooling cylinder fins. The Hercules cylinder had two banks of 20 concentric cooling fins on the top and bottom sections, and 19 eccentric cooling fins in the centre section in between the inlet and exhaust ports. The special Maxi-cut lathe that Bristol helped to develop with the British Drummond Brothers machine tool company could cut the 40 concentric fins on the side of the cylinder barrel in one operation using 78 separate tungsten carbide cutting tools. Later in the war a further development of this Maxi-cut machine allowed cutting either the concentric or the eccentric cooling fins, using up to 100 cutting tools in a completely automatic operation.[61] This seven-ton machine had the rigidity to enable thousands of cylinders to be cut using the same set of cutting tools. The cylinder head consisted of two light aluminium alloy die castings. A standard American Heald Borematic machine was specially adapted to automatically machine all the external surfaces of the cylinder head, the operator simply loading and unloading the work pieces onto the machine.[62]

Manufacturing the sleeve was the most difficult of all the machining operations for the Hercules engine.[63] The sleeve was a 14 in. long cylinder with a diameter of 6 and 1/8 in. and a thickness of 1/10 in., with a thicker eccentric base belt that housed a pocket for the ball joint that turned the sleeve in the cylinder. The Firth-Vickers Co. Ltd. in Sheffield provided Bristol and the

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[58] Bristol Aeroplane Company Minutes of Directors' Meeting in Committee, 21 November, 12 December 1939, BAC Directors' Committees Minutes, Vol. 7.

[59] Neale, M.C., ed.: *An Account of a Partnership-Industry, Government and the Aero Engine: The Memoirs of George Purvis Bulman,* Rolls-Royce Heritage Trust Historical Series No. 31, (Darby, UK, 2002), pp. 180-81.

[60] Oates, 'The Bristol Hercules: Part I', p. 177.

[61] 'Machining Cylinder Fins', *Aircraft Production*, Vol. VI, No. 66, (April 1944), pp. 155-56.

[62] Oates, J.A.: 'The Bristol Hercules: Part II. Production of the Master Connecting Rod, Airscrew Shaft and Cylinder Head: The Sleeve Ball and Housing', *Aircraft Production*, Vol. IV, No. 41, (March 1942), pp. 251-52.

[63] Oates, 'The Bristol Hercules: Part I', p. 183.

shadow firms with nickel-chrome-manganese steel forged sleeves in rough form. The critical aspect of the machining process was to avoid any distortion of the sleeve which would prevent it from fitting in the cylinder barrel. Through trial and error, Bristol found ways of machining the sleeve in successive stages to reduce the risk of distortion, taking off only small amounts of excess material during each operation. British James Archdale and Co. boring machines performed a rough boring of the internal surfaces of the sleeve, while an American Cincinnati Milling centreless grinding machine finished the external surfaces. Later on in the war a six-station American Bullard Multi-Au-Matic performed these operations, with four stations working at the same time while two were loading and unloading the work pieces.[64] Until Bristol developed a special purpose machine for punching out the inlet and exhaust ports on the sleeve, the factories used a specially designed James Archdale Co. four-spindle profiling machine to machine the ports, working on two sleeves at a time. Grinding the base at the bottom of the sleeve took place on a special grinding machine designed to operate on seven sleeves simultaneously. After these operations, the sleeves went through a nitriding process for extra hardening, then final finishing. Strict quality control and inspection throughout the machining process ensured that the maximum ovality of the sleeve did not exceed .0025 in.[65]

Machining the remaining main components of the Hercules— crankcase, crankshaft, master rod and articulated rods, piston, blower and propeller shaft and reduction gear —was more straightforward and followed normal practice for machining these parts, but here too Bristol and the shadow factories developed special purpose machine tools to speed production. The Hercules crankcase was made up of four light alloy forgings, with front, centre and rear sections and a front cover which were bolted together to form the complete unit.[66] The front cover and the three main sections required a large hole to be bored through for the crankshaft, while the three main sections had fourteen positions for attaching the cylinder barrels, with twelve holes drilled around each position to bolt the cylinder barrel to the crankcase. The front cover and centre section required seven holes each for the cranks driving the sleeve-valve

[64] Oates, J.A.: 'Hercules Engine Components: Machining Operations on the Crankcase, Impeller, Sleeve, Cylinder Barrel and Connecting Rods', *Aircraft* Production, Vol. VI, No. 69, (July 1944), pp. 314-15.
[65] Oates, 'The Bristol Hercules: Part I', p. 186.
[66] Oates, 'Hercules Engine Components', p.309.

mechanisms. These repetitive operations provided an opportunity for machines that could perform multiple operations simultaneously or operate on several work pieces at the same time. Production engineers also broke down standard operations on the crankcase into multiple operations for unskilled workers.[67] Much of the initial finishing of the exterior of the crankcase sections took place on a British Alfred Herbert Company turret lathe equipped with multiple tools for drilling and grinding. A twin-head Archdale boring machine bored holes for the two rows of cylinder barrels using two boring tools, with the crankcase temporarily bolted together and mounted on a table, which the operator turned in sequence. To drill holes for the cranks for the sleeve-valves mechanisms, a Heald Borematic drilled all the required holes in a sequence of operations on the same machine without having to remove the crankcase.

As a double-row engine with two banks of cylinders, the Hercules required a two-throw crankshaft to attach the two master connecting rods for each bank of cylinders. The crankshaft was made of three sections, the front section, called the front web, which held a damping device and a splined shaft to connect with the propeller shaft, the centre section, the central crank, and the rear web which also had an attached damping device.[68] The crankshaft sections were steel forgings that were machined to a fine finish. There appear to have been fewer opportunities to build special machine tools for multiple operations on crankshaft sections, though in a few operations two work pieces could be mounted on a single machine. The external profile of the master connecting rods, however, could be machined four at a time on the same milling machine, while another type of milling machine could perform operations on six articulated rods simultaneously.[69]

Bristol engineers developed several special purpose machines to manufacture the blower (supercharger) for the Hercules. The volute casing (the section of the blower that received the fuel/air mixture after compression), an aluminium-alloy casting, had a combination of boring and facing operations carried out on a single Herbert combination turret lathe, the different turret

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[67] 'Turret Lathe Operations on the Hercules Crank Case', *Machine Tool Review*, Vol. 31, No. 184, (March-April 1943), p. 27.

[68] Oates, J.A.: 'The Hercules Crankshaft: Design Features: Machining and Assembly Operations at a Shadow Factory', *Aircraft Production*, (February 1944), pp. 59-66.

[69] Oates, 'Hercules Engine Components', pp. 313-14.

faces holding the necessary tools for each operation.[70] A single three-spindle Archdale drilling machine performed both drilling and tapping operations required on the volute casing.[71] Machining the impeller for the blower presented other production problems, particularly machining the complex shape of the pockets between the blades on the impeller which varied in length and depth.[72] Specially designed milling machines had to be developed to carry out this machining operation, two machines working in pairs with one machine working on the periphery of the forged alloy impeller stamping and the second machine working progressively inward to the centre of the impeller. The operations on both machines were fully automatic and continuous, the work piece attached to a special fixture. These special milling machines were modifications of another type of machine designed to mill the inlet and exhaust port contours on the sleeves and cylinders of the Hercules engine.[73]

Completed components flowed toward the assembly area where teams assembled complete Hercules engines and sent them on for rigorous testing. The assembly and testing processes were far more complex than in automobile assembly. The assembly section had three departments, one to assemble the engine before testing, a second to disassemble and inspect every part in each engine after testing and the third to re-assemble the engines for shipment.[74] Final assembly was the closest approximation to the assembly lines familiar in automobile factories. There were eight stations in the engine assembly section but no continuous moving assembly line. Instead, workers moved the engines, mounted on special cradles, from station to station along rail tracks set into the flooring. Component parts and sub-assemblies arrived at the appropriate station in the proper sequence. Several components and sub-assemblies were added to the engine at each station. In contrast to the moving assembly line in automobile factories, assembly had to be done with great precision, often using torque wrenches set to a specific tension, and the fit and operation of parts tested before moving to the next station. The assembly

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[70] 'The Production of the Bristol Hercules Engine: Methods and Plant Employed in one of the Recently Built Government "Shadow" Factories', *Machinery (London)*, Vol. 60, No. 1528, (January 22, 1942), p. 9.
[71] 'The Production of the Bristol Hercules Engine', p. 9.
[72] 'The Production of Supercharger Impellers', *Machinery (Lon)*, Vol. 60, No. 1535, (March 12, 1942), pp. 169-70.
[73] 'The Production of Supercharger Impellers', p. 173.
[74] Oates, J. A.: 'The Bristol Hercules: Part III. The Gear Department: Engine Assembly and Testing: Heat Treatment and Process Sections: Laboratories and Standards Room', *Aircraft Production*, Vol. IV, No. 42, (April 1942), p. 304.

team at the first station bolted the crankcase onto the engine cradle and added the crankshaft sub-assembly. As the assembly teams moved the cradle along the rail track, the engine gained pistons, sleeves, cylinders, the many gears operating the sleeve-valves, the complete blower assembly and the main accessories (such as carburettors, magnetos and oil pumps). Whether the assembly teams moved with the engine from station to station or remained at a set station, as was the case in automobile assembly lines, is uncertain.

Every single one of the 60,672 Hercules engines built during the war underwent a through test before it left the factory, beginning with a five-hour running in period during which an electric motor drove the engine to test the workings of all components together.[75] The engine next moved to a sound-proof testing station where workers inserted spark plugs and attached oil and gas lines for running the engine on its own power, first a period of running at low power then progressively increasing the throttles to run the engine at rated power for two hours. The engine was run at full power for five minutes and returned to the assembly shop to a separate disassembly line where it was stripped-down, and every individual part subjected to a minute inspection. The component parts of the engine next went to the final build line for re-assembly and a final engine test to check fuel and oil consumption. After this final test, the engine went back to the assembly shop for cleaning and preparation for packing and shipment. It is important to recall that, as with manufacture of the Mercury and Pegasus, inspection and quality control was continuous throughout production, from raw materials to completed engine.

How it Was Done: Setting Up Large-scale Production

The Bristol Aeroplane Company used knowledge gained from other industries, especially from American aero engine manufacturers, and developed completely new production processes developed specifically for Hercules production. This involved an intensive effort at production engineering, setting up the factories for flow production, and process engineering, determining the manufacturing processes and sequences that would be required to build the Hercules engine

[75] Oates, 'The Bristol Hercules: Part III', p. 306.

and the types and number of machine tools that would be needed for quantity production.[76] New production processes most often required new types of machine tools and in developing these tools Bristol relied on the principle of the transfer of skills, from the skilled machinist to the semi- and unskilled machine operator by incorporating new jigs and fixtures for standard machine tools or by designing new types of machine tools with expanded capabilities.[77] To build the Hercules in quantity Bristol would borrow production methods from the principal American aero engine manufacturers, Pratt & Whitney and Wright Aeronautical, and purchase many more machine tools from America's leading machine tool manufacturers.

In September 1939, Air Marshal Sir Wilfrid Freeman, Air Member for Research and Development at the Air Ministry, encouraged the Air Ministry to specifically request Bristol to explore 'Americanising' their production practices, adopting American production methods and American machine tools where possible to attain 'a standard of efficiency which would reduce the number of operations and labour requirements.'[78] The Air Ministry wanted Bristol to determine if, for certain machining operations, American machine tool companies could develop one machine tool that could replace the operations of several others.[79] Bristol had already asked authorization to purchase up to 80% of the machine tools needed for the Accrington factory in America given the large backlog and long delivery dates in the British machine tool industry.[80] The demands for new plant from the factories for No. 2 Shadow Group, as well as from other sectors of the aircraft and munitions industries, had placed huge demands on the British machine tool industry to the extent that deliveries of certain types of machine tools, particularly grinding machines, would take over a year to deliver in quantity.[81] The Air Ministry agreed to Bristol's request and arranged an authorization from the Treasury for Bristol to purchase machine tools in America, with an initial limit of £1.25 million ($5 million).[82] Bristol agreed to send a production

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[76] Muther, *Production Line Technique*, pp. 37-38, 44-55; Lilley, *Problems of Accelerating Aircraft Production*, p. 52.
[77] Hesse, Herman: *Engineering Tools and Process: A Study in Production Technique*, (New York, 1941) p. 345.
[78] NA, AIR 2/3683, Notes on a Meeting at Bristol on 28th September 1939.
[79] Notes on a Meeting at Bristol on 28th September 1939.
[80] NA, AIR 2/3683, Air Council Committee on Supply, New Bristol Engine Shadow Factory at Accrington, Note by P.S.S. (M).
[81] NA, AIR 6/58, The Progress of Production for Air Re-armament, Memorandum by D.G.P., 12 July 1939.
[82] Air Council Committee on Supply, New Bristol Engine Shadow Factory at Accrington, Note by P.S.S. (M).

engineer to the United States to investigate American methods and purchase American machine tools, selecting Frank Whitehead, Bristol's Machine Shop Superintendent, for the job.[83] The Air Council Committee on Supply met on 3 October 1939 to confirm that the Accrington factory would employ American production methods and the funds allocated to purchase American machine tools.[84]

It is important to consider the American production methods Whitehead observed, the advances in production and process engineering the American aero engine manufacturers were implementing, as well as the types of American machine tools he purchased. He left England for America in early October 1939, spent four months visiting manufacturers, and returned to England in March 1940, having placed firm orders for 775 machine tools and conditional orders for an additional 137 machine tools from the leading American machine tool manufacturers, as well as jigs and fixtures.[85] Whitehead apparently wrote a full report on his visit to America, but unfortunately this report has yet to be uncovered. Whitehead visited the Pratt & Whitney aero engine factory in Hartford, Connecticut, and likely spent time at the Wright Aeronautical factory in Paterson, New Jersey, given Bristol's long-standing contacts with Wright.[86] He most likely visited several of the large machine tool companies as well.

The factory layout and production methods at the Pratt & Whitney Hartford factory provided the model for Bristol Accrington and probably the layout of the factories in No. 2 Shadow Group, which depended on Bristol for guidance on production methods for the Hercules.[87] The advances in production engineering at the Pratt & Whitney factories were based on implementing the concept of flow production. The Hartford factory was a large single story rectangular building that was 400 feet wide and 1,000 feet long, giving a total space of 400,000 sq. ft.[88] The company divided this space into separate units, called manufacturing departments,

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[83] NA, AIR 2/3683, Air Council Committee on Supply, New Bristol Engine Shadow Factory at Accrington, Note by P.S.S. (M) (No date).
[84] NA, AIR 2/3683, Air Council Committee on Supply, Summary of conclusions reached at the eightieth meeting held on 3rd October 1939.
[85] NA, Air 2/3863, The Bristol Aeroplane Co. Ltd, No. 3 Engine Factory, Financial Statement 13 February 1940; Norman Rowbotham, Bristol Aeroplane Co. Ltd., to Brian Davidson, Air Ministry, 28 February 1940.
[86] A photograph of Whitehead appears in the March 1940 issue of *The Beehive*, the United Aircraft Corporation, parent of Pratt & Whitney, company magazine.
[87] 'Herculean Development', *Aeronautical Engineering, The Aeroplane*, (November 28, 1941), p. 599.
[88] 'Engines for the Air Force', *American Machinist*, Vol. 83, No. 11, (May 31, 1939), p. 372.

each responsible for a separate component of its air-cooled radial engines, with a further division lengthwise between ferrous and non-ferrous parts. The ferrous side of the factory produced the cylinder barrel, connecting rods, crankshaft and gears, while the non-ferrous side made the aluminium cylinder head, piston, crankcase and miscellaneous parts.[89] Each manufacturing department made a complete component with machining operations set up on the basis of flow production, with raw materials entering the department area at one side and the completed component exiting the opposite side after a thorough inspection, to be carried on trucks to the final assembly section.[90] At the Pratt & Whitney factory flow production speeded up production by arranging for the continuous forward flow of parts through successive machining operations, minimizing the time between operations and ensuring that component parts did not need to be removed for storage between operations.[91]

During the time that Whitehead was in America and visiting Pratt & Whitney, the company completed a new 274,000 sq. ft. factory building next to its original plant exclusively to build its 14-cylinder double-row Twin Wasp engine (similar but slightly smaller than the Hercules).[92] Designed for flow production, the building had separate production lines for different components with production flowing toward a centre aisle for transfer to final assembly. There were three new elements to production that Whitehead may have observed or discussed with Pratt & Whitney factory management. Firstly, Pratt & Whitney had conducted a detailed time study of the production of every component of an aero engine, adding up all the separate operations to determine the number of hours required, dividing this total by the number of working hours in a month to determine the number of parts a machine tool could produce.[93] Calculating this for all the machine tools in the factory, Pratt & Whitney could determine the number of engines it could produce per month, and if it needed to increase output,

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[89] 'P &W Engine Production', *Aero Digest*, Vol. 34, No. 1, (January 1939), p. 58.

[90] 'P &W Engine Production' contains a diagram showing the flow of stores and finished parts through the factory. See also 'Precision is the watchword in the Pratt & Whitney aircraft engine plant. Exacting requirements prompt a technique unique in production methods', *Automobile Industries*, vol. 77, No. 1, (July 3, 1937), pp. 10-12; Ward, J. Carlton, Jr.: 'Plant Layout and Production Methods for Modern Aircraft Engines', *Society of Automobile Engineers Journal (Transactions)*, Vol. 40, No. 5, (May 1937), pp. 178-89.

[91] Ward, 'Plant Layout and Production Methods for Modern Aircraft Engines'.

[92] AuWerter, Jay P.: 'Pratt & Whitney Expands', *Aviation*, Vol. 39, No. 7, (July 1940), pp. 38-41, 116, 118.

[93] AuWerter, 'Pratt & Whitney Expands', pp. 39-40.

it could calculate the number of additional machine tools needed. Secondly, with an increasing number of engines on order justifying the economics, Pratt & Whitney had started developing specialized high-production machine tools to speed up production, designing one machine that could do the work of two or three standard machine tools in its older plant.[94] Thirdly, Pratt & Whitney was facing a growing scarcity of skilled machinists and was working with trade schools in the Hartford area to develop training programs for machinists and its own training programs to increase the number of machinists and tool makers, in addition to a program to train junior executives.[95]

The Bristol Accrington factory followed the Pratt & Whitney model of separate units for component production and the concept of flow production, though the factory's layout was less than optimal. Instead of one large factory building with Pratt & Whitney's straight-through production, the Accrington factory had, as noted, four separate buildings consisting of three machine shops and one assembly building for aero engine assembly and stripping and rebuilding after engine testing.[96] Bristol did not divide production by type of material as Pratt & Whitney had done, but did have each of the three machine shops manufacture complete components, with No. 2 Machine Shop producing crankcases and blowers, No. 3 Machine Shop making all the cylinder barrel components, including cylinder sleeves, cylinder heads and crankshafts, and No. 4 Machine Shop building all connecting rods and all gears for operating the sleeve-valves and propeller reduction gears.[97] Within each machine shop, the operations and machine tools were organized according to the principles of flow production, from raw material to final inspection before being transported to No. 1 Fitting Shop for assembly and testing, though as previously mentioned, the internal blast walls within the machine shops were an inconvenience and no doubt obstructed the uninterrupted flow of materials and parts.[98]

The factories in No. 2 Group also adopted the flow production concept to increase output, arranging machining operations in accordance with the line production concept, placing machine

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[94] AuWerter, 'Pratt & Whitney Expands', p. 116.
[95] AuWerter, 'Pratt & Whitney Expands', p. 118.
[96] NA, AIR 2/3684 contains plans of the Accrington factory complex.
[97] 'Herculean Development', p. 599.
[98] 'Herculean Development', p. 599.

tools in the logical sequence to ensure flow. In some cases the factories took the methods and layouts that Bristol recommended through the Bristol Shadow Industry office and in other cases developed their own methods based on their experience with line production in the automobile factories.[99] Rootes Securities, for example, had also gained valuable experience in production engineering and flow production of complex machines at its shadow factory building the Bristol Blenheim aircraft.[100] This experience may well have helped Rootes in production of the Hercules. As Bristol had done with the first shadow factories, the Bristol Shadow Industry office provided detailed information to the No. 2 Group factories on building design and layout, machine tool balance, jig, fixture and tool requirements as well as detailed instructions and drawings on how to manufacture, inspect and test components.[101] Some of the factories put in conveyor systems in parts of their production lines, but generally the factories did not use conveyors to the same extent as in the automobile factories, using instead specially designed trolleys that could protect components as they moved from machine to machine.[102] As an example of flow production, one of the shadow factories divided manufacture of the three sections of the Hercules crankcase into three separate lines with production flowing towards final assembly so that the three crankcase sections all arrived at the assembly area completely machined and prepared for assembly.[103] The layout of the Standard Motor No. 2 Shadow Factory at Banner Lane earned praise for its efficient production, helping the factory to regularly exceed its production targets, and no doubt benefited from applying Standard's own experience in automobile production to Bristol's recommendations for Hercules production.[104] Again, the presence of blast walls within the machine shops may have restricted the flow of parts.

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[99] 'The Production of the Bristol Hercules Engine: Methods and Plant Employed in one of the Recently Built Government "Shadow" Factories', *Machinery (London)*, Vol. 60, No. 1528, (January 22, 1942), p. 1; 'The Manufacture of the New 8-HP "Flying Standard"', *Machinery (London)*, Vol. 52, No. 1355, (September 29, 1938), pp. 789-811.

[100] Foster, Bruce: 'Producing the "Shadow" Blenheim' Part I. Rootes Factory in Quantity Production: Brief History of the Scheme: Methods Used on Spars, Wings and Control Surfaces', *Aircraft Production*, Vol. III, No. 27, (January 1941), pp.7-16.

[101] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 20.

[102] 'The Production of the Bristol Hercules Engine', p. 1.

[103] 'The Production of Aero engine Crankshafts: Methods Employed at a Government "Shadow" Factory in the Manufacture of the Bristol Hercules Engine', p. 145.

[104] Thoms, *War, Industry and Society*, p. 29.

The Tools

Whitehead's selection of American machine tools was even more important to the quantity production of Hercules engines. After reading a report from Whitehead on his progress in America, Norman Rowbotham wrote to the Air Ministry commenting that 'the acquisition of plant from that country will permit a more rapid start of engine production at the Accrington factory, and will also allow it to operate with workpeople of lesser skill and numerically smaller than plant based on the processes which we are operating at Filton.'[105] The machine tools that Whitehead acquired were a combination of machines designed for high levels of output and special purpose machines that were less common in the British machine tool industry. With a much smaller automobile industry, British machine tool manufacturers had less incentive to develop the specialized and automatic machine tools required for large scale production of automobiles.[106] Instead, British firms concentrated on building standard, universal-type machine tools, relying on imports of specialized machine tools from America and, before the war, from Germany.[107]

During the 1930s the American machine tool industry developed new, improved models that offered superior performance.[108] Stronger, more rigidly built machines allowed faster cutting speeds and cemented carbide and tungsten carbide cutting tools that enabled cuts to far higher tolerances of ten thousandths of an inch. These newer cutting tools enabled machine tools to cope with the new high strength steel alloys required for high-powered aero engines. Precision boring machines, internal and centreless grinding machines, new types of milling machines and surface broaching machines developed for the automobile industry produced much finer surfaces with less risk of flaws that could lead to fatigue failures. To reduce the required number

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[105] NA, AIR 2/3683, Norman Rowbotham, Bristol Aeroplane Company, to J.E. Keel, Air Ministry, 15 January 1940.
[106] Hornby, *Factories and Plant*, p. 325.
[107] Hornby, *Factories and Plant*, pp. 325-27; Lloyd-Jones, Roger and M.L. Lewis: *Alfred Herbert Ltd. and the British Machine Tool Industry, 1887-1983*, (Aldershot, UK, 2006), pp. 168-69; See the paper titled 'Machine Tools-September 1939 to December 1940: Machine Tools for the Production of Machine Tools', no date, AVIA 10/616
[108] Miller, R.E.: 'Machine Tools Developed to Meet Lower-Cost Production', *The Iron Age*, Vol. 133, No. 1, (January 4, 1934), p. 119; '40 Years of Machine Tool Progress', *Automobile Industries*, Vol. 81, No. 7, (October 1, 1939), p. 344; Oliver, F.J.: 'Trends in Metal Cutting Machines and Small Tools', *The Iron Age*, Vol. 143, No. 1, (January 8, 1939), p. 115.

of machine tools and operators, several machine tool companies developed machine tools with multiple spindles, drills or other tools that could perform, automatically, multiple sequential operations such as drilling, boring, reaming and tapping on a single work piece or multiple work pieces.[109] Thus one operator using one 'automatic' machine could replace several operators using multiple machines, while improved electric motors allowed easier and more precise control. In the automobile industry these new machine tools enabled, in some cases, a doubling of production in the same amount of time.[110]

The critical problem facing Bristol Accrington and the No. 2 Group factories was the growing shortage of skilled labour to operate machine tools. As early as May 1938, in a meeting with Air Ministry to discuss expanding Bristol's aero engine production, Norman Rowbotham, Bristol's head of production, had warned that while acquiring the necessary buildings, machine tools and materials would not be without difficulty, the more serious problem was the shortage of skilled labour.[111] During the rest of 1938 and into 1939, Bristol recruited more labour and maintained a high level of skilled workers, some 44% of the Bristol Engine Department being classed as skilled, but by December 1939 Rowbotham was reporting to the Bristol directors that labour shortages were holding up production.[112] The aircraft industry had expanded dramatically, growing from 40,000 employees in 1934-36 to 370,000 by the end of 1939, but the future need was even greater.[113] In discussions with the Ministry of Labour in November 1939, the Air Ministry estimated that to fulfil the Cabinet's plan for production of 2,500 aircraft a month by July 1942, the aircraft industry would need 1,500,000 workers just as the services and other war industries were clamouring for skilled workers.[114] Supplying skilled workers for the aircraft and

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[109] Herb, Charles O.: *Machine Tools at Work*, (New York, 1942), pp. 70-115.

[110] 'Increase in Production Capacity of Machine Tools in Ten Years', *Machinery (New York)*, Vol. 43, No. 5, (January 1937), pp. 325-27.

[111] NA, AVIA 10/151, Air Council Sub-Committee on Supply, Notes on Meetings Held Monday, 16th May 1938, p. 2.

[112] Bristol Aeroplane Company Minutes of Directors' Meeting in Committee, 21 November, 12 December 1939, BAC Directors' Committees Minutes, Vol. 7; NA, , AVIA 10/18, Statement of Production and Employment in the Aircraft Industry, 1st July 1938-31st December 1938; Statement of Labour on Airframes and Engines at Dates Given.

[113] NA, AVIA 10/18, Notes of a Meeting with Representatives of the Ministry of Labour held on 10th November 1939, to Discuss Problems Involved in Securing the Labour Force Necessary to Fulfill the Aircraft Construction Programme .

[114] Notes of a Meeting with Representatives of the Ministry of Labour held on 10th November 1939.

other munitions industries became the principal concern of planners in Government ministries.[115]

The shortage of skilled labour during the war required an intensive focus on process engineering, developing the manufacturing processes and machine tools that would accommodate the influx of less-skilled labour into the factories. Throughout the war, shortages of skilled workers, particularly toolmakers, setters for machine tools and machinists remained chronic.[116] By early 1940 it had become apparent that the solution to the shortage of labour was dilution, the progressive 'deskilling' of manufacturing processes. Through process engineering the work of a skilled machinist was broken down into simpler operations that a semi- or unskilled worker could perform on standard machine tools with special jigs and fixtures. Deskilling also came from increasing use of machine tools that could perform multiple operations but that unskilled workers could operate with a modicum of training, substituting the machine for the skilled worker.[117] Even before the start of the war the Air Ministry had determined that production of the Hercules would require new methods and new types of machine tools to cope with the pending shortage of skilled labour. The existing literature provides little information on how this worked in practice.

The composition of machine tools at the shadow factories changed during the war to accommodate the needs of greater production and the steady reduction in skill levels in the work force. The Bristol Aero Engine Department had begun using some automatic machine tools as early as 1933, but it appears that wartime demand accelerated their use in production.[118] The productivity gains of using so-called 'automatics' were dramatic. During the war, the British Machine Tool Control published a pamphlet demonstrating the benefits of using automatic machines that contrasted three methods of producing a single component (see Table 3-1):

[115] Hornby, *British War Production*, p. 95.
[116] Hornby, *British War Production*, p. 149; Inman, P.: *History of the Second World War, United Kingdom Civil Series, War Production Series: Labour in the Munitions Industries*, (London, 1957), p. 81.
[117] Inman, *Labour in the Munitions Industries*, p. 27.
[118] 'Machining Aero engine Parts on Automatics', *Machinery*, Vol. 41, (February 9, 1933), p. 551.

Table 3-1: Productivity Gains from Automatic Machine Tools

	Method 1	Method 2	Method 3
Machines Required	23 Centre Lathes & 10 Drilling Machines	12 Capstan Lathes	4 6-Spindle Automatic Chucking Machines
No. of Operations	5	2	2 (two machines per operation)
Total Operators & Setters Required	76 per day of 2 shifts	30 per day of 2 shifts	10 per day of 2 shifts

Source: *Intelligent Production Planning*, M.T.C. Leaflet No. 4

Automatic machine tools required less space, fewer operatives and were more productive. Employing more automatic machine tools and more unskilled labour freed up the more skilled workers for other tasks better suited to their skills.

While in America Frank Whitehead purchased multi-spindle drilling machines from Baush Machine Co., automatic vertical, multi-spindle Mult-Au-Matic lathes and boring machines from the Bullard Machine Co., grinding machines from Brown & Sharpe and Cincinnati Milling Machine Co., gear shaping machines from Fellows Gear Shaper Co., turret lathes from Gisholt Machine Co., many internal grinding machines from the Heald Machine Co., cylindrical grinders from the Norton Co. and turret lathes from Warner & Swasey.[119] As well as buying these machines from American machine tool manufacturers, Bristol later sent its own representatives to America to work with American machine tool companies to design machine tools, jigs and fixtures to save time and labour in manufacturing the Hercules.[120] Whitehead ordered the machine tools of the generation that were available in late 1939, or would be available during 1940. He purchased 772 American machine tools at a cost of £1,562,305 ($6,249,219) and placed orders for an additional 137 machine tools costing £349,912 ($1,399,647), exceeding the Treasury's initial allocation of £1.25 million.[121] Most of the machine tools he ordered ranged in price from £1,250 to £3,330 ($4,000 to $13,320), with the most

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[119] The Bristol Aeroplane Co. Ltd, No. 3 Engine Factory, Financial Statement 13 February 1940, Air 2/3863, NA; Albrecht, Albert B.: *The American Machine Tool Industry: Its History, Growth, Restructuring & Recovery*, 3rd Ed. (Cincinnati, OH, 2016), pp. 77-82, 145-46.
[120] Albrecht, *The American Machine Tool Industry: Its History, Growth, Restructuring & Recovery*, pp. 77-82, 145-46.
[121] NA, AIR 2/3683, Bristol Aeroplane Company Limited No. 3 Engine Factory Financial Statement 13 February 1940.

expensive being the Bullard Mult-Au-Matics at £5,250 ($21,000) apiece. As will be seen in Chapters Five and Six, the more advanced machine tools that were introduced in American aero engine factories later in the war would be even more expensive. Illustration 4-3: The Baush multi-spindle drilling machine to drill 14 holes in the Hercules crankcase.

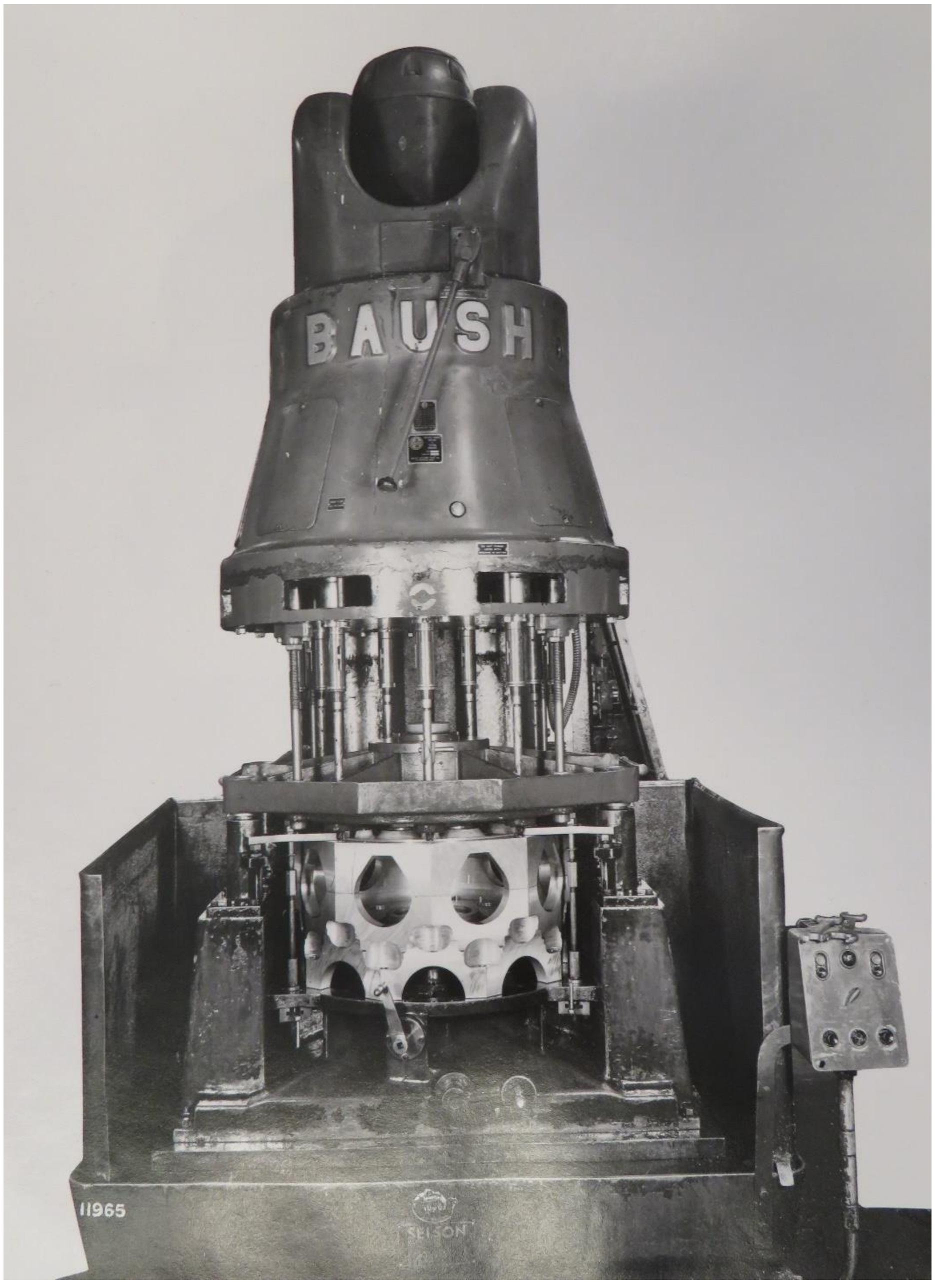

Illustration 3-3: The Baush multi-spindle drilling machine that Bristol designed to drill 14 holes in the Hercules crankcase in one operation. (From 'History of Production of Bristol Aero Engines by the Shadow Industry')

Many of these machine tools featured automatic operation with multiple tools to perform several operations simultaneously with minimal setting up. In one case Bristol worked with the Bausch Machine Tool Co. in America, a builder of multi-spindle drilling machines, to develop a machine to simultaneously drill 14 holes in the Hercules crankcase.[122] Working with the English Drummand Company, Bristol engineers built a Drummand Maxicut lathe to machine the external surfaces of the Hercules cylinder barrel simultaneously, while another machine, designed to cut out and profile the exhaust ports on the side of the cylinder, could perform this operation on four cylinders at the same time. Perhaps most impressive, Bristol production engineers designed a special purpose machine to punch out the ports in the cylinder sleeve without distortion in six minutes.[123] The previous milling and finishing of these ports had taken two and a half hours. All these small incremental improvements, making possible multiple, simultaneous machining operations, machining multiple work pieces at the same time, reducing the need for complicated setting up of a machine tool and cutting the time for machining operations helped speed up manufacture of Hercules components while reducing the need for additional labour. Faster machining, fewer machining operations and less movement of parts between machine tools contributed to higher output of components per day.

While Bristol did take advantage of special-purpose, high production machines, especially where the design of a component was less likely to change over time, a key aspect of Bristol's general policy on machine tools, which the shadow factories apparently followed, was its reliance on as many standard machine tools as possible to cope with changes in design and transition to new models of the Hercules.[124] The machine tools Bristol specified for the shadow factories comprised standard machine tools, standard tools with adaptations for less skilled workers and some specially designed single-purpose machine tools.[125] The bulk of the machine tools used in the shadow factories and at Accrington were, apparently, standard machine tools with a mix of more specialized American machine tools.[126] While the total number of machine tools at the

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[122] Photographs of these machine tools are in *History of Production of Bristol Aero Engines by the Shadow Industry.*

[123] Bristol Co., *The Power Behind Their Wings*, p. 60.

[124] Bristol Co., *The Power Behind Their Wings*, p. 53; *History of Production of Bristol Aero Engines by the Shadow Industry,* p. 53.

[125] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 74.

[126] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 74.

Accrington factory is unknown, based on Bristol's original estimate of a requirement for 2,100 machine tools to build 250 aero engines a month, later increased to 400 engines a month, it is possible that the number of American machine tools amounted to one-quarter to one-third of the total in the factory (by comparison the Rover No. 2 Shadow Factory ordered 1,387 machine tools to make 50 engine sets per week, later increased to 200 per week implying an even greater number of machine tools).[127] Whereas Whitehead would have ordered American machine tools that were on offer in 1939, it also appears from descriptions in contemporary articles describing Hercules production that later American machine tools imported for Bristol and the shadow factories could be classed as part of a second generation of machine tools developed after 1939 in response to demands for higher levels of output. These same articles indicate that the factories do not appear to have used the more advanced, third-generation high-production machine tools that could be found in the American factories building Wright and Pratt & Whitney engines later in the war.[128] In contrast to Bristol, Wright Aeronautical would rely more on replacing standard machine tools with new types of special-purpose, high-production machine tools.

With the shortage of labour at all skill levels, simplifying manufacturing operations through process engineering was even more critical to quantity production of the Hercules yet receives barely a mention in the literature. By the time the Hercules went into production at the shadow factories almost all the skilled workers in the engineering trades were either fully employed in the munitions industries or serving in the armed forces. The shadow factories had no option but to hire women and trainee labour, ending up with around 80% female and trainee workers (see Table 3-2).[129] By June 1942, Bristol Accrington had approximately 7,000 employees,

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[127] NA, AIR 2/3683, Schedule H- Machine Tools, Bristol Acceleration Programme No. 3, 21 March 1939: The Rover Company Limited (Aero Engines) No. 2 Factory, Lode Lane, Solihull, Diary 1939-1945, Note for 1st November 1939, L-RCO-103, British Motor Museum.

[128] See the series of articles in *Machinery (London)* during 1944, such as 'Machining Aero-Engine Cylinder Barrels', *Machinery (Lon)*, Vol. 65, No. 1679, (December 14, 1944), pp. 645-53 and 'Machining Airplane Engine Cylinder Heads', *Machinery (Lon)*, Vol. 65, No. 1681, (December 28, 1944), pp. 701-705, with 'Wright Aero Produces Engines for the B-29 Superfortress', *Machinery (New York)*, Vol. 50, No. 12, (August 1944), pp. 134-44 and Holben, Martin M.: 'Some Aircraft-Engine Production Methods', *SAE Journal (Transactions)*, Vol. 52, No. 10, (October 1944), pp. 492-500.

[129] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 19.

of which 2,250, or 32%, were women.[130] At the shadow factories producing the Hercules the average for women employed reached 34% by the middle of the war.[131] Less than 20% of the workers were classed as skilled, with Accrington having the smallest percentage of skilled workers of any engine factory in England with 13.5%.[132] The shadow factories could, and did, draw on skilled workers from No. 1 Shadow Group. These became foremen supervising teams of semi- and unskilled workers, setters who set up machine tools for less experienced machine operators, inspectors for quality control and training staff for new employees, particularly women.[133] As several observers noted, with an acute shortage of skilled labour, it was vital to the production effort that skilled workers be used effectively.[134] It made little sense to have a skilled machinist doing work that a semi- or unskilled worker could do with proper training.

Table 3-2: Composition of the Work Force at the Shadow Factories 1941-1942

	Total Work Force 8/41	% Women in the Work Force	Total Work Force 3/42	% Women in the Work Force
Bristol Accrington	5,887	25%	6,745	32%
Daimler No. 2	4,275	27%	5,033	28%
Rootes No. 2	4,173	20%	5,090	27%
Rover No. 2	4,182	16%	4,690	27%
Standard No. 2	3,605	26%	5,618	32%

Source: NA, AVIA 10/383, Table of Wage Earners at Engine Factories as of 7 March 1942.

Most of the women coming to work at the shadow factories had no experience of machine tools and needed to go through a one to four-week training course where they were

130 NA, AVIA 15/414, Ministry of Aircraft Production-North West Region, Bristol Aeroplane Co. Clayton-le-Mores, 2nd June 1942.
131 Ministry of Labour and National Service: *Women in Engineering*, (London, No Date) II. Aero Engines and Accessories, p. 1.
132 Ministry of Aircraft Production-North West Region, Bristol Aeroplane Co. Clayton-le-Mores, 2nd June 1942.
133 Ministry of Aircraft Production-North West Region, Bristol Aeroplane Co. Clayton-le-Mores, 2nd June 1942.
134 'Labour', *Aircraft Production*, Vol. III, No. 27, (January 1941), Editorial, p. 2.

given an introduction into factory production, basic principles and mathematics of engineering and practice on a few basic machines.[135] The factory management assigned women to different departments based on their aptitude and suitability. By the middle of the war women workers could be found in most areas of aero engine production, from assembling complete engines to engine testing to inspecting parts throughout the production process, and above all operating machine tools. Women operators worked on all classes of machine tools and machine operations including boring, standard and turret lathe work, drilling, grinding, gear cutting, honing and milling.[136] While some women advanced to higher levels of skill and more complicated machine tools, many worked on automatic machines, special purpose machines or standard machine tools equipped with special jigs and fixtures developed through process engineering.

The process of 'de-skilling' appears in the literature, but rarely with an explanation of what this meant in practice. Deskilling had two components: simplification of processes and specially adapted machine tools. Simplification involved the principle of 'transfer of skills', getting the machine tool designer, the process engineer, the machine tool builder and skilled machinists all working together to break down a complex machining process into simpler steps that unskilled workers could perform.[137] The basic idea was to replicate the accuracy of the skilled machinist on a standard machine tool by designing a fixture to hold the work piece in a machine and adjusting the cutting tools so that 'all that remains to be done by the operator is to insert the work in the fixture, start the machine, and then remove the work after the machining operation is completed' and in this way, 'even an unskilled operator can produce accurate work.'[138] This involved the extensive use of jigs and fixtures, but greatly speeded up production. As one example of process engineering at the shadow factories, production of master connecting rods was split up into 120 separate operations that unskilled or semi-skilled operators could perform.[139]

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[135] Ministry of Labour, *Women in Engineering*, II. Aero Engines and Accessories, p. 5.
Ministry of Labour and National Service: *Women in Industry*, (London, 1945), II. Aero Engines and Accessories, pp. 87-88.
[136] Ministry of Labour, *Women in Engineering*, II. Aero Engines and Accessories, pp. 3-4.
[137] Hesse, *Engineering Tools and Processes*, p. 345.
[138] Hesse, *Engineering Tools and Processes*, p. 345.
[139] Oates, 'The Bristol Hercules: Part II', p. 243.

Subcontracting was a vital part of Hercules production. The No. 2 Shadow Group factories and the Bristol Accrington factory did not have foundries for casting aluminium or magnesium parts, or forges for stamping key components such as cylinder barrels, crankshafts and crankcases. Before the war Bristol relied on specialty firms for many components of the Mercury and Pegasus engines, and this practice continued after the start of the war. Bristol selected specialty suppliers for the shadow factories, contracting with High Duty Alloys Ltd. for example, to supply forged crankcases for the Hercules. When its existing suppliers could not meet the needs of greatly expanded production, Bristol sought out new sources of supply in Britain and America, sending several Bristol representatives to work with the American suppliers.

The Role of No. 1 Shadow Group

The Air Ministry's decision to switch No. 1 Shadow Group to Hercules production as demand for the Mercury and Pegasus wound down led to converting the No. 1 Group shadow factories into component manufacturers for the factories in No. 2 Group. In effect, the two shadow groups merged into a combined manufacturing group for Hercules production, with a peak employment of 41,707 workers in November 1943, a little over half as big as the combined employment at the factories building the Rolls-Royce Merlin.

The shift to Hercules production required a major investment in new machine tools for the No. 1 Group factories to build Hercules components. The Ministry of Aircraft Production's initial target, set in early 1942, to have the No. 1 Group factories build the equivalent of 500 Hercules engines a month required an additional 2,400 machine tools costing £3,442,293, with £263,930 for certain additions to buildings, though it is unclear which factories received these additions.[140] Later, when the Ministry increased the combined production target for No.1 and No. 2 Groups to 1,500 engines a month, the Government financed an additional 393 machine

[140] *Narrative-Aero Engine Production Expansion of Capacity 1935-1945*, Capacity for Production of Bristol Engines, p. 8.

tools at £517,917 and further additions to buildings and services, plant and other equipment at the factories amounting to £404,944.[141]

The Rover No. 1 Shadow Factory gives an example of the transition to building Hercules components at the No. 1 Group factories. The transition took around a year to complete. During July 1942, the Rover No. 2 Shadow Factory transferred production of the Hercules piston to the Rover No. 1 Shadow Factory.[142] Over the next year the transfer process continued, covering numerous small parts, sleeve valve drive gears and, more importantly, work on the cylinder sleeves.[143] As part of the shift, the Rover No. 2 Factory also transferred certain machine tools, such as internal centreless grinders for work on the cylinder sleeves, to the Rover No. 1 Factory. It is unclear from the remaining records how the Daimler and Rootes No. 1 Shadow Factories coordinated with their counterparts in No. 2 Shadow Group, but the assumption is that they, too, made component parts for their larger partner factories, probably in line with the type of parts they had been building. Although it had been intended to assemble Hercules engines at the Austin Shadow factory from parts made at the No. 1 Shadow Group factories, it was determined that it was more efficient to concentrate final assembly and testing at the Rover and Standard Motor No. 2 Shadow Factories, with the Bristol No. 2 Shadow Factory as a reserve.[144]

Productivity at the No. 2 Group and Bristol Accrington Factories

Determining how productivity changed over time at the No. 2 Group factories and at the Bristol factory at Accrington is also difficult. None of the important data, such as man-hours per engine or cost per engine over time, appears to have survived. Hornby's note of caution about relating the size of the labour force at the factories to engine output as a measure of efficiency applies equally to the No. 2 Group shadow factories and Bristol No. 3 factory at Accrington but can still provide a measure of relative labour productivity.

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[141] *Narrative-Aero Engine Production Expansion of Capacity 1935-1945*, Capacity for Production of Bristol Engines, p. 8.
[142] Appendix 3, The Rover Company Limited (Aero Engines) No. 2 Factory, Lode Lane, Solihull, Diary 1939-1945, L-RCO-103, British Motor Museum.
[143] Appendix 3, The Rover Company Limited (Aero Engines) No. 2 Factory, Lode Lane, Solihull, Diary 1939-1945.
[144] NA, AVIA 10/201, No. 1 Shadow Factories-Conversion to Hercules Manufacture, 17 January 1944, in Air Supply Board Meeting No. 284, 20 January 1944.

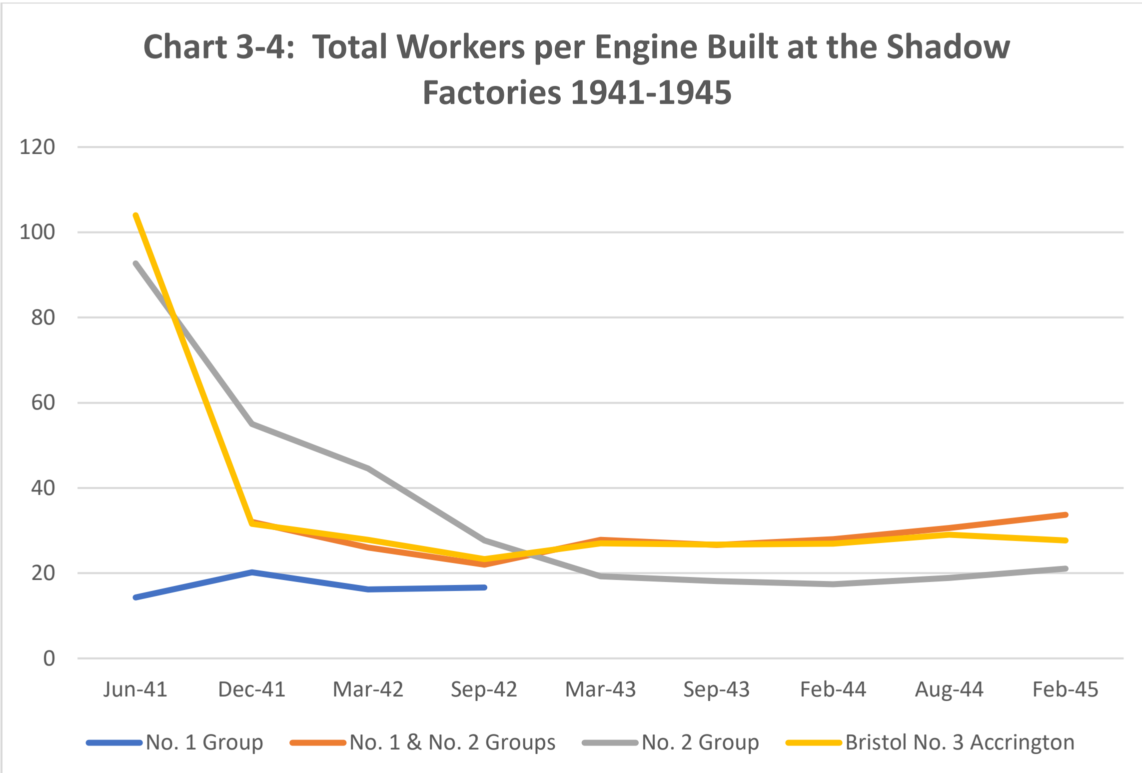
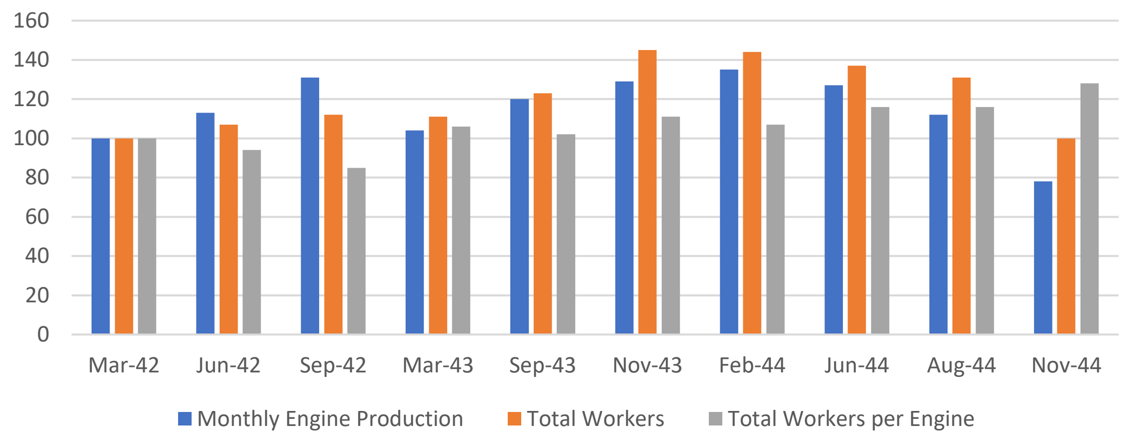


Chart 3-4: Total Workers per Engine Built at the Shadow Factories 1941-1945

Source: Abridged Record of Engines, Spares and Accessory Output from Shadow Industry for 1938-44, *History of Production of Bristol Aero Engines by the Shadow Industry Operating Under the Joint Aero Engine Committee in Conjunction with the Bristol Aeroplane Company Limited*, XC03-8876/066, Royal Air Force Museum; Ministry of Aircraft Production, *Statistical Review 1939-1945*.

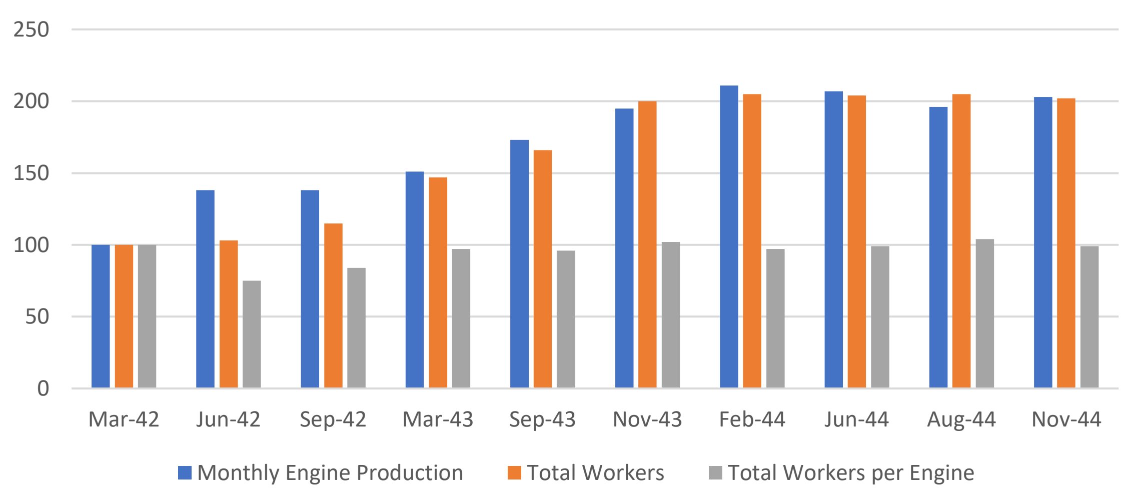
The factories building the Hercules and the factories building the Mercury and Pegasus had a similar learning curve effect (see Chart 3-4). There was a huge increase in productivity at first. As production built up between June 1941 and September 1942, the number of total workers per engine built declined rapidly as workers and management gained experience. From March 1943, by which time the No. 1 Group factories had converted nearly entirely to making components for the Hercules, the productivity of the combined No. 1 and No. 2 Group factories remained relatively flat until August 1944, as does productivity at the Accrington factory, when production of the Hercules began to steadily decline (see Charts 3-4, 3-5 and 3-6). This conforms to the experience of other industries where a stable level of productivity followed a period of intense learning and productivity improvement. The benefit to the No. 2 Group factories of transferring a part of component production to their sister factories in No. 1 Group can be clearly seen in the lower number of total workers per engine at these factories after March 1943.

Chart 3-5: Relationship Between Engines Built, Total Workers, Total Workers per Engine at No. 1 and No. 2 Group Shadow Factories (Mar 1942 = 100)



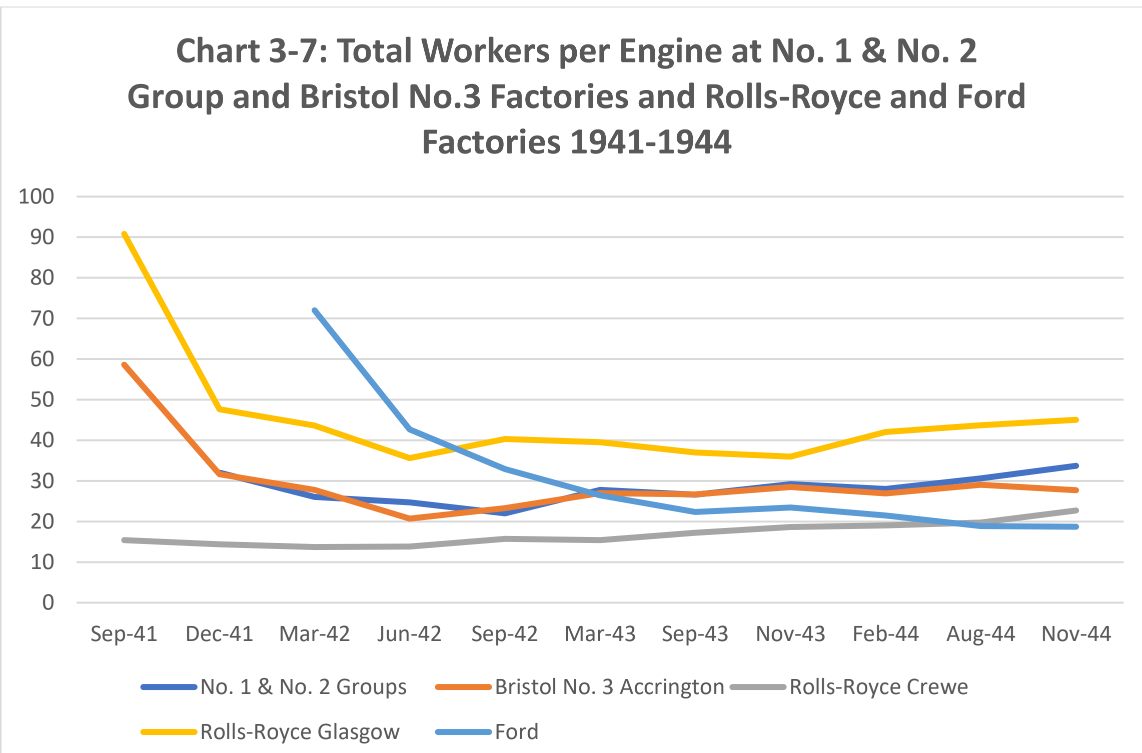
Source: Abridged Record of Engines, Spares and Accessory Output from Shadow Industry for 1938-44, *History of Production of Bristol Aero Engines by the Shadow Industry Operating Under the Joint Aero Engine Committee in Conjunction with the Bristol Aeroplane Company Limited*, XC03-8876/066, Royal Air Force Museum; Ministry of Aircraft Production, *Statistical Review 1939-1945*.

Chart 3-6: Relationship Between Engines Built, Total Workers, Total Workers per Engine at Bristol No. 3 Shadow Factory (Mar 1942 = 100)



Source: Abridged Record of Engines, Spares and Accessory Output from Shadow Industry for 1938-44, *History of Production of Bristol Aero Engines by the Shadow Industry Operating Under the Joint Aero Engine Committee in Conjunction with the Bristol Aeroplane Company Limited*, XC03-8876/066, Royal Air Force Museum; Ministry of Aircraft Production, *Statistical Review 1939-1945*.

The factories building the Hercules appear to be a little over half as productive as the factories building the Mercury and Pegasus. In fact, given the greater complexity of the Hercules, the levels of productivity are comparable. The 14-cylinder Hercules was a much more complex engine than either the nine-cylinder Mercury or Pegasus, having the more complicated sleeve valve system, more than double the number of parts that required a greater amount of machining operations, even with more advanced machine tools, and a lengthier assembly process. What is notable is that the difference in productivity was not greater. The more interesting comparison is with the factories building the Rolls-Royce Merlin and as will be discussed in Chapter Seven, with the American factories building the similar 14-cylinder Wright Cyclone 14 and the Pratt & Whitney 14-cylinder Twin Wasp aero engines.



Source: Abridged Record of Engines, Spares and Accessory Output from Shadow Industry for 1938-44, *History of Production of Bristol Aero Engines by the Shadow Industry Operating Under the Joint Aero Engine Committee in Conjunction with the Bristol Aeroplane Company Limited*, XC03-8876/066, Royal Air Force Museum; Ministry of Aircraft Production, *Statistical Review 1939-1945*.

The No. 1 and No. 2 Group factories, the Accrington factory and three of the factories building the Merlin engine— the Rolls-Royce factories at Crewe and Hillington, Glasgow and the

Ford Trafford Park factory near Manchester --followed a similar pattern, a rapid improvement in productivity due to the learning effect and then fluctuations within a relatively stable band (see Chart 3-7). The Rolls-Royce Glasgow factory, which had nearly double the number of total workers per engine, was an outlier, even though it followed a similar pattern. The Rolls-Royce factory at Crewe appears by this measure to have been the most consistently productive of the major aero engine factories in Britain during World War II, with the Ford factory also showing the greatest proportional decline in the number of total workers per engine. It is difficult to get a real measure of comparative productivity at the factories building the Hercules and the Merlin as the engines were so different in their construction as were the production methods at the different factories. However, it appears as if it took slightly more workers to build a Hercules than it did a Merlin engine, but the disparity was not great.

An aspect of labour productivity that has not been explored is the change in the composition of the work force at the aero engine factories during the war years, in particular the percentage of productive or direct workers compared to the percentage of non-productive workers. One of the attributes of mass production systems was the effort to eliminate as many non-productive, indirect workers as possible, to achieve a better ratio of indirect to direct workers.[145] This was an important focus of Ford and his colleagues as they developed the assembly line at the Ford Highland Park factory. In theory, with mass production systems one would expect to find over time an increase in the number of productive/direct workers at a factory, but at the wartime shadow factories the reverse seems to have been the case. In 1937, roughly 66% to 70% of the Bristol Aero Engine Department were classed as productive/direct workers engaged in aero engine production.[146] Data indicates that by 1941 the percentage of productive workers at the shadow factories averaged 48%. Though there may be problems with definitions, the difference is notable. It is also interesting to note that where data on productive/direct workers is available for the American aero engine factories, the wartime percentage is similar.

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[145] Williams, Karel, Colin Haslem, and John Williams: 'Ford versus 'Fordism': The Beginning of Mass Production?' *Work, Employment & Society*, Vol. 6, No. 4, (December 1992), p. 522.
[146] Bristol Aeroplane Company, Summary of All Employees 31 July 1937, copy in archives of Aerospace Bristol Museum.

A possible answer to this seeming anomaly may be found in another unique attribute of the aero engine industry: the significant documentation requirements of the quality control process and the frequency of design changes. Ensuring quality production required careful tracking and documenting component parts as they made their way through the production process. The Bristol Engine Inspection Department created a record of every engine Bristol built, forming a complete history of the engine and its major components.[147] All major components received a reference number and a record that was maintained and updated throughout the manufacturing process. As sub-assemblies were built up, they, too, received a reference number and records that continued through final testing. Once the engine was shipped the engine record was retained at Bristol's Aero Engine Department. During the war, the shadow factories maintained over 50 forms for each engine built.[148] At peak production this amounted to over 74,000 forms in one month that had to be completed, processed and filed. The significant increase in war time production would have required a greater number of staff to maintain all these records, not to mention the need to document all the design changes that were implemented during the war. There would also likely have been a need for more maintenance staff for the much larger factories, more staff to maintain all personnel records and staff for training. all of which would have contributed to the increase in the number of non-productive workers. While classed as non-productive, these personnel were still necessary for the factories to function efficiently.

The success of quantity production of the Hercules depended on the success of production engineering and process engineering, the ability to sequence operations and lay out machine tools to establish flow production and the ability to 'de-skill' the manufacture of the Hercules through simplification and the adaptation of machine tools to semi- and unskilled workers. The vastly increased demand for aero engines from the Air Ministry created the conditions, incentives and financing necessary for production and process engineers to develop production techniques to 'achieve outputs hitherto deemed impossible.'[149] It is unfortunate that the official histories of wartime production make so little mention of the importance of

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[147] Bristol Aeroplane Company, *Bristol Review*, Engine Issue No. 11, (November 1936), p. 35.
[148] *History of Production of Bristol Aero Engines by the Shadow Industry*, p. 108.
[149] 'New Production Techniques', *Aircraft Production*, Vol. IV, No. 41, (March 1942), p. 221.

production and process engineering, or of the British automobile, aero engine and machine tool engineers who were responsible for this success. It is doubtful that this record of production could have been achieved with the standard methods Bristol employed in the pre-war years; there were simply not enough skilled machinists or machine tools in Britain to have replicated these methods on such a large scale. What is remarkable about this record is that it was so successful, and that success came so quickly, in time and was responsive to the demands for quantity production and continuing qualitative improvement in the Hercules engine.

At the beginning of the war in 1939, Bristol and Rolls-Royce had been building aero engines in the 800 hp-1,000 hp class, principally the Bristol Mercury and Pegasus and the Rolls-Royce Merlin. By the end of the war the companies were building aero engines with in some cases more than twice the power. Bristol was building the Centaurus engine which produced 2,500 hp, Napier had improved the Sabre engine and boosted its power output to 2,400 hp, while Rolls-Royce was building the Griffon with 1,815 hp.[150] There had also been continuous improvement in the performance of the Bristol Hercules and the Rolls-Royce Merlin. Bristol had taken the Hercules from 1,375 hp in 1939 to 1,725 hp by 1943, while Rolls-Royce had boosted the Merlin from 1,030 hp in 1939 to 1,635 hp by 1945. The British aero engine industry succeeded in meeting the challenge of providing both quantity and quality.

The Hercules and the Merlin together accounted for 63% of total British aero engine production during World War II. There were more Merlin engines built than Hercules engines, with over 105,000 built in Britain and an additional 54,000 built in America under license, more than double Hercules production.

The quality of the two engines is difficult to compare. Much depends on the particular engine model, the power output, and particularly the power output at altitude. As engines for bombers, the Hercules and the Merlin were interchangeable. Both types of engines powered models of the Halifax, Lancaster and Wellington bombers. The greater demand for the Merlin reflected the Royal Air Force's preference for liquid-cooled, in-line engines for its single-engine fighters, but also the Merlin's superior performance at altitude. The Hercules achieved its maximum power with full supercharging at medium altitudes, more than the Merlin at the same

[150] Information on these engines is taken from Lumsden, *British Piston Aero-Engines and their Aircraft*.

altitude, but over 20,000 feet the Merlin could produce more power than most models of the Hercules, enough to give the Merlin-powered Lancaster bomber a higher service ceiling than the Hercules-powered Halifax. Still, during the war the Hercules powered 48% of British medium and heavy bombers, a vital contribution to the British war effort.

Chapter Four: Building the Wright Cyclone 9

Introduction

During World War II, American aero engine production was on a completely different scale from production in Britain. This chapter will examine how Wright Aeronautical and its first licensee, the Studebaker Corporation, built the nine-cylinder Wright Cyclone 9 engine in numbers that nearly equalled the total number of all Bristol engines built during the war. The chapter will show how the Cyclone 9 was built in larger factories, with more advanced machine tools and more labour using new methods designed to achieve flow production. The chapter will argue that advances in production and process engineering Wright developed during 1939-1941 in response to British and French orders for Wright aero engines, and subsequently orders from the American military, enabled Wright to shift from batch to large-scale production. These advances formed the basis for production of all Wright engines at the Wright factories, and the factories of its licensees, during the war.

Recognizing that the small pre-war American aero engine industry would be unlikely to build engines in the required numbers, the American Government had, like the British Government, assumed that additional production capacity would have to be brought in from the automobile industry.[1] As in the British case this new capacity did not come through conversion of existing automobile factories, but through organizing production around new Government-owned and contractor-operated factories, building engines under license from aero engine manufacturers. Contrary to the standard narrative of American production during World War II, wartime aero engine production in America was not based on simply transferring automobile mass production methods but, as Zeitlin has argued, through careful adaptation of these methods to aero engine production and through developing entirely new production methods and new types of machine tools that had not been used in the pre-war aero engine industry.

[1] Holley, *Buying Aircraft*, pp. 161-62.

That British and French orders placed in 1939 and 1940 provided an initial stimulus to expanding the American aero engine industry is well-understood.[2] What is less appreciated is how these orders provided the incentive for Wright to develop new methods of production and new types of machine tools that would enable aero engines to be built in unprecedented quantities.[3] The chapter will illustrate how Wright worked with companies in other industries and with machine tool manufacturers to develop new production methods and more advanced high-production machine tools that were not used in the British factories building Bristol engines. Wright would incorporate these methods and advanced machine tools in its own factories and transfer this knowledge to its two licensees, the Studebaker Corporation and later the Chrysler Corporation's Dodge Division. The Studebaker Corporation, an experienced automobile company, would bring its own expertise in mass production to the challenge of building the Cyclone 9 in record numbers.

This chapter will argue that American aero engine factories were better designed for flow production than their British counterparts. American factories did not have to incorporate protections against the threat of damaging air attacks. As a result, they could be designed as large, single-storey buildings with open spaces to accommodate line production, with engine test cells attached to the main machine shops to speed movement of engines between assembly and testing. The American Government made a conscious choice to build very large factories to meet the greatly increased needs for airframe and aero engine production. Using the measure of total workers per engine built the chapter will examine trends in productivity at the Studebaker factories as a basis for later comparisons with other British and American aero engine factories.

The literature says little about production of the Wright Cyclone 9 during World War II. Eltscher and Young's history of the Curtiss-Wright Corporation focuses more on Wright Aeronautical's technical and management problems with the Cyclone 14 and Cyclone 18 and less on methods of production, while Hyde gives a just a brief overview of Studebaker's production effort. Neither of these studies, or any other work, argue that Wright had to shift from batch to large-scale production, or that the key to large-scale production was achieving flow production

[2] Craven and Cate, *Men and Planes*, p. 301.
[3] Lilley, *Problems Accelerating Aircraft Production*, p. 32.

through advances in production and process engineering. There is almost no description of the factories that built the engines. As with the Bristol Aeroplane Company, Wright Aeronautical's wartime corporate records do not appear to have survived. Using articles in contemporary industry magazines, this chapter will examine in detail how Wright and its licensee, the Studebaker Corporation, built over 90,000 Cyclone 9 engines, one of the most important American aircraft engines of World War II, in just three and a half years.

Organizing Production

In 1939, Wright had two principal engines in production, the seven-cylinder Whirlwind and the nine-cylinder Cyclone 9. Wright had begun manufacturing the larger 14-cylinder Cyclone 14, and had an even more powerful engine, the Cyclone 18, under development. The outbreak of war in Europe in September 1939 brought a rush of British and French Government orders for the Wright Cyclone 9 and Cyclone 14 engines.[4] By the end of September 1940, British orders and options for American aero engines, and French orders the British Government had taken over, amounted to 53,000, more than ten times the aero engine industry's rate of production in 1939.[5] When America began its rearmament in May 1940 with President Roosevelt's call for 50,000 aircraft, it quickly became evident that Allied and American orders for aero engines would exceed production capacity at Pratt & Whitney and Wright Aeronautical, even with the expansion of their factories then underway.[6] During the summer of 1940, the Government determined that the only way to meet the requirements for aero engines was to bring in the automobile industry, and that the Government would have to finance the huge expansion in facilities that the automobile companies would manage in addition to expanding facilities at Pratt & Whitney and Wright Aeronautical.[7]

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[4] French Air Commission Situation des Contrats Au 16 Juin 1940, P. 9, in AVIA 38/426, Ministry of Supply and Ministry of Aircraft Production. North American Supply Missions, Second World War, Files. BRITISH AIR COMMISSION. Administrative files. French Air Commission: Contracts. National Archives, Kew; Haight, John McVickar: *American Aid to France 1938-1940*, (New York, NY, 1970), p. 140; *The New York Times*, November 4, 1939, p. 1.

[5] Craven and Cate, *Men and Planes*, p. 303.

[6] Lilley, *Problems Accelerating Aircraft Production*, p. 33.

[7] Craven and Cate, *Men and Planes*, pp. 309-10, 319-20; Lilley, *Problems Accelerating Aircraft Production*, p. 32.

Since the Government was facing an immediate need as opposed to creating war potential, the shadow factory scheme employed in Britain was not an option. Instead, the Government decided to use a system of license production, whereby selected automobile firms would build proven Pratt & Whitney and Wright Aeronautical engines under license.[8] The licensing system shifted full responsibility for building the engine to the licensee, reducing the management burden on the licensor.[9] Unlike in the shadow scheme for building Bristol engines, 'the licensor was not responsible for supervising the licensee's production operations and quality standards' and was 'not required to maintain the extensive follow-up organization needed to supervise subcontractor work.'[10] Wright Aeronautical was initially reluctant to allow any other company to take on full responsibility for building Wright aero engines and preferred to establish its own factories, but in the summer of 1940 at the Government's request Wright did agree to granting licenses.[11]

The Studebaker Corporation, one of the so-called 'independent' automobile companies in the automobile industry, became Wright's first licensee and Wright's partner in building the Cyclone 9. Although Studebaker built far fewer cars than the 'Big Three' (General Motors, Ford and Chrysler), it had a reputation for sound engineering and innovative methods of production.[12] In the fall of 1940, the Army Air Corps selected Studebaker as one of four automobile companies chosen to build engines under license from Wright and Pratt & Whitney.[13] Studebaker's initial contract with the Army Air Corps was to build the larger Cyclone 14 engine, but in May 1941 after President Roosevelt approved a greatly expanded heavy bomber programme, the Air Corps changed the Studebaker contract to building the Cyclone 9 for the Boeing B-17 Flying Fortress.[14] Fortunately the change-over proved straightforward.

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[8] Lilley, *Problems Accelerating Aircraft Production*, pp. 32-33, 68-69.
[9] Lilley, *Problems Accelerating Aircraft Production*, p. 68.
[10] Lilley, *Problems Accelerating Aircraft Production*, p. 68.
[11] Lilley, *Problems Accelerating Aircraft Production*, p. 68.
[12] Geschelin, Joseph: 'Advanced Tooling Produces Newest Studebakers', *Automobile Industries*, Vol. 80, No. 13, (April 1, 1939); Studebaker production figures taken from U.S. Automobile Production Figures, https://en.wikipedia.org/wiki/U.S._Automobile_Production_Figures, accessed 1 June 2019.
[13] War Production Board: Historical Reports on War Administration: Special Studies No. 21, *Aircraft Production Policies under the National Defense Advisory Commission and Office of Production Management, May 1940 to December 1941*, (Washington, D.C., 1946), p. 66.
[14] Special Studies No. 21, *Aircraft Production Policies under the National Defense Advisory Commission*, pp. 94-95.

The Factories

As with aero engine factories in Britain, the key characteristics of factories building the Wright Cyclone 9 were location, size and design. Between 1939 and the end of 1940, as orders for its Cyclone 9 and Cyclone 14 engines poured in from the British, French, and then American Governments, Wright had to rapidly expand its production facilities. Having decided to retain its original factory building in Paterson, New Jersey as its centre of engine production, Wright hurriedly built and acquired factory space in and around Paterson. As Wright built several types of Cyclone engines in its Paterson factories, these new factories became facilities for building components for multiple Cyclone models. These factories fed components to the main Wright factory for final assembly and testing. This system was similar to the first shadow factory scheme building Bristol Mercury and Pegasus engines. Wright came to this system through happenstance and expedience as it rushed to ramp up production in response to British and French orders.

During 1939 and 1940, Wright received substantial financial support from the British and French Governments to expand production. In October 1939, the French Government placed an order for 1,440 Wright Cyclone 9 and Cyclone 14 engines in a contract worth $28.6 million, an amount greater than Wright's total sales in 1938, and agreed to provide $5 million to enable Wright to double its production capacity.[15] In the spring of 1940, the French and British Governments placed orders for even more Cyclone 9 and Cyclone 14 engines.[16] Wright needed more capacity but was reluctant to finance additional facilities with its own limited capital. The French and British Governments agreed to provide financing to Wright to avoid a potential bottleneck in production, granting Wright $16.9 million in capital assistance funding, equivalent to around £4 million, roughly the amount the British Government spent for one of the No. 2 Shadow Group factories.[17] The new facilities that Wright built and acquired around Paterson, using its own funds and financing from the British and French, were a mix of old and new

[15] Haight, John McVickar: *American Aid to France 1938-1940*, (New York, NY, 1970), p. 140.
[16] NA, AVIA 38/421, See Schedule B attached to letter of June 21, 1940 to Air Commodore E.W. Stedman, Air Member Aeronautical Engineering and Supply, Department of National Defence, Canada.
[17] NA, AVIA 38/429, Statement of Capital and Extraordinary Charges as at January 1, 1942; Hornby, *Factories and Plant*, pp. 260, 263.

buildings. These buildings collectively surpassed the total floor area of the Bristol and No. 1 Shadow Group factories by a wide margin. In the space of a year, Wright's total factory floor area more than doubled, increasing from one million to 2.3 million sq. ft..[18] By the end of the war, the total floor area of Wright's Paterson area factories amounted to 3.4 million sq. ft., nearly equal the No. 2 Shadow Group factories.[19]

During the 1920s and 1930s, American industrial factory design shifted from the older 'vertical' plane in multi-story daylight factory buildings to the 'horizontal plane' in large, single-storey buildings to facilitate sequencing operations and placement of machine tools for line production.[20] The idea was to 'build the plant around the process'.[21] The straight line is the best way of arranging line production, and a square or rectangular building allows greater flexibility in laying out production lines of machine tools, as well as greater efficiency if all production processes can be accommodated within one building.[22] Building on Albert Kahn's designs for the Ford River Rouge complex, this new form of factory design incorporated five key elements:

1) A single building consisting of a series of cell-like spaces.
2) New building materials, particularly reinforced concrete and high-strength steel to permit larger spans and larger workspaces within the factory building.
3) Larger workspaces, with wider bays and fewer supporting columns, allowed not just more machine tools to be placed within the factory, but more efficient placement of machine tools for line production.
4) The transfer of responsibility for materials handling from worker to machine, using conveyors, monorails, cranes and motorized trucks within the factory, saving time, space and indirect labour.

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[18] 'New Wright Engine Plant', *Aviation*, Vol. 39, No. 7, (July 1940), p. 50.
[19] AAF Industrial Facilities Expansions: Status Progress and Performance, Data as of 31 March 1945, File 218.7-3, 31 March 1945, AFHRA.
[20] Lewis, Robert: 'Redesigning the Workplace: The North American Factory in the Interwar Period', *Technology and Culture*, Vol. 42, No. 4, (October 2001), p. 671.
[21] 'Build the Plant Around the Process', *Factory Management and Maintenance*, Vol. 97, No.4, (April 1939), p. B-35.
[22] Muther, *Production Line Technique*, pp. 89-90.

5) The switch from overhead shafting and belt-driven machine tools to electrically powered machines, allowing more efficient placement of machine tools in production lines.[23]

As America began its rearmament, the large single-storey building with large unobstructed floor areas ideal for continuous large-scale production became the favoured design.[24] Some 80% of the new factories then under construction for defence production followed this pattern.[25] A new development that began at the end of the 1930s, and that will be seen in the Studebaker factories, was the 'windowless' factory that relied on artificial florescent lighting and air conditioning.[26] Artificial lighting improved working conditions and productivity by ensuring that all areas within the factory space had adequate lighting and when combined with air conditioning made multiple shifts more practical. The factories building Wright engines during the war would incorporate these features.

Wright's main factory building in Paterson, however, followed the older factory pattern. The Plant No. 1 building was a four-story, daylight factory built in 1916 that Wright had expanded over the years, adding three wings to increase the floor space to 675,000 sq. ft..[27] In 1937, Wright hired the firm of Albert Kahn Associates, the leading industrial architectural firm in America, to design an attached four-story wing, an experimental and engine test facility and an enlarged assembly building adjacent to the main factory.[28] The main factory's location in downtown Paterson was a constraint on its expansion. Another multi-story wing was considered the only practical option. The new wing was similar in construction to the original factory building, constructed as a flat slab, reinforced concrete structure with extensive steel sash windows to allow daylight.[29] The new wing, additions to the assembly building and the new experimental test

23 Muther, *Production Line Technique*, pp. 671-72.
24 'What's Happening and What's Ahead in Industrial Plant Development', *Factory Management and Maintenance*, Vol. 99, No. 4, (April 1941), p. B-37, Remarks of H.K. Ferguson.
25 'What's Happening and What's Ahead in Industrial Plant Development', p. B-38, Remarks of George Bryant.
26 Darley, Gillian: *Factory*, (London, 2003), p. 92; 'What's Happening and What's Ahead in Industrial Plant Development', B-38, Remarks of George Bryant.
27 'Wright Aero Will Expend $1,350,000 for Extensions to Factory and New Equipment', *Trade Winds*, Vol. 3, No. 7, (May 1937), p. 2.
28 'Wright Aero Will Expend $1,350,000 for Extensions to Factory and New Equipment', p. 2.
29 'The Wright Aeronautical Corporation Plant at Paterson, N.J.', *Mill & Factory*, Vol. XXIV, No. 6, (June 1939), p. 146.

facility increased Wright's total floor space to 880,000 sq. ft.[30] While the new wing gave more space for manufacturing, the Wright factory was not ideal for large-scale production. As a British observer commented at the time, 'The layout of the Wright shops ensures a good flow, but the installation of its machine tools struck me as being rather crowded, and there is the added disadvantage of the fact that the building is not very modern. It is laid out on three floors, which entails a certain amount of lost work.'[31]

Eight days after receiving a large French contract in October 1939, Wright announced plans to build a new factory on a seventeen-acre tract of land adjacent to its original factory. The new Wright factory, designated Plant No. 2, was designed for line production of engine parts from its inception and can be classed as one of the second generation of aero engine factories, roughly equivalent in size to the factories in No. 2 Shadow Group.[32] It was a large, single-storey building covering 540,000 sq. ft. of factory floor space. The factory was built of reinforced steel beams and columns on concrete floors reinforced with steel mesh to take the weight of machine tools and limit vibration, with concrete and brick walls.[33] Extensive steel sash glass windows admitted natural light. Raw materials entered at one end and finished parts exited at the other, to be trucked to the assembly building at Plant No. 1 nearby. Wider bays and fewer columns permitted twelve double lines of machine tools to cover the floor space, separated by wide aisles to allow movement of parts and materials, with three main cross aisles that served as collecting points.[34] This layout was apparently copied from examples in the automobile industry.[35] Completed in the remarkable short space of 57 days, Plant No. 2 added nearly 50% more floor space, but Wright still lacked the capacity to meet the surge in orders for the Cyclone 9 and Cyclone 14.

When Wright received more financing from the British and French Governments to expand its facilities, the company chose the more expedient route of acquiring a disused factory

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[30] 'Notes on General History of the Wright Aeronautical Corporation and Description of the Factory Located at Paterson, N.J., USA', copy in the Wright Aeronautical files at the Aviation Hall of Fame and Museum of New Jersey, Teteboro, NJ.

[31] Waddington, J.L.: 'American Methods and Modes-II', *Flight*, Vol. XXXVI, No. 1605, (September 28, 1939), p. 271.

[32] 'Modern Plant Insures Clouds of Planes', *Mill & Factory*, Vol. XXVII, No. 1, (July 1940), pp. 57-58.

[33] 'Modern Plant Insures Clouds of Planes', pp. 56-57.

[34] 'Modern Plant Insures Clouds of Planes', p. 58.

[35] 'Modern Plant Insures Clouds of Planes', p. 58.

in the Paterson area rather than building another new factory. The British Government purchased an idle textile mill in Fairlawn, NJ, four miles from Paterson, which it leased to Wright.[36] This became Wright's Plant No. 3, adding 450,000 sq. ft. of floor space and several acres of additional land.[37] The complex had over a dozen buildings, including its own power and steam generating plants. Wright converted one of the buildings to an aluminium foundry for casting aluminium cylinder heads. The factory was available, but not ideal for manufacturing aero engine components and had to undergo considerable renovation. Later the American Government's Defense Plant Corporation took over this building from the British Government.

Wright's expansion continued. In September 1940 the Company started building a new magnesium foundry of 110,000 sq. ft. on the land next to Plant No. 3, the first foundry in America built explicitly to cast magnesium aero engine parts.[38] Later that fall Wright acquired another idle factory complex, a former dying and printing plant in East Paterson, which became Plant No. 4.[39] This added 433, 000 sq. ft. of factory space, with two adjacent multi-story manufacturing buildings, but like Plant No. 3 not ideally suited for heavy machining operations. Wright then acquired a smaller factory that became Plant No. 5. With the addition of Plant No. 3, Plant No. 4 and Plant No. 5, and 160,000 sq. ft. of additional space added to its main factory and assembly buildings, Wright increased its total floor space from 880,000 sq. ft. in July 1939 to 2.8 million sq. ft. by the end of 1940.[40] Later, probably during 1943, Wright added a three-story manufacturing building with 480,000 sq. ft. of floor space at Plant No. 4, taking the total floor area at the Wright's Paterson factories to over three million sq. ft.[41]

Neither Plant No. 3 nor Plant No. 4 were easily adaptable for line production. The main manufacturing buildings were older mill buildings, made from heavy timber framing and brick

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[36] *The Wall Street Journal*, April 13, 1940, p. 11; NA, AVIA 38/611 Contract A-194.

[37] Defense Plant Corporation: *Manufacturing Plant, Fairlawn, New Jersey, Plancor 11-Plant No. 3*, Record Group 234, Records of the Reconstruction Finance Corporation: Defense Plant Corporation, Pamphlets Relating to Manufacturing Facilities, 1940-1945: Box1, 1 to 499, National Archives and Records Administration, (NARA), Washington, D.C.

[38] Defense Plant Corporation: *Manufacturing Plant, Fairlawn, New Jersey, Plancor 11-Plant No. 3*; *The Wall Street Journal*, September 21, 1940, p. 7.

[39] *The New York Times*, October 31, 1940, p. 7.

[40] *The Wall Street Journal*, March 21, 1941, p. 1.

[41] Surplus Property Administration: *Aircraft Plants and Facilities: Report of the Surplus Property Administration to the Congress, January 14, 1946*, p. 48; 'Defense Plant Corporation Authorizes Expansion of Plants Coast to Coast', *American Aviation*, Vol. 6, No. 15, (January 1943), p. 50.

walls, with concrete ground floors and wooden upper floors. They had to be renovated and converted for production of engine parts with a thicker concrete flooring to support heavier machine tools.[42] The wooden upper floors would likely not have supported the weight of the heavier, more advanced machine tools Wright was acquiring, and may have been used for servicing or administrative functions.

Each of the factories in the Paterson area built certain components for all the Cyclone models, feeding finished parts to Plant No. 1, with the distribution as follows:

Plant No. 1: Final assembly and miscellaneous parts.

Plant No. 2: Crankcases, cylinder heads, barrels and cylinder assembly, crankshaft centre sections, and propeller shafts.

Plant No. 3 (the British plant): Casting aluminium cylinder heads, crankshaft parts and assembly, connecting rods and magnesium castings.

Plant No. 4: Gears and cams.

Plant No. 5: Pistons.[43]

This factory system was not ideal for efficient line production as it required transporting parts some distance to Plant No. 1 for final assembly. It reflects the pressure Wright was under in 1939-40 to increase production as rapidly as possible. In essence the system was similar to the British aero engine schemes in No. 1 and No. 2 Shadow Groups, where No. 1 Shadow Group factories fed Hercules components to No. 2 Shadow Group. When the American Government asked Wright to expand production of the Cyclone 14 engine, and later the Cyclone 18, the company would adopt a completely different approach to organizing production.

[42] Surplus Property Administration: *Aircraft Plants and Facilities: Report of the Surplus Property Administration to the Congress, January 14, 1946*, (Washington, D.C., 1946), P. 48, *The New York Times*, November 9, 1947, p. R1, 'Fifteen Curtiss-Wright Factories Speed Defense Output', *Aero Digest*, Vol. 39, No. 4, (October, 1941), pp. 164, 166.
[43] Holley, *Buying Aircraft*, pp. 161-64.

The Studebaker Factories

To build the Cyclone 9, the Studebaker Corporation did not convert its automobile factories to aero engine production as some have supposed. Studebaker's automobile plant in South Bend, Indiana was neither suitable nor available. When Studebaker began planning for large-scale production of Cyclone engines in late 1940, the company had the benefit of starting with a clean slate. Studebaker could design its aero engine factories for large-scale production of a specific level of monthly output. The factories were initially designed with the capacity to build 1,000 engines a month, but after the attack on Pearl Harbor this was increased to 2,000 engines a month.[44]

As the company was starting from scratch, with more space available around the Midwest and with Government financing, Studebaker had the luxury of being able to build large factories better designed for more efficient line production than Wright's hastily acquired factory buildings in Paterson. The principal constraint the company faced was access to labour. The limited pool of labour available in South Bend, Indiana, the site of Studebaker's main automobile factory, forced the company to plan for three separate factories in different locations. Studebaker built one factory in Fort Wayne, Indiana, a second in Chicago, both roughly 90 miles from South Bend, and the third in South Bend itself. The Fort Wayne and Chicago factories built parts and components for the Cyclone 9, feeding them by rail and truck to the larger South Bend factory. This factory made other Cyclone 9 components and carried out final assembly and testing.

The factory at South Bend was the biggest of the three. Studebaker based the size of the factory on an estimate of the company's production capacity, the required number of machine tools to achieve the specified level of output and a belief that it should concentrate on what it

[44] Summary of Engines Shipped, p. 9; Civilian Production Administration: Industrial Statistics Division: *Alphabetic Listing of Major War Supply Contracts, Cumulative June 1940 through September 1945*, Vol. 4 Rey-Z, (Washington, D.C., 1946), p. 783.

did best, machining parts and assembling engines.[45] Studebaker decided to purchase all cast and forged parts from outside vendors, eliminating the need for foundries. Initially the main machine shop building had 790,400 sq. ft. of floor space. In 1943 Studebaker added another section on the east side of the machine shop, built from reinforced concrete framing with a concrete slab roof, giving an additional 166,400 sq. ft. of floor space for a total area of 1.06 million sq. ft. including the basement.[46] The attached engine test cell area, which covered 386,035 sq. ft., brought the total area to nearly 1.5 million sq. ft. This one building was bigger than the all the No. 1 Shadow Group factories combined, and bigger than any of the factory buildings in No. 2 Shadow Group.

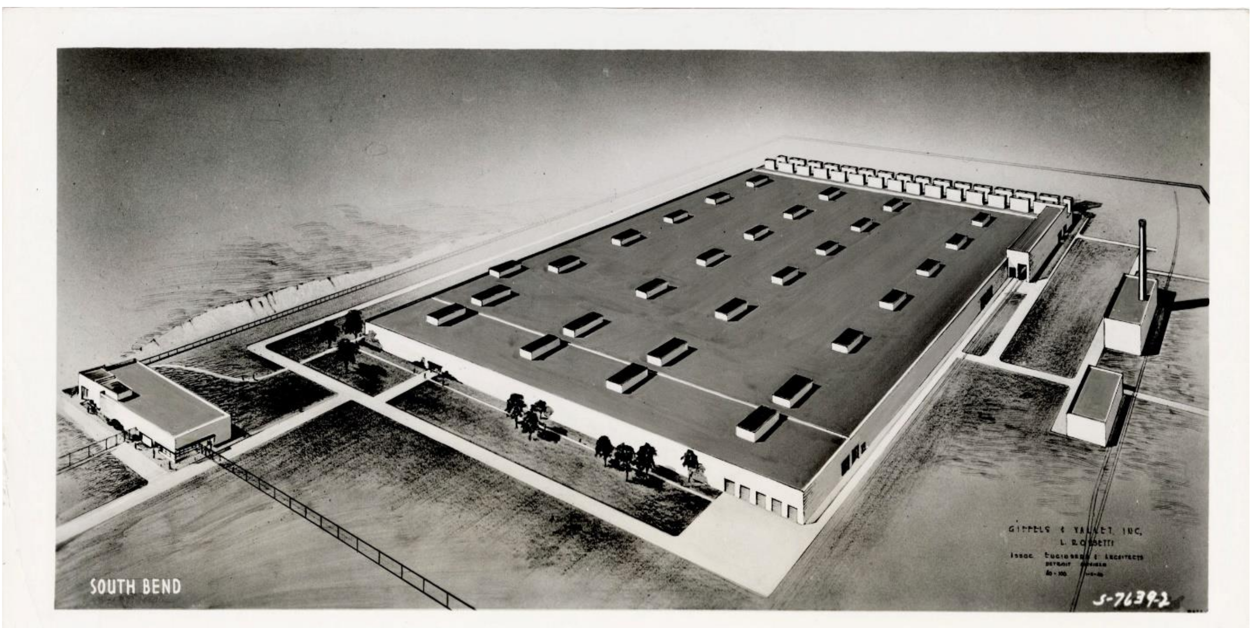

Illustration 4-1: Drawing of the Studebaker South Bend factory. Compare this plan with the plan of the Bristol No. 3 Shadow Factory at Accrington on p. 121. Instead of four separate machine shops, the South Bend factory was one large single-storey building, with a total floor area greater than the Accrington factory. Note also how the engine test cells were attached directly to the main building for easier transfer from final assembly to testing. (Detroit Public Library, Rose & Robert Skillman Branch Library National Automotive History Collection)

[45] Air Technical Service Command Plans (T-5), Logistics Planning Division: *Studebaker Corporation R-2600 Aircraft Engines Construction and Production Analysis*, pp. 3, 15.
[46] Engineers' Semi-Final Report Plancor 40, South Bend & Fort Wayne, Ind & Chicago, Ill., The Studebaker Aviation Division, South Bend, Ind., RG 234, Records of the Reconstruction Finance Corporation, Defense Plant Corporation Engineers Reports and Appendices, Plancor 40, Box 30, NARA.

The Chicago factory was next in size, with a machine shop building having 801,191 sq. ft. of floor space.[47] Responsible for manufacturing a wide range of smaller parts for the Cyclone, the Chicago factory had the most machine tools, totalling 1,638 as of October 1944. Fort Wayne was the smallest of the three, with its manufacturing building having a floor area of 374,400 sq. ft. and a total area of 470,100 sq. ft. accommodating 1,075 machine tools.[48] Both factories had easy access to main rail lines and highways to ship parts to the factory at South Bend. In comparison to their British counterparts, the three Studebaker factories together had a total floor area of approximately 2.9 million sq. ft., some half a million sq. ft. more than the machine shops and assembly buildings at the four factories of No. 2 Shadow Group and more than double the size of Bristol Shadow Factory No. 3 at Accrington.[49]

These Studebaker factories were better suited to flow production than their British counterparts. All three factories had the same rectangular design, incorporating the then-standard idea of a single unit with a large, open manufacturing space that could easily accommodate machine tools for efficient line production.[50] They were windowless following the new trend seen in several airframe and aircraft engine factories then under construction.[51] Air conditioning provided temperature control necessary for precision engineering and fluorescent lighting replaced natural light. The buildings were built of structural steel framing, with brick and tile walls and a metal roof. Column spacing was 40' x 40' to allow placing more machine tools, with an 18 foot ceiling 18. To support heavier machine tools, the floor of each factory was a twelve-inch double reinforced concrete slab covered in 1" x 18" maple blocks, easily sanded to

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[47] *Airplane Engine Plant, Chicago, Illinois, Plancor 40*; Engineers' Semi-Final Report Plancor 40, South Bend & Fort Wayne, Ind & Chicago, Ill., The Studebaker Aviation Division, South Bend, Ind.

[48] *Manufacturing Plant, Fort Wayne, Indiana, Plancor 40*; Engineers' Semi-Final Report Plancor 40, South Bend & Fort Wayne, Ind & Chicago, Ill., The Studebaker Aviation Division, South Bend, Ind.

[49] AAF Industrial Facilities Expansions: Status Progress and Performance, Data as of 31 March 1945, File 218.7-3, 31 March 1945, AFHRA.

[50] Air Technical Service Command Plans (T-5), Logistics Planning Division: *Studebaker Corporation R-2600 Aircraft Engines Construction and Production Analysis*, p. 12. The description of the factories is drawn from this report and Defense Plant Corporation: *Airplane Engine Plant, Chicago, Illinois, Plancor 40; Manufacturing Plant, Fort Wayne, Indiana, Plancor 40; Manufacturing Plant, South Bend, Indiana, Plancor 40,* RG 234, Defense Plant Corporation, Pamphlets Relating to Manufacturing Facilities, 1940-1945: Box1, 1 to 499,, NARA. See also *The Wall Street Journal*, March 26, 1941, p. 7.

[51] ; 'What's Happening and What's Ahead in Industrial Plant Development', B-38, Remarks of George Bryant; see also 'Ford Airplane Engine Plant Has Many Distinctive Features', *Mill & Factory*, Vol. XXIX, No. 4, (October 1941), pp. 59-66.

keep clean. Each factory had overhead traveling cranes capable of lifting up to twenty tons. None of the factories had to incorporate any protection from air attack. There were no blast walls within the machine shops to protect machine tools, the test cells were attached to the main machine shop and assembly building, and most importantly, unlike the factories in No. 2 Shadow Group and at Bristol No. 3 Shadow Factory all machining operations could be placed in one large structure for maximum efficiency.

The machine shop building at South Bend was built on a north-south axis, with parts and raw materials entering in the south end of the building and moving progressively to the engine test cell area that was attached to the machine shop at the north end. Unlike the No. 2 Shadow Group factories, where test cells were separated from final assembly buildings, this arrangement minimized the time it took to move an engine from final assembly to the test cells and back for final inspection. Machining departments began at one side of the plant with the crankshaft rear end section, moving subsequently to the crankshaft front end section, on to the crankshaft counterweights, crankcase front and rear sections, crankcase assembly, pistons, cylinder heads, cylinder barrels, cylinder head and barrel assembly and finally the heat-treating department.[52] After further expansion in 1942, the engine test area had 96 production test cells. A spur line connected the factory to the main railroad, allowing delivery of raw materials and shipment of finished engines to the factories building the B-17.[53] The three Studebaker factories cost the Government $92.8 million (£23.2 million), twice what the Government spent on the Wright factories around Paterson (see Table 4-1).

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[52]Geschelin, Joseph: 'Studebaker Know-how Speeds Flying Fortress Engine Output', *Automobile and Aviation Industries*, Vol. 88, No. 7, (April 1, 1943), pp. 21.

[53] Geschelin, Studebaker Know-how Speeds Flying Fortress Engine Output', p. 21 and *Manufacturing Plant, South Bend, Indiana, Plancor 40*; Engineers' Semi-Final Report Plancor 40, South Bend & Fort Wayne, Ind & Chicago, Ill., The Studebaker Aviation Division, South Bend, Ind.

Table 4-1: Army Air Force Industrial Facilities Expansions as of March 1945

Company	Total Floor Area Sq. Ft.	Cost of Construction	Cost of Machinery	Total Cost	Maximum Monthly Capacity
Wright Paterson Factories	3,442,854 sq. ft.	$9,697,496	$35,439,903	$45,262,719	1,554 Cyclone 9 Engines
Studebaker South Bend	1,536,971 sq. ft.	$15,727,930	$34,366,128	$50,130,791	2,300 Cyclone 9 Engines
Studebaker Chicago	855,441 sq. ft.	$7,199,182	$17,867,468	$25,318,440	Cyclone 9 Components
Studebaker Fort Wayne	505,754 sq. ft.	$4,580,648	$12,800,233	$17,439,251	Cyclone 9 Components

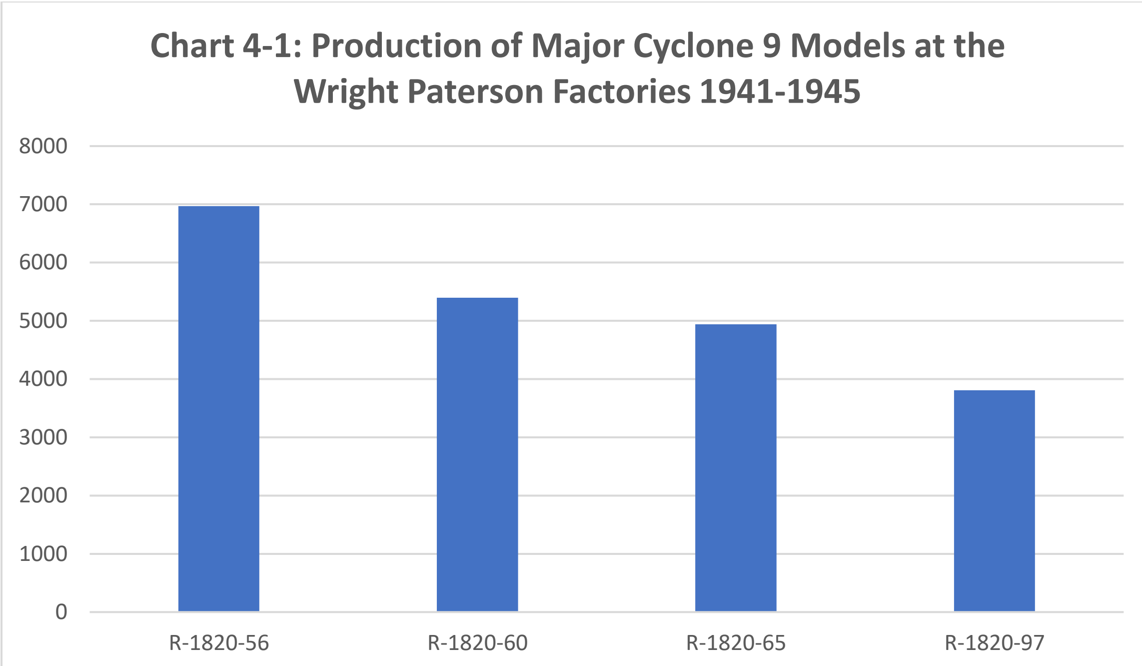
Source: AAF Industrial Facilities Expansions: Status Progress Performance as of March 1945, P. 6 Engines, File 218.7-3, Air Force Historical Research Agency, Maxwell AFB, AL.

The Production Record

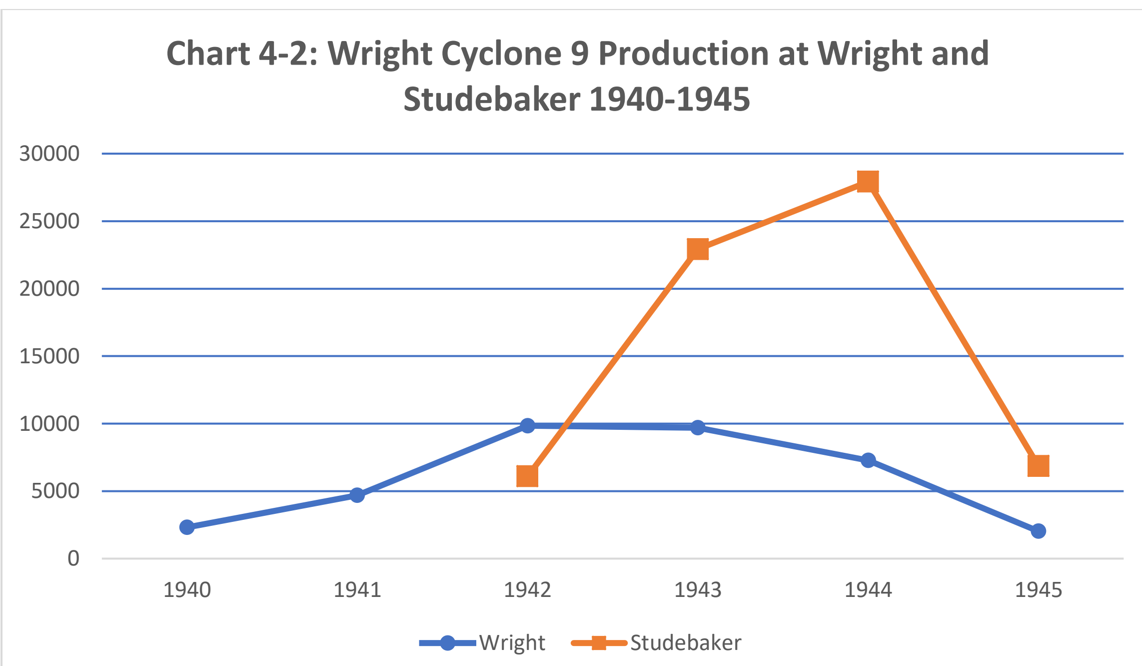
During the war Wright built 35,862 Cyclone 9 engines at its Paterson factories, while also building the seven-cylinder Whirlwind, the 14-cylinder Cyclone 14 and until 1943, the 18-cylinder Cyclone 18 (see Chart 4-1).[54] Wright built eighteen different versions of the Cyclone 9 engine, principally 8,746 -65 and -97 versions for the Boeing B-17, 5,399 -60 engines for the Navy's Douglas SBD dive bomber and 6,969 -56 series for the Navy's General Motors FM-2 fighter.[55] Wright was fortunate that its Cyclone 9 was a mature engine; by 1939 the company had built over 9,000 Cyclone 9 engines so that the factories were familiar with its manufacture.

[54] *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, Engine shipments for 1940-1945.

[55] Wright Aeronautical Order and Contracts Department: Summary of Engines Shipped (On an Invoice Basis) by WAD and Licensees: From 1929 thru August 31, 1960, p. 7.



Source: Wright Aeronautical Order and Contracts Department: Summary of Engines Shipped (On an Invoice Basis) by WAD and Licensees: From 1929 thru August 31, 1960, pp. 11-12.



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946)

Studebaker's contribution to Cyclone 9 production was critical (see Chart 4-2). During 1943, Studebaker built more than twice as many Cyclone 9 engines as Wright, and nearly three times as many in 1944. From 1942 onward, Studebaker's entire production of the Cyclone 9 went to the Boeing B-17. Studebaker's ability to concentrate on just one type of the Cyclone 9 engine, the -97 version, helped its production record immeasurably. In June 1941, the War Department amended Studebaker's contract to cover Cyclone 9 engines, specifying that planned production would reach a peak of 1,000 engines a month by December 1942.[56] After the attack on Pearl Harbor the War Department ordered Studebaker to double production to 2,000 engines a month, a level of output greater than the combined production of the Hercules at the No. 1 and No. 2 Shadow Group factories.[57] Studebaker began building the -65 version of the Cyclone 9 engine in early 1942, and reached a rate of 1,000 engines a month just eight months after starting production. Toward the end of 1942, having completed 3,504 of the -65 version of the Cyclone 9 engine, Studebaker shifted production to the -97 version, which differed only in minor details, building 60,285 by the end of the war.[58] Studebaker reached the required rate of 2,000 engines a month in May 1943, achieving a war-time peak of 2,479 engines in March 1944.[59] From April to November 1944, Studebaker sustained a production rate of over 2,300 engines a month, producing 27,920 engines for the entire year, second only to Buick's production of 30,550 Pratt & Whitney Twin Wasp engines.[60]

[56] *Studebaker Corporation R-2600 Aircraft Engines Construction and Production Analysis*, p. 9.
[57] Summary of Engines Shipped, p. 9; Civilian Production Administration: Industrial Statistics Division: *Alphabetic Listing of Major War Supply Contracts, Cumulative June 1940 through September 1945*, Vol. 4 Rey-Z, (Washington, D.C., 1946), p. 783.
[58] Wright Aeronautical Order and Contracts Department: Summary of Engines Shipped (On an Invoice Basis) by WAD and Licensees: From 1929 thru August 31, 1960, p. 7, Copy in the Wright Aeronautical files, New Jersey Aviation Hall of Fame and Museum.
[59] *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, Aircraft Engine Shipments schedules for 1942-1944.
[60] *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, Aircraft Engine Shipments schedules for 1944.

How it Was Done: Building the Cyclone 9 at the Wright Factories

This section will show how Wright shifted from pre-war batch production to large-scale production in wartime through improvements in production engineering and process engineering. During the 1930s, Wright offered its commercial and military customers different versions of the Cyclone 9 engine, and as a result orders tended to be for small numbers of engines, sometimes fewer than a dozen. Eighteen months after the outbreak of war in Europe, Wright made the shift from batch to large-scale production. In January 1940, the company built 211 aircraft engines, including 85 Cyclone 9 engines.[61] In June 1941, Wright for the first time in its history built over 1,000 engines in a single month, boosting its production of the Cyclone 9 five-fold. What Wright did was to shift to line production in order to speed the flow of parts through the factory and to use more high-production machine tools to cut production time even further, thereby increasing output.

Prior to the war, manufacturing the Cyclone 9 was similar to manufacture of the Bristol Mercury and Pegasus described in Chapter Three. To illustrate the complexity of machining the Cyclone 9, the table below shows the number of machining operations required for the main components of the Cyclone 9 engine and the amount of metal removed from the rough forgings during the machining process:

[61] *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, p. 139.

Table 4-2: Machining Operations on the Cyclone 9

Part Name	No. of Operations	Lbs. Rough Weight	Lbs. Finished Weight
Cylinder Barrel	35	68	16
Cylinder Head	37	37.5	27.5
Cylinder Assembly	85	------	------
Total	157	105.5	43.5
Crankcase Front	45	178	40.5
Crankcase Rear	45	178	36
Crankcase Assembly	57	------	------
Total	147	356	76.5
Crankshaft Front	85	111	76.5
Crankshaft Rear	80	50	22
Counterweight Rear	41	39	19.25
Counterweight Front	36	30	15
Crankshaft Assembly	89	------	------
Total	331	230	102.75

Source: Geschelin, Joseph: 'Studebaker Know-how Speeds Flying Fortress Engine Output', *Automobile and Aviation Industries*, Vol. 88, No. 7, (April 1, 1943), p. 21.

The Wright factory received rough cast or forged parts from the foundry that went through successive stages of machining, heat treatment and painting or plating before final assembly (see Table 4-2). As orders for its engines increased exponentially after the start of the war in Europe, Wright had to find ways to rapidly shift from building engines in small batches to continuous large-scale production, increasing output while maintaining absolute adherence to its standards of quality. Initially, as factories in No. 1 Shadow Group had done, Wright expanded production by adding more workers to get higher utilization from its standard machine tools. The easiest way to increase output was to simply '…duplicate again and again any existing processes and equipment.'[62] In January 1939, Wright had 3,398 employees; by the end of the year Wright had built this to 5,141 employees, and by the end of 1940 had more than doubled the number of employees to 12,408.[63]

By the end of 1939, with their backlog growing rapidly from both foreign and domestic orders, American airframe and aero engine manufacturers were already close to capacity production.[64] There were now questions as to how the aircraft industry could meet the demand.[65] The answer to increasing production of airframes and aero engines was, for many observers outside the industry, simple. As Henry Hill, a project engineer with Wright noted:

> To most people this increased production rate is merely a matter of applying the well-known methods of the automobile industry. This naïve statement has just enough truth in it to confuse the minds of many people both inside and outside the aviation industry. Between the statement and the actual fact the gulf is very wide indeed. It is true that the principles developed by the automobile people in Detroit must be applied to aircraft and engine production, but we are sure that it is equally true that these principles must be modified and further developed to suit the new set of standards and the new tempo required in the aircraft field. Whether we like it or not we must face the fact that in developing the aircraft engine we have also developed a brand-new design and manufacturing technique, which is as far removed from automobile manufacture as the automobile was from carriage building.[66]

During 1939 a widely shared discussion began in the aircraft industry on production issues. That fall, the Society of Automobile Engineers, the professional body for automobile and aeronautical engineers, held a special conference on production problems in the industry, the

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[62] Sutton, Kenneth E.: 'Production and Quality', Wright Aeronautical Corporation (1941), p. 4.
[63] Mr. Haag to Secretary Morgenthau, 'Employment in the Aviation Manufacturing Industry', January 14, 1941, Morgenthau Diaries, Vol. 347, January-13-14, 1941.
[64] 'U.S. Manufacturers Nearing Capacity; Booked Up to Next Summer', *American Aviation*, Vol. 3, No. 12, (November 15, 1939), pp. 1, 6.
[65] Wright, T.P.: 'America's Answer: Gearing Our Aviation Industry to the National Defense', *Aviation*, Vol. 38, No. 6, (June 1939), pp. 26-29, 78, 80, 82, 84; ' Aircraft Expansion: Industry Studies Steps to Increase Output Should Necessity Arise', *The New York Times*, September 21, 1939, p. 1.
[66] Hill, Henry C.: 'More Aircraft Engines for National Defense', Paper presented at the National Aeronautic Meeting of the Society of Automobile Engineers, March 13-14, 1941, p. 4.

National Aircraft Production Meeting.[67] Some three thousand people attended the three-day conference. Wright sent an exhibit of its engines and had Henry Hill deliver a paper on problems in the quantity production of aircraft engines.[68] Over the next two years articles appeared regularly in major aviation and specialized industry magazines describing how airframe and aero engine companies were addressing the problems of increasing production, with detailed descriptions of the new methods they were using.[69]

In November 1940, the Society for Automobile Engineers held its second National Aircraft Production Meeting. For this meeting both Pratt & Whitney and Wright exhibited aircraft engines and sent engineers to give papers.[70] A key theme of the conference was mass production and particularly the application of automobile manufacturing techniques to aircraft production.[71] Two leading engineers from the Curtiss-Wright Corporation, Wright's parent company, noted the many differences between mass production in the automobile industry and aircraft production, but asserted that despite these differences, there were opportunities to apply automobile production methods.[72] They stated that 'careful analysis supports the conclusion that much can be gained through the utilization of automobile methods and practices when combined with a liberal application of common sense.'[73] What this required, they argued, was careful attention to Design, Tool, Production and Process Engineering.[74] This was exactly the approach Wright took to the problem of shifting to large-scale production of aero engines.

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[67] 'SAE Talks Production', *Aviation*, Vol. 38, No. 11, (November 1939), pp. 32-33, 84, 86, 108.
[68] 'SAE Talks Production',, pp. 84, 108; Hill, Henry C.: 'Design Problems in the Quantity Production of Aircraft Engines', *SAE Journal (Transactions)*, Vol. 46, No. 1, (January 1940), pp. 18-24.
[69] See for example 'Modern Plant Insures Clouds of Planes', *Mill & Factory*, Vol. XXVII, No. 1, (July 1940), pp. 55-57; Nutt, Arthur: 'Aviation Faces Biggest Production Problem', *Automobile Industries*, Vol. 83, No. 7, (October 1, 1940), pp. 321-42, 413; 'Bombers in Quantity', *Aviation*, Vol. 39, No. 11, (November 1940), pp.34-37, 108; 'Unusual Processes in Aircraft Production', *Mill & Factory*, Vol. XXVIII, No. 4, (April 1941), pp. 68-74; 'Modern Production at Lockheed', *Mill & Factory*, Vol. XXVII, No. 1, (May 1941), pp. 77-82
[70] 'Only the Productive Can Be Strong-Only the Strong Can Be Free: A Report of the 1940 SAE National Aircraft Production Meeting, held in Los Angeles', *Aviation*, Vol. 39, No. 12, (December 1940), pp. 64, 148.
[71] 'Only the Productive Can Be Strong-Only the Strong Can Be Free', pp. 65, 144.
[72] Berlin, Don R. and Peter F. Rossmann, 'Applying Automobile Methods to Aircraft Production', *Aviation*, Vol. 40, No. 1, (January 1941), p. 42.
[73] Berlin and Rossman, 'Applying Automobile Methods to Aircraft Production', p. 42.
[74] Berlin and Rossman, 'Applying Automobile Methods to Aircraft Production', p. 42.

Production Engineering at Wright

Wright's problem was 'to reduce the time required for all manifold operations comprising the intricate process of aircraft engine manufacture.'[75] To this end, Wright's production engineers concentrated their efforts in four main areas: changing the company's policy on manufacturing engine parts, shifting to line production, reconfiguring processes to speed production and putting much greater emphasis on materials handling. All of these efforts can be characterized as an effort to establish flow production, achieving increases in output by cutting machining and handling time wherever possible.

An observer at the November 1940 National Aircraft Production Meeting remarked on the extent of free exchange of information between companies and the general spirit of cooperation in seeking solutions to production problems.[76] Wright set up a technical production unit to examine the problems of large-scale production and to make recommendations based on a study of production methods in other industries.[77] The unit made a close study of automobile manufacturing methods to see what could be applied to manufacturing aero engines, but went beyond this to study general industrial practices, looking at current production methods, new types of machine tools and new manufacturing processes.[78] The challenge was to determine what changes that would accelerate production could be justified, with the corollary demand that these changes could not affect the quality and reliability of the engines.[79] From these studies came new approaches to production engineering and a new attitude toward measuring processes, machining and assembly operations not in terms of cost in dollars, but cost in time.[80]

For years Wright's policy had been to manufacture nearly all the machined parts for its engines in its own factory in order to exercise complete control over quality.[81] Purchased parts

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[75] Berlin and Rossman, 'Applying Automobile Methods to Aircraft Production', p. 42.
[76] 'Only the Productive Can Be Strong-Only the Strong Can Be Free', p. 65.
[77] Holben, Martin M.: 'Some Aircraft-Engine Production Methods', *SAE Journal (Transactions)*, Vol. 52, No. 10, (October 1944), p. 492.
[78] Holben, 'Some Aircraft-Engine Production Methods', p. 492.
[79] Gagg, R.F.: 'New Production Lines for Aircraft Engines', *Mechanical Engineering*, Vol. 63, No. 3, (March,1941), p. 177.
[80] Hill, 'More Aircraft Engines for National Defense', p. 7.
[81] Sutton, 'Production and Quality', p. 2.

made up less than 25% of the cost of a Wright engine.[82] The company now changed its policy. Increasing sub-contracting to speed production was also a policy that Government mobilization agencies actively encouraged. Sub-contracting reduced the number of employees that Wright needed to train and freed up supervisory personnel and skilled machinists for other tasks.[83]

The shift to line production was a significant change for Wright from past practices. As Wright expanded its production facilities, conversion to line production became possible within each manufacturing building, although the dispersion of Wright's factories around Paterson was not ideal to achieving flow production. In a method that was analogous to No. 1 Shadow Group's production of the Bristol Mercury and Pegasus, Wright chose to view its Paterson factories as a single production unit, composed of greatly enlarged manufacturing operations for particular aero engine parts, each made at a different factory, feeding the main assembly operation in Plant No. 1.[84]

The first step in designing a layout for line production was to determine the number and type of machine tools required for each major line.[85] Analysing the production schedule, the time required to manufacture each part and the number of working minutes each month, helped determine the required number of machine tools. Plant layout engineers prepared a chart showing the types of machines, their placement in the sequence of machining operations and the amount of floor space each machine tool required, making allowance for the spacing needed for the operator, proper placing between machines, storage space for finished work, and aisle space for moving rough and finished parts. This chart determined the floor space each department required, making it possible to calculate the total floor space for a new or converted building. From all this information layout engineers prepared production strips, long pieces of black Upson Board showing the layout of a specific production line, placing on these strips scale templates cut out in the shape of the specific machine tools in their proper sequence. These production strips went on a larger board outlining the factory space available, with spaces added for other processes like heat treatment, painting and assembly operations. Using this visual aid

[82] Sutton, 'Production and Quality', p. 3.
[83] Sutton, 'Production and Quality', p. 3.
[84] Gagg, 'New Production Lines for Aircraft Engines', p. 178.
[85] Gagg, 'New Production Lines for Aircraft Engines', p. 178. The description of plant layout is taken from this article.

production engineers could grasp the overall layout of line production and could make changes to the production strips to assess the implications of changing manufacturing processes or adding new types of machine tools. Unlike the automobile industry, where changes in design tended to be implemented when the factories were gearing up for their annual model change, design changes to aero engines were continuous throughout the year thus putting a premium on building flexibility into line production.[86]

While the straight-line layout was considered the ideal for maximizing flow, under certain circumstances this proved difficult to achieve. Developing a layout for fabrication operations was more difficult than laying out assembly operations and depended on the sequence of operations and the type of machine tools employed for each operation.[87] At Wright's Plant No. 2, the company resorted to a U-shaped line for machining cylinder barrels and cylinder heads and for the final cylinder assembly. To ensure maximum flow, however, Wright laid out the sequence of machining operations so that a part never back-tracked but was always moving forward.[88] Parts moved down one side of a line, would turn and move down the other side, then shift to the next line and repeat the process until machining was complete.

Wright reorganized its foundry operations to conform to line production methods, allowing for an uninterrupted flow of operations from intake of raw materials to finished cylinder head casting.[89] At Plant No. 1 and Plant No. 2, Wright automated painting and electro-plating Cyclone engine parts, removing most hand-held devices and hand operations.[90]

At Plant No. 1, Wright completely revamped its assembly operation. It created a modified version of the assembly line, dividing up the labour of assembly. For years the company had used what it called a 'spot assembly' system, in which four-man teams assembled an entire engine taking a full eight-hour day to complete the job, bringing parts from storage as needed.[91]

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[86] Brown, P.W. and H.E. Linsley: 'Engines from the Ground Up', *American Machinist*, Vol. 84, No. 11, (May 29, 1940), p. 371.
[87] Muther, *Production Line Technique*, p. 87.
[88] Brown and Linsley, 'Engines from the Ground Up', p. 372.
[89] 'New Wright Line-production Foundry Features Company's Plant No. 3 in Fair Lawn, New Jersey', *Trade Winds*, Vol. 5, No. 7, (November 1940), pp. 6-7.
[90] 'Wright Aero's Electro-plating Equipment Among Most Modern and Versatile in Industry', *Trade Winds*, Vol. 5, No. 7, (November 1940), pp. 10-11; 'Wright Aeronautical's Line Conveyor Technique Speeds Painting of Cyclone and Whirlwind Parts', *Trade Winds*, Vol. 5, No. 7, (November 1940), pp. 14-15.
[91] Sutton, Kenneth E.: 'Progressive Assembly of Wright Engines', *Aero Digest*, Vol. 39, No. 4, (October 1941), p. 192.

Assembling a complete engine required a high degree of skill and experience as well as thorough familiarity with all the parts. As production accelerated Wright found that skilled assemblers were not to be had. Instead the superintendent of the assembly department and his foremen worked out a new system that used a coordinated, progressive sequence of operations. The team broke down the process of assembling a Cyclone 9 engine into separate operations on groups of parts that took no more than 24 minutes to assemble.[92] Teams of one to three workers manned long benches set at right angles to the main assembly line. Each team built up one sub-assembly, each worker adding a piece or pieces as needed, the completed sub-assembly joining a main assembly line where it was added to the engine as it passed by.[93] The benefits to this method were the savings in assembly time and the shorter training time, as each assembler no longer had to be familiar with every part of a Cyclone engine, but only the parts that he or she would assemble.

Unlike the assembly lines in automobile factories, every Wright engine went through a sequence of assembly, dis-assembly and re-assembly on three different lines before it was shipped. Even with monthly engine production rates increasing, Wright did not change its standard practice for the most important test of all, the production test of a complete engine. Once assembled under the eyes of inspectors the engine went to the engine test cells where it was mounted on a test stand and connected to fuel and oil lines. During the first or 'green' test, the engine was run for up to seven hours at various speeds, with inspectors recording all data on performance. When the green test was over, the engine went to a dis-assembly line, where every engine was taken completely apart.[94] Sub-assemblies went to separate dis-assembly benches, where they were taken down to their component parts and each part subject to close inspection. After inspection all the parts of the same engine went to a different, re-assembly line for final assembly. Here the parts were put back into their sub-assemblies and the engine re-assembled for a final, shorter test run of 15 to 30 minutes after which the engine went through one more inspection.[95] Most of this assembly and dis-assembly could only be done by hand, but Wright did automate the engine cleaning process that took place after the final test run. Wright installed a

[92] Sutton, 'Progressive Assembly of Wright Engines', p. 192.
[93] Sutton, 'Progressive Assembly of Wright Engines', p. 194.
[94] Sutton, 'Progressive Assembly of Wright Engines', p. 194.
[95] Sutton, 'Progressive Assembly of Wright Engines', p. 194.

continuous washing machine where engines attached to an overhead conveyor passed through several jets of a cleaning solution to remove all traces of dirt and oil before packing and shipment to airframe factories.

From their study of automobile production methods, Wright's production engineers learned that 'machine tools alone are not the total answer to the problem of increased output; proper material flow is of at least equal importance.'[96] As Wright expanded its factories, the company devoted more attention to finding ways of moving materials by machine instead of by hand to speed production. The electro-plating operations in Plant No. 1 and Plant No. 2 involved careful cleaning of parts to be plated in various chemical solutions and then plating operations to cover parts with tin, chromium, lead, or in the case of cylinders that would be subject to saltwater corrosion, with molten aluminium.[97] Painting involved spraying parts with a primer, drying them, then spraying on two coats of enamel before baking. Previous methods involved moving parts from one operation to the next and spraying on paint manually, turning the part to paint all surfaces. In both electro-plating and painting operations Wright installed conveyors to move individual parts through each stage of the process.[98] In its foundry operations, Wright put in automatic hoists, conveyors and roller systems to move heavy moulds, molten aluminium and rough castings.[99] Using an overhead monorail allowed foundry workers to use a larger ladle in place of a smaller hand ladle, allowing faster and more thorough pouring into the mould.[100]

Wright progressively installed conveyor systems along its production lines so that parts moved from machine to machine along the conveyor line.[101] The conveyor systems saved floor space by eliminating the need to store work in process or finished parts alongside a machine tool. This allowed more machine tools to be placed along a production line. Conveyors replaced the hand carts and shop trucks used to move parts from station to station, removing potential bottlenecks and freeing workers for other tasks. As more and more women joined the Wright

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[96] LInsley, H.E.: 'Aircraft Engines on the Production Line', *Mechanical Engineering*, Vol. 65, No. 7, (July 1943), pp. 494.
[97] 'Wright Aero's Electro-plating Equipment Among Most Modern and Versatile in Industry', pp. 10-11.
[98] 'Wright Aeronautical's Line Conveyor Technique Speeds Painting of Cyclone and Whirlwind Parts', pp. 14-15.
[99] 'New Wright Line-production Foundry Features Company's Plant No. 3 in Fair Lawn, New Jersey', p. 6.
[100] 'New Wright Line-production Foundry Features Company's Plant No. 3 in Fair Lawn, New Jersey', p. 7.
[101] Linsley, 'Aircraft Engines on the Production Line', p. 494.

work force, the conveyor system and hand-operated or automatic hoists reduced the need for women to use their own strength to shift heavy parts, thereby removing one of the principal objections to employing women in the factories.[102]

All these methods, purchasing more parts from outside vendors, shifting to line production for key engine parts, reconfiguring manufacturing processes and expanding and improving materials handling saved time and speeded production. This was a process of achieving incremental savings in time all along the manufacturing process, but the increments, when added together, contributed to faster rates of production. But the company's efforts to develop high-production machine tools through process engineering were far more important to increasing Wright's production.[103]

Process Engineering at Wright

In an article written in September 1941, the *Wall Street Journal* commented that 'perhaps no individual company in the aircraft industry has turned to the use of automatic single purpose machines in the same degree as the Wright Aeronautical Corporation'.[104] In contrast to companies who depended on standard machine tools, the *Journal* noted that 'Wright is following the automobile practice of using gigantic machines which are only good for exactly one job.'[105] Wright's dilemma in 1939 was that it was facing, concurrently, a growing demand for its aero engines with a growing scarcity of skilled machinists.[106] The volume of production required— and the fact that the British and French Governments, and later the American Government were willing to provide financing for new machinery —now justified using expensive high-production machine tools that Wright had not found economical for batch production. The machines that Wright now required had to have two key characteristics: first, they had to be more productive than standard machine tools, producing more parts per operation and at a faster rate; and

[102] Linsley, 'Aircraft Engines on the Production Line', p. 495; Wright Aeronautical Corporation: *Application of High Production Machine Tools*, (No date), p. 3.
[103] Klemin, Alexander: 'A Miracle of Production', *Scientific American*, (December 1944), p. 256.
[104] *Wall Street Journal*, (September 22, 1941), p. 18.
[105] *Wall Street Journal*, (September 22, 1941), p. 18.
[106] Holben, 'Some Aircraft-Engine Production Methods', p. 492.

second, they had to be adapted to the limited skills and experience of the workers Wright would hire going forward. To cope with the same dilution of skill levels that Bristol faced in Britain, the skill of the machinist had to be built into the machine, the task of the process engineer.[107] Machines had to be made 'practically fool proof' with operations that were 'completely automatic, except for loading and unloading.'[108]

When Wright began developing high-production machine tools, the company had little experience to draw on. As one Wright executive explained the problem, 'there was no precedent upon which calculations could be based or any guarantee that it would be possible with automatic equipment to hold the extreme accuracy and fine finishes demanded for this class of work'.[109] At first, there was considerable scepticism that automatic machine tools could be used in aero engine production.[110] One principal concern was whether automatic, high-production machine tools could be designed with a degree of flexibility that would accommodate the design changes that were a regular feature of making aero engines.[111] The Paterson factories became a laboratory for developing advanced automatic machine tools for aero engine production.[112]

Wright began working with the major machine tool builders to design machine tools that would meet Wright's requirements, realizing that it was presenting the machine tool companies with an 'almost impossible set of problems'.[113] Wright also undertook a detailed study of machine tools and methods in the automobile industry to determine if there were machine tools that could be adapted to Wright's needs.[114] The American automobile industry was the leader in developing techniques of mass production and had continuously stimulated the machine tool industry to invent new types of machine tools to speed production and achieve greater precision and finer finishes at lower costs.[115]

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107 Sutton, 'Production and Quality', p. 4.
108 Sutton, 'Production and Quality', p. 5.
109 Linsley, H.E.: 'Mass Production for the Aircraft-Engine Industry', *Mechanical Engineering*, Vol. 64, No. 2, (February 1942), p. 100.
110 Linsley, 'Aircraft Engines on the Production Line', p. 493.
111 Linsley, 'Aircraft Engines on the Production Line', p. 493.
112 *Wall Street Journal*, (September 22, 1941), p. 18.
113 Linsley, 'Mass Production for the Aircraft-Engine Industry', p. 101.
114 Linsley, 'Mass Production for the Aircraft-Engine Industry', p. 101.
115 Geschelin, Joseph: 'Conversion for War: Influence of Automobile Mass-Production Methods', *SAE Transactions*, Vol. 50, No. 7, (July 1942), p. 278.

At the same time, Wright applied the tools of process engineering to examine the fabrication of every part of a Cyclone 9 engine to see where and how a process of 'de-skilling' could be applied and a new machine tool designed for a specific operation.[116] Wright found that while the cost of a high-production machine tool was higher than an equivalent standard machine, in most cases there was an actual saving as one high-production machine might replace several standard machine tools.[117] The difficulty Wright faced with increasing production rates using high-production machine tools was that these newly-designed tools took from six to fifteen months to build,.[118] In the interim, Wright continued to use standard machine tools, but replaced them as soon as the new high-production machine tools arrived at the factories.[119]

Wright's shift to relying on more high production machine tools went through three phases. In the first phase, beginning in 1939, Wright simply continued what it was doing, adding more standard machine tools and workers, as the shadow factories building Mercury and Pegasus engines had done. In the second phase, during 1940 and into 1941, Wright purchased semi-high-production machine tools that could be easily acquired, that could produce parts previously made on standard machine tools and that employed semi-skilled workers.[120] It used these machines to test new production methods that it passed on to its new factory at Lockland, Ohio (see Chapter Six), and to gain knowledge and experience that could be applied to designing even more advanced high-production machine tools. These advanced high-production machine tools, many unique to the factories building Wright engines, formed the third phase of machine tool development at Wright. During this period Wright purchased 2,000 machine tools for its Paterson factories at a cost of $28 million, although many of the high-production machine tools Wright ordered would not reach the factories until 1941, beginning the third phase of machine tool utilization.

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[116] Sutton, 'Production and Quality', p. 4.
[117] Linsley, 'Mass Production for the Aircraft-Engine Industry', p. 101.
[118] Sutton, 'Production and Quality', p. 2.
[119] *Wall Street Journal*, (September 22, 1941), p. 18.
[120] Linsley, 'Mass Production for the Aircraft-Engine Industry', p. 100; 'Some Aircraft-Engine Production Methods', p. 493; 'Machining Methods on Wright Aero-Engines', *Machinery (London)*, Vol. 59, No. 1516, (October 30, 1940), p. 113.

Not all the high-production machine tools Wright developed in consultation with the machine tool builders were new designs. Many were derived, after careful study, from machine tools in use with the automobile industry.[121] The most critical aspect of this evolution was to incorporate automaticity into the design to cope with the influx of semi- and unskilled workers.[122] As previously explained, all a semi- or unskilled operator had to do with an automatic machine tool was to load and unload the machine and check the result for accuracy with gauges provided; the machine would automatically complete all machining operations in the correct sequence with no intervention from the operator.[123]

Wright found that, contrary to what was expected, the automatic machine tools it developed were even more accurate that standard machine tools because their heavier construction limited unwanted vibrations.[124] Among the more important types of machine tools that were transferred from the automobile industry were multiple-spindle drilling, tapping and boring machines that could perform these operations in succession on multiple work pieces using a single machine tool; precision boring machines using cemented-carbide tools for rough drilling and a diamond tool for fine finishing; automatic milling machines; internal and external grinding machines and gear finishing machines.[125] Automatic multiple-spindle lathes were another important development for large-scale production.[126] By mounting multiple single-point cutting tools in a specially designed jig, a multi-tool lathe could perform multiple cuts at the same time, for example cutting all the fins on a cylinder barrel or cylinder head in one operation instead of having to shift the work piece from one machine to another for progressive operations.[127] An examination of improved production methods using high-production automatic machine tools to manufacture the main components of Cyclone 9 engines provides numerous examples of the dramatic savings in production time, space and man-power.

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[121] Linsley, 'Mass Production for the Aircraft-Engine Industry', p. 101.
[122] Scranton, Philip: 'From Depression to Globalization: Reconfiguring 20th Century American Machinery and Machine Tool Building', Practical Machinist: 06-14-2003, pp, 29-31.
[123] Sutton, 'Production and Quality', p. 4.
[124] Linsley, 'Aircraft Engines on the Production Line', p. 493.
[125] '40 Years of Machine Tool Progress', *Automobile Industries*, Vol. 81, No. 7, (October 1, 1939), pp. 52-53.
[126] During the war American metal working industries doubled the number of automatic multiple-spindle lathes in use. See Ristuccia, Cristiano Andrea, and J. Adam Tooze: 'Machine tools and mass production in the armaments boom: Germany and the United States, 1929-44', *The Economic History Review*, Vol. 66, No. 4, (2013), pp.963, 966.
[127] 'Multi-tooling for Aero-Engine Production', *Aircraft Engineering*, Vol. XI, No.123, (May 1939), p. 217.

In manufacturing cylinder heads, machines replaced hand operations at the start of the process at the foundry. After a cast cylinder head had cooled and been removed from the mould, excess aluminium and minor irregularities had to be removed from the cast fins. This had been done manually, but Wright designed a special machine to clean up the cylinder heads using an abrasive grinding wheel and a master cam which profiled the cylinder head, moving the grinding wheel automatically.[128] Each cylinder head required a number of holes to be drilled, reamed, countersunk and tapped, including holes for the two spark plugs, holes for the valve springs, holes for the studs holding the intake and exhaust port flanges and holes for the intake and exhaust port rocker box covers. In the 1930s, operators used a single-spindle drill press to make all these holes in the cylinder head, one at a time, having to change the type of tool—a drill, reamer, borer, counterbore or tap—for each operation.[129] With the need to increase production, Wright then designed semi-production machine tools, one of which could drill, ream, countersink and tap spark plug holes in one continuous operation, automatically moving the cylinder head from station to station.[130] But the cylinder head would then have to be moved to another machine to perform these operations on the intake and exhaust ports and a third machine to machine the holes for valve springs and finally a fourth machine to drill holes for rocker box covers.[131] Wright replaced all these machines with what was no doubt the most impressive of the many high-production machine tools Wright developed during the war, the Greenlee Automatic Transfer Machine (described more fully in Chapter Six).

The Greenlee automatic transfer machine was just one of many high-production machine tools Wright developed during the war to manufacture Cyclone engine components. The cylinder barrel for the Cyclone 9 went through two major operations, cutting the cooling fins on the outside of the barrel and creating a smooth finish on the inside. First the cylinder barrel went through a rough finishing process to remove metal from within its interior. Multi-spindle, six-station Bullard Multi-Au-Matic boring machines replaced single-spindle boring machines for this

[128] 'Wright Cyclone Production Speeded up by Special Methods', p. 173.
[129] Holben, 'Some Aircraft-Engine Production Methods', p. 493.
[130] Holben, 'Some Aircraft-Engine Production Methods', p. 494.
[131] Holben, 'Some Aircraft-Engine Production Methods', p. 494.

process.[132] After rough finishing the cylinder barrel and completing the nitriding hardening process, the cylinder barrel was transferred to a Fay automatic lathe with a special magazine tool holder that could cut all 41 cooling fins on the outside of the cylinder at one time.[133] Once the cylinder head was attached to the cylinder barrel, the complete assembly went to a specially designed Heald internal centreless grinder that placed the assembly in position for machining, automatically removed the finished part and loaded a new part onto the machine.[134] A flange at the bottom of the cylinder barrel required twenty holes to be drilled, bored, reamed and countersunk for the studs that attached the flange to the crankcase. Here again a specially designed machine replaced single drilling and reaming machines. A Baker vertical, forty-spindle, five-station machine completed this operation automatically. The cylinder assembly was loaded onto the first station and then moved automatically around the machine to each of the four stations. The second station drilled ten holes in the flange, the third station drilled the remaining ten, while the fourth and fifth stations reamed and countersunk the holes to the required configuration. The Baker machine cut operating time from 6.5 to 1.5 minutes, replaced five standard machine tools and reduced the operators required over three shifts from fourteen to two, saving 85 man-hours.[135]

The front and rear sections of the Cyclone 9 forged steel crankcase went through rough and finish machining and were then joined together and placed on a Foster 'Fastermatic' automatic turret lathe that finished the holes for the cylinder assemblies and the cylinder pad faces where the cylinder assembly flanges would be attached. The fixture holding the crankcase rotated automatically until the 'Fastermatic' had completed machining all nine cylinder holes and cylinder pads.[136] An Ex-cell-o automatic multiple drilling machine drilled twenty holes in the cylinder pads to anchor the cylinder assembly, drilling ten holes in two pads at a time and then

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[132] Brown, P.W.: 'Wright Turns to Line Production', *American Machinist*, vol. 85, No. 13, (June 25, 1941), pp. 600, 602.
[133] Brown, P.W. and H.E. Linsley: 'More Horsepower for National Defense', *Aero Digest*, Vol. 39, No. 4, (October 1941), p. 182.
[134] Brown and Linsley, 'More Horsepower for National Defense', P. 182; *Wall Street Journal*, (September 22, 1941), p. 18.
[135] Linsley, H.E.: 'Automatic Tooling Speeds Production in the New Wright Aero Plant', *Machinery (NY)*, Vol. 48, No. 6, (February 1942), P. 110; Wright Aeronautical Corporation: *Application of High Production Machine Tools*, p.9.
[136] 'Manufacturing the Cyclone, Part II', *Aircraft Production*, Vol. II, No. 5, (May 1940), p. 154.

moving the part automatically to drill the second set of ten. The machining operation moved to a Baush multiple back-counterbore machine which could counterbore sixteen holes at once, automatically moving the fixture holding the crankcase for the next operation. A third machine carried out tapping, finishing the threads for the bolts that would hold the cylinder flange to the crankcase.[137]

During 1941 and 1942 Wright devised a method to speed up machining the articulated rods for the Cyclone 9 at Plant No. 3 in Paterson. Previous practice had been to mill the inner section of each articulated rod separately on a Cincinnati milling machine.[138] When one side of the rod was finished, the fixture holding the rod had to be manually turned over to finish the other side. When grinding the ends of the articulated rods to the correct shape the end of the rod had to be oscillated by hand against the grinding disc, a laborious process subject to inaccuracies. Wright engineers designed a special fixture that would fit on a standard grinding machine. An arbor, a fixture for holding multiple work pieces, held seven articulated rods, and two arbors could fit on the grinding machine. When the machine had finished grinding one side of the rods, the arbors were flipped over to grind the other side so that fourteen rods could be machined at one time. The arbors were then placed on a Mattison grinding machine that automatically oscillated the rod ends while grinding them, eliminating the need for hand oscillation.[139] Two Mattison Grinders replaced five standard machines, reduced the number of operators required from fourteen to four and saved 124 man-hours in production time.[140]

Hounshell states that Greenlee automatic transfer machines at the Wright factory reduced production time from 59 minutes to 8 minutes, but there is insufficient information to estimate relative impact on productivity Greenlee automatic transfer machines overall.[141] Some idea of their importance can be gleaned from a brochure Wright published late in the war

[137] 'Manufacturing the Cyclone, Part II', p. 155.
[138] 'Milling Operations on the Wright "Cyclone"', *American Machinist*, Vol. 78, No.7, (March 28, 1934), pp.245-48.
[139] 'Mass Production Methods for Building Wright Cyclones', *Aeronautical Engineering Review*, (August 1942), p. 13; Herb, Charles O.: *Machine Tools at Work*, (New York, 1942), pp. 413-15.
[140] Wright Aeronautical, *Application of High Production Machine Tools*, p.41.
[141] Hounshell, 'Automation, Transfer Machinery and Mass Production in the U.S. Automobile Industry in the Post-World War II Era', p. 111.

documenting the high-production machine tools it put into operation in its various factories.[142] This brochure listed savings in employees required, production hours and standard machine tools for a range of high-production machine tools, including two large Greenlee automatic transfer machines. On a combined basis, these various high-production machine tools required 470 fewer employees, saved 3,862 production hours, and replaced 163 standard machine tools. It is interesting to note that the two Greenlee machines contributed 45% of the savings in number of employees required, 42% of the savings in production hours, and 46% of the savings in standard machine tools. At Wright factories that employed them there were only one or two Greenlee machines as these machines were costly, as high as 35 times the cost of other high-production machine tools. More data is needed to determine the relative importance of the automatic transfer machines to improved productivity, particularly as Greenlee automatic transfer machines were limited in number, while the number of other types of high-production machine tools in a factory would likely have been greater.

Wright's introduction of forged cylinder heads for the Cyclone 9 in place of cast cylinder heads provides an example of how technological improvements affected production processes. This change required extensive production and process engineering to develop new methods and processes of manufacturing completely new parts. The benefits of using a forged cylinder head were considerable, as it enabled Wright to boost the power output of the Cyclone 9 from 1,200 H.P. to 1,350 H.P. while reducing production time.[143] By December 1941, Wright had an experimental machine shop working on production versions of the forged cylinder head and had placed orders for machine tools in expectation of beginning full scale production in June 1942.[144] Wright believed, optimistically as it turned out, that it could produce enough forged cylinders for 100 Cyclone 9 engines by December 1942.[145] In the event, Wright did not reach its target until October 1943.

[142] Hounshell, 'Automation, Transfer Machinery and Mass Production in the U.S. Automobile Industry in the Post-World War II Era'. Unfortunately, the brochure does not say if all these machines were in one factory or in several factories, or if there were multiple numbers of these high-production machine tools in a given factory.
[143] 'Special Machine Tools Boost Engine Production', *The Tool Engineer*, (November 1943), p. 77.
[144] A.E. Lombard to Merrill C. Meigs, Chief, Aircraft Section, Office of War Production, December 2, 1941, Folder 315.31 Aircraft Cylinder Heads, War Production Board Policy Documentation Files 315.4 Aircraft Engines, RG 179, Entry 1, Box 1120, NARA.
[145] A.E. Lombard to Merrill C. Meigs, Chief, Aircraft Section, Office of War Production, December 2, 1941.

Manufacturing a forged cylinder head proved challenging. When Wright began working on forged cylinder heads, it found that early examples were effectively hand-made and far from ready for quantity production.[146] Wright first had to work out a forging technique that could produce forged cylinders in quantity. The forging process that Wright developed started with a drop hammer forcing aluminium bar stock into the general shape of the cylinder head. After heating to the proper temperature, the semi-finished work piece, or billet, went successively through three dies in a 1000-ton capacity press, the first forming the rocker boxes, the second forming the content of the cylinder head, and the third forming the combustion chamber inside the cylinder head.[147] After this the forged cylinders went through a careful heat treatment process to relieve the internal stresses incurred during forging. This allowed the external cooling fins to be machined accurately with less wear on the cutting tools.[148]

During 1943 Wright developed a special continuous conveyor system linked to two parallel gas-electric furnaces to speed production at its Paterson factories.[149] Twelve rough forged cylinder heads at a time went via the conveyor to the gas furnace where they were heated to 960° F and soaked for six hours. After cooling to 340° F, trays carrying cylinder heads went via the conveyor to the electric furnace where they were heat-soaked for eight hours, followed by another cooling period and then a final five-hour heat-soak at 450° F. Wright found that with the forging process rejections amounted to only 5% of the total, compared to 20% with the casting process, a great savings in materials and production man-hours.[150]

Milling the cooling fins around the uneven contours of the cylinder head was the most difficult problem Wright faced with the forged cylinder head. Wright's initial attempts to mill the fins with standard milling machines proved unsuccessful.[151] Severe vibration caused fatigue cracks in the machined fins. Working together with the Cincinnati Milling Machine Company,

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[146] Holben, 'Some Aircraft-Engine Production Methods', p. 496.
[147] Linsley, 'Forged Cylinder Heads Increase Power of Cyclone Engine', p. 142.
[148] A.E. Lombard to Merrill C. Meigs, Chief, Aircraft Section, Office of War Production, December 2, 1941; Linsley, H.E: 'Machining the Wright Cyclone Forged Cylinder Head', *The Iron Age*, (January 13, 1944), p. 47.
[149] Linsley, 'Machining the Wright Cyclone Forged Cylinder Head', p. 47.
[150] Linsley, 'Forged Cylinder Heads Increase Power of Cyclone Engine', p. 142.
[151] Holben, 'Some Aircraft-Engine Production Methods', pp. 496-97; 'Machining the Wright Cyclone Forged Cylinder Head', p. 52; 'Forged Cylinder Heads Require New Technique', *Aviation*, Vol. 43, No. 6, (June 1944), pp. 142-45, 248, 251.

Wright adapted a Cincinnati Milling Hydro-Tel vertical profile milling machines to mill four forged cylinder heads at a time. The machine used a cam and master template to guide two specially developed 13 inch cutting wheels with nine carbide-tipped teeth to cut four identical fins on the tops of all four cylinder heads.[152] A similar Hydro-Tel machine cut fins on the sides of the cylinder head. One of these Hydro-Tel machines could work on eight forged cylinder heads simultaneously using two rotary fixtures.[153] Wright had the Snyder Tool & Engineering Company build a specially adapted machine tool for the other difficult machining operation; forming the valve pockets and the intake and exhaust ports on the head of the cylinder.[154] Once Wright had perfected these milling operations, a forged cylinder head could be treated much like a cast cylinder head for subsequent machining operations.

A three-section, 124 station Greenlee automatic transfer machine at Wright's Plant No. 2 performed finish milling operations and drilled, reamed, countersunk and tapped all holes required in the cylinder head as well as counterboring seats for valve springs, valve guide holes and valve seats.[155] It took considerably more time to machine a forged cylinder head but forging eliminated the more labour-intensive and time consuming operations of casting cylinder heads.[156]

Wright's development of the forged cylinder head illustrates the intense effort that went into process engineering. A detailed article on the process of machining fins on forged cylinders mentions no less than sixteen different types of machine tools employed during the process, including two separate Greenlee automatic transfer machines.[157] All these machines had to be adapted or specially built to meet the unique requirements of machining forged cylinder heads. It took Wright and the machine tool companies months of experimentation and effort before these machine tools could be placed in operation. Wright's experience in switching to a new method of production for the forged cylinder head shows that the mass production methods

[152] Holben, 'Some Aircraft-Engine Production Methods', p. 497.
[153] Linsley, 'Machining the Wright Cyclone Forged Cylinder Head', p. 53.
[154] Holben, 'Some Aircraft-Engine Production Methods', p. 497.
[155] Linsley, 'Machining the Wright Cyclone Forged Cylinder Head', p. 53.
[156] 'Forged Cylinder Heads Require New Technique', p. 251.
[157] Linsley, 'Machining the Wright Cyclone Forged Cylinder Head', pp. 47-53.

Wright had adapted for aero engine production were more flexible than some later historians posited.

Inspection and Quality Control

In aero engine production, quality control was critical, and far broader in scope than in automobile engine production. It is important to recognize that manufacturing component parts of the Cyclone 9 engine was only one part of the production process. Improvements in production engineering had to build in time and space for inspection to ensure quality control. In shifting to large-scale production, with all the changes in manufacturing processes and the switch to high-production machine tools, the overriding concern of Wright's engineers was that there be no diminution in the accuracy and quality of engine parts and complete engines. As Wright's General Superintendent put it, 'lower quality does not build engines—it builds trouble…for this reason there can be no compromise with quality.'[158] Large-scale production vastly increased the quantities of raw materials and engine parts going through Wright factories, compounding the problem of quality control. By the summer of 1941, when Wright was ramping up its purchases from outside vendors, Wright's Quality Control Department was inspecting 105,000 parts a day.[159] At Wright, quality control began when raw materials and rough forgings or castings arrived at the factory door, continued through the manufacturing process and only ended when the completed engine had passed its final tests.

Wright's Quality Control Department, which in August 1941 had around 1,100 inspectors on staff for the Paterson factories, contained a small group of highly experienced inspectors devoted not to inspection of finished parts but solely to measuring the accuracy of every tool, gauge and fixture in the factories.[160] This function was vital to maintaining accurate manufacturing but is not always considered part of the inspection process. In addition, these

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[158] Sutton, 'Production and Quality', p. 6.

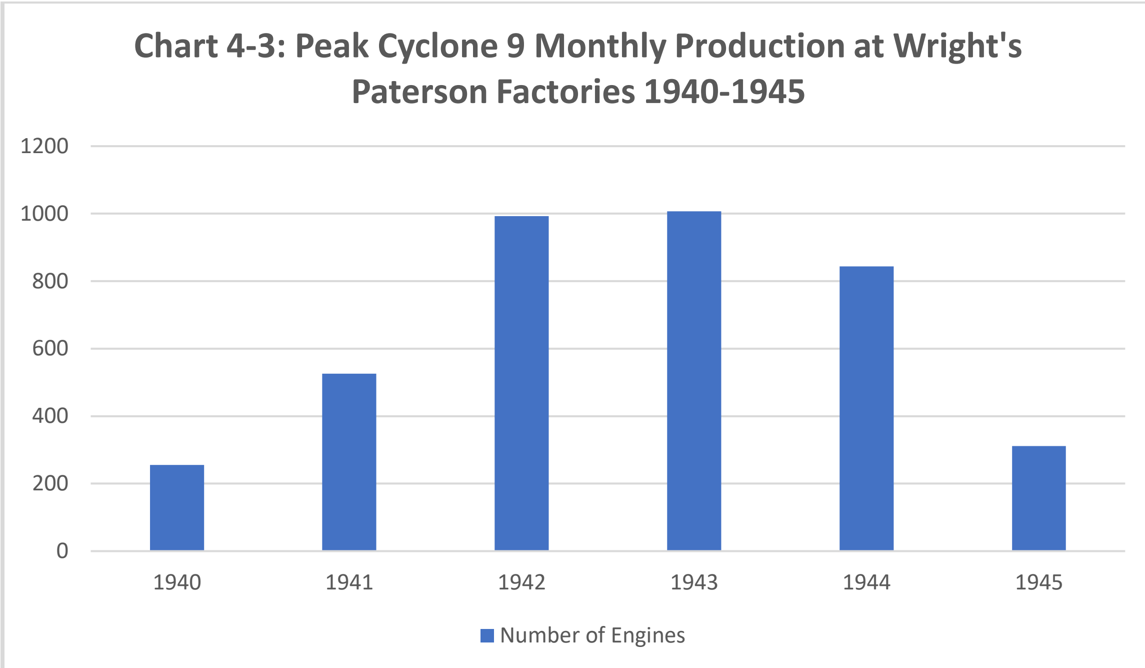
[159] Ray, Samuel: 'Quality Control of Wright Engine Parts', *Automobile Industries*, Vol. 85, No. 4, (August 15, 1941), p. 14.

[160] 'Quality Control of Wright Engine Parts', P. 15. This paragraph is drawn from Ray's article. See also 'Mass Production Brings Mass Inspection', *Western Flying*, Vol. XXII, No. 8, (August 1942), pp. 64-65.

inspectors performed regular checks of all the company's measuring devices using a set of master gauges as well as checking the personal measuring tools that the machinists and inspectors used in their work. The Raw Materials Inspection Department ran tests on any forgings, castings, or metal stock that came into the factories, sending a sample of each to the Laboratory for testing and only releasing the materials with the Laboratory's approval. In manufacturing areas, each production department had its quota of floor inspectors who inspected the first work piece from each new set-up of a machine tool for quality and accuracy. Inspectors at the Heat Treat Department tested each part after heat treatment to check for the required level of hardness. At the completion of machining operations, every component part went through a final inspection measuring dimensions, weight and finish.

The administrative load from inspection must have been considerable, as all major parts subject to high stress had their own individual record cards that were filed and maintained at the factories, even after components had left as part of a completed engine. Inspectors put steel parts through a Magnaflux inspection to detect any minor flaws or defects undetectable by the human eye, while non-ferrous parts were X-rayed. A 'profilometer' used a diamond-tipped stylus to measure the smoothness of surface finishes down to one-millionth of an inch. Parts that failed inspection went to the Salvage Department where a committee of Wright and Army Air Force engineers determined whether the parts could still be used, needed to be reworked or should be discarded. Requirements for accurate record keeping no doubt added more clerical workers to the staffs in the factories and partly explains why nearly 50% of the employees never actually worked on aero engine production.

Reading about aero engine production during World War II it is not readily apparent how critical the effort at quality control was to successful production, or the volume of inspections and the sheer number of parts inspected daily, often by young women with only a few weeks of training. Like much else about wartime aero engine production, quality is simply taken for granted. By all accounts Wright did an excellent job of quality control in the production of the Cyclone 9 engine at its Paterson factories. It is ironic, given the company's commitment to quality, that quality control would cause of so many problems and so much controversy at Wright's Lockland, Ohio and Wood-Ridge, New Jersey factories later in the war.



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946)

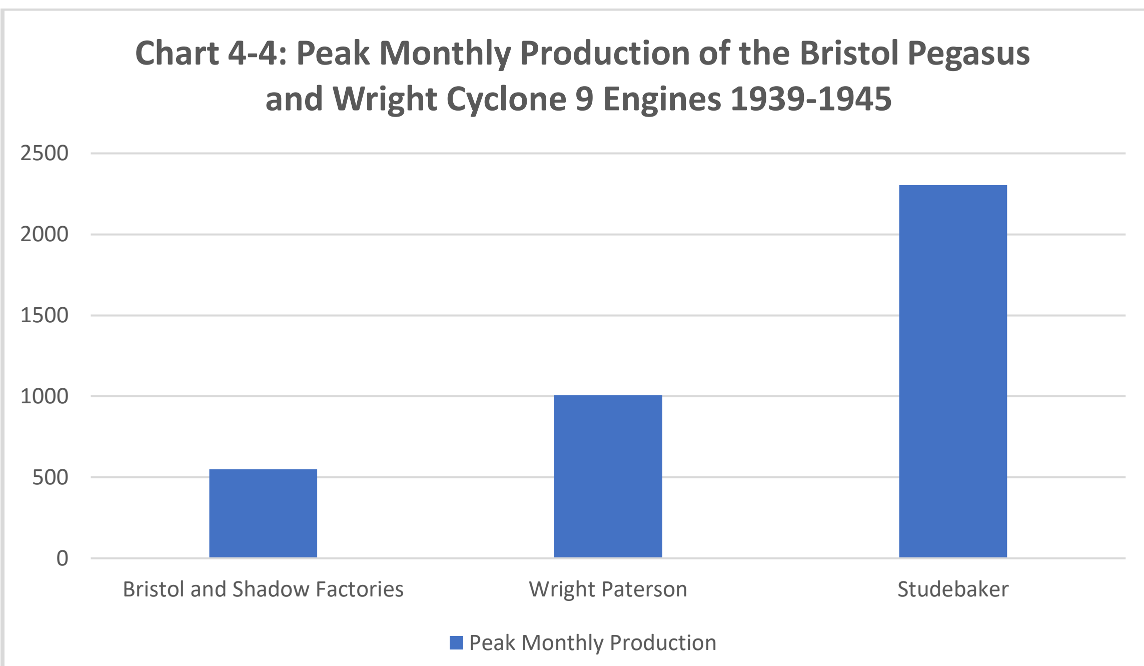
As with improvements that came through production engineering, the cumulative impact of the changes in production output through process engineering and the progressive development of high-production machine tools can be seen in the increases in monthly production rates of the Cyclone 9 at Wright's Paterson factories and especially, as will be seen, at Studebaker (see Chart 4-3). Between 1940 and 1941 production doubled, and then doubled again between 1941 and 1942. By the end of 1941, Wright was building Cyclone 9 engines at a rate of 500 month; fifteen months later the Paterson factories reached their peak production of 1,007 Cyclone 9 engines in a single month, more than ten times the number built in January 1940.[161] It is important to understand that in Wright's successful transition to quantity production of the Cyclone 9 there was no one 'magic bullet', but rather a wide range of continuous incremental gains from a change in manufacturing process or an improved machine

[161] *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, pp. 139, 141, 145.

tool that cut production time or increased the number of parts per operation. When Wright started the process there was no guarantee that it would be successful.

How it Was Done at Studebaker

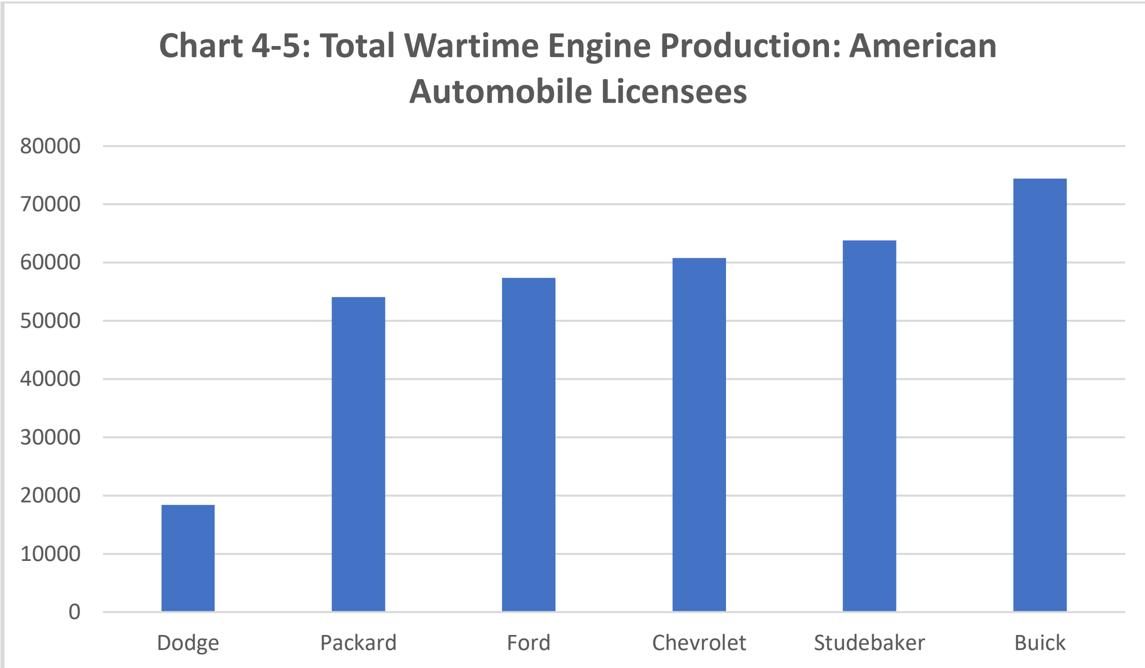
While Wright developed the formula for shifting from batch to large-scale production, Studebaker, with the advantage of starting with a clean sheet, perfected it. Studebaker, using the knowledge Wright had accumulated and its own automobile production experience, went on to establish a record of even greater output and productivity in factories that were better suited to line production (see Charts 4-4 and 4-5). Studebaker's production of the Cyclone 9 engine integrated the size and design of factory buildings, improvements in production engineering and more high-production machine tools. Studebaker's newer and larger factory buildings, designed from the beginning for line production, gave their production engineers greater scope for applying the lessons in production and process engineering they took from Wright.



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946); Ministry of Aircraft Production: *Statistical Review 1939-45*.

In searching for an explanation for Studebaker's wartime production record, it is necessary to start with an understanding of the knowledge and experience the company brought to manufacturing the Cyclone 9 engine. At its main South Bend automobile factory Studebaker was using some of the most advanced machine tools in the automobile industry.[162] To manufacture engines for its new Champion series, introduced in 1939, Studebaker had several Greenlee four-station automatic transfer machines, an early version of the much large transfer machines Wright, Greenlee and Studebaker would develop for machining Cyclone 9 cylinder heads. Studebaker also employed several other types of Greenlee horizontal and vertical drilling machines with four work stations that could hold six engine blocks at a time.[163] Studebaker employed a variety of multi-spindle machine tools, from a Baker Brothers two-way hydraulic machine holding 30 spindles to a massive National Automatic Tool Company (NATCO) unit with 103 spindles for drilling holes in cylinder blocks.[164] The machine tools of other companies—Barnes Drill Company, Cincinnati Milling Machine Company, Norton, Ex-Cell-O and Snyder—were also represented. The new methods and processes that Wright was developing through production and process engineering would, no doubt, have been familiar to Studebaker's own production and tooling engineers.

[162] Geschelin, 'Advanced Tooling Produces Newest Studebakers', pp. 420-32, 438-40.
[163] Geschelin, 'Advanced Tooling Produces Newest Studebakers', p. 426.
[164] Geschelin, 'Advanced Tooling Produces Newest Studebakers', pp. 427, 432.



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946)

Lists of the machine tools purchased for the South Bend and Chicago factories provides evidence supporting the argument that high-production machine tools were an important component of production at these factories.[165] Studebaker used many of the high-production automatic machine tools that Wright had developed, notably Snyder milling machines, Baker, Barnes, Ex-Cell-O and NATCO multi-spindle drilling machines and Bullard Mult-Au-Matic machines, as well as several types of Greenlee multi-station machines horizontal and rotary automatic transfer machines.[166] Some of these machine tools were expensive, with a Bullard eight-spindle machine costing $38,000 (£9,500) and a NATCO multi-spindle machine $18,000 (£4,500) compared to $3,000 to $10,000 (£750 to £2,500) for standard machine tools.[167] All these specially designed machine tools replaced multiple standard machine tools. Studebaker drew on

[165] See Studebaker Corporation Appendix 'A', Schedules From March 1941 Through February 1944, Box 30, Plancor 40, Reconstruction Finance Corporation, Defense Plant Corporation: Engineers Reports and Appendices, Box 30, RG 234, NARA.
[166] Geschelin, 'Studebaker Know-how Speeds Flying Fortress Engine Output', pp. 19-22, 70; Wright Aeronautical, *High Production Machine Tools*.
[167] See Studebaker Corporation Appendix 'A', Schedules From March 1941 Through February 1944, Box 30, Plancor 40, Reconstruction Finance Corporation, Defense Plant Corporation: Engineers Reports and Appendices, Box 30, RG 234, NARA.

the knowledge of these machine tool companies and their experience in building machine tools for Wright's new engine factories.[168]

In building the Cyclone 9, Studebaker followed Wright's methods and processes, but also incorporated its own experience in laying out a factory for efficient production.[169] Interestingly, even with the pervasive emphasis on straight-line production, Studebaker chose a different arrangement for the Fort Wayne gear factory. Manufacturing aircraft engine gears was a challenge for mass production methods as each gear presented a unique production problem due to its design, dimensions, materials and required heat treatment.[170] As this was more akin to batch production, Studebaker arranged the Fort Wayne factory into functional departments rather than setting up progressive straight-line assembly operations, with each of the functional departments covering one type of operation—cutting, grinding, heat treatment, surface finishing—with the gears moving from department to department in the correct sequence.[171] Starting gear production completely from scratch gave Studebaker's production engineers the freedom to work out new manufacturing methods, purchase new machine tools and develop new machine tool designs that were more efficient for machining the complicated gears.[172] Using these new methods and machine tools, the Fort Wayne factory reduced the cost of a set of gears for the Cyclone 9 engine to nearly half of Wright's original estimate.[173]

At the South Bend aircraft engine factory Studebaker paid special attention to materials handling, using mechanized and gravity conveyors and overhead monorails to move parts from machine to machine as well as hoists to lift heavier components.[174] Industrial tractors replaced hand carts to move parts around the factory. To speed assembly operations, Studebaker adopted system similar to what Wright had developed, but as at the Wright factories Studebaker did not employ one long continuous assembly line.[175] Instead of assembly teams that built up an entire

[168] Geschelin, 'Studebaker Know-how Speeds Flying Fortress Engine Output', p. 20.
[169] Geschelin, 'Studebaker Know-how Speeds Flying Fortress Engine Output', p. 19.
[170] Geschelin, Joseph: 'Sixty-three Parts and Assemblies from Studebaker to Cyclones', *Automobile and Aviation Industries*, Vol. 88, No.12, (June 15, 1943), p. 33.
[171] Geschelin, 'Sixty-three Parts and Assemblies from Studebaker to Cyclones', p. 33.
[172] Geschelin, 'Sixty-three Parts and Assemblies from Studebaker to Cyclones', P. 33; *Studebaker Corporation R-2600 Aircraft Engines Construction and Production Analysis*, p.18.
[173] *Studebaker Corporation R-2600 Aircraft Engines Construction and Production Analysis*, p.18.
[174] Geschelin, 'Studebaker Know-how Speeds Flying Fortress Engine Output', p. 20.
[175] *Studebaker Corporation R-2600 Aircraft Engines Construction and Production Analysis*, p. 25.

engine, groups of semi- and unskilled workers assembled parts into sub-assemblies on benches that ran at right angles to the main assembly line. Studebaker set up a motorized conveyor line as in its automobile plant. The conveyor line carried engines in various states of assembly on specially designed hand trucks attached to the motorized conveyor, stopping by the appropriate bench where a sub-assembly would be added. As at the Wright factories in Paterson, the assembly section was split into separate units. At the South Bend factory there was one unit for assembling the engine prior to its 'green' test, one unit that attached accessories (carburettors, magnetos, etc.) prior to the 'green' test, one unit for dis-assembly and inspection following the 'green' test, a unit for re-assembling the engine before the final engine test, a unit for re-attaching the accessories after re-assembly and a final unit for cleaning and packing prior to shipment. Studebaker management came to believe that this multiple-unit assembly system limited the factory's ability to increase production beyond 2,300 engines a month and would have preferred to set up a continuous assembly line as in its automobile factory, if this had been possible.[176] Nevertheless, with experience Studebaker increased the rate of assembly from five to seven and a half engines per hour.[177]

From the early stages of production planning Studebaker had to decide which engine parts should be made in its own factories and which should be purchased from outside vendors. Studebaker apparently went beyond Wright and purchased around 50% of the labour content of the Cyclone 9 from outside its own factories, although later in the war the percentage of subcontracting appears to have dropped below this level.[178] Early on, Studebaker decided to purchase all steel castings for the crankshaft, crankcase and cylinder barrels and engine gears from specialist foundry firms removing the need to build foundries at any of the three factories. Studebaker divided production of the remaining parts for the engine between its three factories, with the South Bend factory building one-half, and Chicago and Fort Wayne the rest, but in most cases, this work involved machining castings or forgings acquired from other subcontractors.[179]

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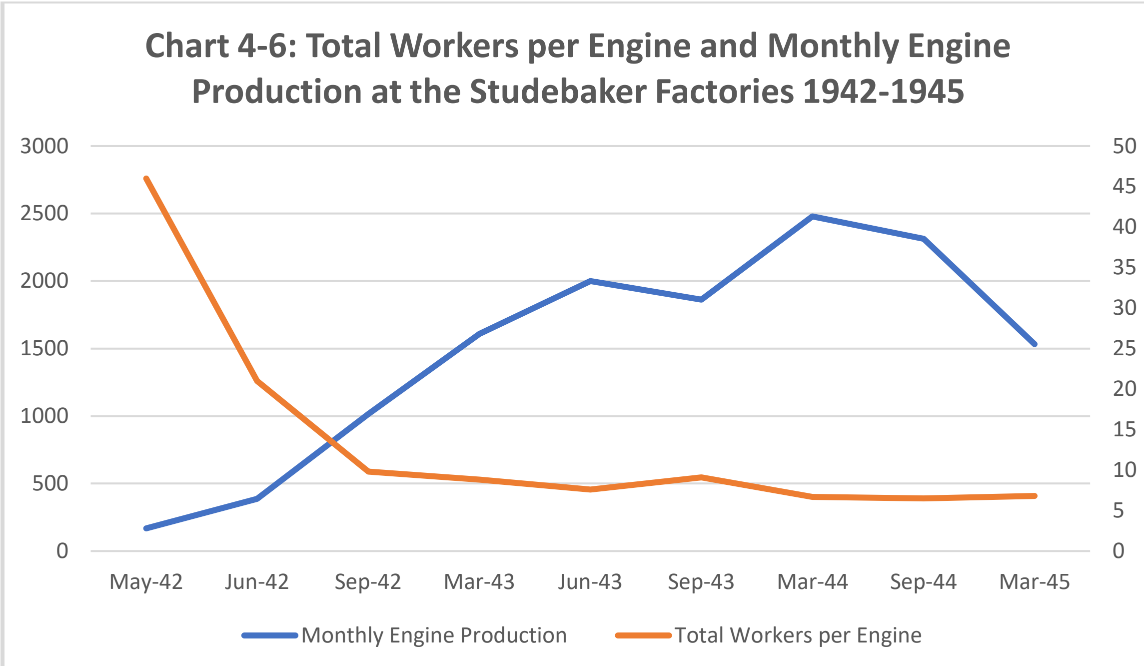
[176] *Studebaker Corporation R-2600 Aircraft Engines Construction and Production Analysis*, p. 25.
[177] *Studebaker Corporation R-2600 Aircraft Engines Construction and Production Analysis*, p. 25.
[178] *Studebaker Corporation R-2600 Aircraft Engines Construction and Production Analysis*, p. 36; see Air Technical Service Command: *Labor Statistics for the Aircraft Industry*, November 1944-May 1945, File 218.6-7, AFHRA.
[179] *Studebaker Corporation R-2600 Aircraft Engines Construction and Production Analysis*, p. 36.

Studebaker did employ more workers than the shadow factories building the Mercury and Pegasus, but these workers built proportionately more engines. In November 1943, the month of peak employment at the Studebaker factories, there were 17,551 total employees with nearly half working at the South Bend factory.[180] This compares to 11,883 workers at all the shadow factories in September 1941, the year of peak Mercury and Pegasus production. This figure may not include management and engineering staff at the shadow factories, so that the actual difference between total number of employees at Studebaker and shadow factories may have been less. The important point is that with approximately 50% more workers, the Studebaker factories built 181% more engines in November 1943 than the shadow factories built in September 1941.

Measuring Productivity

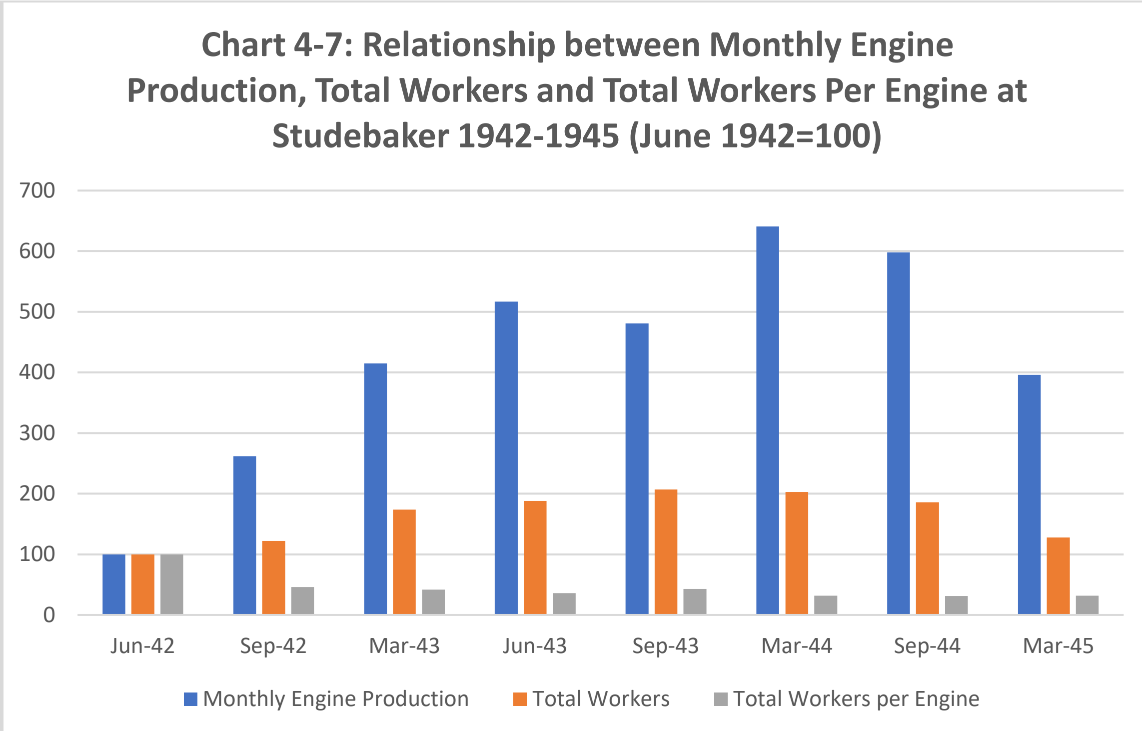
Measuring productivity at the Wright Paterson factories is difficult since these factories were not only building several different models of Wright engines, but also heavily involved in engine development and production engineering. As Hornby notes, these activities directly affected the relationship between the labour force and engine output. The better measure of productivity in building the Cyclone 9 is to look at Studebaker's experience. While information is available on the percentage of direct workers at the Studebaker factories, for comparative purposes total workers per engine will be used as a measure of productivity instead.

[180] *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, p. 190.



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946)

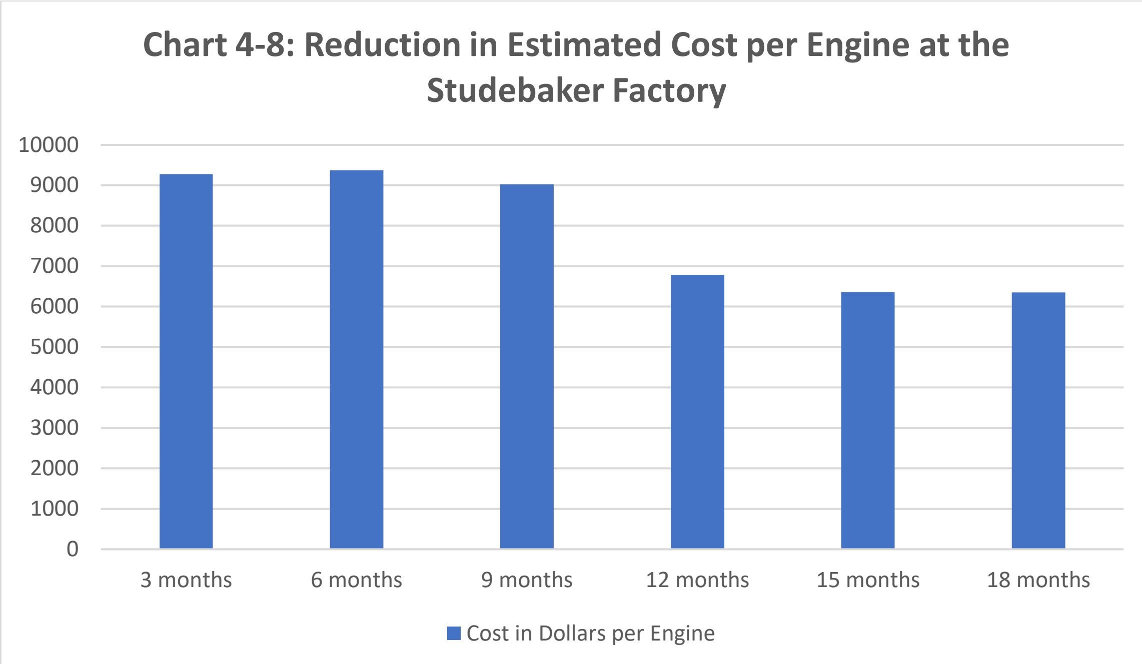
There are several noteworthy aspects of the trend in total workers per engine built (see Chart 4-6). First, the speed with which the Studebaker factories moved down the learning curve. In May 1942, the factories built 168 Cyclone 9 engines with 46.2 total workers per engine. By September 1942, four months later, production had reached over 1,000 engines a month and the number of total workers per engine had been reduced to 9.8. In June 1943, fifteen months after the start of production, the Studebaker factories built 2,000 engines a month. Second, while productivity appears to have held steady during 1943, there was a noticeable improvement in productivity during 1944 (see also Chart 4-7). During that year, Studebaker factories built 22% more Cyclone 9 engines than in 1943 with the same number of total workers. Third, as will be discussed more fully in Chapter Seven, Studebaker built the nine-cylinder Cyclone 9 with roughly half the number of total workers building the equivalent Mercury and Pegasus engines at the first shadow factories. From June 1941 to September 1942, the shadow factories averaged 16 total workers per engine, while from September 1942 until March 1945 Studebaker averaged 7.9 total workers per engine.



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946)

As production increased and management and workers gained experience, Studebaker continually reduced the cost per Cyclone 9 engine (see Chart 4-8). The cost to the Government of the first production Cyclone 9 engines was $10,061 (£2,515) per engine, but at the point of maximum production Studebaker had reduced the cost per engine to $6,430 (£1,607), a 36% reduction in cost.[181]

[181] The Studebaker Corporation Aviation Division, Cost of Shipments and Sales Statistics, December 31, 1943, copy in the Studebaker Museum Archives, South Bend, Indiana.



Source: The Studebaker Corporation Aviation Division, Cost of Shipments and Sales Statistics, December 31, 1943, copy in the Studebaker Museum Archives, South Bend, Indiana.

Studebaker's ability to accelerate production of the Cyclone 9 was considered to be '…better and more even than that of most other manufacturers.'[182] There are several reasons behind Studebaker's performance. First, as with the Mercury and Pegasus, the Cyclone 9 was a proven engine with a long production record. Technical drawings and engineering information were readily available from Wright Aeronautical and Studebaker had the benefit of Wright's advances in production and process engineering. Second, Studebaker's production was almost entirely devoted to a single model of the Cyclone 9, limiting the disruptions from changing over to a new engine model. Thirdly, Studebaker brought to the Cyclone production programme managers with years of experience in quantity production and with the strategic realism to focus on what Studebaker could do best, machining components and assembling engines.[183]

The story of production of the Wright Cyclone 9 engine during World War II is a story of success that, in retrospect, appears seamless but in fact involved intense effort, ingenuity and faith on the part of engineers at Wright, Studebaker and the machine tool companies. This impressive wartime record was not a 'miracle of production' but the methodical application of

[182] *Studebaker Corporation R-2600 Aircraft Engines Construction and Production Analysis*, p. 3.
[183] *Studebaker Corporation R-2600 Aircraft Engines Construction and Production Analysis*, pp. 3-4.

production and process engineering. It is important to bear in mind that in the beginning of America's expansion of airframe and aero engine production there was no guarantee of success and little previous experience of large-scale production of aero engines to draw on. What was available was the knowledge and experience of other industries, principally the automobile and machine tool industries. These industries generously shared information with the aero engine manufacturers through direct exchanges, professional associations and industry publications. Successful large-scale production came through integrating factory size, production engineering and process engineering. As in Studebaker's case, larger factory buildings gave greater scope for applying more efficient methods of production and process engineering. To build the bigger and more complex Cyclone 14 and Cyclone 18 engines in quantity would require even larger factories and more advanced high production machine tools.

Chapter Five: Building the Wright Cyclone 14 and Cyclone 18

Introduction

This chapter will provide, a detailed examination of how Wright Aeronautical and its licensee, the Chrysler Corporation's Dodge Division, built the fourteen-cylinder Cyclone 14 and eighteen-cylinder Cyclone 18 double-row, air-cooled radial engines in quantity. Production of the Cyclone 14 at the Wright factory at Lockland, Ohio, and the Cyclone 18 at the Dodge Division factory in Chicago and a new Wright factory at Wood-Ridge, New Jersey, was radically different from production of the Bristol Hercules. Wright and the Dodge Division built these engines on a massive scale in what were the largest single-storey industrial buildings in the world, using the most advanced, automatic, high-production machine tools. This was precision engineering of large, complex aero engines on a size and scale that was unimaginable before the war.

The Wright Lockland and Dodge Chicago factories were huge, dwarfing the aero engine factories in Britain. In total floor area, the Chicago factory was larger than all the factories building Bristol engines combined. The Wright Lockland and Dodge Chicago factories reflected a trend toward what Joshua Freeman has called 'industrial giantism', a move to build truly giant factories.[1] This chapter will argue that these giant factories, and in particular the Wright Lockland factory, were not the unqualified success that one might infer from the 'miracle of mass production' narrative. More specifically, this chapter will argue that the giant Wright Lockland factory created new management and production problems that proved challenging to overcome. At Lockland, Wright ran into diseconomies of scale that interfered with the production effort. The concept of economies of scale—how increases in the scale of production can reduce average product costs—is well-known; the concept of diseconomies of scale perhaps less so.[2]

[1] Freeman, Joshua B.: *Behemoth: A History of the Factory and the Making of the Modern World*, (New York, NY, 2018), pp. xiii-xv.
[2] Pratten, C.F.: *Economies of Scale in Manufacturing Industry*, (Cambridge, 1971), p.3.

Diseconomies of scale refers to conditions where costs can increase and efficiency declines, as output increases.[3]

Though the Lockland and Chicago factories were, successively, the largest single-storey industrial buildings found anywhere in the world, they have received surprisingly little mention, even in works devoted to their designer, the famous industrial architect Albert Kahn. Despite the fact that the Chicago factory was the largest Army Air Force-sponsored project of the war, larger in total area and in total cost than the more famous Ford Willow Run factory, it is Willow Run that is cited as the biggest factory built during the war. The story of the construction of the Lockland and Chicago factories has rarely been described, and never before in the detail provided here.

This chapter will argue that the key to achieving flow production at these factories was not size per se but actually the new methods of production engineering and process engineering that Wright developed during 1940-1941 at its Paterson factories. The chapter will show that production at the Wright Lockland factory was significant not simply because Lockland was the first of the truly giant aero engine factories, but more because the factory became renowned for its reliance on new types of advanced high-production machine tools Wright had developed with the American machine tool manufacturers, notably the Greenlee automatic transfer machine. This chapter will describe how Wright first introduced the Greenlee automatic transfer machine at the Lockland factory and then over the next several years progressively expanded the automatic transfer machine's capabilities at the Studebaker and Dodge Chicago factories.

The automatic transfer machine was only one of many advanced machine tools Wright developed specifically for aero engine production. The Lockland and Chicago factories were at the forefront of Wright's continued development of automatic, high-production machine tools. The chapter will show how these advanced machine tools replaced large numbers of standard machine tools, cut the number of operators and speeded production. Whereas Bristol continued to rely on standard machine tools in building the Hercules, this chapter will also argue that Wright and Dodge chose to replace standard machine tools with these advanced, high-production machine tools wherever possible. While productivity at these giant factories, as measured by the

[3] See Greenwald, Douglas, ed: *Encyclopaedia of Economics*, (New York, NY, 1982), pp. 327-29.

number of total workers per engine, may not have equalled the records of other American aero engine factories, the chapter will argue that the record of the Wright Lockland and Chicago factories was superior to that of the factories building the Bristol Hercules.

If the story of these giant factories is now obscure, the story of the advanced machine tools Wright developed during the war is even more so. The story of American machine tool development during World War II has yet to be written. David Hounshell has related the contribution of Wright's wartime development of the Greenlee automatic transfer machine to the post-war development of the automated automobile factory, but Hounshell's account does not cover the progressive development of the automatic transfer machine nor its use at the Studebaker and Dodge Chicago factories. Because many of these advanced automatic machine tools appear to have been built specifically for the few large Wright and Pratt & Whitney aero engine factories, and were not commercially available, there are few mentions of these machines in contemporary industry literature outside of articles on aero engine production. With the decline of the American machine tool industry and the merger or bankruptcy of many wartime machine tool companies, it is uncertain if any archives related to wartime machine tool development survived.

Organizing Production

In May 1940, Secretary of the Treasury Henry Morgenthau called the leading aircraft and aircraft engine manufacturers, including senior Wright Aeronautical executives, to a conference in Washington, D.C. to discuss expanding production facilities for President Roosevelt's recently announced national defence programme.[4] There was an immediate need to expand production capacity for the Wright Cyclone 14.[5] The French and British Governments had placed large orders for this engine, and now the American Army Air Corps and U.S. Navy were planning similar orders. Five days later Wright presented a plan to the Government to expand its aero engine production, particularly for the Cyclone 14. Wright's plan called for a new factory that would have more than

[4] *Trade Winds*, (April 1941), p.9.
[5] Special Studies No. 21, *Aircraft Production Policies under the National Defense Advisory Commission and Office of Production Management, May 1940 to December 1941*, p. 36.

1,000,000 sq. ft. of floor space.[6] It would be designed from the beginning for line production and build only the Cyclone 14, with a peak capacity of 1,000 engines a month.[7] Wright's plan quickly received Government approval and its proposed factory was one of the first to be financed under the newly-established Defence Plant Corporation. After the attack on Pearl Harbor, the Army Air Force instructed Wright to expand capacity at this factory to 4,000 engines per month.[8]

In the fall of 1941, the newly re-designated Army Air Force (AAF) decided to expand heavy bomber production creating a demand for more Wright Cyclone 18 engines than Wright could build on its own.[9] With the other major automobile companies already committed to aero engine production, the Chrysler Corporation was the most likely candidate to take on the Cyclone 18.[10] Chrysler became Wright's second licensee and the last of the major automobile companies the Government brought into aero engine production. Chrysler was one of the 'Big Three' American automobile companies and in 1940 second only to General Motors, with sales of 1,044,290 vehicles during that year.[11] At the beginning of the war, Chrysler had over 80,000 employees and 19 factories in the United States and Canada using more than 20,000 machine tools.[12] On January 30, 1942, the AAF issued a letter of intent to Chrysler covering production of 10,000 Wright Cyclone 18 engines at a rate of 1,000 engines a month and granted approval for Chrysler to begin construction of a large factory.[13] For comparison, the first production versions of the 18-cylinder Bristol Centaurus sleeve-valve engine were expected in October 1942 with planned production to reach a peak of 80 engines a month thereafter.[14]

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[6] *Trade Winds*, Vol. 5, No. 6, (October 1940), p. 3.
[7] *Trade Winds*, Vol. 5, No. 6, (October 1940), p. 3.
[8] See letter Col. S. R. Brentwell, Office of the Assistant Chief of Air Staff, to General B. E. Chidlaw, 21 February 1944, R-2600 Engine Part I, Section I, R-2600 Case Study, Vol. 2, p. 729, File 202.2-13, AFHRA.
[9] *Aircraft Production Policies under the National Defense Advisory Commission*, p. 100.
[10] *Aircraft Production Policies under the National Defense Advisory Commission*, p. 100.
[11] Hyde, Charles K.: *Riding the Roller Coaster: A History of the Chrysler Corporation*, (Detroit, MI, 2003), p. 120.
[12] 'Motor Cars to Munitions: Chrysler: Didn't Wait for New Machines; Revamped the Ones They Had', *American Machinist*, Vol. 86, No. 12, (June 1942), p. 549.
[13] Note of January 30, 1942, p. 11, Dodge Chicago Plant Chronology 1942, p.7-p.50; United States Air Force: United States Air Force Numbered Historical Studies, No. 40: *Expansion of Industrial Facilities under AAF Auspices 1940-1945*, (No Date), p. 113.
[14] *Narrative: Reciprocating Aero Engines and Engine Accessories Production and Programmes*, paragraph 213.

The Factories

The Wright Lockland Factory

The Wright factory at Lockland, Ohio was the first of the giant aero engine factories to be built. In 1940 the Government preferred, for strategic reasons, that the new airframe and aero engine factories it was commissioning be located well away from either coast in an area between the Appalachian Mountains in the East and the Rocky Mountains in the West,.[15] Wright chose to locate the factory near the small town of Lockland, Ohio, a dozen miles from Cincinnati, a centre of the machine tool industry. The Defence Plant Corporation allocated $37 million to purchase a 219-acre plot near Lockland and construct the factory, with an additional $55 million to purchase machine tools and other equipment.[16] The Lockland factory would ultimately cost $141,196,000.[17]

Wright hired Albert Kahn, who had designed the new wing at the Wright Paterson factory in 1939, to design the new factory Albert Kahn and his firm, Albert Kahn Associated Architects and Engineers, designed all the giant aero engine factories building Wright and Pratt & Whitney aero engines. Kahn had been the lead architect on the Ford River Rouge complex. In the early 1930s, Kahn and his firm designed several giant factories as part of the Soviet Government's plans for rapid industrialization.[18] Among these were the Stalingrad tractor factory covering 960,700 sq. ft. of floor space, with an assembly building of 422,000 sq. ft., and the even larger tractor factory at Chelyabinsk covering 1,780,000 sq. ft. with an enormous assembly building of 975,000 sq. ft.[19] As the American automobile industry recovered from the depths of the Depression, Kahn received new commissions for large new factories from several automobile manufacturers,

[15] Holley, *Buying Aircraft*, p. 307.
[16] *Wall Street Journal*, August 22, 1940, p. 1.
[17] Civilian Production Administration: *Authorizations of War Industrial Facilities Financed with Public and Private Funds June 1940-July 1945*, (Washington, D.C., 1946)
[18] See Freeman, *Behemoth*, Chapter 5.
[19] Melnikova-Raich, Sonia: 'The Soviet Problem of Two 'Unknowns': How an American Architect and a Soviet Negotiator Jump-Started the Industrialization of Russia, Part I: Albert Kahn', *The Journal of the Society for Industrial Archeology*, Vol. 36, No. 2, (2010), pp. 68, 70.

including the 1,450,000 sq. ft. Ford Press Shop building at the Ford River Rouge complex built in 1939.[20] The Press Shop was, at that time, the largest single-storey factory building in the world.[21]

The factory Kahn and his associates designed was even bigger than Wright's original estimate. Kahn's ideal for industrial factory buildings was 'the one-story structure of incombustible materials with enormous uninterrupted floor spaces under one roof with a minimum of columns.'[22] His industrial factory designs followed certain core principles: a building designed for efficient straight-line production but with the flexibility for future expansion; wide column spacing to minimize interference with production lines; proper ventilation and lighting; optimal location of power, storage and other ancillary buildings as well as easy access to transportation.[23] Kahn was especially concerned about flow within the factory building and the need to determine how and where raw materials would enter the building and how and where the finished product would exit.[24]

At Lockland, Kahn designed a single-storey rectangular main machine shop and assembly building with 1,468,000 sq. ft. of production floor space, covering nearly 35 acres, with basement area of more than 225,000 sq. ft., and additional space for fans and air conditioning units, for a total area of over 1,800,000 sq. ft.[25] This made the factory the largest single-storey industrial building in America, eclipsing the River Rouge Press Shop. The factory could produce 3,000 aircraft engines a month, tripling the initial production specification.[26] The machine shop and assembly building had structural steel framing and steel trusses with a reinforced concrete floor and 8-inch brick exterior walls with a seven foot continuous band of steel sash windows on the sides of the building. Long roof monitors allowed in additional daylight, though there was fluorescent lighting throughout the factory. Kahn incorporated exceptionally wide bays within the factory, with column spacing 60 ft. by 75 ft. to allow both uniform working areas and

[20] Hildebrand, Grant: *Designing for Industry: The Architecture of Albert Kahn*, (Cambridge, MA, 1974), pp. 137, 164-72.
[21] Freeman, *Behemoth*, p. 141.
[22] 'Industrial Buildings…A Buildings Type Study', *Architectural Record*, Vol. 91, No. 1, (January 1942), p. 65.
[23] Kahn, Albert: 'Design of Plants for Mass Production', *Aero Digest*, Vol. 39, No. 4, (October 1941), p. 156, 'What the Manufacturer Wants from His Architect', *Architectural Forum*, Vol. 69, No. 2, (August 1938), p. 96.
[24] Kahn, 'Design of Plants for Mass Production', p. 156.
[25] 'Wright Plant Sets New Size Record', *Engineering News-Record*, Vol. 127, No. 1, (July 3, 1941), p. 52.
[26] Wright Aeronautical Corporation, Plancor 10, Engineer's Final Report, Part 1, p. 60, Reconstruction Finance Corporation, Defense Plant Corporation Engineer's Reports, Box 4, Plancor 10, RG 234, NARA.

maximum flexibility in placing machine tools on the production lines. As with the Studebaker factories, the Lockland factory had no protection against air attack, a virtue of its location far from the East coast. There were no walls or barriers in the main machine shop and assembly building to interrupt production. A test cell building and an office building were attached to the machine shop and assembly building, with an aluminium foundry nearby. To begin with, the factory complex had over 2 million sq. ft. of floor space, bigger than either the Standard Motor No. 2 Shadow Factory or the Bristol No. 3 Shadow Factory. During the war this would be more than doubled.[27]

With more than 12,000 employees working at the factory complex, the movement of workers during shift changes and meal breaks could disrupt the flow of work on the production floor. Kahn's real innovation was to locate all employee services for the machine shop and assembly building in the large basement. Kahn described this as 'one of the finest features we believe we've ever hit upon in industrial plant design.'[28] The basement was in the shape of a large cross underneath the main floor. Employees entered the factory by descending stairs into the basement area where they followed passageways to their lockers and to stairs leading directly to their assigned work areas.[29] These stairs and passageways also led to employee cafeterias and toilets. At the shift change, the employees working on the production floor simply reversed the process, exiting the factory building through the basement. In this way, traffic on the production floor was kept to a minimum. The area within the main machine shop and assembly building was free from obstructions, allowing optimum placement of machine tools and mechanical conveyor systems.

Contractors began laying concrete in December 1940 and erecting the steel framing in January 1941.[30] The factory complex, now designated Plant No. 6, was ready on 12 June 1941, two months ahead of schedule.[31] To speed getting into production, Kahn divided the machine shop into twelve areas. As the contractors completed each area, they enclosed it with partitions

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[27] This description of the Lockland factory is drawn from 'Wright Plant Sets New Size Record', Kahn, 'Design of Plants for Mass Production', and Engineer's Final Report, Part II, Box 4, Plancor 10, RG 234, NARA.
[28] Kahn, 'Design of Plants for Mass Production', p. 157.
[29] 'Producer of Production Lines', *Architectural Record*, Vol. 91, No. 6, (June 1942), p. 43.
[30] 'Wright Plant Sets New Size Record', p. 52.
[31] 'The Industry's Largest Engine Factory', *Aero Digest's Aviation Engineering*, Vol. 39, No. 1, (July 1941), p. 156.

to allow Wright to start installing production machinery. Wright laid out the production lines so that the machine tools could be shifted with little difficulty when construction was completed.[32] Pilot production lines, set up to test the arrangement of machine tools and production flow, began producing parts for the Cyclone 14 in April 1941.[33] The Lockland factory completed its first Cyclone 14 engines in June and by the end of the year had sent 246 engines to the military.[34]

After America's entry into the war Wright received approval to expand its newly completed factory at Lockland to boost production capacity to 4,000 engines per month.[35] Two new machine shops, the South Shop Building No. 14 and the North Shop Building No. 13, went up next to the main machine shop and assembly building.[36] These buildings allowed Wright to expand production of components, with finished parts moving from the new shops to the main machine shop and assembly building for final assembly. The North Shop building was specifically for cylinder production. The South Shop Building, like the North Shop Building, used structural steel in its construction, allowing wide bays on the main floor of 832,000 sq. ft. With a large basement of 572,000 sq. ft., the building had 1,478,000 sq. ft. of floor space, nearly as big as the main machine and assembly building. In addition to the two new machine shops, Wright added new, large aluminium and magnesium foundries and other ancillary buildings, taking the total floor area of the Lockland factory to over 5,600,000 sq. ft., bigger than the total floor space of the entire American aircraft engine industry in January 1940.[37]

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[32] 'Wright Plant Sets New Size Record', p. 52.
[33] 'The Industry's Largest Engine Factory', p. 159.
[34] *U.S. Military Acceptances 1940-1945*, p. 141.
[35] See letter Col. S. R. Brentwell, Office of the Assistant Chief of Air Staff, to General B. E. Chidlaw, 21 February 1944, R-2600 Engine Part I, Section I, R-2600 Case Study, Vol. 2, p. 729, File 202.2-13, AFHRA.
[36] *Trade Winds*, Vol. 6, No. 11, (April 1943), p.16.
[37] 'Manufacturing Plant, Lockland, Ohio, Plancor 10', copy in Record Group 270, War Assets Administration, Real Property Disposal Case Files 1947-1951, Box 684, Wright Aeronautical Corporation, NARA, Chicago office; Modley, *Aviation Facts and Figures 1945*, p. 2; The Defense Plant Corporation's brochure *Advance Listing of Industrial Plants and Plant Sites to be Disposed of by Defense Plant Corporation, Oct. 14, 1944*, (Washington, D.C., 1944), lists the total floor area of the Wright Lockland factory as 5,622,171 sq. ft. and Willow Run as 5,022,177 sq. ft.. The Dodge Chicago factory was even bigger with a total floor area of 6,430,000 sq. ft.

The Dodge Chicago Factory

Kahn outdid his own Lockland factory with the Dodge Chicago factory. The key features of the Dodge Chicago factory were its sheer size, the fact that it was the only American aero engine factory that had its own on-site forges and its unique method of construction which used less structural steel. With a total floor area of 4,323,000 sq. ft., the main machine shop and assembly building became the largest single-storey industrial building in the world. The 6,430,000 sq. ft. of all 19 buildings at the complex made the Dodge Chicago factory the largest of all the airframe and aircraft engine factories the Government financed during World War II, and at $173,000,000 for land, buildings and machinery, the most expensive of all Government-financed projects, nearly double the cost of the Ford Willow Run factory.[38] The Dodge Chicago factory was bigger than all the No. 2 Shadow Group factories and the Bristol No. 3 Shadow Factory combined, and four times bigger than the Rolls-Royce shadow factory at Hillington.

When Chrysler received the AAF contract for 10,000 Cyclone 18 engines, the Dodge Chicago Division (a new organization Chrysler set up to manage the factory building these engines) calculated that this could only be accomplished with a greatly expanded factory complex with a total floor area of 5,551,744 sq. ft., including a massive machine shop and assembly building that would cover 82 acres under one roof.[39] The AAF directed Chrysler to build the new factory in either Chicago or Milwaukee.[40] After a survey of both cities, Chrysler chose Chicago as the location for the new factory.[41] Chrysler also turned to Albert Kahn, who had designed several of Chrysler's automobile factories and a large Government-financed factory where Chrysler was to build tanks for the American Army. While the AAF was concerned that Kahn's firm was over-loaded with defence work, Chrysler's management felt confident that the firm could do the job adding that 'if this was a job of our own we would not think of employing any other architect.'[42]

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[38] Defense Plant Corporation: *Advance Listing of Industrial Plants and Plant Sites to be Disposed of by Defense Plant Corporation, Oct. 14, 1944*, (Washington, D.C., 1944); Smith, R. Elberton: *The Army and Economic Mobilization, United States Army in World War II: The War Department*, (Washington, D.C., 1959), p. 496.
[39] Note of April 11, 1942, p. 35, Dodge Chicago Plant Chronology 1942, p. 7 -p. 50.
[40] Note of January 5, 1942, p. 7, Dodge Chicago Plant Chronology 1942, p. 7 -p. 50.
[41] Note of January 5, 1942, p. 10, Dodge Chicago Plant Chronology 1942, p. 7 -p. 50.
[42] H.S. Wells, Staff Plant Engineer, Telegram of March 13, 1942, p. 25, Dodge Chicago Plant Chronology 1942, P. 7 - P. 50.

Albert Kahn's design for the machine shop and assembly building was a large rectangle, measuring 2,344 ft. by 1,525 ft. with a floor area of 3,575,633 sq. ft.[43] The building had 72 30-foot bays running along the length of the building and 36 38-foot bays along its width, with the concrete arches supported by 3,363 concrete columns.[44] The concrete ribs supporting the roof arches had five-ton crane attachments for moving heavy parts and machinery. The machine shop, with its long lines of machine tools, took up roughly 4/5ths of the building, with the assembly section taking up the remainder. The building was oriented on a north-south axis, with materials from the foundries, forges and outside suppliers entering at the south end and moving progressively north toward the assembly section and then to the test cells attached to the end of the building. The ten bays in the assembly section were air conditioned, while the machine shop area had fresh air supplied through filtered supply units. Lighting in the machine shop and assembly building was a combination of natural light through steel sash windows along the sides of the building and artificial lighting. The walls of the building were built from brick rising 8 ½ feet from the floor, topped by the 12 ½ foot steel and wood window sash.[45]

Though the machine shop and assembly building dwarfed the aluminium and magnesium foundries, the latter were still considerable buildings, each nearly 500,000 sq. ft. in area. As at Lockland, the foundries were also rectangular, with open production areas and slightly larger 30 foot by 40-foot bays to accommodate extensive conveyor systems and electrical hoists needed to carry molten metal and castings. The Dodge Chicago factory complex had its own heat-treating shop and light and heavy forging buildings to forge parts for the Cyclone 18 using huge hammers and presses. The forge buildings, made with structural steel to absorb the vibration from forging hammers, were located some 4,000 feet away from the machine shop and assembly building to ensure that the vibrations didn't interfere with the precision machining operations in the

[43] This description is drawn from the Defense Plant Corporation pamphlet 'Airplane Engine Plant, Chicago, Illinois Plancor 792-Brochure A', and 'Aluminum & Magnesium Castings Airplane Engine Plant, Chicago Illinois, Plancor 792-Brochure B', copy in War Assets Administration, Real Property Disposal Case Files 1947-1951, Box 243, Chrysler Corporation, Record Group 270, National Archives and Records Administration, Chicago office.
[44] 'Dodge Chicago Plant Division of Chrysler Corp.', p. 54.
[45] 'Multiple-Arch Concrete Roof Saves Steel', p. 100.

machine shop.[46] In total, the Dodge Chicago factory complex had 19 buildings on its nearly five hundred acres.

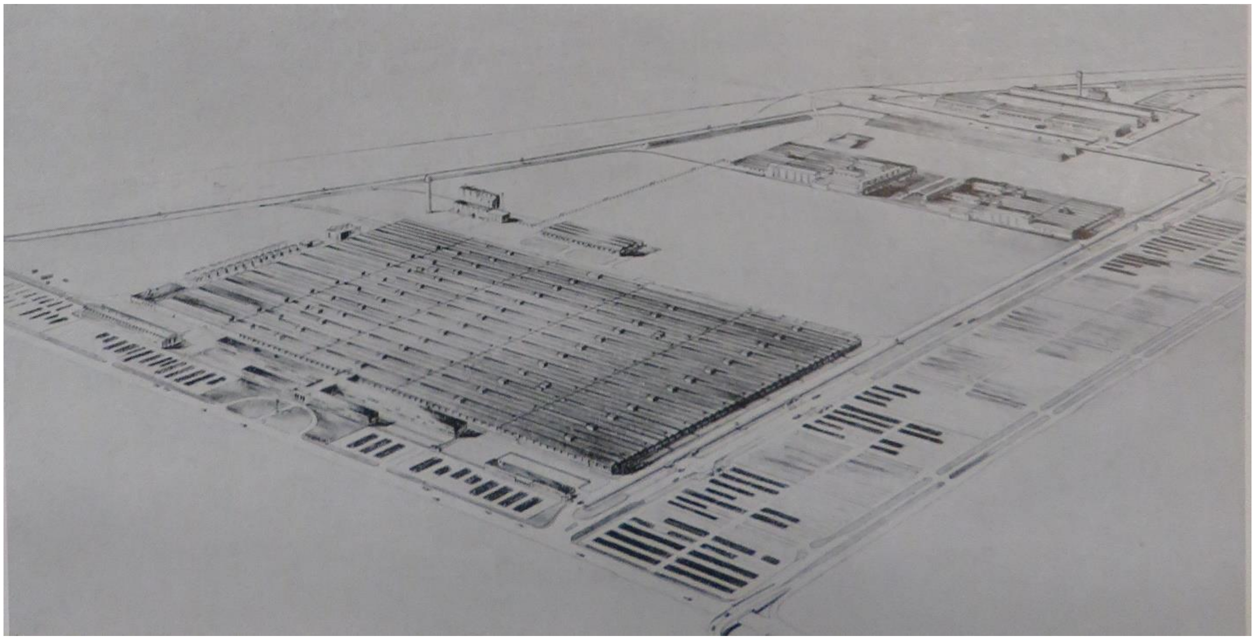

Illustration 5-1: A drawing of the Dodge Chicago factory, showing on the left the main machine shop and assembly building, the largest single-storey industrial building in the world at the time. To the right are the aluminium and magnesium foundries, with the forges behind them. To give perspective on size, the parking area to the right of the factory complex was a mile long. (Detroit Public Library, Rose & Robert Skillman Branch Library National Automotive History Collection)

As he had done at the Wright Lockland factory, Kahn placed all employee services below the main factory production floor. His design incorporated a basement covering 621,000 sq. ft. The area comprised two longitudinal tunnels, each 88 feet wide, running the length of the building and connecting to the large employee parking lot at the south of the building. When the Chicago factory was nearing peak employment, 22,000 employees would enter the factory between 0700 and 0730 and leave between 1630 and 1700.[47] A lateral tunnel ran through the centre of the basement connecting the two longitudinal tunnels. The basement area had nine

[46]See 'Heat Treating and Forging Facilities, Aircraft Engine Plant, Chicago, Illinois, Plancor 792-Brochure C', copy in, War Assets Administration, Real Property Disposal Case Files 1947-1951, Box 243, Chrysler Corporation, RG 270, NARA, Chicago office; 'Dodge Chicago Division of Chrysler Corporation', *Factory Management and Maintenance*, Industrial Plant Section, Vol. 102, (April 1944), pp. B-72-76.

[47] Management Control, Central District, AAF Air Technical Service Command: *History of Dodge Chicago*, September 1945, p. 240, File 204.11-2, AFHRA

cafeterias that could seat 4,000 employees at a time, washrooms and toilets, offices, locker facilities and stairways to the production floor.[48] As at Lockland, employees would enter and exit the machine shop and assembly building through the basement, resulting in what the *Architectural Forum* called one of the Dodge factory's greatest achievements: traffic planning. 'At no point', the *Architectural Forum* noted, 'do the two flowing streams—people and products—meet except where they are intended to.'[49]

Perhaps the most important feature of the Dodge Chicago factory was its unique method of construction. In early 1942, as Kahn was finishing the design of the factory, with supplies of steel becoming critically short, the Government instructed Chrysler to remove nearly all structural steel from the Dodge Chicago factory buildings design.[50] Albert Kahn responded to this challenge by developing an entirely new method of construction. He employed this method, which came to be called the 'warspeed' method because of the speed of construction, to build the new giant aero engine factory in Chicago as well as two other large aero engine factories.[51] The 'warspeed' method employed a known cantilever reinforced concrete slab design that harkened back to Kahn's reinforced concrete factory designs from forty years earlier. Kahn introduced a completely new concept of building the factory's structural support system. This concept used a large wooden form that moulded a steel mesh reinforced concrete roof and supporting beams and columns reinforced with steel bars.[52] This replaced structural steel beams and girders. In this method the building was built as an open-sided shed structure, with the roof and columns in place but no floor or walls. When completed, workers laid a concrete floor and built the supporting walls.[53] With the 'warspeed' method, the steel required was kept to a minimum. The reinforced concrete roof slabs used a steel wire mesh, while the supporting beams

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[48] 'Hitler's 500 Acre Headache', Popular Mechanics Magazine, (November 1943)
[49] 'Dodge Chicago Plant Division of Chrysler Corp.', p. 52.
[50] Report of May 14, p. 48, 1942, Dodge Chicago Plant Chronology 1942, p. 7 - p. 50.
[51] These were the Wright Wood-Ridge factory previously mentioned, which was built prior to the Dodge Chicago factory and appears to have been the first test of the 'warspeed' construction method, and an even bigger aircraft engine factory for Pratt & Whitney outside Kansas City, Missouri, built to manufacture the 18-cylinder Pratt & Whitney Double-Wasp engine. The main manufacturing building at this factory had 2,321,000 square feet of floor area, a third larger than the Wright Lockland factory.
[52] '"Warspeed" System of Construction in Concrete', *Architectural Record*, Vol. 92, No. 6, (December 1942), p. 52.
[53] 'Single-storey Concrete Factory-A War-inspired Innovation', *Engineering News-Record*, Vol. 129, No. 17, (October 22, 1942), pp. 118-19.

and columns used steel bars, but the savings in steel over conventional structural steel construction were considerable. Using Kahn's reinforced concrete arched roof structure, the amount of steel needed was only 2.7 lbs. per sq. ft. of floor area compared to 12.7 lbs. a sq. ft. using conventional methods.[54]

Construction commenced in June 1942 and took a year to complete. Chrysler had hired the George A. Fuller Company as its general contractor. Working with Albert Kahn and his colleagues, Fuller engineers used 'warspeed' construction to build the Dodge Chicago factory buildings. The construction company built movable wooden structures, dubbed 'Trojan Horses' to carry the forms for moulding the reinforced concrete arched roof sections, supporting girders and columns. These forms were long enough to allow for a 120-foot roof section to be poured at one time. The Trojan Horses had wheels that travelled along rails laid down in front of them. Moveable towers hoisted the wet concrete to the top of the structure to be poured over the moulds for the three-inch roof sections reinforced with sections of steel mesh. The construction company built 60 traveling Trojan Horses, and to speed up construction of the huge machine shop and assembly building, construction started at both ends at the same time, with the Trojan Horses traveling toward the middle of the building. Completing the machine shop and assembly building took eight months with workers pouring the last concrete for the building on 26 February 1943.[55] Construction of the entire factory complex ended in July 1943.[56]

The Production Record

During the war, the Lockland factory built two models of the Cyclone 14, the 1,700 hp Cyclone 14BA and the more powerful 1,900 hp Cyclone BB, completing 60,546 Cyclone 14 engines by war's end. Following the outbreak of war in Europe, orders for the Cyclone 14 expanded rapidly. By the end of July 1940 total military orders for the Cyclone 14 amounted to 22,722, roughly 139

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[54] 'Multiple-Arch Concrete Roof Saves Steel', p. 99.

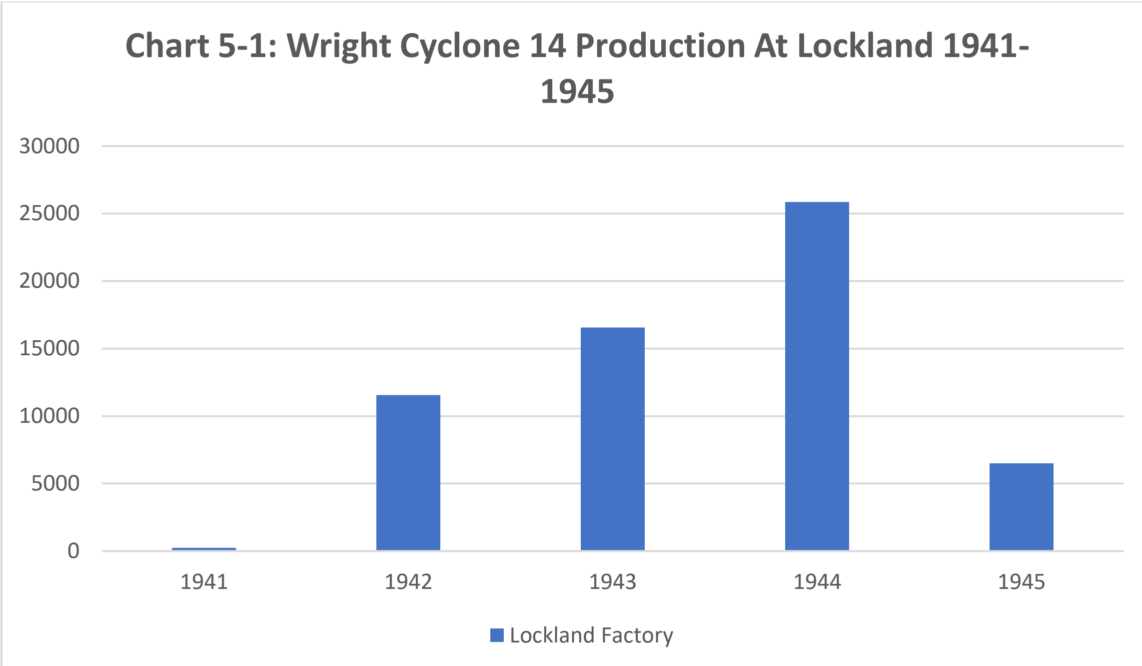
[55] Note of July 1, 1942, p. 65, Dodge Chicago Plant Chronology 1942, P. 51-102; *The Wall Street Journal*, February 23, 1943, p. 8.

[56] Memo of July 1, 1943, p. 135. Dodge Chicago Plant Chronology 1943, P. 103-153. Ironically, although the Dodge Chicago factory was intended to be a 'temporary' building, to last only seven to ten years, it is still in operation today as the main factory for the Tootsie Roll Company making a variety of candies.

times the number of Cyclone 14 engines Wright had built during 1939. After the attack on Pearl Harbor orders for the Cyclone 14 more than doubled. By the end of December 1941, total orders for the Cyclone 14 amounted to 61,000 with additional orders in later years.[57] Production at Lockland began in June 1941 and peaked in July 1944 when the factory completed 2,723 Cyclone 14 engines (see Chart 5-1).[58] This was also the peak year of Cyclone production at Lockland, with the factory building 25,860 Cyclone 14 engines, as shown in Chart 5-1. During 1945, the Lockland factory shifted to building the Cyclone 18, but continued production of the Cyclone 14 in declining numbers until October. In total, the Lockland factory built 73% of the 84,891 Cyclone 14 engines built during the war. After the Lockland factory started production, Wright continued to build the Cyclone 14 at its Paterson factories but as output grew at Lockland, production at the Paterson factories steadily declined. The Paterson factories built their last Cyclone 14 engine in November 1944, having completed 24,345 between 1940 and 1944.

[57] Office of Production Management, Aircraft Branch, Aircraft Engine Report 9-I, February 26, 1942, Report on Airplane Engine Deliveries (January 1, 1942 through April 30, 1944), Papers of Harry L. Hopkins, Special Assistant to the President, 1941-1945, Office of Production Management Reports, Aircraft Branch, November 28, 1941-January 20, 1942, Container 207, Franklin D. Roosevelt Library and Archives, Hyde Park, NY.

[58] *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*.



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946)

The Dodge Chicago factory's record of 18,413 Cyclone 18 engines completed during the war represented 57% of the entire production of the engine (see Chart 5-2). While it took nearly two years for the Chicago factory to begin production, once begun production increased rapidly and the factory was consistently ahead of its planned production schedule, reaching peak production of 1,600 Cyclone 18 engines a month in March 1945 just fifteen months after completing the first production engine. The Chicago factory built only two variants of the Cyclone 18 and a single variant (the -23) made up 90% of the Chicago factory's production. The factory began building a fuel-injection version of the Cyclone 18 during 1945, completing 1,986 of this version by the end of the war.

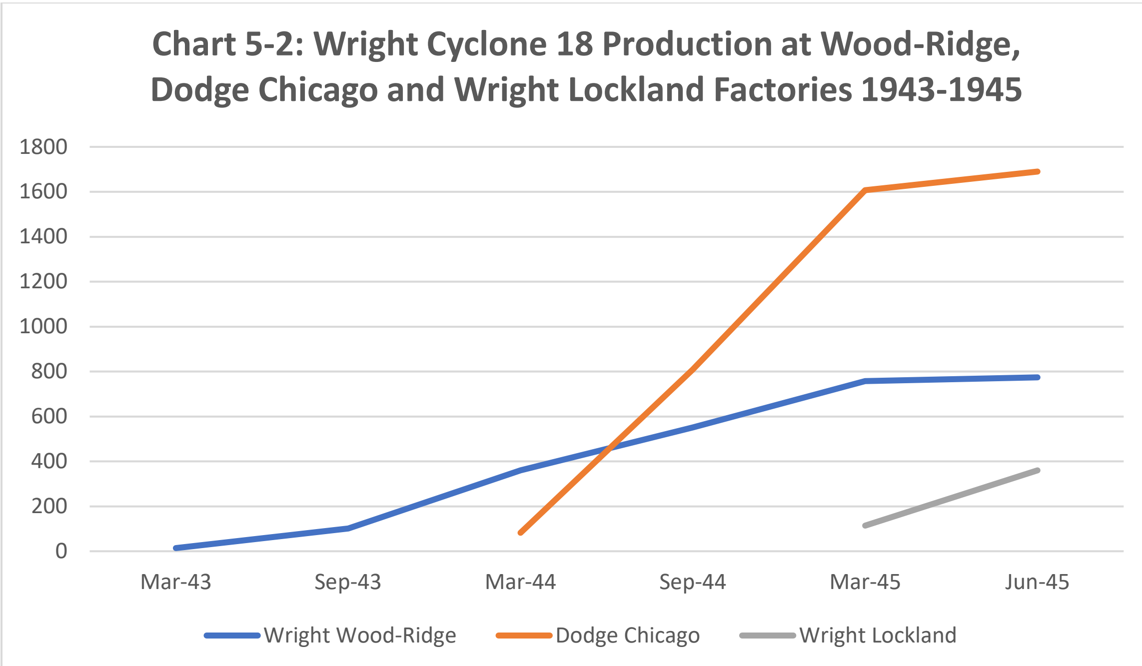


Chart 5-2: Wright Cyclone 18 Production at Wood-Ridge, Dodge Chicago and Wright Lockland Factories 1943-1945

Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946)

To augment Cyclone 18 production at the Chicago factory, the Government financed a large new factory for Wright at Wood-Ridge, New Jersey, which became Wright Plant No. 7, eight miles southeast of the main Wright factories at Paterson. Production of the Cyclone 18 at Wood-Ridge began in February 1943 with parts supplied from the Paterson factories. It took longer for the Wood-Ridge factory to build up production. By war's end, the Wood-Ridge factory had completed 11,793 Cyclone 18 engines, building seventeen different models of the Cyclone 18. The Lockland factory built an additional 1,867 during 1945, taking total wartime production of the Cyclone 18 to 32,240.

How it Was Done: Building the Cyclone 14 at the Wright Lockland Factory

In contrast to Wright's pre-war practice of building almost all engine components in its own factories, the Lockland factory adopted a different approach to production. As America began to rearm, the National Defense Advisory Council recognized that 'dependence on subcontractors for a substantial amount of work was essential to a maximum utilization of facilities and expansion of production.'[59] As a result of the Council's advice and Government urging, the Lockland factory relied far more on subcontractors than other Wright factories, even for core components of the Cyclone 14. The Lockland factory maintained a higher than average dependence on sub-contractors until the end of the war, running at 40% of the value of the Cyclone 14 engine compared to an industry average of 29%.[60] Among the thousands of subcontractors brought into the aircraft industry were many firms that supplied parts to the automobile industry. In January 1941, Wright placed contracts with the Graham-Paige Motor Company for Cyclone 14 connecting rods, the Eaton Manufacturing Company for propeller shafts, the Ohio Crankshaft Company for Cyclone 14 crankshafts and the Hudson Motors Car Company for Cyclone 14 pistons and rocker arms.[61] Wright also engaged the Otis Elevator Company in New Jersey to make finished crankcases for the Cyclone 14.[62]

Production of the Cyclone 14 began with casting the aluminium alloy cylinder heads in the Lockland factory's aluminium foundry. While Wright had adopted line production methods for its foundry operations, making the sand moulds for cylinder heads remained a labour-intensive process. Mould makers had to pack sand by hand around a bronze pattern of half the cylinder head and insert 750 headless nails in each half of the mould to support the walls of the cooling fins, the two halves being bolted together to form the finished mould.[63] To speed production, a conveyor carried the finished moulds through an oven for seven hours to harden the mould before receiving the molten aluminium. Once cooled, machines removed excess metal. Casting of magnesium sections for the crankcase nose and the supercharger housing followed a similar process of preparing sand moulds, pouring molten metal and removing the

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[59] Special Studies No. 21, *Aircraft Production Policies under the National Defense Advisory Commission and Office of Production Management, May 1940 to December 1941*, p. 155.

[60] See Maj. Frank W. Lavista, AAF Resident Representative, to Commanding General, AAF Material Command, Comments on Bureau of the Budget Report Dated 18 February 1944 Reference: Wright Aeronautical Corporation, Lockland, Ohio, 24 February 1944, R-2600 Case Study, Vol. 2, p. 730, File 202.2-13, A2070, AFHRA. See also Manpower Office, Management Control, Air Technical Service Command, Army Air Forces: *Labor Statistics for the Aircraft Industry*, November 1944-July 1945, File 218.6-7 Labor Statistics, AFHRA.

[61] *The Wall Street Journal*, January 7, 1941, p. 7; February 10, 1941, p. 1; 'Crankcases by Otis Elevator', *Trade Winds*, Vol. 6, No. 11, (April 1943), pp. 6-7, 18; 'Hudson Builds Cyclone Parts', *Trade Winds*, Vol. 6, No. 9, (October 1942), pp. 6-7; 'Crankshaft by Ohio', *Trade Winds*, Vol. 6, No. 10, (February 1943), pp. 8-9, 18.

[62] *The Wall Street Journal*, January 7, 1941, P. 7; February 10, 1941, p. 1; 'Crankcases by Otis Elevator', *Trade Winds*, Vol. 6, No. 11, (April 1943), pp. 6-7, 18.

[63] 'Cylinder Heads: A Cyclone 14 Begins its Growth with Casting of Cylinder Heads', *Trade Winds*, (May 1941).

excess when the part had cooled. After rough finishing, cast parts went to the machine shop for machining and assembly.

Wright estimated that manufacturing the 8,500 parts in the Cyclone 14 engine required over 80,000 machining operations and 50,000 inspections, although there were probably fewer machining operations at the Lockland factory because of the level of subcontracting.[64] The Wright Lockland factory incorporated all the lessons Wright had learned shifting from batch to quantity production at its Paterson factories. The Lockland factory combined line production methods with high-production machine tools and a vast floor area in the main machine shop and assembly building.[65] The unobstructed floor area allowed machine tools to be placed in an optimal sequence of operations, ensuring a one-way flow of parts from rough stores to final assembly. To speed the flow of parts the Lockland factory complex contained over five miles of conveyors, mechanical tracks and overhead lines.[66] In its first configuration, the main machine shop and assembly building at Lockland was divided into twelve sections or manufacturing departments, each of which was a factory by itself to manufacture a particular part or component. Manufacture of complete cylinders, for example, began in a department devoted to machining cylinder barrels with a separate department for machining cylinder heads. The finished parts moved to a department that completed assembly, attaching the cylinder head to the cylinder barrel. All parts from the foundries and sub-contractors entered the west end of the machine shop and assembly building, moving steadily east to the inspection department, the assembly area and the 'green' and final engine test cells. Constructing the large South Shop Building and the smaller North Shop Building provided Wright with space to expand each manufacturing department.

Assembly of the Cyclone 14 followed the line production assembly methods developed at the Wright Paterson factories, with sub-assemblies feeding into the main assembly line at 20 assembly stations. Once workers attached each set of parts or sub-assemblies to the engine, a powered conveyor moved the dolly supporting the engine to the next station. After assembly, an engine went through a seven hour 'green' test followed by disassembly and inspection of all

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[64] Geschelin, Joseph: 'Wright Ready to Power Bombers', *Automobile and Aviation Industries*, Vol., No., (February 1, 1942), p. 22.
[65] 'Cornfield to Mass Production in A Single Year-That's the Storey of Wright's Cincinnati Division', *Trade Winds*, (November 1941), p. 8.
[66] 'The Ohio Plant Today', *Trade Winds*, Vol. 6, No. 11, (April 1943), p. 13.

parts, before being reassembled and passed on to the final test for an additional five and a half hours.

The most important feature of the Lockland factory was its extensive use of high-production machine tools, many designed specifically for the factory and leading *The Wall Street Journal* to pronounce that at the Lockland factory 'breath-taking things are being done to arm America' through 'the wholesale use of automatic machinery.'[67] The Lockland factory benefited directly from the experimental work done at the Paterson factories on developing high-production machine tools.[68] The Lockland factory initially had over 2,000 machine tools installed; by the end of the war the total had reached almost 6,000, a third more than the number at the Studebaker factories at Chicago, Fort Wayne and South Bend.[69] The Lockland factory employed many more of the latest in automatic and semi-automatic machine tools.[70] As an example, the factory used several different types of multiple-spindle drilling machines, including a 21-spindle Foote-Burt drill to drill 21 holes in the crankcase simultaneously, a Baker multiple-spindle drill that automatically drilled 24 holes in the supercharger housing and many Bullard Mult-Au-Matic machines, three of these machines replacing 18 standard machines used at the Paterson factories.[71] A reporter noted that the Lockland factory 'has few single-spindle machines, whereas in Europe today there are almost no multiple-spindle machines in an aviation plant.'[72] For the first time, Wright used Heald internal centreless grinders to machine finish the inside of the cylinder barrel, cutting the machining time for this process in half.[73] A specially designed Greenlee multi-station machine reduced the machining time on supercharger front sections from 224 minutes to 24 minutes.[74] Using these automatic machine tools not only speeded up production, but reduced the total number of machine tools required to build the Cyclone 14, and enabled Wright to hire thousands of semi- and unskilled workers in the Cincinnati area who were put

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[67] *The Wall Street Journal*, June 16, 1941, p. 1.
[68] *Wall Street Journal*, (September 22, 1941), p. 18.
[69] Geschelin, 'Wright Ready to Power Bombers', p. 25; 'Manufacturing Plant, Lockland, Ohio, Plancor 10' brochure.
[70] Joseph Geschelin's article, 'Wright Ready to Power Bombers', contains a list of these machine tools on p. 25.
[71] 'Wright's Ohio Engine Plant Opens Mass Production Era', *American Aviation*, Vol. 5, No. 3, (July 1, 1941), p. 46.
[72] 'Wright's Ohio Engine Plant Opens Mass Production Era', p. 46.
[73] 'Wright's Ohio Engine Plant Opens Mass Production Era', p. 46.
[74] 'Cylinder Heads by the Mile', *Trade Winds*, (November 1941), p. 13.

through short, intensive training courses on the very machines they would be using in the machine shops.[75]

One of the most complicated and time-consuming operations in building a radial engine was preparing the cast cylinder head, drilling, reaming, countersinking and tapping the many holes required for the spark plugs, valve springs, intake and exhaust ports and rocker box covers. As previously described, in the 1930s, operators used a single-spindle drill press to make all these holes in the cylinder head, one at a time, having to change the type of tool—a drill, reamer, borer, counterbore or tap—for each operation.[76] With the need to increase production, Wright designed semi-production machine tools, one of which could drill, ream, countersink and tap the spark plug holes in one continuous operation, automatically moving the cylinder head from station to station.[77] But the cylinder head would then have to be moved to another machine to perform these operations on the intake and exhaust ports and to a third machine to machine the holes for the valve springs and finally to a fourth machine to drill holes for the rocker box covers.[78] Wright replaced all these machines with what was no doubt the most impressive of the many special-purpose machine tools Wright developed during the war, the Greenlee Automatic Transfer Machine, mentioned briefly in Chapter Four and now described in detail.

[75] 'Cornfield to Mass Production in A Single Year-That's the Storey of Wright's Cincinnati Division', *Trade Winds*, (November 1941), pp. 8-9.
[76] Holben, 'Some Aircraft-Engine Production Methods', p. 493.
[77] Holben, 'Some Aircraft-Engine Production Methods', p. 494.
[78] Holben, 'Some Aircraft-Engine Production Methods', p. 494

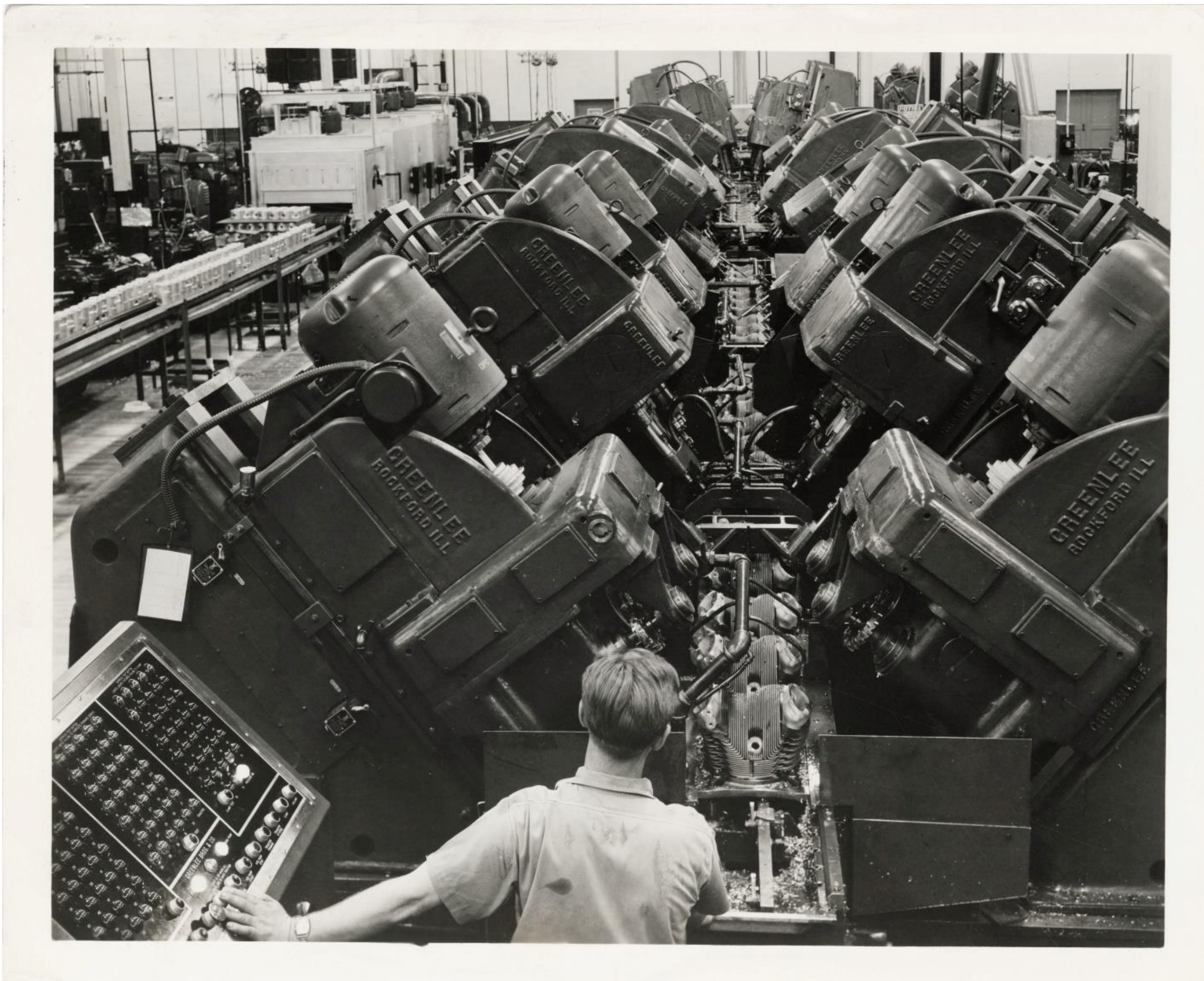

Illustration 5-2: This photo shows a section of a Greenlee automatic transfer machine at one of factories building Wright engines. The cylinder heads are moving progressively from station to station under the watchful eye of the operator. (Detroit Public Library, Rose & Robert Skillman Branch Library National Automotive History Collection)

A transfer machine is ‘a multi-head automatic machine [tool] which performs a sequence of operations simultaneously on a series of product-units which are automatically indexed forward from one machine station to the next.’[79] In 1940 the Nash-Kelvinator Corporation, one of the small American independent car companies, and the International Harvester Company, a maker of diesel tractors and diesel tractor engines, worked with the Greenlee Brothers & Company to develop transfer machines to drill and bore holes in engine blocks.[80] The transfer

[79] Hounshell, David A.: ‘Automation, Transfer Machinery and Mass Production in the U.S. Automobile Industry in the Post-World War II Era’, *Enterprise & Society*, Vol. 1, No.1, (2000), pp. 100-101.

[80] Hounshell, ‘Automation, Transfer Machinery and Mass Production in the U.S. Automobile Industry’, pp. 109-110.

machine incorporated a linked series of individual multi-spindle machine tools placed on both sides of an automatic conveyor to form a mini-production line.[81] The key feature of the transfer machine was that it 'indexed', or moved, the work piece from machine to machine automatically, saving a considerable amount of time because the operator didn't need to move the work piece from machine to machine. All the operator did was load the work piece at the front of the machine and unload it at the end of the machining operations.

Working with Wright engineers, Greenlee developed an automatic transfer machine that could drill and bore holes in aircraft engine cylinder heads in sequence, automatically. In 1941, the Lockland factory became the first Wright factory to employ the Greenlee automatic transfer machine. The rate of Cyclone 14 production expected at Lockland made the automatic transfer machine vital to achieving this production goal as the need for fourteen cylinders per engine meant more cylinder heads had to be manufactured. To reach the scheduled rate of production of 3,000 Cyclone 14 engines a month required 42,000 cylinder heads, roughly 1,350 per day. The automatic transfer machines reduced the number of machine tools and operators and dramatically speeded up cylinder head production. Working with Greenlee Brothers, Wright helped design and develop an automatic transfer machine that would automatically drill, ream, bore, countersink and tap all the required holes in a cylinder head for the Cyclone 14 in one continuous operation.[82] The first automatic transfer machine at Lockland consisted of two machines linked together to form one machine 80 feet in length. The first machine had 16 machining stations performing 25 different operations. The cylinder heads, mounted on steel plates, passed via a conveyor to the second machine with 53 stations, which performed 46 operations on the front of the cylinder head. At the end of the machining cycle a washer automatically cleaned the parts. The machine could turn out a finished cylinder head in two minutes, compared to 35 minutes using previous methods.[83]

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[81] Linsley, 'Mass Production for the Aircraft-Engine Industry', p. 101.
[82] Linsley, 'Mass Production for the Aircraft-Engine Industry', p. 102.
[83] 'High Output Machine Tools, In-Line Production Speed Up Manufacture of Engines at Cincinnati', *Trade Winds*, (July 1941), p. 7.

Wright soon replaced this early model with a more advanced and even longer set of three Greenlee automatic transfer machines that totalled 154 feet in length.[84] The first machine had 16 stations that performed 25 operations on the front of the cylinder head and 20 operations on the rear cylinder head as the cylinder head moved down a conveyor, automatically stopping at each station for machining. After passing through a washing operation, the cylinder heads travelled to the second machine that had 56 stations performing 46 operations on the front of the cylinder head and 37 operations on the rear. The longest operation required 48 seconds to complete, so that the cylinder heads moved to the next station in line at this pace, every 48 seconds. While the entire machining operation on a cylinder head took just under an hour, this more advanced automatic transfer machine effectively completed a cylinder head every 48 seconds. Once the cylinder heads had been attached to the cylinder barrels forming a complete unit, they were placed in a third Greenlee automatic transfer machine with 25 stations for the final drilling and boring operations. Collectively, these three machines replaced 75 other types of machine tools, required 202 fewer operators and saved 1,671 production hours.[85] The Greenlee automatic transfer machines required only 24 operators for three shifts. Twenty of these would be unskilled, whereas using the previous semi-production machines required semi-skilled operators and many more skilled workers to set them up.[86]

In 1942 Studebaker, who had also worked with the Greenlee company, added automatic transfer machines for the Cyclone 9 at its factory in South Bend.[87] The new Greenlee machine added milling operations to the drilling, reaming, countersinking and tapping built into the previous versions.[88] This machine was 176 feet in length, composed of three sections with 50 workstations. In between the stations washing machines cleaned the cylinder heads after they had gone through machining operations. At full operation, the Greenlee automatic transfer machine held 203 cylinder heads and turned out a completed head every 50 seconds. Later in

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[84] This description is drawn from Linsley, H.E.: 'Cyclone Engines Mass Produced', *The Iron Age*, (October 9, 1941), pp. 53-61 and 'Mass Production for the Aircraft-Engine Industry', *Mechanical Engineering*, Vol. 64, No. 2, (February 1942), pp. 100-105.

[85] Wright Aeronautical Corporation: *Application of High Production Machine Tools*, (No date), pp. 5, 8.

[86] Linsley, H.E.: 'Cyclone Engines Mass Produced', p. 55.

[87] Hounshell, 'Automation, Transfer Machinery and Mass Production in the U.S. Automobile Industry in the Post-World War II Era', pp. 110-112.

[88] Geschelin, Joseph: 'Studebaker Know-how Speeds Flying Fortress Engine Output', p. 70.

the war Wright added automatic transfer machines at its Plant No. 2 in Paterson for both the Cyclone 9 and Cyclone 14 cylinder assemblies and at the Wright Wood-Ridge, New Jersey, factory that built the Cyclone 18 engine. The Dodge Chicago factory would also employ the Greenlee automatic transfer machines, setting up two machines that were even bigger than those at the Wright Lockland factory.

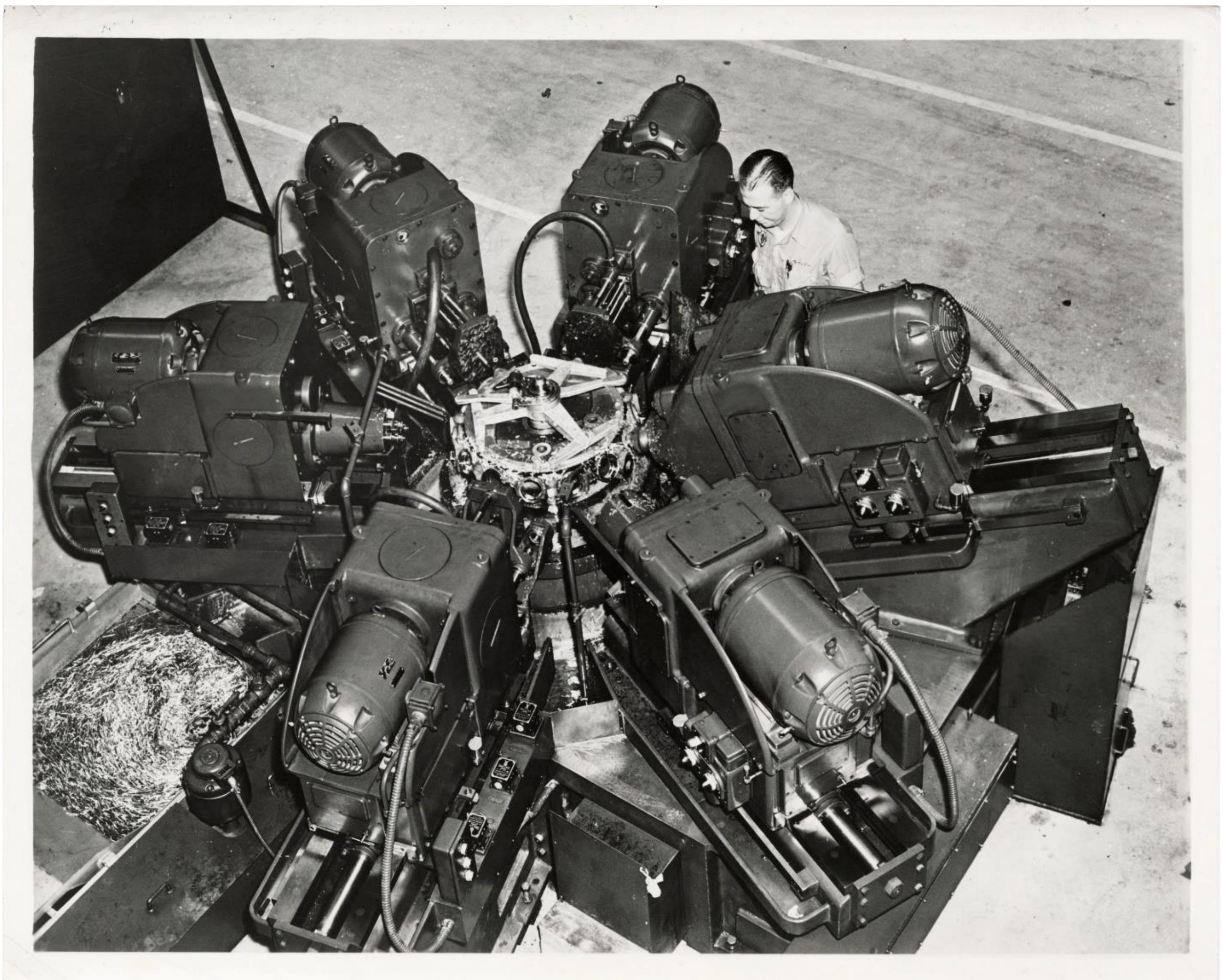

Illustration 5-3: A Greenlee rotary, six-station, automatic indexing machine that Studebaker developed with Greenlee. The machine moved the work piece automatically from station to station. (Detroit Public Library, Rose & Robert Skillman Branch Library National Automotive History Collection)

During the war Greenlee Brothers, working with Wright, Studebaker and other aircraft engine manufacturers, developed other types of high-production machine tools. Studebaker, for example, worked with Greenlee to develop a rotary, six-station, automatic indexing machine that would automatically perform more drilling, tapping and other operations on the completed cylinder assembly, moving the work piece automatically from station to station.[89] Greenlee produced a series of these horizontal, rotary automatic indexing machines.[90] Wright and Greenlee developed a more advanced 14-station rotary automatic indexing machine that would drill, bore and face holes in the front section of the Cyclone supercharger.[91] Two of these 14-station machines replaced seven standard machines, reducing the number of operators from 19 to two, and production hours from 139 hours to 17.4 hours.[92] Later in the war the Dodge Chicago factory used an 18-station automatic indexing machine.[93]

Wright worked with Greenlee to develop automatic machine tools specifically for machining crankcases for the Cyclone 14. Each crankcase had 14 flat deck pads to which the cylinders were attached. Each deck pad had to be machined to a smooth surface and then have 20 holes drilled, reamed, counterbored and tapped so the cylinder flanges could be bolted to the crankcase, totalling 280 holes for all fourteen cylinder deck pads. This process normally took 25 machine tools and 571 production hours to complete. Using four Greenlee four and six station machines cut the production time to 65 hours and reduced the number of machine operators from 66 to nine.[94]

Wright did not restrict the new methods of production and process engineering it had developed to the Lockland factory, but, in at least one case, passed these methods on to one of Lockland's main subcontractors, the Ohio Crankshaft Company, Inc. who manufactured crankshafts for the Cyclone 14. The company had many years' experience building crankshafts for large gasoline and Diesel engines, so was an ideal subcontractor for the Lockland factory. Soon after receiving the crankshaft contract, the Ohio Crankshaft Company received $4.5 million in Government financing to build a new 200,000 square foot factory and an additional $3 million

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[89] *Studebaker Corporation R-2600 Aircraft Engines Construction and Production Analysis*, p. 32.
[90] 'Wright Aero Produces Engines for the B-29 Superfortress', *Machinery (New York)*, Vol.50, No. 12, (August 1944), pp. 133-44.
[91] Wright, *Application of High Production Machine Tools*, p. 15.
[92] Wright, *Application of High Production Machine Tools*, p. 15.
[93] 'Wright Aero Produces Engines for the B-29 Superfortress', *Machinery (New York)*, Vol.50, No. 12, (August 1944), pp. 133-44.
[94] Wright, *Application of High Production Machine Tools*, pp. 21-23.

to purchase 310 new high-speed machine tools.[95] The Cyclone 14 crankshaft had three sections—centre section, rear and counterweight sections and front section—and contained 30 parts.[96] Manufacturing the crankshaft required 607 separate operations as follows:

- Centre Section:

  Rough forging, 65 lb. Finished, 26 lb. Operations, 135

- Rear and Counterweight Sections:

  Rear- rough, 85 lb. Finished, 46 lb. Operations, 240.

- Counterweights:

  Front counterweight-rough, 30 lb. Finished, 16 lb.

  Rear counterweight-rough, 24 lb. Finished, 10 lb.

  Operations for both weights, 50

- Front Section:

  Rough, 118 lb. Finished, 52 lb. Operations, 70.[97]

As at the Lockland factory, the new Ohio Crankshaft Company factory building was laid out according to the principles of line production.[98] The Company divided the factory floor space into three areas corresponding to the main sections of the crankshaft—centre section, rear and counterweight sections and front section—with the machine tools in each section laid out for straight line production. A system of 96 overhead cranes moved heavy forgings and finished sections along the production line. The latest types of automatic machine tools performed the required machining, grinding, precision-boring and finishing operations, although final finishing was done with hand-held tools.[99] Each finished crankshaft passed through three inspections at various stages of production, one from Ohio Crankshaft, one from Wright, and one AAF inspector before a final inspection by all three representatives and shipment to the Lockland factory.[100]

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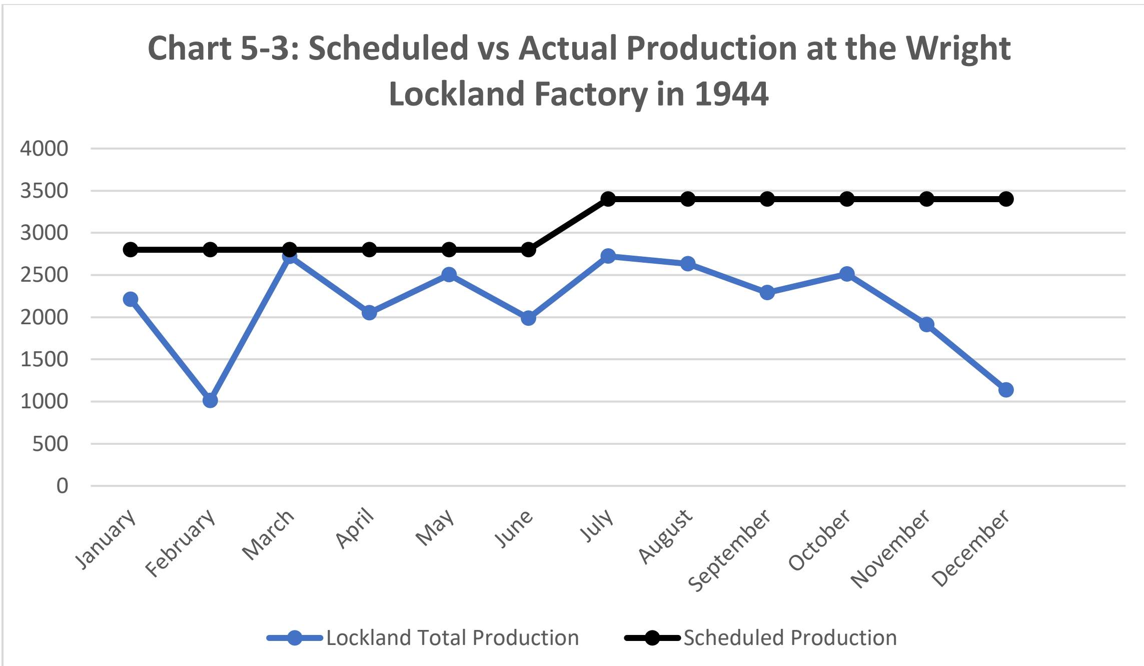
[95] McCarthy, J.F.: 'Precision Machining Operations on the Cyclone 14 Crankshaft', *Aero Digest's Aviation Engineering*, Vol. 39, No. 6, (December 1941), p. 198.
[96] Geschelin, Joseph: 'Crankshafts for the Wright Cyclone', *Automobile and Aviation Industries*, Vol. No. (March 1, 1942), p. 9.
[97] Geschelin, Joseph: 'Crankshafts for the Wright Cyclone', p. 9.
[98] Geschelin, Joseph: 'Crankshafts for the Wright Cyclone', p. 10.
[99] Geschelin, Joseph: 'Crankshafts for the Wright Cyclone', p. 15.
[100] Geschelin, Joseph: 'Crankshafts for the Wright Cyclone', p. 15.

During 1944, Wright developed a new means of increasing the cooling area on the cylinder barrel to improve cooling on higher power Cyclone engines, such as the Cyclone 14BB built at Lockland. This involved increasing the depth of the cooling fins on the cylinder barrel through an entirely new method of production, using new types of machine tools. The previous method involved machining the cooling fins on the steel cylinder barrel forging, using an automatic lathe to cut the 46 fins in one operation, removing 17 lbs. of steel per cylinder barrel in the process.[101] Increasing the depth of fins on the cylinder barrel would have required a much heavier forging to get the additional fin depth, resulting in a heavier cylinder barrel, and complicated machining. Instead, Wright engineers developed a completely new method invented at the Scandia Manufacturing Company which used thin aluminium fins, in the shape of a 'W', inserted in grooves cut into the sides of the cylinder barrel.[102] Using this method, 60 aluminium fins replaced 46 steel fins, increasing the cooling area by 55%, reducing the required thickness of the cylinder barrel, cutting the machining time to less than one-third of the previous method and saving an estimated 12,000 tons of nitralloy steel a year.[103] Wright modified automatic lathes to cut 30 grooves on the cylinder barrel for the aluminium fins, and developed special machine tools to roll thin aluminium sheets into the 'W' shape, insert the fins into the cut grooves on the cylinder barrel and caulk the fins to lock them in place.[104]

One of the most important aspects of line production was production control, defined as 'the planning, scheduling, dispatching, and expediting of machines, materials, and men within the plant.'[105] To maintain quantity production through progressive flow required timely delivery of parts and raw materials to the factory, often ordered months in advance to ensure supply, the correct placement of machine tools in the proper sequence of operations and a schedule to maintain the pace of production from start to finish, 'feeding parts and subassemblies to the various work areas at the rate and time required.'[106] Engineering and design changes, such as the shift to using the 'W' aluminium cooling fins, disrupted this flow and had to be planned well in

[101] 'Aluminum Fins Rolled On Aircraft Engine Cylinders', *The Iron Age*, (February 22, 1945), pp. 66-67.
[102] 'Aluminum Fins Rolled On Aircraft Engine Cylinders', p. 66.
[103] 'Aluminum Fins Rolled On Aircraft Engine Cylinders', pp. 67-68.
[104] 'Aluminum Fins Rolled On Aircraft Engine Cylinders', pp. 68-70.
[105] Muther, *Production-Line Technique*, p. 187.
[106] Muther, *Production-Line Technique*, p. 195.

advance. But there were other unplanned interruptions that the Lockland factory had to deal with, particularly changes in aero engine production schedules and problems with subcontractors.



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946); Lilley, Tom, et al: *Problems of Accelerating Aircraft Production During World War II*, (Cambridge, MA, 1947), Table 20.

In early 1943 the Army Air Force's production schedule for the Lockland factory had called for the factory to reach peak capacity of 4,000 Cyclone 14 engines a month by May 1944, based on aircraft requirements.[107] During that year the AAF revised the schedule downward, the November 1943 schedule calling for the Lockland factory to reach a peak of 3400 engines a month by July 1944 and maintain this production rate thereafter (see Chart 5-3). Even though this would result in a cumulative engine deficit compared to requirements, the AAF could manage the deficit

[107] Based on Aircraft Production Board Report 9-L of January 1943. See Delivery Schedule of Aircraft Engines Aircraft Report 9-L November 1, 1942 through October 31, 1944, War Production Board Reports, Aircraft Branch, Dec 31, 1942-Jan 15, 1943, Papers of Harry L. Hopkins, Container 240, FDR Library.

by reducing stocks of spare engines.[108] In January 1944, the AAF decided to cut production of the Cyclone 14 at the Lockland factory and convert the factory to building the higher-priority Cyclone 18, beginning in November 1944.[109] Even with the AAF's subsequent decision to cut back peak Cyclone 14 production to 3,000 engines a month starting in July 1944, the changes played havoc with scheduling Cyclone 14 production for the rest of the year.[110] In April 1944 the Navy requested additional Cyclone 14BB engines from the Lockland factory that had not been planned for. This led to the fifth revision in Lockland's production schedule since January, causing one AAF officer to comment that 'Wright Aeronautical Corporation are now so confused that they feel it is practically impossible to furnish any kind of production commitment for either the R-2600-B [Cyclone 14BA] or the R-3350 engine [Cyclone 18].'[111]

In early 1944 the Lockland factory experienced another unplanned disruption in production when the Graham-Paige Company produced flawed master rods due to poor management control and machining processes, causing the loss of 1,850 engines from production in February, March and April, resulting in a production loss of 4,481 engines for the year.[112] By halting or reducing aircraft programmes that depended on the Cyclone 14 the AAF restored some semblance of balance to requirements.[113] As part of this re-balancing, the AAF agreed to Wright's proposal to cut back production for much of 1944 to 2,500 a month.[114] Despite the fact that the Lockland factory built 25,680 Cyclone 14 engines these schedule changes during 1944 caused

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[108] See the memo 'The November 4th Aircraft Engine Schedule', Morris L. Copeland, Assistant Director, Munitions Branch Statistical Department, to Donald Davis, Vice Chairman, War Production Board, December 7, 1943, War Production Board Select Document File, Aircraft Schedule-Standardization, Box 29, Entry 3A, RG179, NARA.

[109] Summary of the R-2600 Engine Project, p. 6, Case History of the R-2600 Engine Project, Part I, Section I, File 202.2-13, A2070, AFHRA.

[110] Summary of the R-2600 Engine Project, p. 6.

[111] Maj. Gen. C.E. Branshaw, Material Command, to Assistant Chief of Staff, M.M. &D., 11 April 1944, Case History of the R-2600 Engine Project, Part I, Section I, pp. 775-76, File 202.2-13, A2070, AFHRA.

[112] Office of Assistant Chief of Staff, Material, Maintenance, and Distribution, Inter-Desk Memorandum, 17 February 1944, R-2600 Engine Part I, Section I, R-2600 Case Study, Vol. I, p. 724, File 202.2-13, A2070; Maj. Gen. C.E. Branshaw, Material Command, to Assistant Chief of Staff, M.M. &D., 11 April 1944, Case History of the R-2600 Engine Project, Part I, Section I, pp. 775-76, File 202.2-13, A2070, AFHRA.

[113] Aircraft production numbers based on *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*. See also memo to General Meyers, Engine Situation Resulting from Airplane Cuts, 22 May 1944, Case History of the R-2600 Engine Project, Part I, Section I, pp. 794-96, File 202.2-13, A2070, AFHRA.

[114] Brig. Gen. Orval R. Cook, Chief, Production Division, to Deputy Chief of Staff, Wright Field, R-2600-B and R-3350-BA Engine Production at Wright Aeronautical Corporation Plant, Lockland, Ohio, 13 May 1944, Case History of the R-2600 Engine Project, Part I, Section I, pp. 787-93, File 202.2-13, A2070, AFHRA.

‘serious operating problems’.[115] Lockland never managed to reach its full production capacity of 4,000 engines a month or the revised target of 3,400 engines a month. It is unclear exactly what problems prevented the Lockland factory from meeting its production target. There may have been problems with the adequate supply of parts from subcontractors, but this failure may also have been due in part to problems with Wright’s management, which emerged in embarrassing fashion during 1943.

Real concern with the quality of management at the Lockland factory stemmed from an investigation by the Senate Special Committee to Investigate the National Defense Program, better known as the Truman Committee from its chairman, Senator Harry S. Truman. Responding to complaints of improper inspection procedures, in the spring of 1943 the Truman Committee reported that the Lockland factory had delivered defective engine parts through lax inspection procedures, faulty record-keeping and management pressure to favour production over inspection.[116] In response to the Truman Committee’s investigation, the AAF conducted its own review of the Lockland factory and severely criticized Wright management and its own supervision staff for allowing incompetent management at lower levels, inadequate numbers of trained inspectors, improper handling of salvaged and rejected parts and ‘excessive machinery, floor space, and manpower’, which seems an odd comment given the factory’s scheduled monthly production target.[117] The AAF reduced the Lockland factory’s Quality Inspection Control rating from A to B.[118]

The AAF’s report concluded that the quality control and inspection systems that experienced personnel used at the Paterson factories were poorly documented and insufficiently rigorous for the new and inexperienced inspection personnel at the Lockland factory.[119] While

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[115] Summary of the R-2600 Engine Project, p. 8.

[116] Riddle, Donald H.: *The Truman Committee: A Study in Congressional Responsibility*, (New Brunswick, NJ, 1964), pp. 122-24.

[117] Summary of the R-2600 Engine Project, Part II: Lockland Investigation, R-2600 Case Study, Vol. 3, p. 859, File 202.2-13, AFHRA.

[118] An A rating, the highest quality control rating, indicated that the AAF had complete trust in the organisation’s quality control methods and had assigned all responsibility for inspection to the rated facility and performed only spot checks. With the B rating, the AAF inspectors carried out inspections on a certain percentage of parts, duplicating and checking on the methods and procedures of the organisation. Report of Conditions at Wright Aeronautical Corporation New Jersey Plants, Vol. I., p. 13, File 208,8A, AFHRA.

[119] Report: Truman Sub Committee Investigation of Wright Lockland Engine Plant, 11 April 1943, R-2600 Case Study, Vol. 3, p. 923, File 202.2-13, AFHRA.

praising the factory manager for the 'magnificent job' he had done building up the new organization at Lockland and training the machine operators, the report found that training of inspection personnel was inadequate.[120] The AAF report admitted that the planned expansion in capacity from 1,000 to 4,000 engines a month was an enormous undertaking, but criticised Wright's senior management for failing to send a senior executive from Wright's head office in New Jersey to oversee the expansion and to provide competent assistants to take on more responsibility for the full range of activities at the factory.[121] Once the deficiencies came to light, the AAF instituted more stringent inspection procedures, assigned more AAF inspectors, imposed weekly reporting requirements to improve inspection and increased the engine run-in time from seven to ten hours to ensure no defective parts slipped through.[122]

The problems with production of master rods at the Graham-Paige Company a few months later was another indication of problems with management at the Lockland factory. The AAF blamed the problems on the failure of the Materials Control System at the factory and Wright's inadequate supervision of its subcontractor.[123] By the summer of 1944, the AAF believed that all the problems at Lockland had been resolved. The AAF representative at the Lockland factory was confident that the factory could meet the revised target of 3,000 engines a month, but deliveries in July 1944 were still short of the objective. The Lockland factory never reached its objective before converting to production of the Cyclone 18 in late 1944.[124]

The management and production problems Wright encountered at the Lockland factory raise the question of whether Wright simply ran into diseconomies of scale at Lockland. There can be many sources of diseconomies of scale, such as limits on the supply of a factor of production (raw materials, labour, machinery, etc.) or declining efficiency in the use of a

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[120] Report: Truman Sub Committee Investigation of Wright Lockland Engine Plant, 11 April 1943.
[121] Lt. Gen. William Knudsen, Memorandum for Robert A. Lovett, Assistant Secretary of War for Air, April 17, 1943, R-2600 Case Study, Vol. 3, p. 932, File 202.2-13, AFHRA.
[122] Summary of the R-2600 Engine Project, Part II: Lockland Investigation, R-2600 Case Study, Vol. 3, pp. 859-60, File 202.2-13, AFHRA.
[123] Col. S.R. Brentnall, Office of the Chief of Air Staff, Material, Maintenance, and Distribution, AAF, to Gen. B.W. Chidlaw, 21 February 1944, R-2600 Case Study, Vol. 2, p. 723, File 202.2-13, A2070, AFHRA.
[124] Col. S.R. Brentnall, Office of the Chief of Air Staff, Material, Maintenance, and Distribution, AAF, to Gen. B.W. Chidlaw, 21 February 1944.

production factor as its use increases, but management and organisational structure can also be a key contributor to diseconomies of scale.

Management effectiveness may decline as the scale of the organization increases.[125] As C.F. Pratten argues, 'as scale increases, the costs of coordinating and organising production may rise more than proportionally. The effectiveness of management may decline as the chain of management is extended because of delays in making decisions brought about by the length of the management chain and/or the tendency of those making decisions to get out of touch with relevant events.'[126] In particular, the quality of information may decline as the levels of management expand with the increase in scale, as the 'accuracy and amount' of information passing upwards declines.[127] Oliver Williamson references the issue of 'communication distortion', where lower-level managers tell their superiors what they think their superiors want to hear, thereby distorting the reality of the situation.[128] There may also be, as seems apparent at the Lockland factory, a direct relationship between scale and the quality of management at middle and lower levels.[129] As firms expand rapidly, as so many did during World War II, they may not be successful in recruiting enough capable managers.

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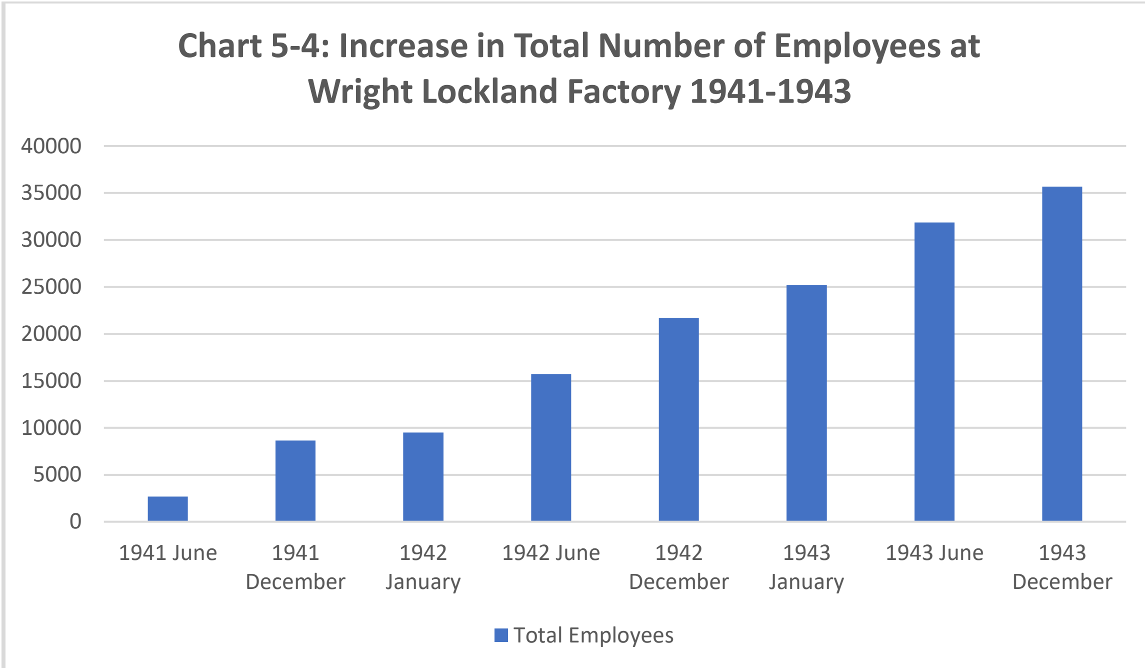
[125] Pratten, *Economies of Scale in Manufacturing Industry*, p. 15.
[126] Pratten, *Economies of Scale in Manufacturing Industry*, p. 15.
[127] Pratten, *Economies of Scale in Manufacturing Industry*, p. 297.
[128] Williamson, Oliver E.: *Markets and Hierarchies: Analysis and Antitrust Implications: A Study in the Economics of Internal Organization*, (New York, NY, 1975), p. 122.
[129] Williamson, *Markets and Hierarchies,* p. 298.



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946)

After the AAF's decision to increase production capacity from 1,000 to 4,000 engines a month, employment at the Lockland factory expanded rapidly (see Chart 5-4). The initial plan for the Lockland factory was to build up to a total of 12,000 employees, but within two years from starting production the total had more than doubled.[130] The situation at Wright's Paterson factories was similar. Between January 1941 and December 1943, the total number of employees at Paterson and the Wood-Ridge factory nearly tripled.[131] Managing this rate of expansion would be challenging at any time, but during war time with intense pressure to meet production schedules it must have been extra difficult. It is remarkable that in 1939 Wright had a little more than 3,000 employees and four years later had over 70,000. Where and how Wright acquired its middle-management and supervisory staff for its seven factories is a question that remains unanswered but warrants further research.

The problems with management, production and inspection at the Lockland factory did lessen, but the AAF remained concerned with the lack of qualified senior level managers for

[130] '30,000 Workers in 6 Wright Plants to Build 3,780,000 H.P. Monthly', *Trade Winds*, (April 1941), p. 4.
[131] These numbers are taken from *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production.*

production, production control and material controls.[132] The AAF was fortunate that it could meet the shortfall in Cyclone 14 production during 1944 by cutting production of aircraft that used the Cyclone 14. The Wright Lockland factory's record demonstrates that managing a giant factory was not simply a matter of extrapolating methods and processes used at smaller factories. The experience of Chrysler's Dodge Chicago Division in managing the giant Chicago factory provides a study in contrasts.

How it Was Done: Building the Cyclone 18 at the Dodge Chicago Factory

In contrast to the Wright Lockland factory, the Dodge Chicago factory was designed for integrated production of the Cyclone 18, relying less on subcontracting. The Dodge Chicago factory's facilities were more comprehensive than those at the Wright Lockland or Wood-Ridge factories. As previously mentioned, the Chicago factory had large aluminium and magnesium foundries, with two separate forges for heavy and light forging. The initial plan was to have the Chicago factory make 305 separate parts for the Cyclone 18 as follows:

- Machined parts 113
- Assemblies 107
- Forgings 75
- Magnesium castings 8
- Aluminium castings 2

Total 305[133]

The number of machined parts was increased from 113 to 158 when suitable subcontractors could not be found and when engineering changes added parts to the Cyclone 18. This increase proved more than the Chicago factory could accommodate.[134] The AAF agreed that the required parts could be manufactured in other Chrysler and Dodge Division factories.[135] By the end of

[132] Maj. C.J. McKinsey, Acting AAF Resident Representative, Wright Aeronautical Corporation Lockland, Ohio, to District Supervisor, Central Procurement District, AAF Material Command, April 28, 1944, R-2600 Case Study, Vol. 3, p. 1163, File 202.2-13, AFHRA.

[133] Report of C.E. Dalton, January 31, 1943, p. 109, Dodge Chicago Plant Chronology 1943, Pg. 103-153.

[134] Memo of C.E. Dalton, February 29, 1944, p. 15, Dodge Chicago Plant Chronologyn1944, Pg. 1-50.

[135] Memo of F.J. Damborn, March 2, 1944, p. 16, Dodge Chicago Plant Chronology 1944, Pg. 1-50.

1944, the level of subcontracting at the Chicago factory was about half that of the Lockland factory.[136] This was partly the result of timing. By late 1942 Dodge found it difficult to find subcontractors as most of the suitable firms were already heavily committed to other munitions manufacturers.[137] Fortunately, the Chicago factory did not depend on subcontractors for any of the main parts of the Cyclone 18, and unlike the Lockland factory, never suffered a delay in production from the failure of a subcontractor to deliver parts.[138]

The Dodge Chicago factory was the only aircraft engine factory in America that made its own forgings. The two foundries made crankcases, crankshafts, cylinder barrels and other smaller steel parts for the Cyclone 18. The foundry used 35,000 lb. steam hammers to make the three sections of the main crankcase. These came to the foundry as steel billets 24" in diameter.[139] A rotary hearth furnace heated the billets to 2300° F. The nine-man furnace crew removed the heated billet and placed it on the lower half of the die on the steam hammer which hammered the billet against the die with 15 to 20 hard blows.[140] The forging next went to a trimming press which removed excess metal and punched a ten inch hole in the centre of the piece. When cooled, the forged crankcase sections went to the machine shop and assembly building for finishing and then to final assembly. The steel crankshafts went through a similar process. Cylinder barrels were formed from solid steel billets using an upsetter, a forging machine where the work piece was placed between two dies and pressure exerted horizontally, as opposed to vertically. A furnace heated the steel billet until the front section was red hot. A team of three or four workmen removed the billet from the furnace and placed it in the upset forge, where the dies and hammers forged a hollow cylindrical barrel of the right size and shape and cut it off from the billet automatically, dropping the finished work piece onto a conveyor to a cooling bin.[141]

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[136] Memo of William Butler, Chief, Aircraft Section, Munitions Branch, Bureau of Planning and Statistics, War Production Board, May 15, 1944, File 315.3043 Aircraft Engines-Deliveries and Shipments, War Production Board Policy Documentation File 315.3043-315.3143, Box 1126, Entry 1, RG 179, NARA.

[137] Management Control, Central District, AAF Air Technical Service Command: *History of Dodge Chicago*, September 1945, p. 156, File 204.11-2, AFHRA

[138] *History of Dodge Chicago*, p. 161.

[139] 'Dodge Chicago Plant Makes Own Forgings for Army B-29 Super-Fortress Plane Engines', *Industrial Heating*, Vol. XI, No. 10, (October 1944), p.1588.

[140] Humphrey, William V.: 'Aircraft Engine Forging Operations', *Industrial Aviation*, (July 1944), p. 58.

[141] The Chrysler documentary from 1945, 'Engines for Superbombers', shows this procedure.

The aluminium and magnesium foundries at the Chicago factory were the largest of their type in America.[142] The aluminium foundry concentrated solely on casting aluminium cylinder heads for the Cyclone 18. Completing 1,600 Cyclone 18 engines required 28,800 cylinder heads a month, eighteen per engine, which works out to casting about 930 a day (as well as 930 cylinder barrels). In addition, the Chicago aluminium factory made cast cylinder heads for the Wright Wood-Ridge factory, sending 209,924 Cyclone 18 cylinder heads to Wood-Ridge during 1944.[143] The Chicago factory used the same casting process that Wright did, creating sand moulds hardened in an oven before receiving the molten aluminium. The Chicago factory developed a process of reinforcing the fins in the sand mould that required only 240 steel pins per mould, substantially less than the 1,400 that Wright used, allowing for faster mould assembly.[144] The magnesium foundry made castings for the front section of the crankcase, the front and rear housings of the supercharger, and several other smaller parts. Both foundries were designed for line production and made extensive use of mechanical overhead and roller conveyors to speed production. Production flowed through 'moulding, baking, core assembly, pouring, shaking out, cleaning and inspection.'[145]

Machining parts for 1,600 Cyclone 18 engines a month ultimately required over 10,000 machine tools, nearly three times as many as in the Wood-Ridge factory.[146] The Chicago factory benefited from the work Wright had done developing high-production machine tools. The Chicago factory used many of the same types of machine tools used to build the Cyclone 18 at Wright's Wood-Ridge factory, such as Bullard Mult-Au-Matic multi-spindle drilling and boring machines, Cincinnati Hydrotel vertical milling machines, Ex-Cel-O automatic thread grinders, Greenlee three-, five-, seven-, nine- and eighteen-station horizontal machines, Heald Boromatics

[142] Gude, William G.: 'Aluminum Castings by Dodge Chicago Plant', *The Foundry*, Vol. 72, No. 9, (September 1944), p. 80.
[143] Letter of K.T. Keller, President, Chrysler Corporation, January 9, 1945, p. 1, Dodge Chicago Plant Chronology 1945, Pg. 1-50.
[144] Fuller, Curtis: 'Superfort Power Plant', *Flying*, Vol. 35, No. 1, (July 1944), p. 72.
[145] Gude, William G.: 'Magnesium Castings by Dodge Chicago Plant', *The Foundry*, Vol. 72, No. 8, (August 1944), p. 79.
[146] Report of E.G. Nelson, Machine Records, February 24, 1945, p. 25, Dodge Chicago Plant Chronology 1945, Pg. 1-50.

and Rehnbert-Jacobson multi-station automatic indexing machines.[147] Two eighteen-station Greenlee horizontal automatic indexing machines could drill, ream and counterbore 100 holes in the supercharger front section, replacing eight radial drilling machines and two radial tapping machines, reducing the handling operations from ten to two.[148] To round the edges of the many gears used in the Cyclone 18, Wright replaced a time-consuming process using portable tools with a Packer-Matic machine with automatic indexing to reduce the process from 150 minutes to three minutes per gear.[149]

Given the quantity of cylinder assemblies required for 1,600 Cyclone 18 engines every month, the Greenlee automatic transfer machine was arguably even more important to production at the Dodge Chicago factory than at Lockland. Plans for the machine shop and assembly building incorporated stronger foundations for three Greenlee automatic transfer machines, the largest of which weighed 275,000 lbs.[150] In fact, the Chicago factory set up only two Greenlee automatic transfer machines. These were even bigger than the transfer machines at Lockland. Each transfer line had three sets of machines that were 209 feet long, 55 feet longer than the Lockland machines. These machines performed 269 operations, more than the Lockland machines, and could turn out a completed cylinder head every 45 seconds.[151] Using the automatic transfer machines the Chicago factory could complete 70% of all the machining operations the cylinder head required in a fraction of the time of previous methods.

The massive machine shop and assembly building was ideal for line production with nothing to interfere with the placement of rows of machine tools except the heat treatment department on the east side of the building. Materials and parts entered the south end of the building and moved progressively north toward the final assembly section, a 22-acre space that was fully air conditioned, before the fully assembled engines moved to the engine test cells. Like

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[147] 'Wright Aero Produces Engines for the B-29 Superfortress', *Machinery (New York)*, Vol.50, No. 12, (August 1944), pp. 133-44.

[148] 'Wright Aero Produces Engines for the B-29 Superfortress', pp. 141-42.

[149] 'Wright Aero Produces Engines for the B-29 Superfortress', pp. 139-40.

[150] The outline for these Greenlee machines appears on a set of original plans for the Dodge Chicago factory from October 1942 in the possession of Albert Kahn Associates in Detroit, Michigan. I would like to thank Donald Bauman, Director of Architecture and Historic Preservation for giving me access to these plans.

[151] *Steel*, Vol. 115, (September 4, 1944), p. 74; Mansfield, J.H.: 'Production Robots Cut Machining Costs', *Society of Automobile Engineers Journal*, Vol. 55, (February 1947), p. 44

the Lockland factory, production at the Chicago factory was organised around components, with each component having its own section of the building. The work flowed past rows of machine tools via conveyors. Since Dodge had been unable to find enough subcontractors to manufacture the many gears needed for the eighteen cylinders in the Cyclone 18, Dodge had to manufacture these itself at the Chicago factory and at other Chrysler and Dodge factories.

Manufacturing gears for the Cyclone 18 provides another example of how the aero engine companies borrowed knowledge and experience from the automobile industry to develop new methods of large-scale production. Within the machine shop and assembly building at the Dodge Chicago factory, the gear department took up more space than any other component.[152] The big Wright Cyclone 14 and 18 double-row engines required many gears of different sizes and shapes for the propeller reduction gear, to operate the cams controlling the intake and exhaust valves, the supercharger, generator and other accessories. Making gears was laborious.[153] Gears started as a steel alloy forging. A gear cutter cut the rough outline of the gear teeth and then the gear went through a hardening process. Wright had developed a method of hardening the gear first, then grinding the gear teeth to the proper shape using a special two-wheel gear shaper that would remove .004 to .006 inch of metal from each side of the gear teeth using abrasive wheels. The final process, finish grinding, was to round off sharp corners of the gear teeth by hand, a delicate task, and one not suited to large-scale production. However, it was the accepted practice in the aero engine industry.[154]

Before the war the automobile industry, with its high demand for gears for automobile transmissions, developed a different method of manufacturing gears better suited to large-scale production. This method, called gear shaving, used a cutting edge to shave off excess metal instead of a grinding machine.[155] Shaving instead of grinding gears saved considerable time allowing a higher rate of production with fewer machine tools. It was more accurate and less

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[152] See the documentary 'Engines for Superbombers'.
[153] See 'Wright, Leader in Gear Design, Created Profile, Now Standard', *Trade Winds*, (May 1941); Brown, P.W. and Earle V. Farrar: 'Design and Manufacture of Aircraft Gearing', *Machinery (NY)*, Vol. 49, No. 3, (November 1942), pp. 219-221.
[154] Pfeffer, Charles G.: 'Shaved Aircraft Engine Gears', *The Iron Age*, Vol. 155, No. 15, (April 12, 1945), p.54.
[155] Pfeffer, 'Shaved Aircraft Engine Gears', p.54.

dependent on the skill of the operator.[156] Faced with a looming shortage of gear finishing machine tools, the War Department instructed the aero engine companies and their licensees to switch to gear shaving where it was practical to do so.[157] Wright undertook an experimental development program to work out a method of using gear shaving for aero engine gears, that would take into account the difference between automobile and aero engine gears in design and performance requirements.[158] This program was successful and the factories building Wright engines shifted to this new method of manufacturing gears.

The Chicago factory had to cope with changes in the number of parts to be machined at the factory, and the need to produce parts for other Wright factories building the Cyclone 18. In January 1943, even before completing construction of the factory buildings, the Chicago factory began machining work on the initial list of 113 parts to be machined at the factory for the Cyclone 18, increasing this to 158 parts later in the year. From May through September 1944, Dodge brought the total number of parts machined at the factory to 184.[159] The Chicago factory transferred some production to other Chrysler-Dodge factories, but continued to produce about 130 machined parts until the end of the war.[160] The Chicago factory also machined 135 different parts for the Wright Wood-Ridge factory, sending 75,674 machined parts and 209,924 cylinder heads to Wood-Ridge during 1944.[161] The Chicago factory also provided Cyclone 18 parts to the Lockland factory as it transitioned from building the Cyclone 14 to the Cyclone 18.[162] In addition to finished engines and parts for other Wright factories, the Chicago factory produced over 34 million spare parts for Cyclone 18 engines from the fall of 1943 to the end of the war.[163] To get other Dodge factories into production, the Dodge Chicago factory provided skilled staff and machine tools. Over the summer of 1944, the Dodge Main factory took over production of oil

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[156] Pfeffer, 'Shaved Aircraft Engine Gears', p.54.
[157] Harris, A.W.: 'Shaved Gears for Aircraft Engines', *The Iron Age*, Vol. 152, No. 6, (August 5, 1943), p. 59.
[158] Pheffer, 'Shaved Aircraft Engine Gears', p. 54.
[159] Report by the Engineering Special Division, Dodge-Chicago Plant, August 21, 1945, p. 99, Dodge Chicago Plant Chronology 1945, Pg. 51-100.
[160] Report by the Engineering Special Division, Dodge-Chicago Plant, August 21, 1945, p. 99, Dodge Chicago Plant Chronology 1945, Pg. 51-100.
[161] Letter of K.T. Keller, President, Chrysler Corporation, January 9, 1945, p. 1, Dodge Chicago Plant Chronology 1945, Pg. 1-50.
[162] Memo of C.E. Dalton, Chief Liaison Executive, Dodge Chicago Plant, January 12, 1945, p. 2, Dodge Chicago Plant Chronology 1945, Pg. 1-50.
[163] Chrysler Corporation press release of March 23, 1945, p. 38, Dodge Chicago Plant Chronology 1945, Pg. 1-50.

pumps for the Cyclone 18 from Dodge Chicago. The Chicago factory built up a 30-day supply of oil pumps, then shipped 479 machine tools to the Dodge Main factory where they were added to newly ordered machine tools and other tools shipped from other Dodge factories. With support from Dodge Chicago, the Dodge Main factory began manufacturing oil pumps before the 30 days had run out.[164] In total, the Chicago factory transferred production of 34 separate parts and 13 assemblies to other Dodge factories.[165]

Production at the Chicago factory was not without its challenges. New processes had to be integrated into the existing production lines and production of a new fuel injection Cyclone 18 engine had to be ramped up as quickly as possible. Shifting to the new aluminium 'W' shaped fins on the cylinder barrel resulted in scrapping many automatic lathes, acquiring new machine tools to make the cuts in the cylinder barrel and insert the aluminium fins and a major revision of the cylinder barrel production line.[166] The shift from building carburettor to fuel injection engines was among the 6,427 engineering changes to the Cyclone 18 the Chicago factory had to deal with between the start of production and the end of the war.[167]

Getting the fuel injection Cyclone 18 into production was fraught with problems. At several points along the way, Chrysler had to persuade the AAF to allow the Dodge factory to continue production of the carburettor engine so as not to disrupt production and cause labour and machine tools to be idle.[168] General Arnold had called for 120 B-29s with fuel injection engines to be built by October 1944.[169] This proved hopelessly unrealistic. When the AAF approached Chrysler about building the fuel injection Cyclone 18 at the Dodge Chicago factory, Chrysler stated that the company had no experience with fuel injection engines.[170] Chrysler was completely dependent on Wright for engineering drawings and guidance on production methods,

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[164] Memo of J.B. Morrow and D.E. Newsted, July 12, 1944, p. 57, Dodge Chicago Plant Chronology 1944 pg. 51-118.
[165] Report by W.L. McNeil, Central Planning, October 3, 1944, p. 88, Dodge Chicago Plant Chronology 1944 pg. 51-118.
[166] Stout, *Great Engines and Great Planes*, p. 27.
[167] Stout, *Great Engines and Great Planes*, p. 46.
[168] Telegram of L.A. Moehring, Comptroller, Chrysler Corporation, December 11, 1944, p. 109, Dodge Chicago Plant Chronology 1944, Pg. 51-118.
[169] Memo of C.E. Dalton, Dodge-Chicago, covering meeting at Wright Field, July 5, 1944, pp. 54-55, Dodge Chicago Plant Chronology 1944, Pg. 51-118.
[170] Memo of C.E. Dalton, Dodge Chicago Factory, July 4, 1944, p. 53, Dodge Chicago Plant Chronology 1944, Pg. 51-118.

and on the Bendix Corporation for fuel injectors. The fuel injector system consisted of two pumps, one for each row of cylinders, with nine plungers in each row that forced a set mixture of fuel and air into the combustion chamber of each of the Cyclone 18's eighteen cylinders.[171]

The fuel injection Cyclone 18 had 97 new parts that were different from the standard Cyclone 18 built at the Dodge factory and was in many ways a new engine. The fuel injection engine required new materials, new machine tools, fixtures, and gauges and new subcontractors as Dodge decided it could build only eight or nine of the new parts required.[172] Despite not having all the necessary machine tools and fixtures, the Dodge Chicago factory completed its first fuel injection engine for test purposes in September. However, with continued engineering problems, the need for new and different machine tools and delays in getting fuel injection systems from Bendix, the Chicago factory did not begin manufacturing fuel injection engines until January 1945.[173]

In the interim, Chrysler engineers used their extensive experience to redesign, at the AAF's request, the fuel lines leading from the fuel injection pumps to the cylinders which in Wright's original design were 'routed tortuously and inaccessibly; hard to install, and harder to service: if a line broke, it could not be replaced without removing the engine from the nacelle, a job of as much as 400 man-hours.'[174] Dodge engineers redesigned the fuel lines so that a mechanic could completely remove the lines and reinstall them in two hours. As production of the fuel injection engine built up over the next few months, the AAF ordered the Chicago factory to plan to stop production of the standard carburettor engine in November 1945 and to progressively switch to the fuel injection engine, increasing production to a level of 1,600 engines by that same month.[175]

The Chrysler Corporation and the Dodge Division's extensive experience with mass production enabled the Dodge Chicago factory's Engineering Department to improve

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[171] Stout, *Great Engines and Great Planes*, p.34.
[172] Manpower Office, Management Control, Air Technical Service Command, Army Air Forces: *Labor Statistics for the Aircraft Industry*, November 1944-July 1945, File 218.6-7 Labor Statistics, AFHRA.
[173] C.E. Dalton, Dodge-Chicago, January 17, 1945, p. 5, Dodge Chicago Plant Chronology 1945, Pg. 1-50.
[174] Stout, *Great Engines and Great Planes*, p.35.
[175] Letter of Brig. Gen. E.W. Rawlings, Administrator Aircraft Production Board, June 11, 1945, p. 68, Dodge Chicago Plant Chronology 1945, Pg. 51-100.

manufacturing methods for the Cyclone 18 that speeded production and cut costs, mostly by eliminating unnecessary features on the engine.[176] The Engineering Department introduced 25 major changes to the Cyclone 18 engine. These changes cut 174 machining operations, eliminated 62 assembly operations and cancelled 58 unnecessary parts from the engine.[177] Dodge engineers developed a special test stand fixture that cut the time needed to install an engine in the test cell from two hours to ten minutes. In another innovation, Dodge connected the engines under test directly to generators to generate electricity for the factory around the clock.[178] Chrysler estimated that these improved manufacturing techniques reduced the cost per engine, and saved the Government upwards of $100 million (£25 million).[179] The Chicago factory cut the cost of building the Cyclone 18 engine dramatically, from an estimated cost of $25,314 per engine (£6,328) to an actual cost of $11,357 (£2,839) for the standard version and $12,954 (£3,238) for the fuel injection version.[180]

Another innovation that the Chicago factory introduced, again borrowed from the automobile industry, was to adopt shot peening to strengthen connecting rods. Shot peening was a process of bombarding the metal surface of the connecting rod with tiny metal or ceramic pellets to strengthen the surface layer where fatigue failures often started.[181] Shot peening also eliminated the need to polish the connecting rod, saving 36 man-hours of production time per engine.[182] Developing this method was a joint effort of the aero engine manufacturers and their licensees through the Aircraft Engine Division of the Automobile Council for War Production, a grouping that combined representatives of the two industries to work out new production methods that would speed up production and reduce labour.[183]

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[176] Engineering Report #PE-6-1, Dodge Chicago Plant, pp. 75-76, Dodge Chicago Plant Chronology 1945, Pg. 51-100.
[177] Engineering Report #PE-6-1, Dodge Chicago Plant.
[178] These two examples are drawn from the Chrysler documentary 'Engines for Superbombers'.
[179] Address by K.T. Keller, President, April 17, 1945, p. 46, Dodge Chicago Plant Chronology 1945, Pg. 1-50.
[180] Stout, *Great Engines and Great Planes*, pp. 45-6.
[181] Horger, O.J.: 'Mechanical and Metallurgical Advantages of Shot Peening', *The Iron Age*, Vol. 155, No. 13, March 1945, p. 40.
[182] Stout, *Great Engines and Great Planes*, p.36; 'Shotblasting Aircraft Engine Parts', *American Machinist*, Vol. 87, No. 13, (June 24, 1943), p. 88.
[183] 'Shotblasting Aircraft Engine Parts', p. 88.

Production Challenges at the Chicago Factory

The Chicago factory's experience with production control provides another, if different, example of how challenging organising large-scale production was during the war. The Dodge factory never experienced the disruptions and management control problems of the Lockland factory. The biggest challenge the Dodge management faced was simply getting into production. Shortages of machine tools persisted for months. The problems that had to be overcome to build the Cyclone 18 in quantity covered a broad spectrum of challenges in engineering, production, availability of materials and labour, scheduling, choice of engine model and coordination that at times must have seemed insurmountable. The breadth of these problems and the urgency of the Cyclone 18 and the B-29 program taxed the management of Wright, Chrysler and its Dodge Division and the AAF to the limit. Despite the urgency, it took the Dodge Chicago factory 29 months from contract date to reach a production rate of 500 engines a month, longer than the average of 15 to 20 months for other aircraft engine factories.[184]

Setting up the production line, however, is dependent on having a design that is ready for production. Only then can the production engineers determine the machine tools and the machining operations required, together with the necessary labour, parts and raw materials. Once the factory has put all the components of the production line in place, production control is relatively straightforward.[185] When the Chrysler Corporation received the contract to build the Cyclone 18, the engine was far from ready for production. In 1942 the Cyclone 18 was still very much an experimental engine. Between the time Chrysler received the contract in February 1942 and November 1943, as production was about to begin, Wright put through more than 2,000 engineering changes on the Cyclone 18. Some 500 of these changes required changes in machine tools and their tooling.[186] As the Harvard Business School study on the problems of accelerating aircraft production noted, 'the early months of the R-3350 [Cyclone 18] history indicate the

[184] Lilley, *Problems of Accelerating Aircraft Production*, pp. 84-85.
[185] Muther, *Production-Line Technique*, p. 23.
[186] Summary of the R-3350 Engine Project, p. 3, Case Study of the R-3350 Engine Project, p. 5, File 202.2-12, A2070. AFHRA.

futility of commencing to tool a shop for an engine too far in advance of the time when its design is reasonably well established.'[187]

Delays in getting machine tools affected the Dodge Chicago factory's ability to set up a production line. In March 1942, Dodge received from Wright a list of 4,999 machine tools required to build the Cyclone 18, with the less than helpful note that the list 'had been prepared hurriedly and would undoubtedly be subject to considerable revision.'[188] The AAF then decided to give priority to accelerating machine tool deliveries to the Wright Wood-Ridge factory in the hope of getting Cyclone 18 production at Wood-Ridge underway ahead of the Chicago factory, which was still under construction.[189] By April 1943, the Dodge factory had placed orders for 7,050 machine tools but had received only 32% of the tools on order.[190] More importantly, the Dodge Chicago factory had received only 50% of the machine tools needed to set up a pilot production line, where Dodge engineers could actually test manufacturing methods and confirm the sequence of operations.[191]

The AAF did not help matters by changing its requirements for the Cyclone 18. In April 1942 the AAF ordered Chrysler to plan for production of 1,500 Cyclone engines a month instead of 1,000 a month, and instructed Chrysler to plan to build 750 Cyclone 18BA engines and 750 Cyclone 18BB a month.[192] As these engines had important differences in their construction, they required separate production lines. Chrysler began ordering machine tools for the two different engine models and setting up production lines for the BA and BB models, only to have the AAF decide in October 1943, once the process was well underway, to drop plans for the Dodge Chicago factory to build the Cyclone 18BB and instead to build 1,500 Cyclone 18BA engines a month, quickly raised to 1,600 a month to be achieved by May or June 1945.[193]

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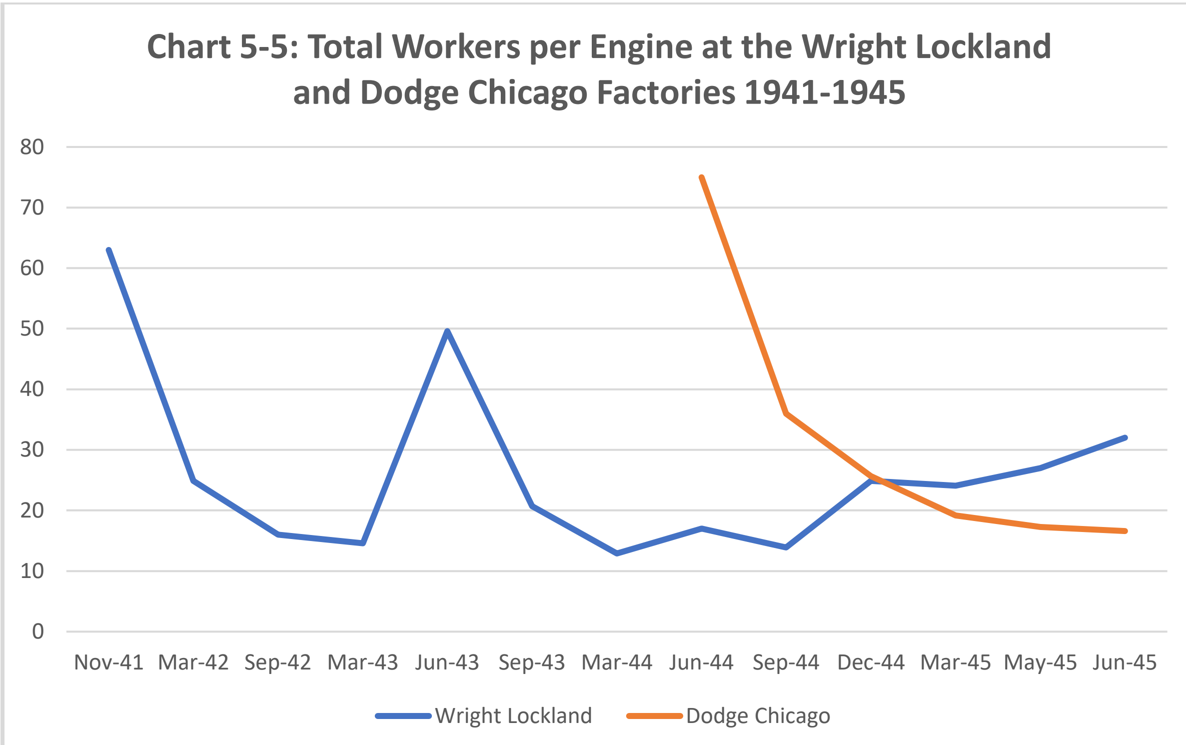
[187] Summary of the R-3350 Engine Project, p. 87.
[188] R.H. Hetrick, Comptroller's Office, Memo of March 20, 1942, p. 29, Dodge Chicago Plant Chronology 1942 pg. 7-50.
[189] Report of C.E. Dalton, May 4 and May 5, 1943, p. 125, Dodge Chicago Plant Chronology 1943 Pg. 103-153
[190] Report of K.H. Kingsley, April 5, 1943, p. 121, Dodge Chicago Plant Chronology 1943, Pg. 103-153.
[191] Progress Report File, March 25, 1943, p. 118, Dodge Chicago Plant Chronology 1943 Pg. 103-153.
[192] Memo of T.P. Wright, April 11, 1942, p. 35; Report of Meeting, L.B. Colbert, Operations Manager, April 22, 1942, Dodge Chicago Plant Chronology 1942 pp. 7-50.
[193] Report of C.E. Dalton, May 15, 1943, p. 130, Dodge Chicago Plant Chronology 1943 pg. 103-153;Report of C.E. Dalton, October 7, 1943, pp. 164-65; Memo of Meeting, October 15, 1943, Dodge Chicago Plant Chronology 1943 pg. 154-179.

When the AAF cancelled the order for the Cyclone 18BB, Dodge found that only 752 out of 2,537 machine tools the factory had ordered for the Cyclone 18BB production line could be transferred to the Cyclone 18BA line.[194] By the end of 1943 the factory was still short of machine tools.[195] The start of Cyclone 18 production at the Chicago factory had to be pushed back from March 1943 to July 1943 and finally to January 1944, nearly two years from the date of Chrysler's receiving the contract. The rapid increase in production at the Dodge factory during 1944 demonstrates how important production control was to quantity production. With a standardized engine ready for production, production processes could be put in sequence, parts and raw materials obtained from vendors, and necessary machine tools acquired and placed in production lines. Production could then accelerate rapidly.

Measuring Productivity

While Army Air Force studies of labour in the airframe and aero engine manufacturing industries during the war do provide indications of the number of direct workers involved in the factories, because of definitional problems and the lack of comparable data on the equivalent British factories, the measure of total workers per engine built will be used to compare labour productivity at the Lockland and Chicago factories as shown in Chart 6-5. It is important to bear in mind Hornby's caveats. While neither factory was involved in experimental engine development work, the Lockland factory for example had had a higher reliance on subcontracting than the Chicago factory. This affects the number of total workers per engine built, in this case possibly making the Lockland factory appear more productive than the Chicago factory, which may not have been the case.

[194] Memo of Meeting, C.E. Dalton, October 15, 1943, p. 166, Dodge Chicago Plant Chronology 1943, Pg. 154-179.
[195] Report of K.H. Kingsley, December 31, 1943, p. 179, Dodge Chicago Plant Chronology 1943, Pg. 154-179.

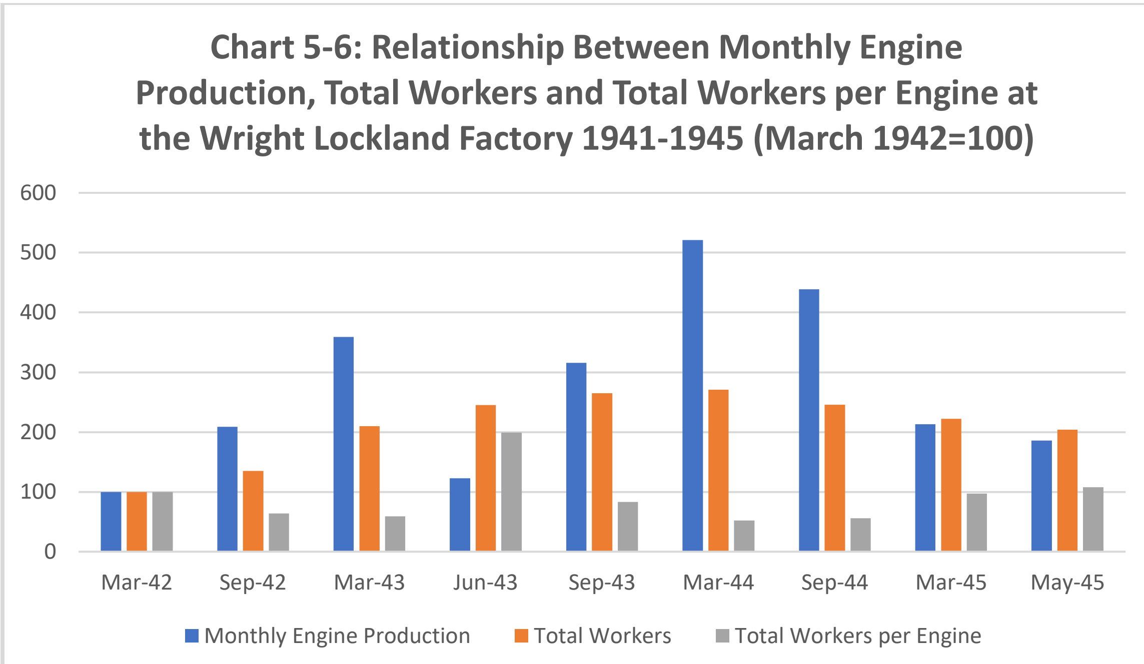


Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946)

The Lockland factory struggled to sustain the productivity improvements that came with the learning effect (see Charts 5-5 and 5-6). As can be seen both factories experienced a steep learning curve with productivity improving rapidly as production increased and the work force gained experience (Chart 5-5). The uneven record at Lockland reflects the management problems that disrupted production during 1943, the problems with subcontractors in early 1944 and the transition to building the Cyclone 18 concurrently with the Cyclone 14 into 1945. It is likely that the Lockland factory experienced a second steep learning curve learning how to manufacture the Cyclone 18 which would have depressed productivity. A crude measure of total workers per Cyclone 18 engine built from January to July 1945 implies that this was the case.

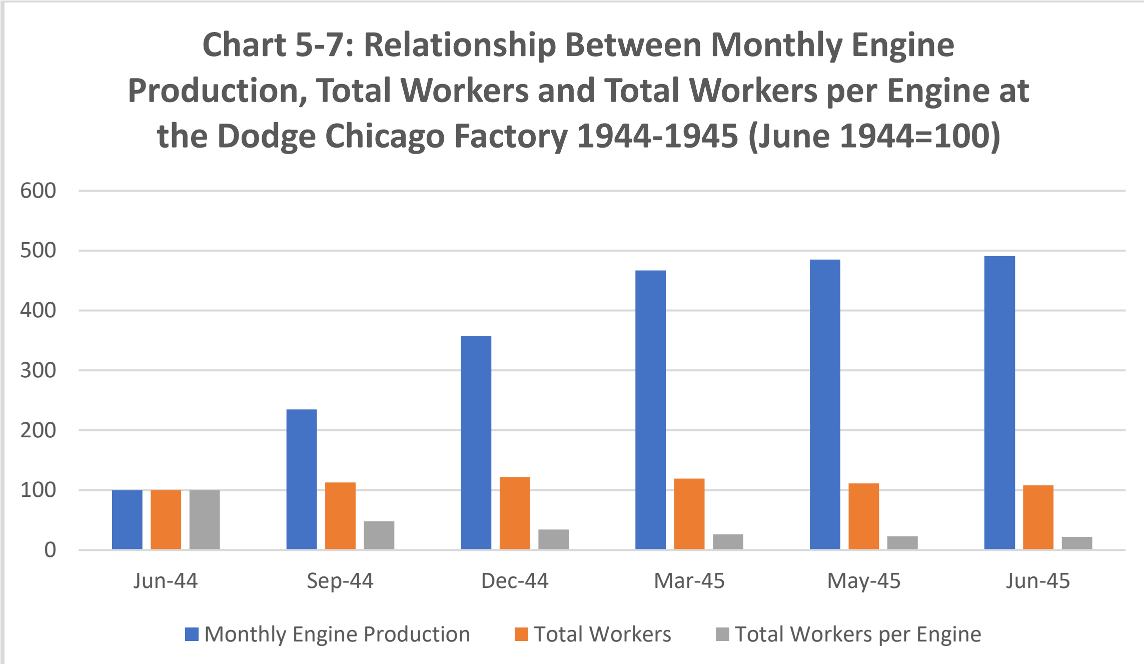
While the Chicago factory never reached the same number of total workers to engines built that was achieved at the Lockland factory, certainly the factory's level of productivity in the final months of the war was superior to the Lockland factory. Productivity at the Chicago factory, however, can be considered comparable to the Lockland factory. At their best levels of total workers per engine built, the Chicago factory had 29% more total workers per engine than the

Lockland factory, not a significant gap when the differences between the Cyclone 14 and the Cyclone 18 and the different levels of subcontracting are considered. The Cyclone 18 the Chicago factory was building had approximately 60% more component parts than the Cyclone 14 while the Chicago factory was less reliant on subcontractors than the Lockland factory.



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946)

The decline in productivity during the middle of 1943 reflects the management problems at the Lockland factory, but shows the recovery of productivity later in the year (Chart 5-6). Through 1944 productivity improved as monthly production increased while the total number of workers declined during the year. Despite the disruptions from problems with subcontracting early in the year, 1944 was the Lockland factory's most productive year in terms of total engines built and the number of total workers per engine. Chart 5-6 also illustrates how productivity declined as the Lockland factory transitioned from manufacturing the Cyclone 14 to manufacturing the Cyclone 18 during 1945.

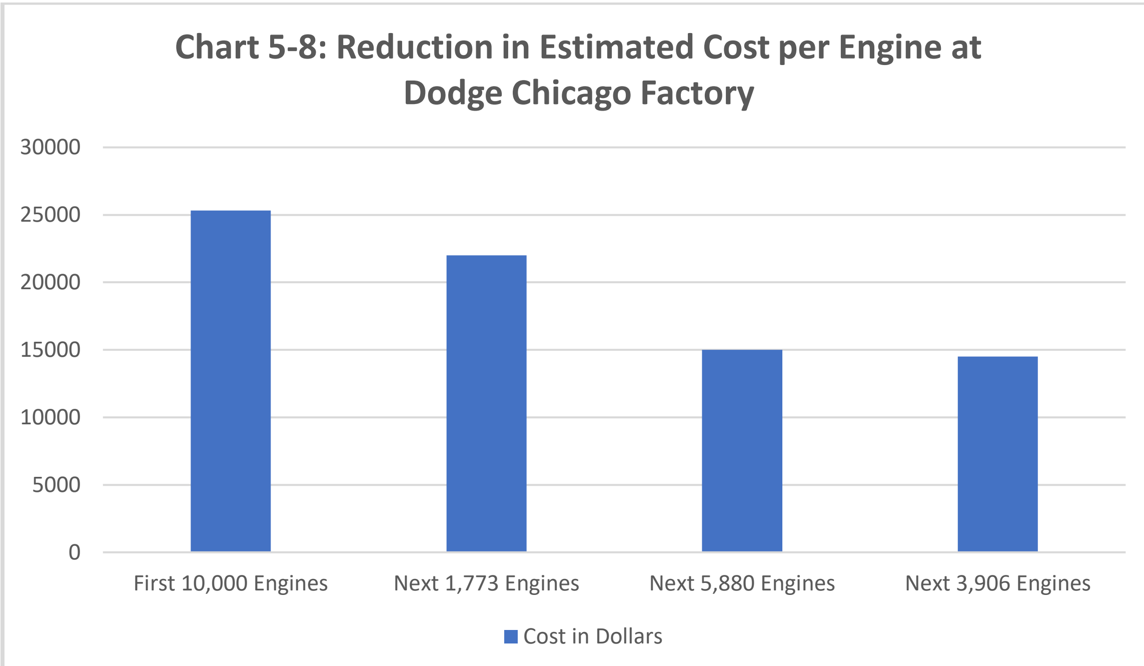


Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946)

The Chicago factory's record of productivity was superior to the Lockland factory, at least in terms of trends if not in number of total workers per engine (Chart 5-7). Unlike at the Lockland factory, productivity at the Dodge Chicago factory steadily improved as engine production increased, particularly as the total number of workers began to decline at the beginning of 1945, before reaching a plateau in June 1945. From December 1944 to June 1945, the total labour force at the Dodge Chicago factory declined by 10% while monthly engine output increased by 38%. In November 1944, the Chicago factory built 1,079 Cyclone 18 engines with 31,393 total workers, a ratio of 29 total workers per engine built.[196] Seven months later, in June 1945, the factory completed 1,690 engines with 28,037 total workers for a ratio of 16.6 total workers per engine built.[197] The factory achieved this improvement despite a growing number of strikes and labour actions during the spring and early summer of 1945.[198] The Dodge factory management attributed the improvement to the manufacturing efficiencies Dodge had introduced in Cyclone

[196] Manpower Office, Management Control, Air Technical Service Command, Army Air Forces: *Labor Statistics for the Aircraft Industry*, November 1944-July 1945, Report for November 1944, File 218.6-7 Labor Statistics, AFHRA.
[197] *Labor Statistics for the Aircraft Industry*, November 1944-July 1945, Report for June 1945.
[198] *The Chicago Tribune*, May 30, 1945, p. 3; *The Wall Street Journal*, July 27, 1945, p. 2.

18 production and the increasing efficiency as individual operators gained experience with their machines.[199]



Source: Letter dated February 15, 1945, from L.A. Moehring, Comptroller, Chrysler Corporation, pp. 20-21, Dodge Chicago Plant Chronology 1945 Pg.1-50.

There is some data from the Chicago factory showing the impact of the learning curve on manufacturing costs (Chart 5-8).[200] The factory had provided the Army Air Force with an initial estimate of the cost for each Cyclone 18 engine as $25,314 (£6,328) for a production run of 10,000 engines. For each successive procurement of engines, the cost of production dropped as productivity at the Chicago factory improved. By the time the factory had completed the second round of procurement, the cost for the subsequent procurement of 5,800 engines was 40% lower than for the initial 10,000 engines. Confirming the pattern of a flattening of the learning curve over time, the cost reduction between the third and fourth estimates was only 3%. The Chicago factory had a similar experience of the learning effect with the fuel-injection Cyclone 18. The

[199] Memo of C.E. Dalton, Chief Liaison Executive, Dodge-Chicago Plant, August 1, 1945, p. 95, Dodge Chicago Plant Chronology 1945 pg. 51-100.
[200] Letter dated February 15, 1945, from L.A. Moehring, Comptroller, Chrysler Corporation, pp. 20-21, Dodge Chicago Plant Chronology 1945 Pg.1-50,

factory's initial cost estimate on an Army Air Force contract for 16,923 fuel-injection engines was $21,057 (£5,264) per engine for the first 5,880 engines, $18,848 (£4,712) for the next 2,934 engines, and $16,225 (£4,056) per engine for the final 8,109 engines, a 23% overall reduction in cost.[201]

A comparison of productivity at the Wright Lockland and Dodge Chicago factories with productivity at the factories building the Hercules is enlightening and intriguing. At peak production, the combined No. 1 and No. 2 Shadow Groups had a ratio of 28 total workers per engine built, while the Bristol No. 3 Shadow Factory had a ratio of 26.9. In comparison, at peak production the Lockland factory had a ratio of 12.9 total workers per engine built, less than half the figure for the factories building the Hercules. The Chicago factory, building the more complex 18-cylinder Cyclone 18 with nearly double the number of parts in a Hercules engine, had a ratio of 16.6 total workers per engine, again more than half the ratio of the British factories. How productivity at the Chicago and Lockland factories compared to the other American aero engine factories, and why the American factories appear to have had better productivity than their British counterparts is the subject of the next chapter.

[201] Supplemental Agreement #50 dated May 17, 1945, p. 56, Dodge Chicago Plant Chronology 1945 Pg.51-100.

Chapter Six: Comparing Labour Productivity

Introduction

A comparative study of British and American aero engine production during World War II raises the issue of comparative labour productivity. Using the number of total workers per engine as a measure, this chapter will show that in both America and Britain labour productivity in the aero engine factories steadily improved as the factories gained experience. While productivity varied from factory to factory, the chapter will also show that the factories with the best labour productivity tended to be those factories run by the automobile companies, not the aero engine manufacturers or their branch factories. This chapter will show that in general the American aero engine factories were more productive than their British counterparts and will consider several variables that might explain the differences.

During the war, the American aero engine industry built three times the number of engines, in a shorter period, than the British aero engine industry. This chapter will argue that there were two principal factors involved: the size and design of factories and greater use of high-production machine tools. Looking at how each country addressed the 'quantity versus quality' issue, M.M. Postan has argued that the British system of flexible production in smaller factories with standard machine tools was better suited to the constant modifications demanded in wartime than the American system of larger factories equipped with high production, special-purpose machine tools and using mass production methods. Against this I will argue that the production methods used in many of the American aero engine factories were perhaps not as rigid and inflexible as Postan suggests.

It is important to bear in mind the differences in scale between the two economies and between certain key industries as well as the historic differences in labour productivity. Stephen Broadberry has argued that since the late 19th Century America has maintained an advantage in productivity over Britain, particularly in manufacturing.[1] Even during the Depression years, American productivity in manufacturing was double that of Britain.[2] Broadberry attributes the difference to 'a distinctive American machine-intensive and resource-using technology that economised on skilled shop floor labour.'[3] This was particularly true for certain sectors of manufacturing producing large quantities of standardized products, such as the automobile industry, where unskilled labour could be combined with machines to greatly expand production.[4] Broadberry contrasts the American mass production approach with the European 'flexible production technology' that relied more on readily available skilled labour than machine tools and confronted markets demanding greater product differentiation.[5] It can also be argued that the two different approaches utilised different types of machine tools which directly affected productivity. American mass production methods required more special-purpose, high-production machine tools, while standard machine tools were better suited to the European flexible production approach.

There were obvious differences between factories in the type of aero engine produced—single-row versus double-row, nine, fourteen or eighteen cylinders—and in how many models of a particular engine were built, the number of shifts and hours worked per week, the number and types of machine tools available, the size and layout of the factory space, the number of feeder factories and subcontractors and the demand for engines and size of contracts with the military among other variables. It is also important to recall that the aero engine manufacturing companies had many more responsibilities than their licensees. The distribution of employees at the parent firms included many working in design, development and administration as well as in experimental machine shops. Coming up with a meaningful measure of comparative productivity is thus challenging.

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[1] Broadberry, Stephen N.: *The Productivity Race: British Manufacturing in International Perspective, 1850-1990*, (Cambridge, 1997), p. 3; Broadberry, Stephen and Mary O'Mahony: 'Britain's Productivity Gap with the United States and Europe: A Historical Perspective', *National Institute Economic Review*, No. 189, (July 2004), p. 76.

[2] *The Productivity Race: British Manufacturing in International Perspective, 1850-1990*, Table A3.1(c), p. 48.

[3] *The Productivity Race*, p. 89.

[4] *The Productivity Race*, pp. 79-80.

[5] Broadberry and O'Mahony: 'Britain's Productivity Gap with the United States and Europe: A Historical Perspective', p. 76. This is also Jonathan Zeitlin's argument. See, for example, Zeitlin, Jonathan: 'The Historical Alternatives Approach', in Jones, Geoffrey G. and Jonathan Zeitlin, eds.: *The Oxford Handbook of Business History*, (Oxford, 2008), pp. 120-40.

It is also important to point out that at the time productivity was less important than production. There was far greater emphasis on meeting monthly production schedules than on reducing man-hours per engine.[6] As Alexander Field has observed, at a time when Government contracts were on a cost-plus basis, 'success is measured by one's ability to produce large quantities of ordnance quickly'.[7] The difficulty, as Field notes, is that there are few detailed studies of war time productivity, particularly on an individual industry basis.[8] From the records surveyed, there does not appear to have been much effort at the time to determine relative productivity in the aero engine factories in either Britain or America, though there is much information on monthly production targets.[9] In the British Ministry of Aircraft Production's planning process, the more important questions for programme planning for an aero engine factory were the date when production would start and how fast it would take to reach peak production.[10] In the British system of production, with frequent modifications and changes in engine models, the expectation was that few aircraft or aero engine models would reach peak production before modifications required changes in production processes.[11] The more important calculation was to estimate labour requirements at the factories for a given rate of production in order to determine the manpower allocation among the Admiralty, Ministry of Aircraft Production and the Ministry of Supply.[12]

Comparing American Aero Engine Factories

This section will compare productivity at the major American wartime aero engine factories building high-performance, air-cooled radial engines. These factories fell into two groups: first,

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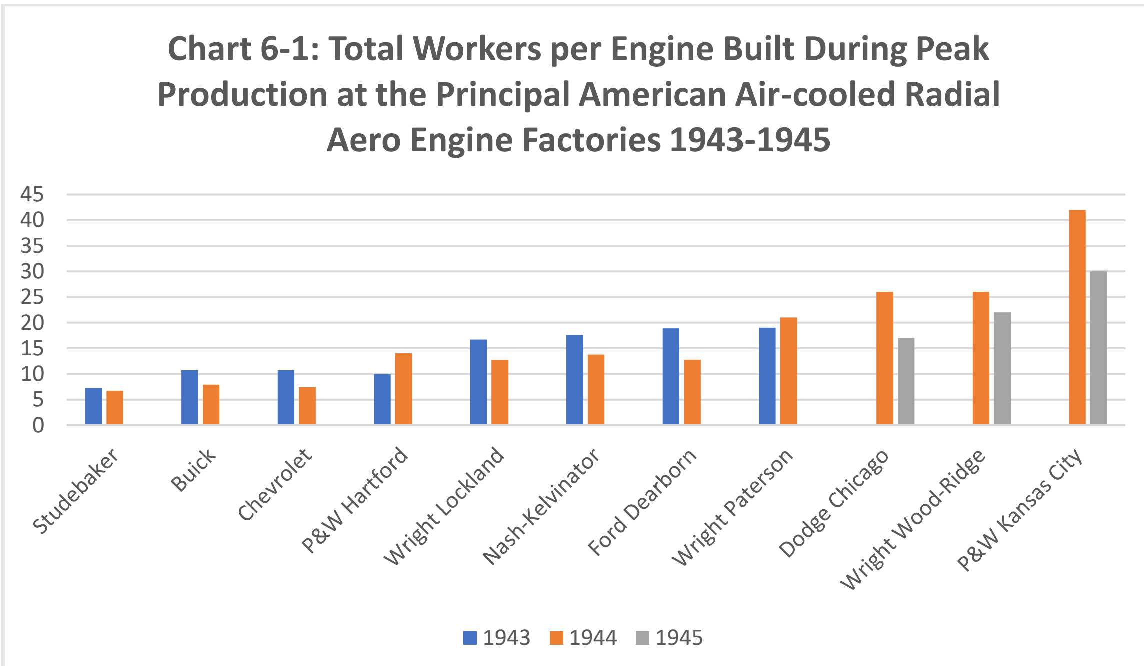
[6] This observation comes from Dr. Cristiano Ristuccia, Faculty of Economics, Cambridge University.
[7] Field, Alexander J.: 'The Impact of the Second World War on US Productivity Growth', *The Economic History Review*, New Series, Vol. 61, No. 3 (August 2008), p. 676.
[8] 'The Impact of the Second World War on US Productivity Growth', p. 672.
[9] See for example 'The November 4th Aircraft Engine Schedule', Morris L. Copeland, Assistant Director, Munitions Branch Statistical Department, to Donald Davis, Vice Chairman, War Production Board, December 7, 1943, War Production Board Select Document File, Aircraft Schedule-Standardization, Box 29, Entry 3A, RG179, NARA. This memo focuses exclusively on aircraft engine requirements compared to planned production schedules to determine if there will be surpluses or deficits in production of engines.
[10] Devons, Ely: *Planning in Practice: Essays in Aircraft Planning in War-time*, (Cambridge, 1950), p. 44
[11] *Planning in Practice*, p. 45.
[12] Inman, P.: *Labour in the Munitions Industry*, (London 1957), pp. 201-05.

Pratt & Whitney and its automobile licensees Buick, Chevrolet, Ford and Nash-Kelvinator (for a description of Pratt & Whitney's wartime production see Appendix I); and second, Wright and its automobile licensees Dodge and Studebaker. All the automobile licensee factories, as well as Pratt & Whitney and Wright branch factories built specifically for wartime production. Little data has surfaced on the man-hours required to build aero engines at these wartime factories but data is available on total employment during the war.[13]



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C.

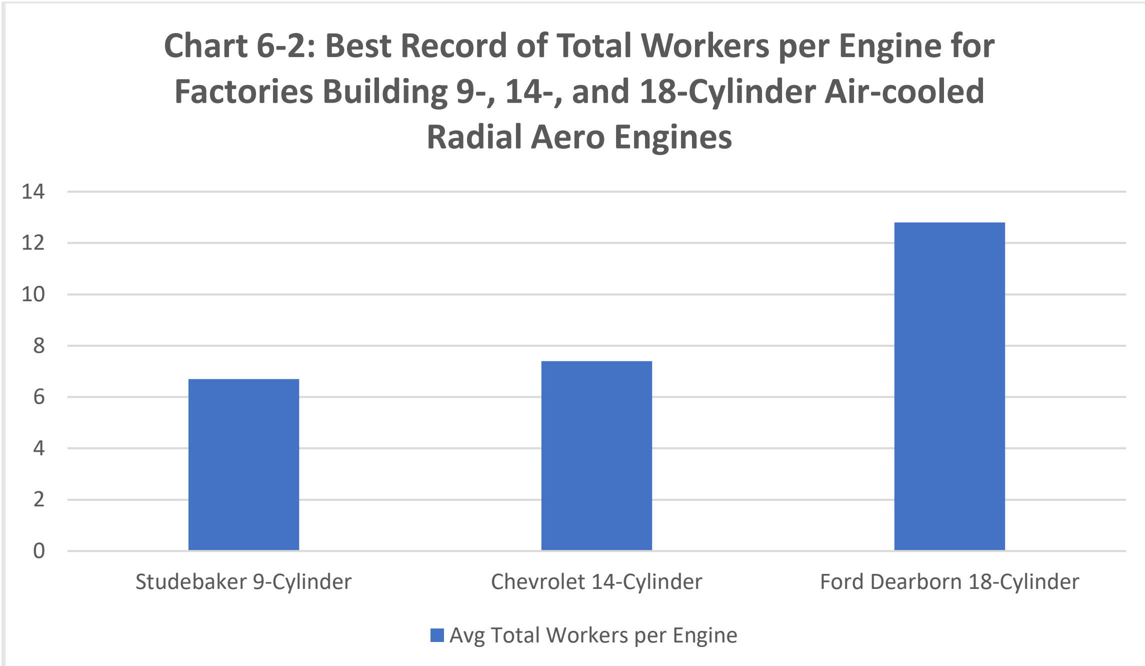
Labour productivity varied considerably among these factories (see Chart 6-1). The three most productive factories were those managed by three automobile companies--Studebaker, Buick and Chevrolet—building engines under license. The two biggest aero engine factories—the Dodge Chicago factory and the Pratt & Whitney factory at Kansas City—required more workers per engine built. The Wright Lockland factory was the only giant factory to approach the

[13] Manpower Office, Management Control, Air Technical Service Command, Army Air Forces: *Labor Statistics for the Aircraft Industry*, November 1944-July 1945, does provide figures for man-hours per engine in the July 1945 issue.

productivity levels of the automobile licensees in comparatively smaller factories, although sustaining productivity at Lockland proved difficult. This finding belies the assumption that giant factories were, or should be, more productive. The function of the giant factory was to increase output and improve efficiency through economies of scale, yet these productivity figures imply that in fact this was not the case.[14]

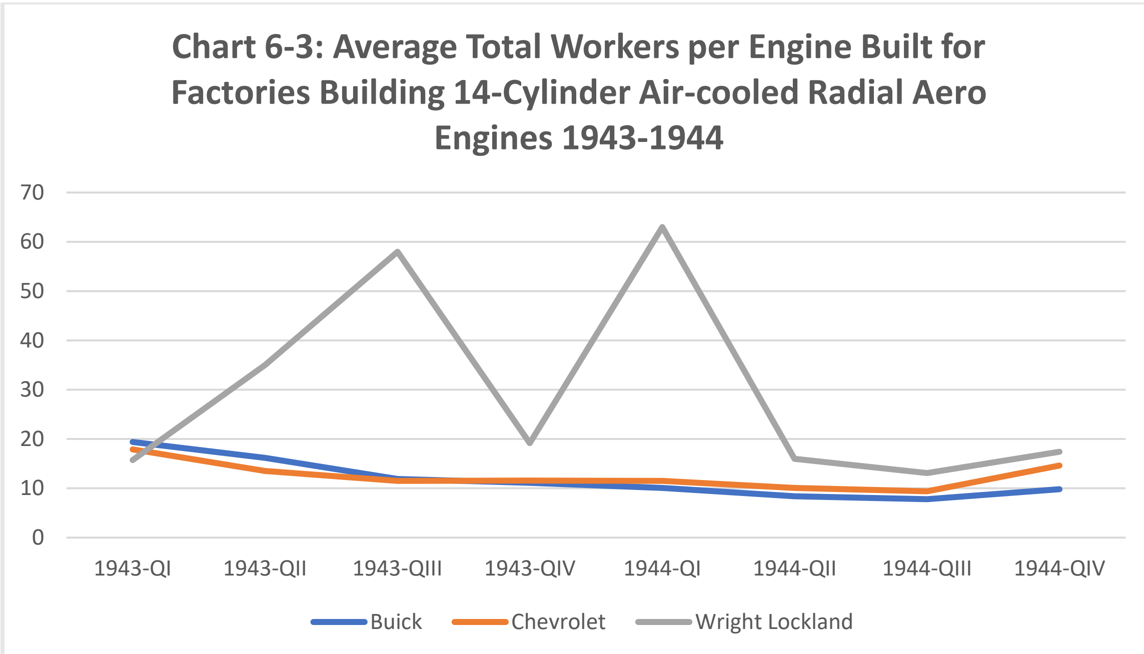
Explaining these variations in productivity is difficult as there are multiple variables to consider and comparable data on these variables is not always available. Three factors that can be considered are the type of engine in production, the reliance on subcontracting and production experience. Regarding the type of engine, the Harvard Business School study makes clear that except for the Dodge Chicago factory, the licensees of Pratt & Whitney and Wright benefited from being assigned established engine models that had been in production prior to America's entry into the war.[15] The Pratt & Whitney and Wright branch factories building newer model engines—the Pratt & Whitney Kansas City factory and the Wright Wood-Ridge factory—had a more problematic record. The Wright Wood-Ridge factory had continual problems attracting labour and ran into the same management control problems that plagued the Wright Lockland factory. Pratt & Whitney set up its Kansas City factory to build the C series Double Wasp engine, a complete re-design of earlier models.[16] These two factories experienced long delays in getting into large-scale production. Building proven engines with fewer variants, where the licensee companies could draw on the technical and production knowledge of the parent firms, clearly improved productivity.

[14] *Behemoth*, p. xiv.
[15] *Behemoth*, p. xiv.
[16] White, Graham: *R-2800: Pratt & Whitney's Dependable Masterpiece*, (Shrewsbury, UK, 2001), p. 144.



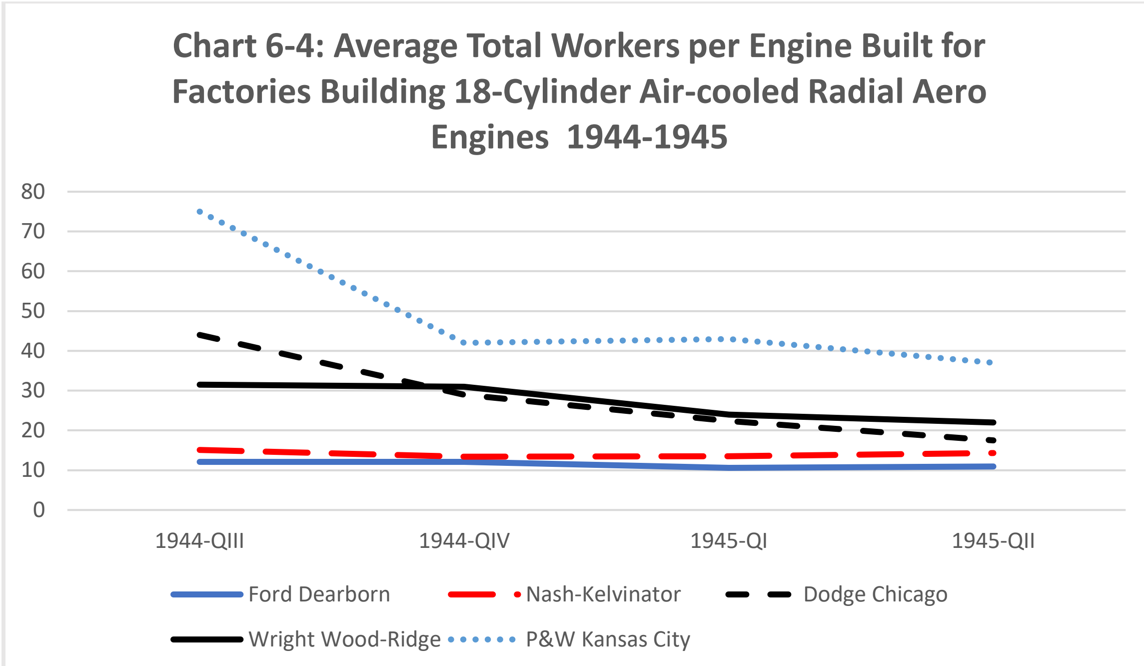
Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946); Holley, Irving Brinton, Jr.: *Buying Aircraft: Material Procurement for the Army Air Forces, United States Army in World War II: Special Studies* (Washington, D.C. 1964), pp. 580-81; Manpower Office, Management Control, Air Technical Service Command, Army Air Forces: *Labor Statistics for the Aircraft Industry*, November 1944-July 1945, File 218.6-7 Labor Statistics, AFHRA.

The complexity of the engine was a critical factor in productivity (Chart 6-2). Building an 18-cylinder engine with nearly three times the number of parts was, not surprisingly, more demanding than building a nine-cylinder engine. As the chart shows, the Ford Dearborn factory building the 18-cylinder Pratt & Whitney Double Wasp engine required nearly twice as many total workers per engine as Studebaker building the nine-cylinder Cyclone 9.



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946); Holley, Irving Brinton, Jr.: *Buying Aircraft: Material Procurement for the Army Air Forces, United States Army in World War II: Special Studies* (Washington, D.C. 1964), pp. 580-81; Manpower Office, Management Control, Air Technical Service Command, Army Air Forces: *Labor Statistics for the Aircraft Industry*, November 1944-July 1945, File 218.6-7 Labor Statistics, AFHRA.

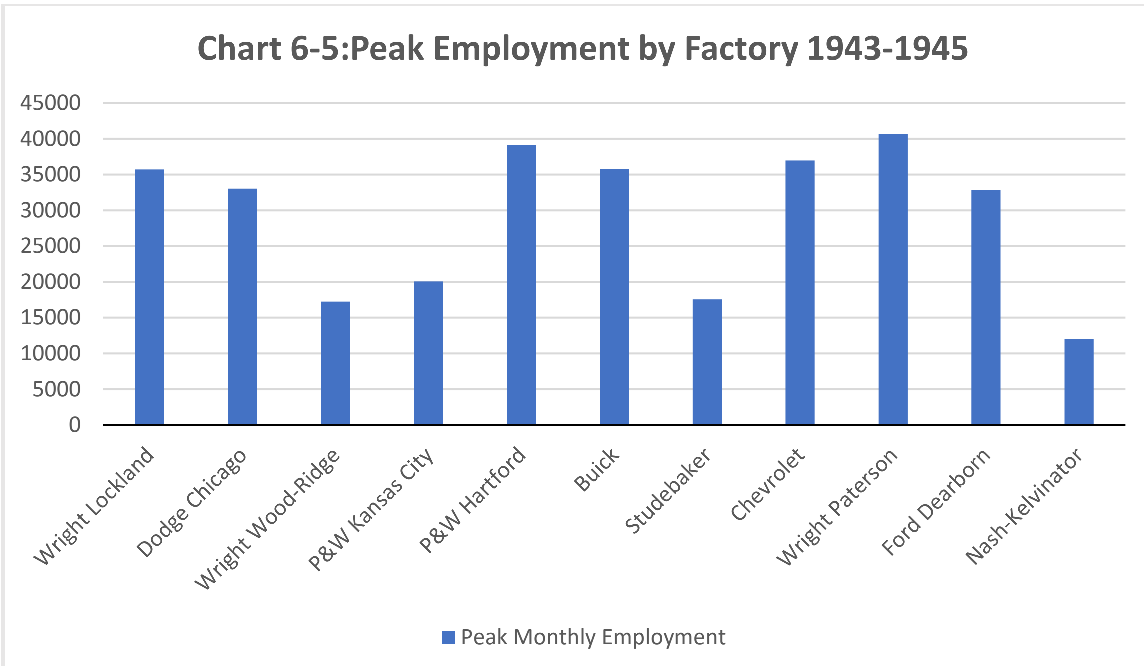
Another way to examine comparative productivity is to look at factories that were building comparable engines, for example the Wright Lockland factory building the 14-cylinder Cyclone 14 against the Buick and Chevrolet factories building the 14-cylinder Pratt & Whitney Twin Wasp (see Chart 6-3). The smaller Buick and Chevrolet factories, roughly half the size of the Lockland factory, appear to have been more productive. Neither the Buick nor the Chevrolet factories experienced the problems that affected Lockland's production during 1943 and 1944. The Lockland factory did come close to the level of the Buick and Chevrolet factories during Quarter III of 1944 and was admittedly the most productive of the giant factories, but as Chart 6-3 indicates the Lockland factory's labour productivity was erratic. Lockland did not experience the sustained productivity that Buick and Chevrolet achieved.



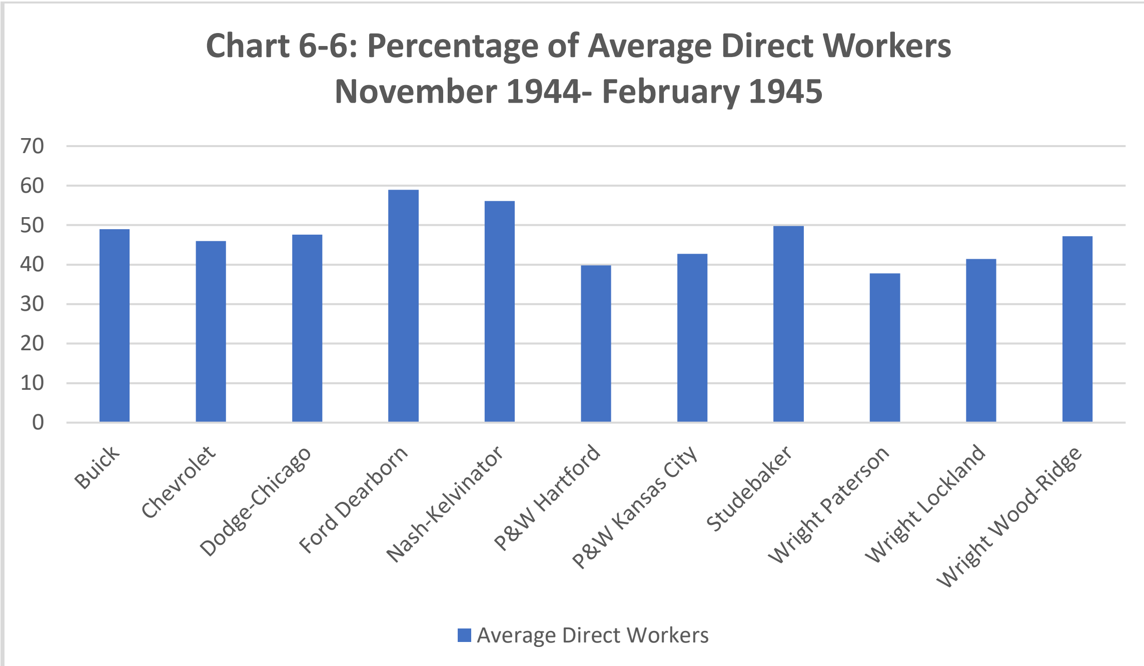
Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946); Holley, Irving Brinton, Jr.: *Buying Aircraft: Material Procurement for the Army Air Forces, United States Army in World War II: Special Studies* (Washington, D.C. 1964), pp. 580-81; Manpower Office, Management Control, Air Technical Service Command, Army Air Forces: *Labor Statistics for the Aircraft Industry*, November 1944-July 1945, File 218.6-7 Labor Statistics, AFHRA.

There was much greater variability in productivity among the factories building the larger 18-cylinder engines, particularly the giant Dodge Chicago and Pratt & Whitney Kansas City factories, and the Wright Wood-Ridge factory (see Chart 6-4). The Ford Dearborn and Nash-Kelvinator factories built the Pratt & Whitney Double Wasp engine but had started production a year or more before the other three began production. By 1944, Ford and Nash-Kelvinator had built up considerable production experience, hence their lower and stable average of total workers to engines built. On average, the Ford Dearborn and Nash-Kelvinator factories were twice as productive as the two giant factories.

Of the two giant factories, the Dodge Chicago factory proved to be the most productive. By July 1945, the last month of full production for the American aero engine factories, the Dodge Chicago factory had nearly reached the level of productivity of the Ford Dearborn and Nash-Kelvinator factories. By this same date, a year and a half after the start of production, the Pratt & Whitney Kansas City factory still required more total workers per engine than the other factories building 18-cylinder engines. This record belies the assumption that increases in scale automatically lead to increases in efficiency. Only the Dodge Chicago factory appears to have successfully overcome the combined technical and managerial challenges these factories faced.



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946)

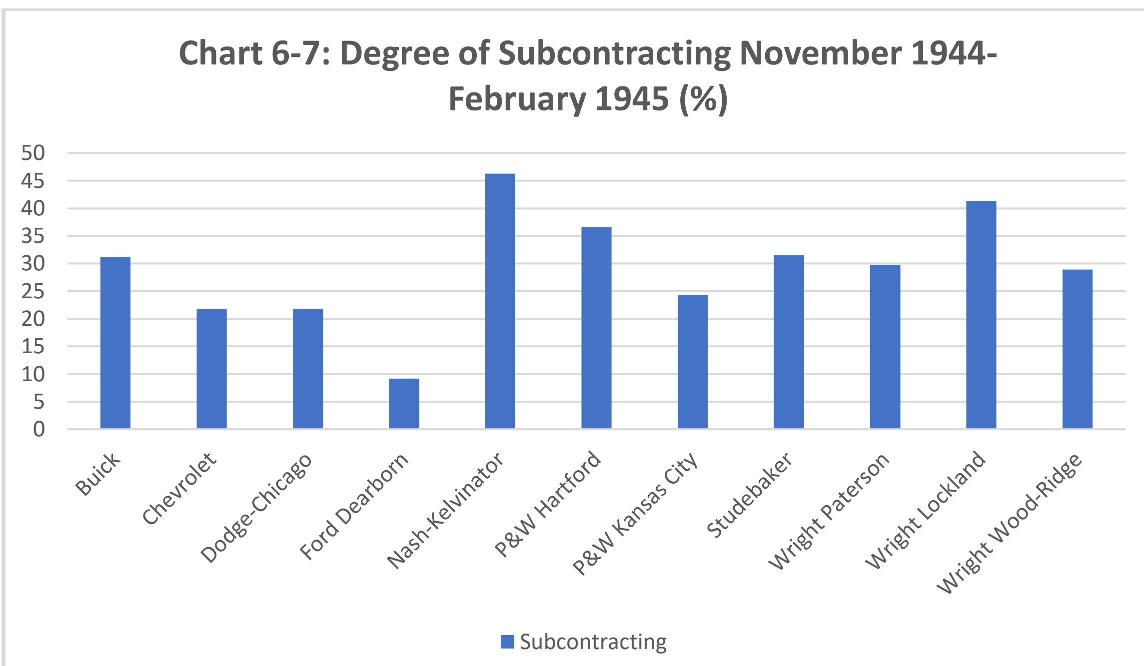


Source: Manpower Office, Management Control, Air Technical Service Command, Army Air Forces: *Labor Statistics for the Aircraft Industry*, November 1944-July 1945, File 218.6-7 Labor Statistics, AFHRA.

The largest factories employed tens of thousands of workers, nearly as many as the big airframe manufacturers (see Chart 6-5). Most factories reached their peak level of employment during 1943-44, the years of peak engine production. Only some of these workers were called 'direct workers', actually involved in production (see Chart 6-6), but there were many non-direct workers vital to production, those involved in maintenance, cleaning and clerical staff maintaining the extensive records required in engine production. The Army Air Force's Air Technical Service Command published a series of bulletins on labour statistics that provide detailed figures for the number of workers directly involved in aero engine production and the reliance on subcontracting at each of the major aero engine factories from November 1944 through February 1945 (see Chart 6-7). The bulletins defined direct workers as those involved in the 'fabrication, processing, assembly, test, tear-down and preparation…for shipment.'[17] The industry average for the proportion of direct workers was 46.9% of total employees for the

[17] Manpower Office, Management Control, Air Technical Service Command, Army Air Forces: *Labor Statistics for the Aircraft Industry*, for December 1944, p. v, File 218.6-7 Labor Statistics, AFHRA.

period. The average for the individual factories ranged from a low of 37.8% at the Wright Paterson factories to 58.9% at the Ford Dearborn factory. The Pratt & Whitney Hartford and the Wright factories at Paterson had lower levels of direct workers no doubt due to the larger numbers of administrative and development engineering staff. Intuitively it would seem that having a higher proportion of direct workers would lead to better productivity, and there does seem to be some evidence that this was the case when comparing factories building similar engines. Of the factories building 14-cylinder engines, Buick and Chevrolet had higher proportions of direct workers than the Lockland factory (Buick 49%, Chevrolet 46%, Wright Lockland 41.4%) and were more productive than the Lockland factory. Among the factories building the 18-cylinder engines, Ford Dearborn and Nash-Kelvinator had significantly higher proportions of direct workers, at 58.9% and 56.1% respectively, and were the most productive factories in this class. Yet the Dodge Chicago factory, with a lower proportion of direct workers, was in the final months of the war nearly as productive as Ford or Nash-Kelvinator.



Source: Manpower Office, Management Control, Air Technical Service Command, Army Air Forces: *Labor Statistics for the Aircraft Industry*, November 1944-July 1945, File 218.6-7 Labor Statistics, AFHRA.

A possible correlation between the degree of subcontracting and productivity is even less clear-cut. Again, the *Labor Statistics for the Aircraft Industry* bulletins for November 1944 through

February 1945 provide exact figures for the percentage of 'outside production', a term for subcontracting, for the main factories. The percentages given for the value or parts this period are not directly comparable and may not be an accurate reflection of the true reliance on subcontracting at earlier periods in the war. The Studebaker factory, for example, relied on subcontractors for the parts that in terms of labour amounted to 50% of the Cyclone 9 engine, while in early 1943, on a different basis of calculation, the Wright Lockland factory depended on subcontracting for 65% of the parts in the Cyclone 14.[18] It would seem that a higher reliance on subcontractors would result in a higher output of engines per worker at the aero engine factories. The Ford Dearborn and Nash-Kelvinator figures do not support this assumption. For 1944 Ford and Nash-Kelvinator had almost identical numbers of direct workers per engine, yet Ford's reliance on subcontracting (assuming the *Labor Statistics for the Aircraft Industry* bulletins are correct) was one fifth that of Nash-Kelvinator. Similarly, the Wright Lockland factory had a greater reliance on subcontracting than either the Buick or Chevrolet factories (nearly double the percentage at Chevrolet) but was not notably more productive.

The implication is that it was not necessarily the number of direct workers or the level of reliance on subcontractors that determined productivity, but the organisation of production within the factory; that is, how well management deployed methods of production and process engineering. It is noteworthy that the factories that were the most productive, and that had the most sustained record of productivity, were the factories managed by automobile licensees. As the Harvard Business School study notes, these firms brought to aero engine production '…management organizations that knew how to carry out production engineering in all its phases.'[19] This is perhaps most evident in the record of the three factories building the biggest and newest air-cooled radial engines: Dodge Chicago, Pratt & Whitney Kansas City and Wright Wood-Ridge. Chart 7-4 shows clearly that the Dodge factory continued to improve productivity in the final year of the war, while the Pratt & Whitney and Wright factories were less successful in this effort.

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[18] Air Technical Service Command Plans (T-5), Logistics Planning Division: *Studebaker Corporation R-2600 Aircraft Engines Construction and Production Analysis*, p. 36; NA, AVIA 10/99, The Fedden Mission to America December 1942-March 1943, Final Report, Section 4: Engines, Power Plants and Propellers, Air Ministry and Ministry of Aircraft Production: Miscellaneous Unregistered Papers. Miscellaneous. Visit to America: report by Sir Roy Fedden.
[19] *Problems of Accelerating Aircraft Production During World War II*, p. 55.

The Learning Curve Effect and Labour Productivity Improvements

Productivity increased from the learning curve effect. The concept of the learning curve emerged from the work of T.P. Wright, Director of Engineering at the Curtiss-Wright Corporation, who determined that as the quantity of units produced increases the direct labour required to produce each unit decreases thereby reducing the cost per unit.[20] Wright found that the greater the number of units which had been produced, the lower the per unit cost.[21] Used initially in the airframe industry in World War II to estimate production costs and production times, the learning curve concept initially focused on direct labour in the manufacture and assembly process and the idea that productivity improved as workers gained experience.[22] Studies found that there were significant reductions in costs and required man-hours in the early stages of production, but over time these gains came at a declining rate.[23] Long production runs, however, allowed manufacturers to maximize the benefits of learning.[24]

After the war, the learning curve concept spread to other manufacturing industries and a broader definition of the contributing factors to organisational learning emerged. Learning within an organisation was not restricted to direct workers, but was instead an 'integrated adaptation effort' combining direct and indirect labour, technical and managerial personnel.[25] While no studies of the learning curve concept at a wartime aero engine manufacturer appear in the literature, a post-war study of a large American machine tool company provides a useful comparison. In this study Werner Hirsch identified four areas that contributed to the learning function within the enterprise:

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[20] Wright, T.P.: 'Factors Affecting the Cost of Airplanes', *Journal of Aeronautical Sciences*, Vol. 3, No. 4, (February 1936), pp. 122-128; Asher, Harold: 'Cost-Quantity Relationships in the Airframe Industry', Rand Corporation Report 291, (July 1956), pp. 1-3.

[21] 'Factors Affecting the Cost of Airplanes', p. 40.

[22] Yelle, Louis E.: 'The Learning Curve: Historical Review and Comprehensive Survey', *Decision Sciences*, Vol. 10, No. 2, (April 1979), p. 303. See Hartley, K.: 'The Learning Curve and Its Application to the Aircraft Industry', *The Journal of Industrial Economics*, Vol. 13, No. 2, (March 1965), pp. 122-28.

[23] 'The Learning Curve and Its Application to the Aircraft Industry', p. 123.

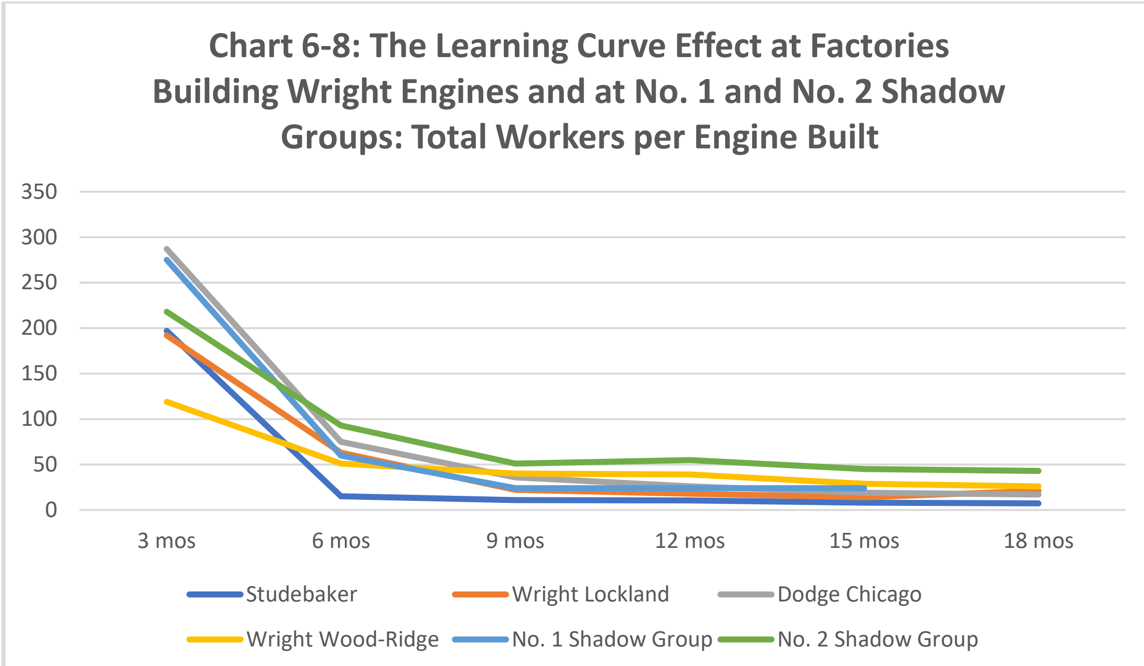
[24] 'The Learning Curve and Its Application to the Aircraft Industry', p. 123.

[25] Baloff, Nicholas: 'The Learning Curve: Some Controversial Issues', *The Journal of Industrial Economics*, Vol. 14, No. 3, (June 1966), p. 277.

a) Progress of direct labour: Workers learn through experience in both machining and assembly operations.
b) Progress of management: Over time management gains experience and introduces improvements in production processes, factory layout, flow of materials and labour scheduling.
c) Progress in engineering: With experience engineering departments can re-design parts for ease of manufacture and develop new types of machine tools and production processes to speed production.
d) Progress at material suppliers: This same process takes place at a firm's subcontractors speeding the flow of components and improving quality.[26]

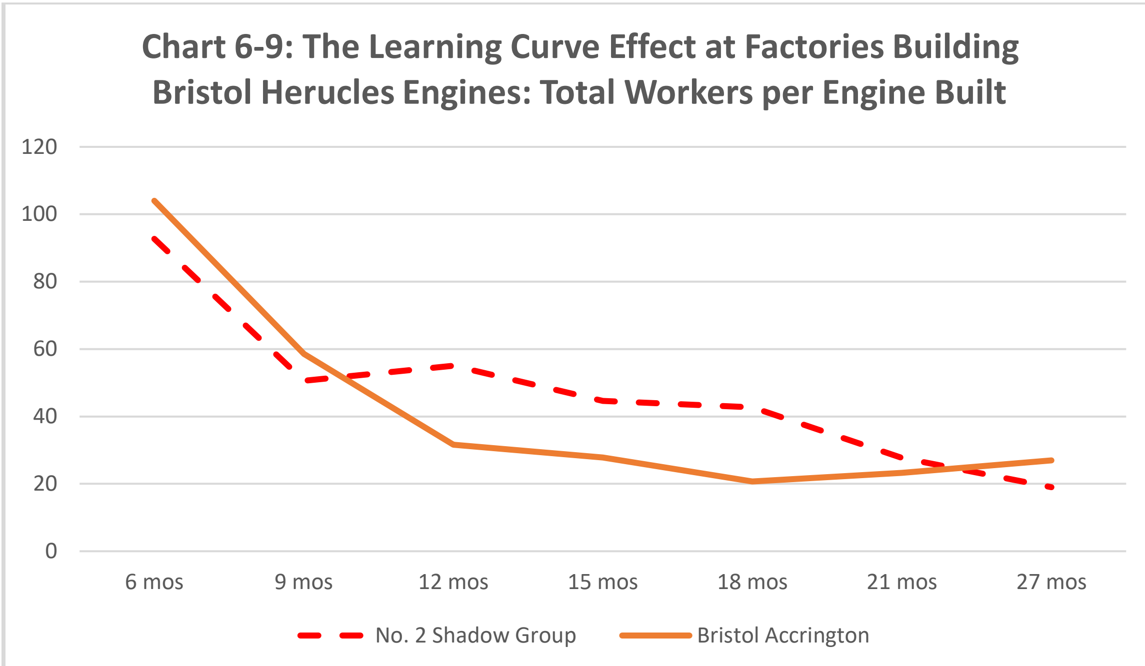
The factories building Bristol and Wright engines during the war all experienced gains in productivity over time. Arguably all four learning factors were present at these factories. While there is insufficient data to determine the improvement in productivity over production runs, the number of total workers per engine built can serve as a proxy.

[26] Hirsch, Warner: 'Manufacturing Progress Functions', *The Review of Economics and Statistics*, Vol. 34, No. 2 (May 1952), pp. 146-47.



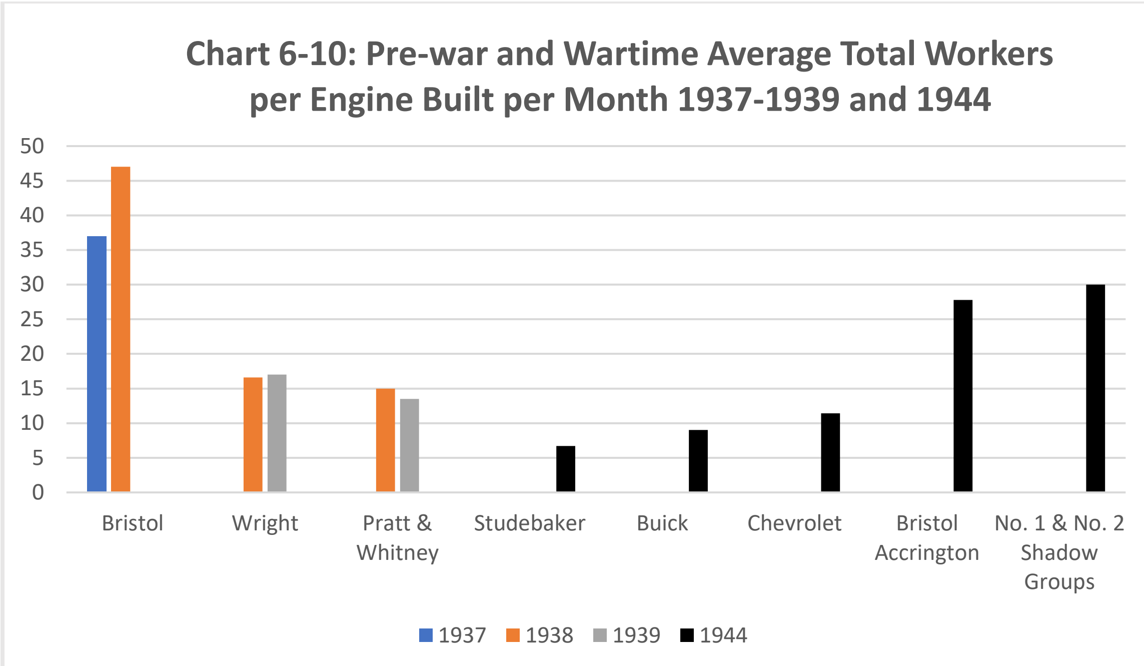
Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946); Holley, Irving Brinton, Jr.: *Buying Aircraft: Material Procurement for the Army Air Forces, United States Army in World War II: Special Studies* (Washington, D.C. 1964), pp. 580-81; Manpower Office, Management Control, Air Technical Service Command, Army Air Forces: *Labor Statistics for the Aircraft Industry*, November 1944-July 1945, File 218.6-7 Labor Statistics, AFHRA.

In every case productivity increased sharply, especially at first, from the moment production started, just as the learning effect would suggest (see Chart 6-8). The peaks in productivity occurred during 1944, also the peak year of American aero engine production, when most of the factories were in their third year of production. The Dodge Chicago and Wright Wood-Ridge took between six months and nine months for these factories to work down the learning curve to their peak level of productivity, with Studebaker the fastest and consistently the most productive. A partial explanation for the steepness of the learning curve was that in the initial stages of accelerating production the factories were trying to hire as many workers as quickly as possible, so that in the first few months of initial production there were far more employees than were initially needed.



Source: Ministry of Aircraft Production: *Statistical Review 1939-45*.

As in the American case, the British factories building the Hercules engine had a steep initial learning curve reaching a plateau after the initial learning period (see Chart 6-9). The chart brings out the fact that the Bristol Accrington factory, designed around American manufacturing methods and advance machine tools, appears to have improved productivity at a faster rate than the No. 2 Shadow Group factories over the first eighteen months of production. By March 1943, the measure of productivity at the No. 2 Shadow Group factories surpassed that at Bristol Accrington, the combined output of the four factories in the Group was more than double the rate of production at Accrington, an indication that perhaps these factories had reached a scale of production that brought greater efficiencies than at the Accrington factory. The No. 2 Shadow Group factories also had an advantage in that by March 1943 the No. 1 Shadow Group factories were building many Hercules components for the No. 2 Shadow Group factories. This illustrates the difficulty of making strict comparisons between factories.



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946); Lilley, Tom, et al: *Problems of Accelerating Aircraft Production During World War II*, P. 12; Manpower Office, Management Control, Air Technical Service Command, Army Air Forces: *Labor Statistics for the Aircraft Industry*, November 1944-July 1945, File 218.6-7 Labor Statistics, AFHRA; Mr. Haag to Secretary Morgenthau, 'Employment in the Aviation Manufacturing Industry', January 14, 1941, Diaries of Henry Morgenthau, Vol. 347-January 13-14, 1941, FDR Library Digital Collections; Bristol Aeroplane Company, Summary of All Employees for 1937 and 1938, copy in the archives of Aerospace Bristol Museum.

An analysis of total workers per engine at Bristol, Pratt & Whitney and Wright Aeronautical prior to the war shows that labour productivity at the two American manufacturers was more than twice that of Bristol (see Chart 6-10). The chart shows a similar pattern of labour productivity at the wartime shadow factories and three of the American licensee factories, with the best American factories still more than twice as productive.

Comparing American and British Aero Engine Factories

Comparing productivity at American and British aero engine companies is more challenging, not simply because of the multiple variables between factories already discussed, but more so because of a lack of data on British aero engine factories. With minor exceptions, data is available on employment and production on a monthly basis for nearly every airframe and engine factory in America from 1940 to 1945.[27] The equivalent publication from the Ministry of Aircraft Production provides only averages of engine production by quarter for most major factories, but combines production at No.1 and No. 2 Shadow Groups into one figure, making it impossible to determine a breakdown of production at the different factories.[28] Estimating total workers is also difficult due to the relative paucity of information on employment during the war. The Ministry of Aircraft Production's *Statistical Bulletin* lists employment of 'operatives' at the different air frame and aircraft engine factories, but only for selected periods from March 1942 to September 1945. The more comprehensive lists of labour at the different factories that were used to produce this data do not seem to have been preserved in the records of the Ministry of Aircraft Production.

Because of constraints on the supply of labour in Britain during the war, calculations of productivity were important to the Ministry of Aircraft Production as a basis for calculating labour requirements. Calculating productivity at the factories was never easy. M.A.P.'s own calculations often underestimated increases in productivity.[29] Part of the problem was that the firms themselves had 'little experience of measuring labour requirements under conditions of large scale production, with a much higher degree of tooling, etc., than they were accustomed to.'[30] Reports on productivity improvements have yet to surface in the archives. It is clear that there were variations in levels of productivity as well as improvements in productivity over time as production increased.

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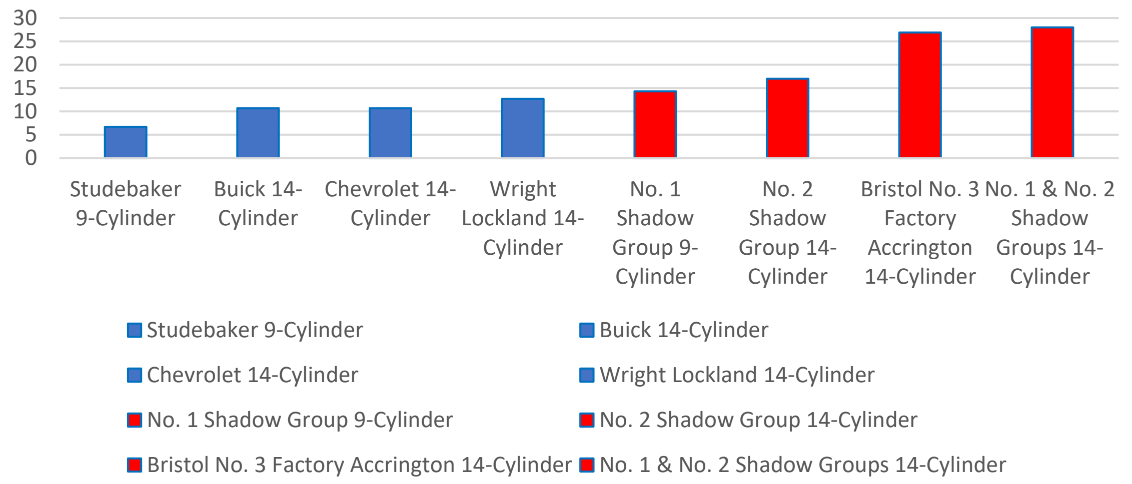
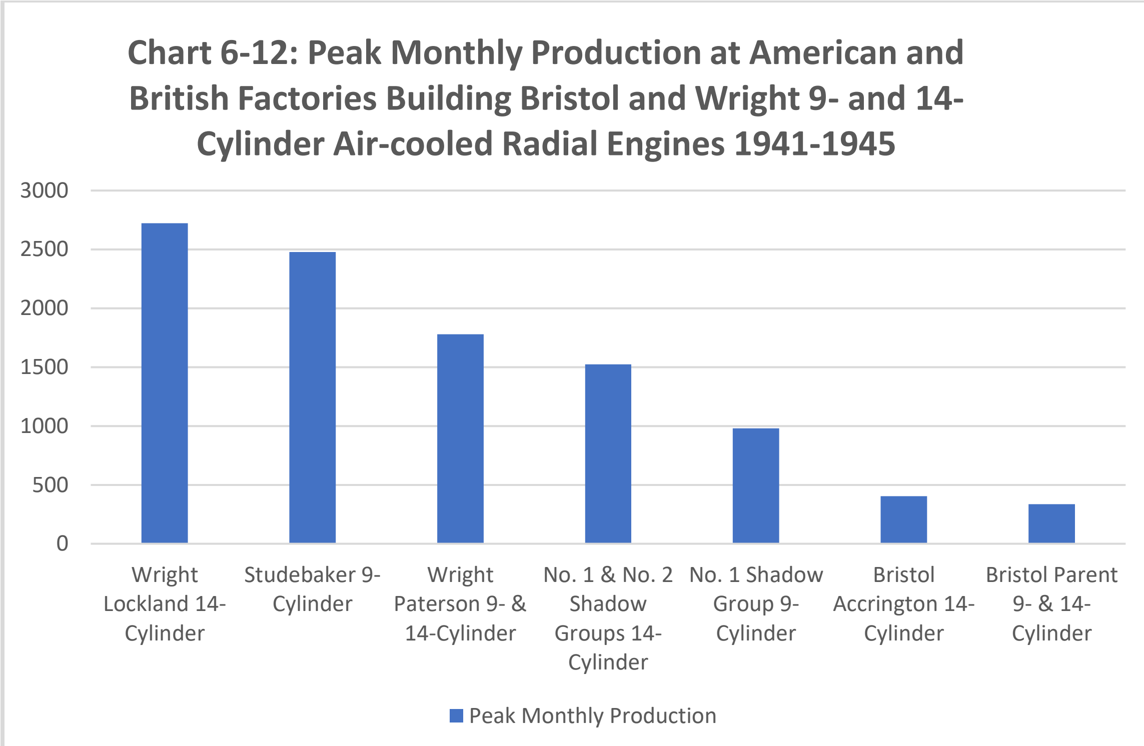
[27] This data was compiled in U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946). *Problems of Accelerating Aircraft Production During World War II* also has data on monthly production going back to 1938 for Pratt & Whitney and Wright Aeronautical.
[28] See Ministry of Aircraft Production: *Statistical Review 1939-45*.
[29] Inman, *Labour in the Munitions Industry*, p. 205.
[30] Inman, *Labour in the Munitions Industry*, p. 206.

Chart 6-11: Average Number of Total Workers per Engine for American and British Factories for Peak Month of Production 1941-1945

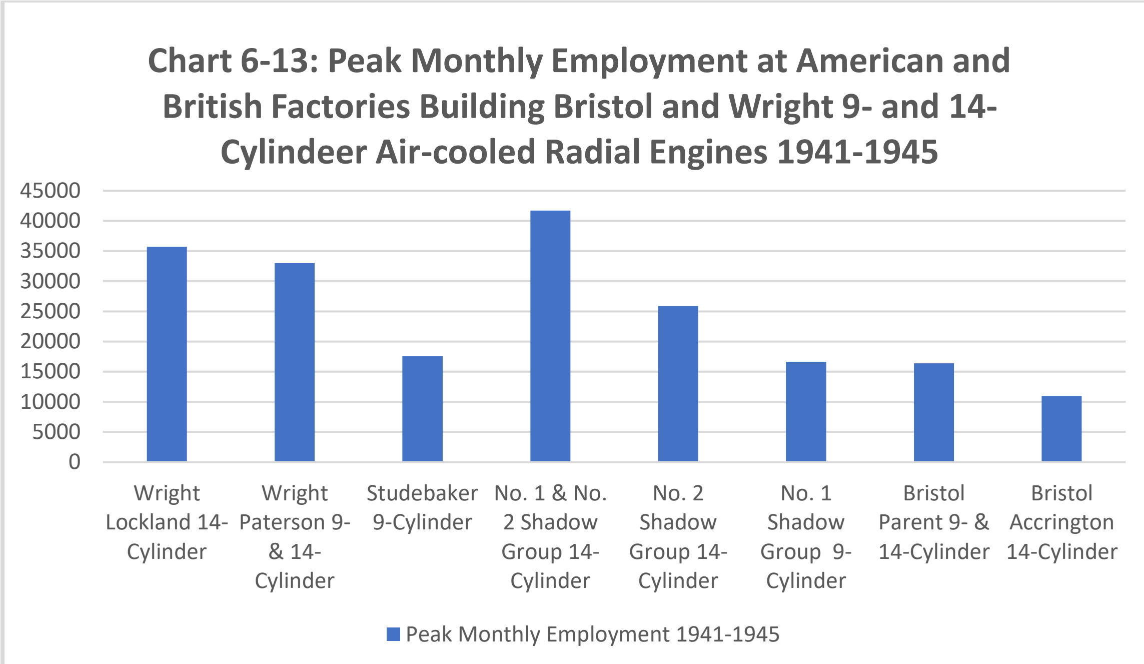


Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946); Ministry of Aircraft Production: *Statistical Review 1939-45*.

Almost all the American aero engine factories were more productive than their British counterparts, particularly when looking at factories that built similar types of engines (see Chart 6-11). No. 1 Shadow Group and Studebaker both built nine-cylinder engines, while the most appropriate comparison for the Bristol Accrington factory, which built the 14-cylinder Hercules, would be the Buick, Chevrolet and Wright Lockland factories that also built 14-cylinder engines. Studebaker was twice as productive as the factories in No. 1 Shadow Group. Buick, Chevrolet and Wright Lockland were twice as productive as the factories in No. 1 and No. 2 Shadow Groups and the Bristol No. 3 Shadow Factory at Accrington.



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946); Ministry of Aircraft Production: *Statistical Review 1939-45*; History of Production of Bristol Aero Engines by the Shadow Industry, Abridged Record of Engines, Spares and Accessory Output from Shadow Industry for 1938-44.



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946); Ministry of Aircraft Production: *Statistical Review 1939-45*.

Production at the American factories building Wright nine- and 14-cylinder engines was on a different scale to production of Bristol engines, both in terms of monthly production and employment (see Charts 6-12 and 6-13). Only the combined factories in No. 1 and No. 2 Shadow Groups approached the American factories in terms of peak monthly production and peak employment.

Hornby notes that there was a wide variation in productivity at the different British factories and asserts that it was related to the degree of subcontracting.[31] Hornby describes the difficulties in expanding capacity at specialist subcontractors for the aero engine manufacturers after war began. He states that while some of the new aero engine factories operated with a lower than normal reliance on subcontracting, many others had a higher level as limitations on civilian production allowed other manufacturers to switch to manufacturing components for the aero engine factories.[32] In these cases, which did vary from factory to factory, Hornby says the level of subcontracting at the aero engine factories approached that of the airframe factories,

[31] Hornby, *Factories and Plant*, p. 263.
[32] Hornby, *Factories and Plant*, pp. 264-65.

where subcontracting reached a level of 50% and often higher, compared to an average of 40% at the American aero engine factories.[33]

Unfortunately, information on the level of subcontracting at the factories building Bristol engines does not seem to have survived. However, anecdotal evidence suggests that these factories were heavily reliant on subcontracting, at a level that was at least equal to or higher than the levels at the Wright Lockland and Studebaker factories. For example, none of the factories in No. 1 or No. 2 Shadow Groups, nor the Bristol Accrington factory, had their own foundries for casting aluminium or magnesium engine parts nor facilities for forging engine parts. They were therefore entirely dependent on outside suppliers for cylinder heads, cylinder barrels, crankshafts and crankcases, as well as specialized bearings, piston rings, carburettors and magnetos.

It is clear that America used more special purpose machine tools and put them in very large factories better suited to flow production. Alan Millward has argued that America had greater ability to develop new types of high-production, special purpose machine tools than other combatants in World War II because America had greater manufacturing and engineering resources.[34] As Millward notes, the increase in the number of special purpose machine tools in American wartime factories represented a significant change in the production process.[35]

But why the difference? Here the scale of intended production played some part. There was a vast difference between British and American production targets.[36] Where the target for the Bristol Accrington factory was 400 Hercules engines per month, the target for the Wright Lockland factory was 3,000 Cyclone 14 engines a month. When faced with unprecedented demands for engines, Wright turned to the mass production methods and machine tools developed for large-scale production in the automobile industry and adapted them to large-scale production of Wright engines, passing on these methods and machines to Wright's two licensees, Studebaker and Dodge.

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[33] Hornby, *Factories and Plant*, pp. 227, 265.
[34] Milward, Alan S.: *War, Economy and Society,* (London, 1977), p. 189.
[35] Milward, *War, Economy and Society,* p. 188.
[36] Ritchie, *Industry and Air Power*, p. 262.

While Wright was focused on machine tools that would facilitate large-scale production and replace many standard machine tools, Bristol, while incorporating a certain number of high-production machine tools as a complement to standard machine tools, preferred to rely on these standard machine tools, mirroring the contrasting characteristics of American and European production methods. While Bristol and the shadow factories did make use of special purpose machine tools, many designed by Bristol and manufactured in America, most of the machine tools at these factories were standard types.

The size and design of the factories that built these engines in America and Britain were in sharp contrast. The shadow factories in Britain had to incorporate measures to reduce their vulnerability to air attack. Instead of large factory buildings, the Government recommended several smaller buildings placed apart to reduce the risk of damage to all, and protective blast walls built within buildings to contain an explosion to one area of the building.[37] The Bristol Accrington factory is an example of how the constraints that air raid precautions imposed on factory design resulted in a factory layout that was less than ideal for flow production. The Accrington factory, it will be recalled, had five separate machine shops with engine test cells separated from the final assembly shop, an arrangement that was not conducive to efficient flow production. The other factories in No. 2 Shadow Group also had multiple buildings. These factories were smaller than almost all their American counterparts. At around 800,000 square feet of floor area the Accrington factory was some 200,000 square feet smaller than the Studebaker factory at South Bend, Indiana, and even smaller than the larger Lockland and Dodge-Chicago factories. To contrast the size of British and American aero engine factories, Illustration 6-1 shows the outline of the Accrington factory superimposed on the outline of the Wright Lockland factory's main machine shop and assembly building. The entire Accrington factory could fit within the main machine shop and assembly building with room to spare. This was the difference between the second and third generations of aero engine factories.

[37] *Wartime Building Construction*, (New York, NY, 1942), pp. 124, 125-28.

FACTORY COMPARISON

BRISTOL No. 3 SHADOW FACTORY ACCRINGTON

1. No. 1 Fitting Shop: Engine assembly and testing
2. No. 2 Machine Shop: Machining crankcase and blower covers
3. No. 3 Machine Shop: Machining cylinder head, barrel, sleeves, crankshaft
4. No. 4 Machine Shop: Machining master connecting rod and articulated rods, gears
5. No. 5 Engine Equipment Shop: Exhaust rings, engine cowls, flame dampers

WRIGHT LOCKLAND FACTORY

A. North Shop: Cylinder production
B. Test Cells
C. Test Cell Building
D. Main Machine Shop and Assembly Building: Machining engine components, engine assembly and testing.
E. South Shop: Machining engine components
F. Magnesium Foundry: Casting magnesium parts
G. Foundry: Forging steel engine parts
H. Aluminum Foundry: Casting aluminium cylinder heads

Total Engine Production	Peak Employment
Bristol Accrington: 14,379	Bristol Accrington: 10,936
Wright Lockand: 62,414	Wright Lockand: 35,702

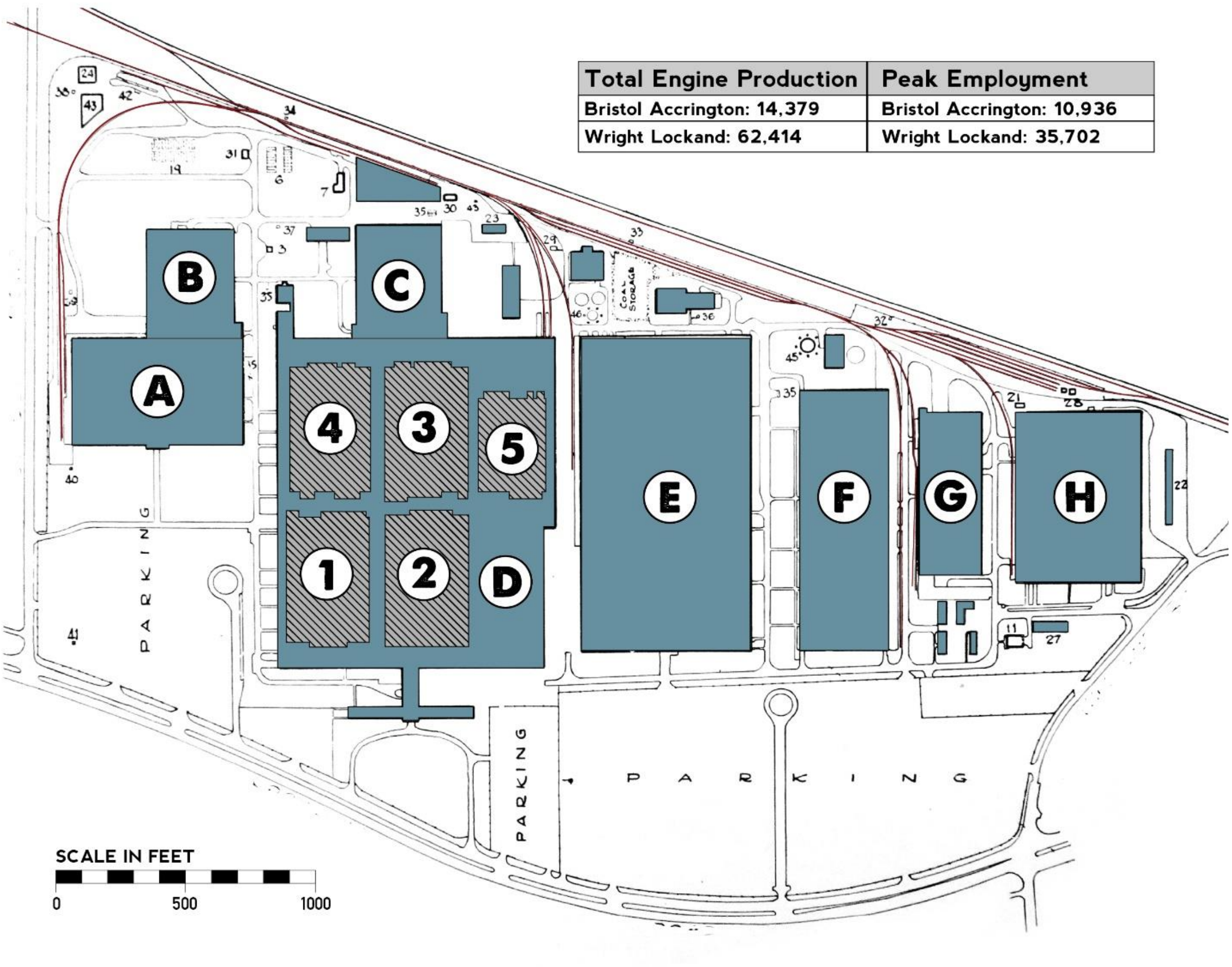

Illustration 6-1: The outline of the Bristol No. 3 Shadow Factory superimposed on the main machine shop and assembly building at the Wright Lockland factory.

The Missions to Study Production

The reports of British and American government missions to study American and British production methods in the fall of 1942 support the argument that the superior productivity of the American factories stemmed from advantages in factory size, greater attention to production engineering in factory layout and greater use of special-purpose, high-production machine tools. In September 1942, the Ministry of Aircraft Production sent a small group of executives from the Society of British Aircraft Constructors, A.V. Roe, Boulton-Paul, Vickers, Vickers-Armstrong, Ford, and High Duty Alloys to visit airframe, aero engine, component and materials manufacturers in the United States.[38] The mission spent two weeks in America and visited the major airframe and aero engine manufacturers, including Packard, Ford's Dearborn aero engine factory, the Wright factories in Paterson and the Pratt & Whitney factories at Hartford. The scale of American airframe and aero engine production greatly impressed the mission, with some factories 'four to five times the size of our largest factories.'[39] In its report the members of the mission focused on three key elements of the American system of production: the characteristics of the factories, quality of the engineering departments and methods of production.

The mission stressed the size of American factories as their most important characteristic. Size determined the manufacturing methods that could be used, but more importantly, the layout of the factories. The American factories were designed for large scale production from the start. The mission concluded that 'the fundamental difference in the average size of the plants—large units in the U.S.A. and dispersal into small units forced upon us by conditions in the U.K.—vitally affects the methods of production.'[40] In America vulnerability to air attack was not an issue, and with greater space available American factories could be built on a scale surpassing factories in Britain. The mission was impressed that many of the American factories were windowless and used artificial lighting and air conditioning. The lighting was superior to conditions in British factories, and the combination of artificial lighting and temperature control

[38] NA, AVIA 10/104, Report of the British Mission to the United States of America to Study Production Methods (September-October 1942), Air Ministry and Ministry of Aircraft Production Miscellaneous Unregistered Papers. Missions and Visits. British Mission to America to Study Production Methods: report of High Duty Alloys Ltd.
[39] Report of the British Mission to the United States of America, p. 2.
[40] Report of the British Mission to the United States of America, p. 3.

meant that day and night shifts could operate under the same conditions, a definite improvement over British factories.[41] The mission believed that better lighting and the light coloured walls of the factories were 'valuable aids to production.'[42]

In general, the factories the mission visited had much larger engineering departments than equivalent British factories, and a greater number of engineering staff relative to direct production workers.[43] The mission's members gained the impression that in the American engineering departments there was less of a 'watertight division' between design and manufacture than in Britain, and that American engineers were as concerned with problems of manufacturing as with problems of design.[44] They noted, as a result, the larger number of engineering staff devoted to production planning. As one example of this orientation, the mission found that as an aid to productivity engineering departments prepared considerable numbers of perspective drawings of parts, which were easier for unskilled workers to interpret than standard engineering drawings.[45]

The two aspects of American production methods that impressed the mission the most were the extensive use of moving assembly lines, powered conveyor systems and special purpose machine tools. Moving assembly lines, mostly using powered conveyors, were 'standard practice' in the factories the mission visited.[46] The mission found that regardless of the extent of moving assembly lines, 'all plants go to considerable trouble to lay out their shops to avoid unnecessary movement of material, and to arrange their final assembly lines to this end.'[47] The extensive powered conveyor systems the mission saw in the American factories they visited were clearly better suited to these large factories than to the smaller, dispersed factories in Britain, but where the level of production could justify the cost, the mission concluded that 'a substantial savings in man hours can be achieved' and recommended that more British factories adopt these systems.[48] The mission recognized clearly that the benefit of moving assembly lines was 'to control and

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[41] Report of the British Mission to the United States of America, p. 3.
[42] Report of the British Mission to the United States of America, p. 3.
[43] Report of the British Mission to the United States of America, p. 5.
[44] Report of the British Mission to the United States of America, p. 5.
[45] Report of the British Mission to the United States of America, p. 6.
[46] Report of the British Mission to the United States of America, p. 9.
[47] Report of the British Mission to the United States of America, p. 9.
[48] Report of the British Mission to the United States of America, p. 10.

stimulate the production of the component parts which the assembly line demands in order that progress be maintained', one of the most critical features of mass production.[49]

The mission observed that 'the experience of the American automobile industry is probably responsible for the practice in aircraft manufacture of using special purpose machinery to save handling time to a greater extent than in the case in the U.K.'[50] Not surprisingly, the mission stated that the 'best example of this outlook' was the Greenlee automatic transfer machine the mission saw in operation at the Wright factory in Paterson, New Jersey. The mission gave a detailed description of how the automatic transfer machine could produce one completed cylinder head every 50 seconds, noting that this large machine required only nine male operatives and 'three girls' to perform all loading, unloading and gauging duties.[51] However, the mission realised that introducing these systems into British factories where, as at the Bristol Accrington factory, blast walls interfered with the flow of work in the shop and where not all components were manufactured in the same building would be a difficult undertaking.[52]

Critical to the argument this chapter is making on comparative productivity, the mission's report stated clearly that the American aero engine factories the mission visited made much greater use of special-purpose machine tools than comparable British factories.[53] This reflected, the mission believed, the underlying principle of American manufacturing that 'economy of labour is regarded as more important than economy of equipment', the same point that Stephen Broadberry would make some fifty years later.[54] The mission noted that 'where complicated and expensive multi-purpose tools can be employed there appears to be little difficulty in obtaining suitable machines specially designed for the job.'[55] The mission attributed this tendency to use special purpose machinery in aero engine manufacturing to the experience of the American automobile industry and its development of high-production machine tools.

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[49] Report of the British Mission to the United States of America, p. 10.
[50] Report of the British Mission to the United States of America, p. 32.
[51] Report of the British Mission to the United States of America, p. 33.
[52] Report of the British Mission to the United States of America, p. 33.
[53] Report of the British Mission to the United States of America, Section 2. p. 32.
[54] Report of the British Mission to the United States of America, p. 10.
[55] Report of the British Mission to the United States of America, p. 11.

At the end of 1942 a second British mission arrived in America at the invitation of the American Government.[56] Sir Roy Fedden, Bristol's former head of engine development but serving as a special advisor to the Minister of Aircraft Production, led a group of eleven British aeronautical engineers and production specialists. The purpose of the mission was to investigate American airframe and aero engine production and coordination of British and American technical and design efforts.[57] The Fedden Mission to America, as it was called, spent three months visiting the major airframe, aero engine, and component manufacturing plants across the country. With more time available than the earlier Ministry of Aircraft Production's mission, Fedden and his team conducted a more thorough review of American production practices. Among the aero engine factories they visited were the Packard plant in Detroit building the Rolls-Royce Merlin under license, the Ford Detroit plant building the Pratt & Whitney R-2800 under license, the Allison factory in Indianapolis that built the liquid-cooled V-1710 aero engine, the Wright factories in Lockland and Paterson, and the Pratt & Whitney factories at Hartford.

The Fedden Mission's conclusions provide additional support to the argument that factory size, layout and greater use of special purpose machine tools were the key factors behind America's greater productivity. The Mission concluded that the layout of the American aero engine factories was superior to the layout of British factories. The Mission's report noted that while manufacturing practices had much in common, 'the actual layout of shops and the use of line production with or without conveyors is quite different…and it is felt that we have been slower to take advantage of this than the Americans.'[58] The liaison between design and production was closer in American factories, with a larger staff devoted to working out the details of shop layout and machine placement for a given rate of engine production. The Mission was impressed with the layout for line production at the parent aero engine factories, but commented that 'in some of the "shadow" plants [the automobile licensee factories they visited] the layout is really excellent.'[59] While acknowledging the difficulties that air raid precautions

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[56] *The New York Times*, January 3, 1943, p. 31.
[57] *The New York Times*, January 3, 1943, p. 31.
[58] NA, AVIA 10/99, The Fedden Mission to America December 1942-March 1943, Final Report, Section 4: Engines, Power Plants and Propellers, 4A-1.01-02, Air Ministry and Ministry of Aircraft Production: Miscellaneous Unregistered Papers. Miscellaneous. Visit to America: report by Sir Roy Fedden.
[59] The Fedden Mission to America Final Report, 4A-1.02

imposed in Britain, the Mission believed that 'considerable improvements in the layout of British shops are still possible.'[60]

The Mission came to these conclusions after making a careful study of the production organisation at the aero engine factories they visited. The Mission's report noted that 'the most important lessons are to be learnt from the general planning and laying out of the American engine factories and the administrative details.'[61] The most important point was that the American factories had devoted time and effort toward efficient planning from the start, by implication more than comparable British factories had done. The departments responsible for production engineering derived the plant layout from a thorough study of the delivery programme and standard times for machine tool operations, working out the placement of machine tools with the goal of obtaining balanced line production and eliminating unnecessary movement between machining operations. As with the M.A.P. Mission, the Fedden Mission was impressed with how American factories made extensive use of conveyor systems to speed the flow of work from machining operations to final assembly. While recognizing the difficulties British factories faced from dispersal and the need for blast walls and shelters within factories, the Mission believed British factories 'could benefit by more careful study when laying out both machine and assembly shops.'[62] By implication, British factories had devoted less attention to speeding up the flow of parts within the factory.

The members of the Fedden Mission were equally impressed with the special purpose machine tools they saw at the American aero engine factories, concluding that 'more American special machine tools for use in Britain would assist our engine factories to greater production.'[63] Visiting the aero engine factories, the Mission saw that 'first class, new, and in many cases specialized machine tool equipment is used throughout all the engine manufacturing plants.'[64] The Mission's report made note of several types of special purpose machine tools that apparently were not used in British factories but were common in the American factories they visited, among them multi-head tapping machines, special multi-head horizontal drilling machines and multi-

[60] The Fedden Mission to America Final Report, 4A-1.02
[61] The Fedden Mission to America Final Report, 4A-4.01.
[62] The Fedden Mission to America Final Report, 4A-3.01.
[63] The Fedden Mission to America Final Report, 4A-1.02.
[64] The Fedden Mission to America Final Report, 4A-3.01.

spindle boring machines.[65] They were less enthusiastic about the Greenlee automatic transfer machines they saw, arguing that a stoppage at one point along the machine would disrupt the entire operation and noting that in British factories such a large machine had greater risk of damage from air attack.[66]

In return for the American Government's sponsoring the Ministry of Aircraft Production's mission to review the American aircraft industry, the Ministry invited a group of representatives of the American aircraft industry to visit Britain.[67] None other than the discoverer of the learning curve effect, Theodore P. Wright, the aeronautical engineer and executive with the Curtiss-Wright Corporation, then serving as Deputy-Director of Aircraft Production at the War Production Board, led a group of eight senior executives from different companies to Britain from October 6 to November 11, 1942. During their time in England the group visited more than 22 factories building airframes, aero engines, propellers and metal components.[68] Included in the tour were visits to the Standard Motor No. 2 Shadow Factory building the Bristol Hercules and the Ford factory at Trafford Park building the Rolls-Royce Merlin.[69] On his return to America, Wright wrote up a report on the group's observations of British production.

Wright observed that the greatest difference between British and American factories was the need for dispersal in Britain to avoid the risk of air raids. 'Naturally,' his report commented, 'it is difficult to carry out much line production under these conditions. As this situation is quite general, it naturally prohibits the efficiencies which we hope to attain in this country.'[70] Wright and the other American representatives noted that in the British factories 'the extent of the use of machine tools in England is far less than here [America] while the use of conveyor systems was 'almost nil.'[71] Wright found that there were not many single purpose tools in evidence at the

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[65] The Fedden Mission to America Final Report, 4A-4.01.
[66] The Fedden Mission to America Final Report, 4A-4.02.
[67] *Flight*, (December 3, 1942), p. 600-01.
[68] *Flight*, (December 3, 1942), p. 601.
[69] Minutes of Meeting on 20 November 1942, Standard Motor Company Board Minutes 1939-1945. The minutes reported that the layout of the factory had received 'the highest compliments' from the members of the American mission.
[70] Wright, T.P.: 'U.S. Aircraft Production Mission to England, October 6 to November 11, 1942: Report on Personal Observations of the Chairman', *Articles and Addresses of Theodore P. Wright*, Vol. II: Aircraft Production, Uses of Aviation, (Buffalo, NY, 1961), p. 212.
[71] 'U.S. Aircraft Production Mission to England', p. 212.

factories, leading him to conclude that 'the conception of true line production was far less' than in America. Overall, Wright did not believe that output per man or per man-hour was as high as in America, a condition he attributed to the differences in factory facilities and the types of machine tools in use at the factories.[72] Wright estimated that British output was probably 20% lower due to the dispersal of factories and bombing precautions in the factories, probably referring to blast walls.[73] Although noting that the working hours were some 15% greater than in America, the more important factor was the use of less-productive machine tools. 'The use of older tools and general-purpose tools as against single purpose tools', he said, 'is a factor which naturally decreases production.'[74]

These reports from the three missions were all from the end of 1942, when the demand for capital equipment in both Britain and America had, for the most part, peaked.[75] Thereafter the gap between American and British use of high production machine tools almost certainly increased. Although declining, the Ministry of Aircraft Production's requirements for machine tools continued into 1944.[76] There may, however, have been constraints on the number of high production machine tools Britain could import from America. In November 1943, machine tools were removed from Lend-Lease, which meant Britain would have had to purchase additional machine tools using its foreign exchange reserves.[77] Indeed, British imports of machine tools from America dropped from $69 million in value in 1943 to $19 million in value in 1944.[78] American high production machine tools were expensive. Most appear to have cost between $8,000 and $16,000, four to five times the cost of standard machine tools, but some advanced types ranged from $25,000 to $53,000 for the larger Bullard multi-spindle Multi-au-matics and

[72] 'U.S. Aircraft Production Mission to England', p. 213.
[73] 'U.S. Aircraft Production Mission to England', p. 213.
[74] 'U.S. Aircraft Production Mission to England', p. 213.
[75] Hall, Hessel D.: *History of the Second World War, United Kingdom Civil Series, War Production Series: North American Supply*, (London, 1955), p. 406.
[76] By the end of 1943 Britain's of labour were 'almost exhausted'. See Inman, *Labour in the Munitions Industry*, P. 195. The comment on the Ministry of Aircraft Production's need for high production machine tools is in Hornby, *Factories and Plant*, pp. 316-17.
[77] Hall, *North American Supply*, p. 406.
[78] Stoughton, Bradley: *History of the Tools Division War Production Board*, (New York, 1949), p. 85.

Greenlee multi-station machines used in the factories building Wright engines.[79] We do not know what was imported later but these types of high-production machine tools do not appear on the list of machine tools Britain acquired through Lend-Lease during 1943.[80] We also know from contemporary late war periodicals describing Bristol shadow factories and the Wright Lockland and Wood-Ridge factories, and lists of machine tools at the Wright and Pratt & Whitney factories, that British factories were not using high-production machine tools.

Holley's Dilemma of Mass Production: Quantity versus Quality

Finally, there is the question of which production system, American or British, was better suited to respond to the quantity versus quality dilemma. As Irving Holley noted, obtaining quantity in production with continuous improvement in quality is 'an ideal combination that is hard to obtain.'[81] During the war, the constant demand for improvements in weaponry called for continual modifications and changes in design, but changes in design are inimical to large-scale production. The trade-off, as David Edgerton says, is 'between scale efficiency and flexibility: large-scale production was more efficient, but flexibility in production was essential to accommodate new weapons and modifications.'[82] In his history of British war production, M.M. Postan argues that 'when modifications were so frequent, methods of mass production in elaborate production lines, equipped with special-purpose tools, lost much of their value.'[83] Comparing British factories with what he described as the more specialized American factories, Postan said that 'it remains true that the less specialized factories with their simpler equipment found it easier to introduce modifications and to change over from one type or mark of weapon to another than the factories elaborately equipped for mass production.'[84]

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[79] Wright Aeronautical Corporation, Cincinnati, Ohio, Factual Appendix 'A', Plancor 10, and Wood-Ridge, New Jersey, Factual Appendix 'A', Plancor 994, Defense Plant Corporation Engineers' Reports and Appendices, Plancors 993-994, Boxes 4 and 403, RG 234, NARA.
[80] Forester Weekly List of M/T Requirements, Operating Offices Files 1940-45, Bureau of Supplies and Requirements and Supplies Branch, Box 1600, Entry 323, Foreign Economic Administration, RG 169, NARA
[81] Holley, *Buying Aircraft*, p. 512.
[82] Edgerton, David: *Britain's War Machine: Weapons, Resources and Experts in the Second World War*, (London, 2011), pp. 207-08.
[83] Postan, *British War Production*, p. 411.
[84] Postan, *British War Production*, p. 411.

Postan addresses his argument principally to airframe production, contrasting the British approach of piecemeal modification on the production line with the American approach of freezing a design to obtain larger production runs and using separate modification centres to incorporate modifications.[85] Jonathan Zeitlin similarly argues in favour of the British flexible system of production, arguing that 'the American system of temporarily frozen designs and retrospective modifications rather than continuous improvement during the course of production likewise exerted a negative impact on both the quality and quantity of combat-ready aircraft.'[86] David Edgerton comes to a similar conclusion on airframe production, arguing that while American airframe factories may appear to have been more productive than their British counterparts, when the additional labour required at modification centres is factored into American production, 'the overall productivity was the same.'[87]

Whether this argument applies equally as well to aero engine production is debatable. Postan extends his argument about airframe production to aero engine production, giving as his example the fact that during the war the more specialized, production-oriented Ford Trafford Park factory could produce the Merlin engine with a single-stage, two-speed supercharger more rapidly than the Rolls-Royce factories, but was unable to change over to the Merlin with a two-stage supercharger 'without a complete re-equipment of the machining and assembly shops.'[88] The Ford factory was more efficient, but less flexible in its ability to introduce new models. Postan's argument implies that the British aero engine factories were more effective at modifying their engines than the American factories, but were they? None of the major Allied aero engines went through the war without some modification. The question is where and how was this done, and how efficiently and timely did the factories introduce modifications into production.

It is noteworthy that in contrast to American airframe production during World War II, there were no modification centres in America for aero engines. Modifications were done at the factories, just as in Britain. And as in Britain, almost all the modifications to an engine came from the parent engine manufacturer and were passed on to the licensee or branch factories. And

[85] Postan, *British War Production*, pp. 342-43.
[86] Zeitlin, *Flexibility and Mass Production at War*, p. 60.
[87] Edgerton, *British War Machine*, p. 208.
[88] Postan, *British War Production*, p. 411.

engines were modified. Between 1931 and 1941, for example, Wright built 41 variants of the Cyclone 9 for the commercial airlines and the military services.

The Army Air Force and the Navy used dash numbers to designate major changes in an engine model, for example, the -65 and -97 to designate different variants of the Cyclone 9, and the -9, -20, -23 and -29 for variants of the Cyclone 14. It is uncertain whether a change in the dash number for an American aero engine is the same as a change in mark number for a British aero engine. If they are roughly comparable, then in comparison to the more than 41 marks of the Merlin engine that Rolls-Royce produced during the war, Wright produced 31 variants of the Cyclone 9 and 22 variants of the Cyclone 14. From another perspective, just ten of the of the many marks of the Merlin made up approximately 75% of total Merlin engine production, while eight variants of the Wright Cyclone 9 made up 91% of production, seven variants of the Wright Cyclone 14 made up 86% of production and six marks of the Bristol Hercules made up 98% of production. It is difficult to argue that Wright, in taking the Cyclone 18 from its initial power rating of 1,800 HP to 2,500 HP in the Cyclone 18BB model, was less capable of modifying its engines than Rolls-Royce. In other words, the patterns were very similar; both British and American engine manufacturers boosted the power output of their engines through continuous development. But it is possible that America did not have to make so many design changes because it had many more high-powered engines to choose from.

Rolls-Royce's progressive development of the Merlin, taking the engine from 1,030 hp in 1939 to 1,710 hp by 1944 was a remarkable achievement, but arguably Rolls-Royce had no alternative, as Rolls-Royce's initial efforts to develop an engine of greater power than the Merlin were not successful.[89] The 1,750 hp Vulture, Rolls-Royce's first attempt, was a failure, while the Griffon, which ultimately produced 2,000 hp, was delayed until late in the war.[90] Pratt & Whitney and Wright did not introduce the same number of modifications to their 1939 model engines, the Pratt & Whitney Twin Wasp and the Wright Cyclone 9, because they had no need to, as they

[89] Although there was also a great deal to be gained by keeping the Merlin in production to use existing factories, plant and experienced workers.

[90] None of the British engines of 2,000 HP or greater were built in quantity during the war. The 2,000 HP Napier Sabre suffered prolonged development problems, while the Bristol Centaurus also suffered delays in getting into production. Rolls-Royce built 4,748 Griffon engines, Napier built 4,991 Sabres and Bristol completed 2,767 Centaurus engines by the end of the war.

both produced high power engines as well—they were more successful than Rolls-Royce in making the jump from 1,000 hp to 2,000 hp. Rolls-Royce achieved a 66% increase in power over four years of development of the Merlin. Wright achieved the same by moving from the Cyclone 9 at 1,200 hp, to the Cyclone 14, an initial increase of 41% in power, and on to the Cyclone 18, which gave an 83% increase in power over the Cyclone 9. Pratt & Whitney achieved something similar moving from the 1,200 hp Twin Wasp to the 2,000 hp Double Wasp engine. America, fortunately, had the industrial, technical and financial resources to accomplish this.

There are other counterarguments to Postan's critique of the Ford Trafford Park plant's supposed inability to switch to another model of the Merlin. Postan's critique implies that Rolls-Royce or some government authority wanted Ford to switch to the two-stage Merlin but decided against this due to the inability of Ford to build the newer engine with its existing machine tools. It is not clear, however, that this was the case. Ford continued building the single-stage Merlin because this was the engine that powered the AVRO Lancaster, which also remained in production until the end of the war. There was also pressure from the Ministry of Aircraft Production to keep older models of the Merlin in production to avoid the risk of any shortages.[91]

Secondly, Postan implies, but gives no evidence to support his claim, that the Rolls-Royce factory at Derby could switch to the two-stage Merlin *without* re-equipping their machine shops. Given the extent of changes between the two versions of the Merlin, this seems questionable. Even standard machine tools would have required changes in tooling and fixtures to manufacture new parts. So the issue is surely about relative costs of changing, and no information is provided. The mass production methods in use at the Ford Trafford Park factory and in the American aero engine factories that Postan criticises may well have incorporated more flexibility than he assumed. As a contemporary text book on production commented, 'line production offers opportunity for the introduction of far more flexibility than is generally assumed.'[92] Although conversion of a factory to a new layout or new equipment was not without costs and problems, it was not unusual. The 'complete re-equipment of the machining and assembly shops' that Postan decries was an expected element, and cost, of the manufacturing process in time of peace

[91] Lloyd, Ian: *Rolls-Royce: The Merlin at War*, (London, 1987), p. 122.
[92] Muther, *Production-Line Technique*, p. 253.

or war. The reality was that companies had to cope with changes in the design of products, fluctuations in demand, the discontinuation of a product and new production processes as part of their normal business.[93]

Given the record of the factories building Bristol and Wright engines it is difficult to agree with Postan's conclusion that 'factories elaborately equipped for mass production' were less capable of coping with frequent design changes, modifications to engines in production, shifting to production of different variants of an engine and converting to production of a completely new engine models than the less-specialized factories he praises.

[93] Muther, *Production-Line Technique*, p. 253.

Conclusion

The aim of this dissertation has been to examine how two companies, the Bristol Aeroplane Company in Britain and the Wright Aeronautical Corporation in America made the transition from pre-war, low-volume batch production to large-scale production of aero engines during World War II. That this transition was successful is clear from the record of wartime aero engine production in Britain and America. How these companies achieved this transformation has, heretofore, remained unexamined. The standard narrative on production in World War II assumes a straightforward transfer of mass production methods common in the automotive industry to all phases of armaments production. This dissertation has argued instead that successful large-scale production of aero engines in Britain and America was not based on mass production but, as Jonathan Zeitlin has argued, new forms of production developed in response to wartime requirements for aero engines in unprecedented quantities. Wartime aero engine production witnessed construction of new, purpose-built factories, a transformation in manufacturing methods and advances in machine tools.

The British and American Governments financed a vast expansion in capacity for aero engine production. With few exceptions, this effort did not involve converting existing automotive factories to aero engine production, as some believed possible, but primarily constructing entirely new factories built at government expense. As the war continued, successive generations of factories became progressively larger. In Britain, the factories in No. 2 Shadow Group were several times larger than the factories built under the first shadow scheme, a distinction that is not clear in the historiography. There was a pronounced difference in scale between aero engine factories in Britain and America. In America, the Government's decision to concentrate production in single large factories resulted in massive factory buildings, some double the size of equivalent factories in Britain, and in the case of the Dodge Chicago factory the largest single-storey industrial building in the entire world. There were differences as well in design and layout between British and American aero engine factories. With no need for protection against air attack, American factories could incorporate machining operations, engine assembly and testing in a single large building. As a result, the American aero engine factories were better suited to the new manufacturing methods developed for wartime production.

The transformation in aero engine manufacturing methods was a response to two factors: the demand for aero engines in unprecedented quantities requiring a rapid shift to large-scale production and the shortage of the skilled workers the aero engine manufacturers had relied on in the pre-war period. The challenge was to make this transition with a product that demanded a level of precision engineering and quality control far greater than any product previously built using mass production methods. What was undertaken had never been done before. The solution to large-scale production was not the wholesale adoption of mass production methods, but the careful adaptation of these methods to achieve flow production. Through production engineering the aero engine factories worked out the sequencing of machining operations, the placement of ancillary operations and streamlined the assembly process to cut manufacturing times and speed up production.

This dissertation has tried to show that where the standard narrative of wartime production implies that mass production methods were imposed on other industries through straightforward adoption, the reality was more nuanced and reflected instead a collaborative learning process. The aero engine manufacturers did study automotive mass production methods and carefully selected methods that had the flexibility to be adapted to the demands of aero engine production. In seeking solutions to the problems of large-scale production through production and process engineering, the aero engine manufacturers, as the Harvard Business School study noted, had a wealth of experience to draw on from the automotive and machine tool industries, and did so. Similarly, the automotive firms that managed aero engine factories could not impose their standard mass production methods onto aero engine production but had to learn to adapt these methods to building aero engines, a task unlike any they had undertaken before. That the factories the automotive firms managed proved to be the most productive implies that mass production methods may have had a greater degree of flexibility than Postan, for example, recognized.

To cope with the progressive dilution of skill levels in a rapidly expanding workforce, the British and American aero engine manufacturers had to resort to deskilling, shifting to methods and machines suitable for semi- and unskilled workers. This involved a transformation in the types of machine tools employed for aero engine manufacture. There was a progressive shift from using unmodified standard, universal machine tools common in the pre-war aero engine factories to standard machine tools with specially designed jigs and fixtures and more semi- and fully automatic machine tools that could perform multiple operations on a single machine with little intervention by the machine operator. The American aero engine factories building the bigger, more complex high performance air-cooled radial engines were ahead of the British factories in developing even more advanced high-production machine tools. The epitome of this generation of machine tools was the Greenlee automatic transfer machine, but this was just one of a range of new high-production machine tools employed at the Wright Aeronautical and Pratt & Whitney factories, and their licensee factories, that were developed during the war specifically to expand aero engine production. Wright Aeronautical's experience supports the findings of Ristuccia and Tooze that during the war America invested heavily in advanced machine tools that were more productive than similar classes of machine tools in Europe. And, as they note, the greater scale of production in America more than justified the investment in expensive but high-production machine tools.

Improved productivity was vital to large-scale production during the war. Both Britain and America experienced productivity improvements during the war. Alan Millward has noted that these improvements were a result of the new production methods introduced during the war.[1] Postan, Zeitlin and Edgerton argue, however, that there was no difference between British and American productivity in airframe production. This was not the case in aero engine production. The American aero engine factories were more productive than their British counterparts requiring fewer workers per engine built than comparable British factories. In terms of labour productivity, the best American factories were at least twice as productive. The American factories built substantially more aero engines with a manufacturing system that was sufficiently flexible to cope with constant design changes, shifts to new models of an engine and completely new types of aero engines. The American factories were just as capable of making modifications as the British factories. The larger American factories were better designed to exploit the

[1] Milward, *War, Economy and Society*, P. 230.

transformative potential of flow production, with fewer interruptions in the sequence of operations and greater scope for mechanical conveyor systems to speed the flow of parts through the factories. Coupled with more high-production machine tools, the American factories achieved monthly production rates that were two to three times greater than British factories and dwarfed those of Germany and Japan.

America built far more high-powered aero engines, of 2,000 hp or greater, than any other combatant in World War II. During the late 1930s, both Britain and America tested large 18-cylinder air-cooled radial engines, in Britain the Bristol Centaurus and in America the Pratt & Whitney Double Wasp and the Wright Cyclone 18. But only the American 18-cylinder engines went on to large-scale production. While the Centaurus powered a small number of late war British aircraft, the Double Wasp powered nearly 40,000 American Army Air Force and Navy fighter planes and over 12,000 medium bomber, patrol and transport aircraft and the Cyclone 18 equipped the 3,970 Boeing B-29 Superfortresses built during the war. The American dominance in high-performance, air-cooled radial piston engines continued long after the war and contributed to the widespread sales success of American piston-engine airliners until the advent of the jet airliner in the late 1950s. While the Bristol Hercules and Centaurus saw long service in several military transport aircraft, their success in powering commercial airliners was limited. Economical jet airliners that could compete on a cost-basis with piston-engine airliners had to wait until the aero engine manufacturers had developed more efficient jet engines.[2] In the interim, the Douglas and Lockheed families of airliners, powered by big Pratt & Whitney and Wright air-cooled radial engines, dominated the world's commercial airline market.

[2] See Miller, Ronald, and David Sawers: *The Technical Development of Modern Aviation,* (New York, 1970), Chapter VI.

Appendices

Appendix I: Pratt & Whitney and Rolls-Royce Production in World War II

Pratt & Whitney Production

The Pratt & Whitney Aircraft company was, with Wright Aeronautical, the principal supplier of aero engines to the American military during World War II. Founded in 1925, Pratt & Whitney, like Wright, had concentrated on the development and production of high-performance air-cooled radial engines for the military and commercial users. During the 1920's and 1930's, the two firms competed for contracts from the Army Air Corps, the U.S. Navy, American airlines and foreign buyers. From the mid-1920's to the mid-1930's, Pratt & Whitney's leading engines were the nine-cylinder radial Wasp and Hornet engines, which with progressive development reached 600 hp and 875 hp respectively.[1] To compete with Wright's Cyclone 9 engine, which offered greater power than the Pratt & Whitney Hornet, the company developed the 14-cylinder, two-row radial Twin Wasp engine that matched the Cyclone 9 in horsepower.[2] While Wright had more success selling the Cyclone 9 to American and foreign airlines than Pratt & Whitney did with the Twin Wasp, the Pratt & Whitney engine found much favor with the Army Air Corps and the U.S. Navy. When Pratt & Whitney learned that Wright was developing the 1,600 hp Cyclone 14 and the even more powerful 18-cylinder Cyclone 18, the company responded with its own 18-cylinder engine, the Double Wasp, which initially offered 1,800 hp like the Cyclone 18, but soon reached 2,000 hp. During World War II the Pratt & Whitney Twin Wasp would be built in greater numbers than any other Allied piston engine, while the Double Wasp would be the second most-produced American aero engine.

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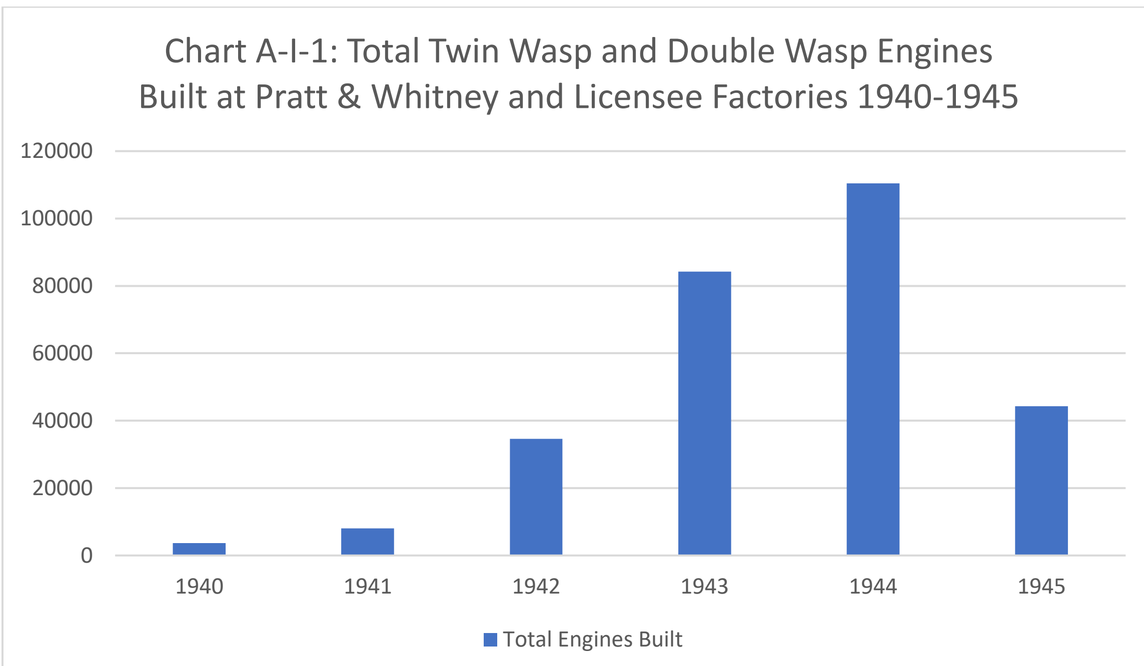
[1] Conners, Jack: *The Engines of Pratt & Whitney: A Technical History*, (Reston, VA, 2010), pp. 67-78.

[2] Conners, *The Engines of Pratt & Whitney: A Technical History*, pp. 83-95; United Aircraft Corporation: *The Pratt & Whitney Story*, (1950), pp. 110-11.

The outbreak of war in Europe led to a surge in orders for Pratt & Whitney engines from the British and French Governments. By June 1940, Pratt & Whitney had orders for nearly 10,000 engines from foreign governments, while President Roosevelt's '50,000 aircraft' program called for 35,000 Pratt & Whitney engines.[3] As with Wright, the volume of engines required from Pratt & Whitney greatly exceeded the company's capacity, even with greatly expanded facilities leading the government to bring the automobile industry into aero engine production. Unlike Wright, Pratt & Whitney's management was happy to license production of its engines to the automobile firms.[4] Pratt & Whitney 'believed that there were definite limits to its ability to handle greatly increased manufacturing commitments and preferred to turn over the volume production of established models to others.'[5]



Source: U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946)

[3] Memo of aircraft and aircraft engine requirements, June 10, 1940, Aeronautical Section, National Defense Commission, Diaries of Henry Morgenthau, Book 269, June 5-6, 1940.
[4] Lilley, *Problems Accelerating Aircraft Production*, p. 33.
[5] Lilley, *Problems Accelerating Aircraft Production*, p. 33.

Pratt & Whitney licensed production of the Twin Wasp to the Buick and Chevrolet divisions of General Motors and production of the Double Wasp to the Ford Motor Company and to the Nash-Kelvinator Company; Chevrolet converted to building the Double Wasp beginning in 1944.[6] Continental and Jacobs, two firms that built small engines for the general aviation market, took on licensed production of Pratt & Whitney's smaller engines for training airplanes. As with Wright's licensees, the automobile factories building the Twin Wasp and Double Wasp built fewer variants of these engines than the Pratt & Whitney factories, typically five or six variants, although the Ford factory build eleven variants of the Double Wasp. All the factories, however, had to cope with constant changes in design and modifications. The record of production of the Twin Wasp and Double Wasp at Pratt & Whitney and its licensee factories was:

Pratt & Whitney

R-1830 Twin Wasp:	42,814
R-2800 Double Wasp:	33,846

Buick

R-1830 Twin Wasp:	71,874
R-2000:	2,458
Total:	

Chevrolet

R-1830 Twin Wasp:	56,484
R-2800 Double Wasp:	4,282

Ford

R-2800 Double Wasp:	57,637

Nash-Kelvinator

R-2800 Double Wasp:	17,108

[6] Lilley, *Problems Accelerating Aircraft Production*, P. 33; United Aircraft Corporation: *The Pratt & Whitney Story*, pp. 130-32.

Total Pratt & Whitney Twin Wasp and Double Wasp Engine Production

R-1830 Twin Wasp: 171,172
R-2800 Double Wasp: 112,873
Total all Pratt & Whitney engine models: 355,985[7]

Table A-I-1: Pratt & Whitney and Licensee Factory Total Floor Space

P&W Hartford	P&W Satellite Factories	P&W Kansas City	Buick	Chevrolet	Ford Dearborn	Nash-Kelvinator
2,763,000 sq. ft.	1,223,000 sq. ft.	2,875,626 sq. ft.	2,496,915 sq. ft.	2,134,779 sq. ft.	2,217,808 sq. ft.	1,017,064 sq. ft.

Source: Air Technical Service Command: AAF Industrial Facilities Expansions 31 March 1945, File 218.1-3, AFHRA

Production at the Pratt & Whitney and its licensee factories mirrored in many ways production at the factories building Wright engines. As shown in Table A-I-1, by 1945 Pratt & Whitney and its licensees had a combined floor area of 14,068,232 sq. ft. The factory buildings were typically large, single-story rectangular buildings containing all machining and assembly operations. In size they ranged from the 204,800 sq. ft. Nash-Kelvinator machine shop to the Pratt & Whitney Kansas City factory, one of the giant aircraft engine factories built during the war.

Even before the war, Pratt & Whitney had switched its factories in Hartford to a form of line production.[8] The licensee companies were already familiar with line production from their automobile assembly operations and quickly adapted these methods to aero engine production.[9] All the factories building the Twin Wasp and Double Wasp used the latest high-production machine tools. Using their experience in automobile production, several of the

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[7] Holley, *Buying Aircraft*, p. 580.

[8] See Ward, J. Carlton, Jr.: 'Plant Layout and Production Methods for Modern Aircraft Engines', *Society of Automotive Engineers Journal (Transactions)*, Vol. 40, No. 5, (May 1937); 'P &W Engine Production', *Aero Digest*, Vol. 34, No. 1, (January 1939), pp. 57-59.

[9] See for example Geschelin, Joseph: 'Buick's Warplane Engine Plant', *Automotive and Aviation Industries*, Vol. 86, No. 11, (June 1, 1942), pp. 20-27, 82; Geschelin, Joseph: 'Ford War Plant Facilitates Straight-Line Production", *Automotive and Aviation Industries*, Vol. 86, No. 11, (June 1, 1942), pp.18-24, 102, 104.

licensee firms developed entirely new types of machine tools to speed production and replace more conventional standard machine tools.[10]

Rolls-Royce Production

Rolls-Royce built more aero engines during World War II than any other British aircraft engine manufacturer.[11] While Bristol Aeroplane Company concentrated on air-cooled radial aero engines, Rolls-Royce dominated the market for high-performance liquid-cooled aero engines. The company entered aero engine production during World War I, initially building French engines, but went on to design and manufacture the Eagle and Falcon liquid-cooled aero engines. By the end of the war Rolls-Royce had built more aero engines than any other British manufacturer.[12] In the period between the wars Rolls-Royce continued to build liquid-cooled aero engines, almost entirely for the Royal Air Force, completing 4,778 Kestrel 600 hp engines between 1928 and 1938.[13] Since the RAF's need for Rolls-Royce aero engines in the years leading up to rearmament was modest, the company, like Bristol, operated using batch production methods. Up to 1938 the company built less than 200 engines a month. As the British Government's rearmament programme accelerated, so too did the RAF's demand for the more powerful Rolls-Royce Merlin engine for the RAF's new single-seat fighters, the Hawker Hurricane and the Supermarine Spitfire.

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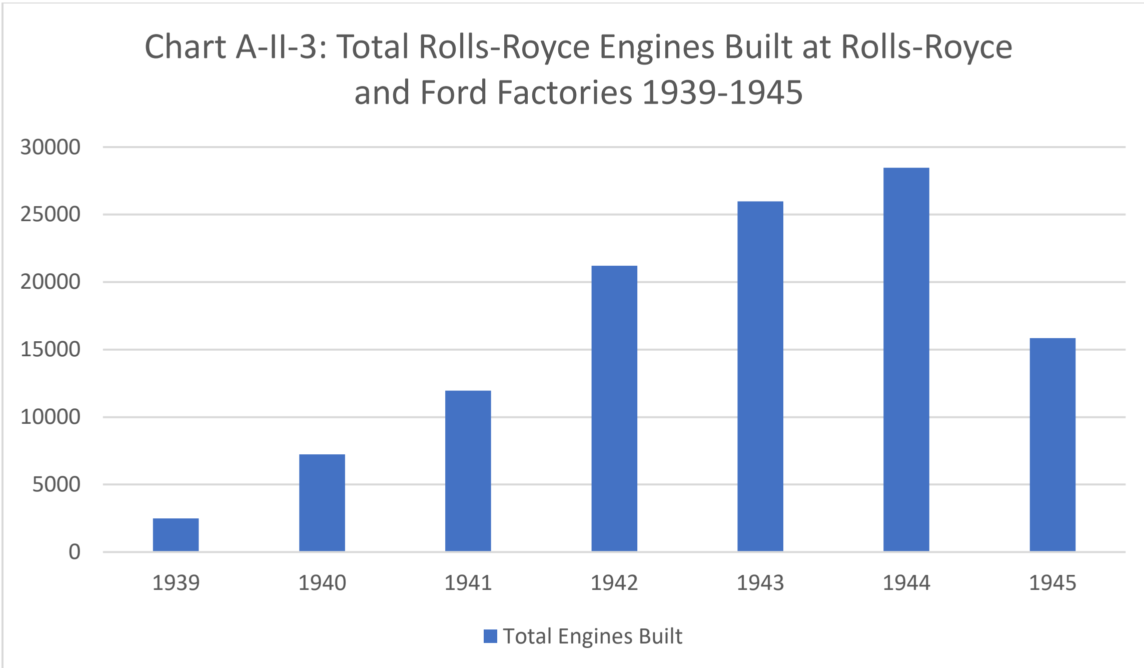
[10] Geschelin, Joseph: 'Buick's Know How Speeds Production of Airplane Engine Parts', *Automotive and Aviation Industries*, Vol. 87, No. 10, (November 15, 1942), p. 21.

[11] Unlike the Bristol Aeroplane Company, there are several good histories of the Rolls-Royce Company. See Ian Lloyd's three volumes (*Rolls-Royce: The Growth of a Firm* (London, 1978); *Rolls-Royce: The Years of Endeavour*, (London, 1978; and especially *Rolls-Royce: The Merlin at War*, (London, 1978) as well as Peter Pugh's history of the company. The Rolls-Royce Heritage Trust has published a long series of monographs on Rolls-Royce aero engines including several on the Merlin. Sebastian Ritchie's study of the expansion of British aircraft production contains a useful discussion of Rolls-Royce's position and production problems during the years of expansion. See Ritchie, *Industry and Air Power: The Expansion of British Aircraft Production, 1935-1941*, pp. 115-21.

[12] Jones, H.A.: *The War in the Air*, Vol. VI, (Oxford, 1937), pp. 45-51.

[13] Lloyd, Ian: *Rolls-Royce: The Merlin at War*, (London, 1978), pp. 232-33.



Source: Ministry of Aircraft Production: *Statistical Review 1939-1945*

The Rolls-Royce Merlin, the best known of all British aero engines, was built in greater numbers than any other British aircraft engine and second only to the Pratt & Whitney Twin Wasp among British and American aero engines. The Merlin was a twelve-cylinder, in-line liquid-cooled aircraft engine, essentially a scaled-up version of the Kestrel. Rolls-Royce undertook development work on the Merlin in the mid-1930's and in 1937 the first production engine, the Mark I, produced 1,030 hp.[14] The Merlin underwent continuous development during the war and the final marks of the Merlin produced 1,830 hp, an increase of nearly 80% in engine power. Built more than 50 different marks during the war, the Merlin powered the quartet of the RAF's most famous airplanes of World War II: the Hurricane, Spitfire, de Havilland Mosquito and AVRO Lancaster as well as converting the North American P-51 Mustang into perhaps the best fighter aircraft of the war. Such was the demand for the Merlin that the British Government arranged for the Packard Motor Company in America to build the

[14] Alec Lumsden provides a good overview of the technical development of the Merlin. See Lumsden, Alec: *British Piston Aero-Engines and Their Aircraft*, reprint of 1994 edition, (Ramsbury, Marlborough, UK, 2003), pp. 115-25.

engine under license, completing 54,714 engines by the end of the war. In total, Rolls-Royce and Packard built 164,264 Merlin engines between 1938 and 1945.

In 1939, Rolls-Royce began work on the Griffon, intended as a replacement for the Merlin. The Griffon was also a twelve-cylinder liquid-cooled, in-line engine, but had a greater capacity than the Merlin of 2,240 cu. in.[15] The first marks of the Griffon produced 1,720 hp., but by the end of the war had pushed the power output to 2,440 hp. Introduced later in the war the Griffon was built in limited quantities compared to the Merlin. Rolls-Royce completed 4,778 Griffon engines by the end of the war.

When the Air Ministry sought to expand Merlin production, Rolls-Royce preferred to retain control of production and to use extensive subcontracting to increase quantity, rather than agreeing to the Air Ministry's shadow factory scheme of bringing the automobile industry into aircraft engine production.[16] Instead of setting up a shadow factory scheme for the Merlin, the Air Ministry agreed to finance construction of a new factory under Rolls-Royce's management at Crewe in Cheshire, northwest of Birmingham.[17] When the RAF requested a doubling of Merlin production capacity, Rolls-Royce proposed building a third, 'shadow' factory, under Rolls-Royce's management at Hillington outside of Glasgow.[18] The Crewe and Hillington factories were intended to focus on production, leaving the main Rolls-Royce factory at Derby to concentrate on engine development.[19] After the outbreak of the war in 1939, the RAF had an even greater need for expanded Merlin production. The Ford Motor Company (UK) came in as the only British automobile firm to manufacture the Merlin.[20] Ford brought its considerable experience of mass production to a new factory built at Trafford Park near Manchester. Since it could concentrate on the same basic mark of the Merlin, the Ford Trafford Park factory achieved the highest monthly production rate of any British aircraft engine factory, reaching an

[15] Lumsden, *British Piston Aero-Engines and Their Aircraft*, pp. 126-33.
[16] Ritchie, *Industry and Air Power*, p. 129.
[17] Ritchie, *Industry and Air Power*, pp. 130-34.
[18] Lloyd, *Rolls-Royce: The Merlin at War*, pp. 190-99; Hornby, *Factory and Plant*, p. 257.
[19] Lloyd, *Rolls-Royce: The Merlin at War*, p. 197.
[20] Hornby, *Factory and Plant*, p. 257.

average of 900 engines a month in late 1944.[21] Production of all types of Rolls-Royce aircraft engines at the different factories was as follows:

Derby: 31,879

Crewe: 28,341

Hillington: 23,395

Ford: 29,487

Total Rolls-Royce: 113,102

Table A-I-2: Rolls-Royce Factory Expansion: Total Floor Area 1935-1944

Year	Derby	Crewe	Hillington	Dispersal Premises	Total Floor Area
1935	803,520 sq. ft.	N/A	N/A	N/A	803,520 sq. ft.
1939	1,115,060 sq. ft.	412,680 sq. ft.	N/A	109,200 sq. ft.	1,636,940 sq. ft.
1941	1,235,910 sq. ft	742,050 sq. ft.	1,833,000 sq. ft.	991,450 sq. ft.	4,804,410 sq. ft.
1943	1,516,040 sq. ft	965,400 sq. ft.	2,153,500 sq. ft.	1,464,530 sq. ft.	6,601,770 sq. ft.
1944	1,621,790 sq. ft.	1,107,700 sq. ft.	2,211,500 sq. ft.	1,958,330 sq. ft.	7,228,520 sq. ft.

Source: Rolls-Royce Ltd: *Services Rendered 1939-45*, (Derby, No Date), p. 3.

The size of the factories building the Merlin varied with location. The factories at Crewe, Trafford Park and Hillington all had separate buildings reflecting the requirement to limit potential damage from air attack. The factory at Crewe consisted of four rectangular single-story buildings sited adjacent to each other while the Ford Trafford Park factory had three

[21] Hornby, *Factory and Plant*, p. 257.

buildings, including one very large rectangular building. The Glasgow factory consisted of fourteen separate buildings, each building having an area of 120,000 square feet, arranged in three rows of four buildings adjacent to one another, and one row of two buildings.

Rolls-Royce used a form of line production in its factories, though this seems to have varied by location.[22] The layout of the factory buildings was, however, not ideal for continuous flow production with buildings and processes separated one from another. At Crewe, for example, a building housing the auxiliary departments for heat treating, plating, the test department and others needs was located in between the two main machine shops.[23] At the Glasgow factory, raw materials and parts flowed from east to west along the line of separate buildings, and from south to north to the buildings performing final assembly of the engines.[24] The Ford Trafford Park factory divided production of the Merlin into three production units, one for machining non-ferrous metal engine parts, one for machining steel engine parts, and a third unit for receiving stores, heat treating parts, manufacturing valve springs and pipes.[25] The machine tools and other equipment in each unit followed line production methods, with conveyors helping the flow of work.[26]

The type of machine tools in use also varied by factory. The factories at Derby, Crewe and Glasgow had to cope with recurring changes in marks of the Merlin. During 1943 the Glasgow factory manufactured five marks of the Merlin, and during 1944 built ten different marks, including Merlin engines with single-stage superchargers and Merlin engines with two-stage superchargers which required different tooling and manufacturing processes.[27] At Crewe, at least in the early years of the war, standard machine tools predominated, though in many cases using special jigs and fixtures adapted for less-skilled workers.[28] Later in the war, after the

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[22] During the war *Aircraft Production* and *Machinery (London)* featured a series of articles on production at the different Rolls-Royce factories and the Ford Trafford Park factory that discuss production methods and types of machine tools in considerable detail. These articles are listed in the Bibliography.
[23] 'The Manufacture of Rolls-Royce Aero-engines', *Machinery (London)*, Vol. 55, No. 1427, (February 15, 1940), p. 528.
[24] 'The Production of the Merlin Engine', *Machinery (London)*, Vol. 65, No. 1671, (October 19, 1944), p. 422.
[25] 'Line Production of the Rolls-Royce Merlin Engine', *Machinery (London)*, Vol. 61, No. 1567, (October 22, 1942), p. 450.
[26] 'Line Production of the Rolls-Royce Merlin Engine', pp. 450-51.
[27] Hornby, *Factories and Plant*, p. 261.
[28] 'The Manufacture of Rolls-Royce Aero-engines', p. 534.

Merlin had been in production for several years, the factories shifted to using more special purpose machines, including some high-production machines built in England or imported from America, to manufacture parts and components that had remained unchanged.[29] Concentrating on fewer marks of the Merlin allowed the Ford Trafford Park factory to employ more special-purpose, high production machine tools, particularly multi-spindle machines to drill, bore and ream the many holes required in the Merlin cylinder block and crankcase.[30] The machine tools used to manufacture the Merlin in the British factories differed from those in use at the Packard factory in Detroit. A British reporter from the magazine *Aircraft Production*, visiting the Packard factory in August 1944, commented that 'it would be an understatement of say that the machine shops are large and well equipped. A considerable number of very elaborate specially designed machines are in use, among which multiple-spindle drilling and boring machines are particularly noticeable…It is unlikely that examples of many of these machines are in use in England.'[31]

[29] 'Manufacturing the Rolls-Royce Merlin XX, Part I', *Aircraft Production*, Vol. IV, No.45, (July 1942), p. 433.
[30] 'Line Production of the Rolls-Royce Merlin Engine'; 'Machining Aero-Engine Cylinder Blocks', *Machinery (London)*, Vol. 61, No. 1570, (November 12, 1942), pp. 533-38; 'Machining Aero-engine Crankcase Castings', *Machinery (London)*, Vol. 61, No. 1471, (November 19, 1942), pp. 561-65; 'Machining Aero-engine Crankshafts and Camshafts', *Machinery (London)*, Vol. 61, No. 1572, (November 26, 1942), pp. 589-96; 'The Manufacture of Aero-engine Connecting Rods', *Machinery (London)*, Vol. 61, No. 1573, (December 3, 1942), pp. 617-23; 'The Manufacture of Aero-engine Pistons', *Machinery (London)*, Vol. 61, No. 1574, (December 10, 1942), pp. 645-49; 'Ford Methods in Rolls-Royce Merlin Engine Production', *Machinery (London)*, Vol. 62, No. 1579, (January 14, 1943), pp. 29-33; 'The Production of the Rolls-Royce Merlin Engine', *Machinery (London)*, Vol. 62, No. 1580, (January 21, 1943), pp. 57-60; 'Valve Spring Manufacture', *Machinery (London)*, Vol. 62, No. 1581, (January 28, 1943), pp. 85-89; 'Special Equipment in the Production of the Merlin Engine', *Machinery (London)*, Vol. 62, No. 1582, (February 4, 1943), pp. 113-17.
[31] 'The Packard-Built Merlin', *Aircraft Production,* Vol. VI, No. 70, (August 1944), p. 391.

Appendix II: Bristol and Wright Air-cooled, Radial Engines of World War II

Bristol Engines

The Mercury

The Bristol Aeroplane Company introduced the Mercury engine in 1932 as a replacement for its famous Jupiter. The Mercury offered greater horsepower than the Jupiter and was smaller in diameter, making it an ideal engine for the bi-plane fighters of the era. The Mercury was a nine-cylinder, poppet-valve, single-row air-cooled radial engine with a capacity of 1,520 cubic inches, a bore of 5.75 inches and a stroke of 6.5 inches.[1] A re-design of the cylinder fins gave 50% more area than on the Jupiter. The first production version, the Mercury IVS.2, introduced in 1932 had a normal output of 510 hp and maximum output of 560 hp. Continued development led in 1934 to the Mercury VIS, which boosted the output to 605 hp.[2] In 1936, Bristol introduced the Mercury VIII, the first engine to be built at the new shadow factories. The Mercury VIII featured progressive improvements in the design of the cylinder head and barrel with greatly increased cooling area, new pistons and valves and strengthened components to allow for using higher octane fuels.[3] The Mercury VIII offered a significant increase in power, with a rated power output of 825 hp and maximum power of 840 hp at 14,000 feet altitude. Two years later Bristol came out with the Mercury XV, which was similar to the Mercury VIII, but adapted to run on 100 octane fuel. The Mercury VIII and XV powered two of the aircraft that were important to Britain's rearmament in the late 1930's, the Bristol Blenheim light bomber and the Gloster Gladiator, the last bi-plane fighter in the RAF. By the beginning of the war, however, the Mercury's 840 hp was no longer deemed adequate for combat aircraft. The Mercury was also built under license in Czechoslovakia, Finland, France, Italy, Japan and Poland.[4]

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[1] Lumsden, *British Piston Engines and their Aircraft*, p. 104.
[2] 'The "Bristol" Mercury & Pegasus Engines', *The "Bristol" Review*, Engine Issue No. 4, (March 1932), pp. 6-8.
[3] 'The New Series "Bristol" Mercury and Pegasus Engines', *The "Bristol" Review*, Engine Issue No. 10, (June 1936), pp. 12-14.
[4] Heaven, John: *Bristol Piston Engines Since 1914*, unpublished manuscript, copy in the possession of the Rolls-Royce Heritage Trust, Filton.

The Pegasus

The Bristol Pegasus was introduced in 1932 at the same time as the Bristol Mercury. It was a larger engine intended for bomber and transport aircraft. Like the Mercury, the Pegasus was a nine-cylinder, poppet-valve, single-row air-cooled radial engine with a capacity of 1,753 cubic inches, a similar bore of 5.75 inches, but a longer stroke of 7.5 inches as in the Jupiter engine.[5] The diameter of the Pegasus was about four inches wider than the diameter of the Mercury. With greater capacity came more power. In 1932 with various levels of supercharging the first models of the Pegasus offered 590 to 635 BHP.[6] As with the Mercury, progressive development led to engines of greater power. The Pegasus X of 1936 had a take-off power rating of 920 BHP and a maximum rated power of 875/915 BHP at 6,250 feet altitude.[7] The Pegasus was suitable for larger aircraft and in the late 1930's powered a wide range of British and European commercial and military aircraft, including the large Imperial Airways Empire class flying boats. Rearmament of the RAF's bomber force depended on the Pegasus which equipped the Handley Page Hampden and the Vickers Wellington, the principal RAF bombers in the early years of the war. The Pegasus powered several of the RAF's flying boats, including the Short Sunderland, and the Fairey Swordfish of the Royal Navy's Fleet Air Arm. Like the Mercury, the Pegasus was built under license in Czechoslovakia, France, Italy, Japan and Poland.[8] While a few of the late model Pegasus engines could generate 1,000 HP, by the late 1930's the engine had reached the end of its potential development. More power had to come from a completely new engine.

The Hercules

The Hercules was Bristol's response to the demand for airplane engines of ever greater power. When it was introduced in 1937, the Hercules was rated at 1,375 BHP making it at the time the most powerful British aircraft engine to have passed its type test.[9] The distinctive characteristic

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[5] Lumsden, *British Piston Engines and their Aircraft*, p. 108.
[6] '"Bristol" Engines for 1932', *The "Bristol" Review*, Engine Issue No. 4, (March 1932), p. 9.
[7] 'The New Series "Bristol" Mercury and Pegasus Engines', *The "Bristol" Review*, Engine Issue No. 10, (June 1936), p. 14.
[8] Heaven, *Bristol Piston Engines Since 1914*.
[9] *Flight*, (December 2, 1937).

of the Hercules engine was the sleeve-valve mechanism which offered certain advantages over the standard poppet-valve mechanism in engines like the Mercury and Pegasus.

The sleeve-valve replaces the valves used in poppet-valve engines that take in the fuel-air mixture into the cylinder and eject the exhaust gases after combustion.[10] Instead, the cylinder in the sleeve-valve engines had three inlet and two exhaust ports cut into the cylinder's side. A metal sleeve, placed between the inner wall of the cylinder and the piston, moved in a reciprocating-vertical, elliptical motion during the combustion cycle. As it did so, four ports cut out in the sleeve aligned with the ports on the cylinder wall to allow the fuel-air mixture to enter the cylinder and the exhaust gases to be forced out. The advantage of the sleeve-valve was that it did away with the entire valve mechanism, and all its component parts, in the poppet-valve engine.[11] The removal of the valve mechanism reduced maintenance and the number of components that needed to be manufactured thereby reducing manufacturing costs, though manufacturing a cylinder with the sleeve-valve mechanism created its own unique production challenges that proved to be difficult to overcome.

The origins of the Bristol Hercules aero-engine can be traced back to Roy Fedden's contacts with Harry Ricardo in the 1920's. Ricardo, an independent researcher and consulting engineer on internal combustion engines, had been exploring with the support of the Air Ministry the possibilities of using the single sleeve-valve mechanism to improve the efficiency of petrol engines given the poor anti-knock qualities of fuels then available and the tendency for extremely hot exhaust valves to fail, a reliable method for cooling the exhaust valve having yet to be developed.[12] Fedden thought Ricardo's work was promising, and in 1926 Bristol began an intensive program to develop an aero-engine employing the single sleeve-valve, also with financial support from the Air Ministry.[13] In 1934, after eight years of research and thousands of

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[10] Judge, *Aircraft Engines*, Vol. Two, pp. 151-54.

[11] Hassell, Patrick: 'The Bristol Sleeve Valve Aero Engines', in Starr, Fred, Edward L. Marshall, and Bryan Lawton: *The Piston Engine Revolution: Papers from a Conference on the History of the Reciprocating Internal Combustion Engines Held at the Museum of Science and Industry, Manchester, 14-17 April 2011*, (Manchester, UK, 2012), p. 120.

[12] Marshal, E.L.: 'A Lifelong Love Affair—Sir Harry Ricardo and the Sleeve Valve', *The International Journal for the History of Engineering and Technology*, Vol. 83, No. 1, (January 2013), p. 73.

[13] Hassel, 'The Bristol Sleeve Valve Aero Engines', p.116;

hours of testing, Bristol introduced the Perseus, a nine-cylinder air-cooled sleeve-valve aero-engine offering maximum power of 760 HP.[14] At the time of the Perseus' debut, Bristol claimed that not only that the cost of manufacture would be cheaper than comparable poppet-valve engines, but also, interestingly, that 'Greater scope is afforded for large production with unskilled labour.'[15] Bristol followed the Perseus with the Aquila, a smaller 500 HP sleeve-valve engine, but knowing that other competitors were working on more powerful double-row air-cooled radial engines to meet the never-ending demand for greater power, Fedden and his team began working on a design for a 14 cylinder two-row sleeve-valve engine using the same cylinders as in the Perseus.[16] Bristol had come to recognize that the nine-cylinder radial engines of up to 1,000 HP would no longer meet the requirements of the aircraft manufacturers who would need aero-engines of 2,000 HP or greater.[17] By early 1935, Fedden had worked out a design that promised an initial power output of 1,320 HP well-above the Pegasus or the Perseus nine-cylinder engines then available.[18] In November 1936, the Hercules successfully passed a 50-hour civil type test and created a sensation when it went on display at the Paris Air Show that same month.[19] The Hercules made its British debut at the Society of British Aircraft Constructors show at Hatfield in June 1937, but by then the new Bristol engine was already under consideration to power new bombers for the Royal Air Force.[20]

During the war, the Bristol Hercules powered four of the RAF's bombers– the Short Sterling, Vickers Wellington, the Handley Page Halifax and AVRO Lancaster -- and Bristol's own twin-engine Beaufighter, a night fighter and long-range strike fighter. Arguably the most significant application of the Hercules was in the Wellington and the Halifax. The Air Ministry had instructed Vickers to develop a version of the Wellington with the Hercules III engine as the Wellington Mk III back in 1938, but the difficulties with Hercules development and production

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[14] Heaven, *Bristol Engines Since 1914*, pp. HIS5/3-4.
[15] 'The "Bristol" Perseus Sleeve Valve Engine', *The "Bristol" Review*, Engine Issue No. 7, (July 1934), p. 18.
[16] Heaven, *Bristol Engines Since 1914*, P. HIS7/1; Bristol Aeroplane Company Minutes of Directors' Meeting in Committee, 15 October 1935, BAC Directors' Committees Minutes, Vol. 5, 3 January 1935 to 22 December 1936
[17] 'The New Double-Bank Sleeve-Valve Engine', *The "Bristol" Review*, Engine Issue No. 12, (June 1937), p. 15.
[18] Bristol Aeroplane Company Minutes of Directors' Meeting in Committee, 26 February 1935, BAC Directors' Committees Minutes, Vol. 5, 3 January 1935 to 22 December 1936
[19] 'Power at the Salon', *Flight*, (November 26, 1936), p. 579.
[20] 'Engines at Hatfield', *Flight*, (June 24, 1937), pp. 642-43.

delayed the Wellington Mk III's entry into service until 1941.[21] The first production Wellington Mk III flew in May 1941, now equipped with the Hercules XI which the shadow factories had begun building.[22] Vickers built 1,519 Wellington Mk III bombers before switching to the improved Wellington Mk X with the more powerful Hercules VI engine.[23] The Bomber Programme, and the Hercules VI, gave the Wellington a new lease on life. Under the Target Programme of July 1941, production of the Wellington was to begin tapering off in July 1942, declining to less than a hundred aircraft a month by January 1943, but under the Bomber Programme Wellington production was planned to increase and expand to 300 aircraft a month by June 1943 to meet the Prime Minister's targets.[24] Production of the Wellington increased by nearly 50% from 1941 to 1942, and continued at more than 2,000 aircraft a year through 1944.[25] Ultimately Vickers would build 3,804 Wellington Mk X aircraft for Bomber Command, and over 1,500 Wellingtons for R.A.F. Coastal Command.[26]

The principal reason for the surge in demand for the Hercules was the decision to convert the Handley Page Halifax from the Rolls-Royce Merlin engine to the Hercules engine. In July 1941, the Ministry of Aircraft Production became concerned with a possible shortage of Rolls-Royce Merlin XX engines for the Halifax and the AVRO Lancaster then coming into production and requested Handley Page to fit a Halifax with the Hercules VI as a trial.[27] A prototype Halifax with the Hercules first flew in October 1942 and proved to have superior performance to the Merlin-engine versions, which by this time had been found to be inferior to the Lancaster in terms of ceiling, bomb load and range.[28] The Halifax and the Hercules proved to be a winning combination, giving an increase in power at take-off compared to the Merlin, critical for heavily loaded bombers, higher maximum and cruising speeds and an improved ceiling. Designated the Halifax Mk III, the first production version made its first flight in August

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[21] Andrews and Morgan, *Vickers Aircraft since 1908*, pp. 332-33.
[22] The Vickers Wellington Medium Bomber, AVIA 46/121, NA.
[23] Andrews and Morgan, *Vickers Aircraft since 1908*, pp. 335, 337-39.
[24] Postan, *British War Production*, Table J and Table K, pp. 476-77.
[25] Ministry of Aircraft Production Statistical Review 1939-1945, pp. 5, 16-17.
[26] Ministry of Aircraft Production Statistical Review 1939-1945, pp. 5-6.
[27] The Handley Page Heavy Bomber, AVIA 46/112, NA.
[28] Furse, *Wilfird Freeman*, P. 322; The Handley Page Heavy Bomber, AVIA 46/112, NA.

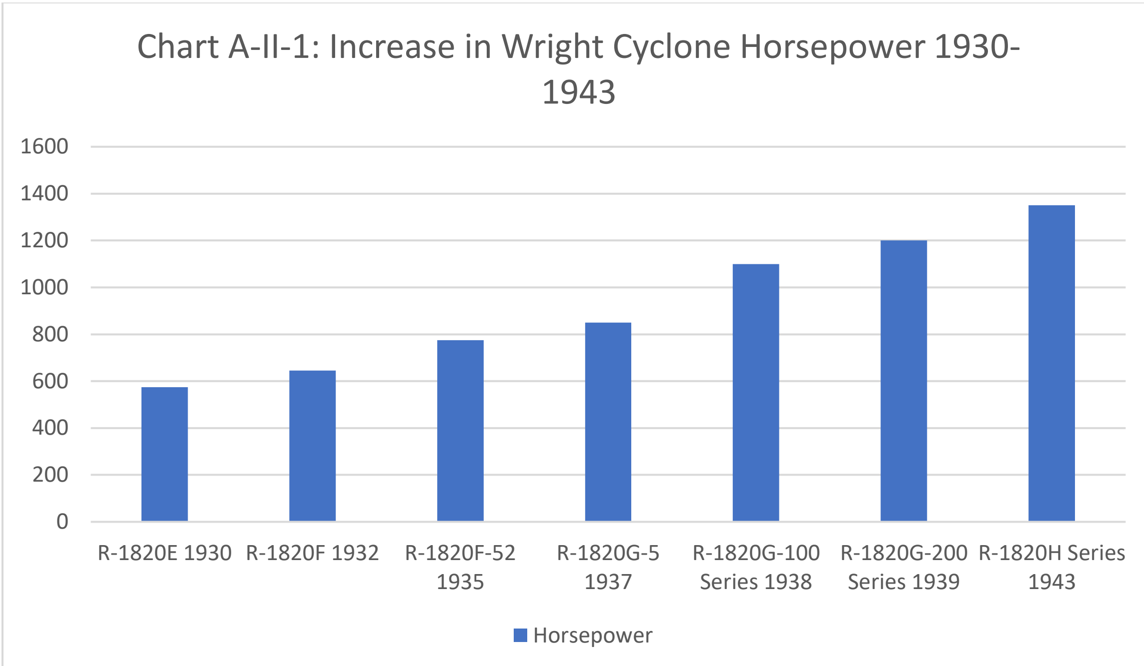
1943 and series production began soon after with a change in the engine to the Hercules XVI.[29] The Halifax Mk III was built in greater numbers than any other version of the Halifax, 2,091 being completed by the end of the war.[30] It is perhaps too much to claim that the Hercules resurrected the Halifax from possible oblivion, but in giving the Halifax improved performance the Hercules helped sustain the bombing offensive against Germany in the final year and a half of the war.

The Hercules did not fare as well as the big Pratt & Whitney and Wright air-cooled, radial engines in the post-war commercial airliner world, but did see long service powering military transport aircraft. Civil versions of the Hercules powered the Bristol 170 Freighter, the Handley Page Hermes airliner, which served with the British Overseas Airways Corporation and the Vickers Viking regional airliner. Bristol had more success with the Hercules in military transports. The RAF purchased 144 Hercules-powered Handley Page Hastings transports, which served until 1977, and 415 twin-engine Vickers Varsity and Valetta aircraft, based on the Viking. The French firm SNECMA Moteurs (Société nationale d’études et de construction de moteurs d’aviation) acquired a license from Bristol to build the Hercules, rated at 2,089 hp, for the Nord Noratlas military transport which served in the French l’Armée de l’Air, the German Budesluftwaffe, the Israeli Air Force and several African air forces into the 1990’s.[31]

[29] The Handley Page Heavy Bomber, AVIA 46/112, NA; Barnes, *Handley Page Aircraft Since 1907*, p. 404.
[30] Barnes, *Handley Page Aircraft Since 1907*, p. 404.
[31] Ibid., pp. 435-74; Andrews, C.F. and E.B. Morgan: *Vickers Aircraft since 1908*, New Edition, (London, 1988), pp. 395-416; Barnes, C.H.: *Bristol Aircraft since 1910*, 3rd Ed., (London, 1988), pp.330-42; Thetford, Owen: *Aircraft of the Royal Air Force since 1918*, 8th Ed., (London, 1988), pp. 325-27, 566-70.

Wright Aeronautical Engines

Cyclone 9



Source: *Aerosphere 1939*; *Jane's All the World's Aircraft 1945/46*.

In a little more than a decade, Wright Aeronautical more than doubled the power of the Cyclone 9 engine, better known as the R-1820, its military designation. Development of the Cyclone 9 began in 1924, when the U.S. Navy requested Wright to develop a new nine-cylinder air-cooled radial engine with greater power than the 200 hp Wright Whirlwind engine.[32] This led to the first Cyclone engine, introduced in 1927, the P-2 with the military designation R-1750, which rated at 525 hp.[33] To get more power, Wright widened the bore of the Cyclone to increase the capacity to 1,823 cubic inches, hence its military designation of R-1820.[34] While the same overall size as the R-1750, the bigger capacity of the R-1820's cylinders boosted the horsepower to 575 hp. As Chart A-II-1 illustrates, following the R-1820's introduction in 1930

[32] *The Aerosphere 1939*, p. 804.
[33] *The Aerosphere 1939*, p. 805.
[34] *The Aerosphere 1939*, p. 813.

Wright progressively increased the power output so that by 1939 the Cyclone 9 R-1820G-200 series was putting out 1,200 hp, double the power output of the R-1820E.[35]

Table A-II-1: Comparative Data: Wright Cyclone 9 and Bristol Pegasus XVIII

	Wright Cyclone 9	**Bristol Pegasus XVII**
No. of Cylinders	9	9
Total Cylinder Volume	1,823 cu. In.	1,753 cu.in.
Diameter	55 in.	55.3in.
Dry Weight	1,310 lbs.	1,180 lbs.
Max. Take-off Power	1,200 hp	1,050 hp

Source: *Jane's All the World's Aircraft 1945-46*, (London, 1946)

The Wright Cyclone 9 R-1820-G-200 series engine, the model built in greatest quantity during World War II, was a nine-cylinder, single-row, air-cooled radial engine with a dry weight of 1,310 lbs. Like the Bristol Mercury and Pegasus, the Cyclone 9 was a poppet-valve engine, but with only one intake and one exhaust port in contrast to the four ports on the Mercury and the Pegasus. The G-200 series was a major redesign of the Cyclone. With the G-200, Wright decided that improved performance was more important than interchangeability of parts with earlier models of the Cyclone.[36] The cylinder heads were cast from an aluminium alloy and to improve cooling Wright re-designed the cylinder head to increase the cooling area by 20%, deepening the cooling fins from 1 ½ inches in depth to 2 ¼ inches, although this improvement presented an even greater challenge to the Wright foundry casting the cylinder heads.[37] Wright

[35] *Aerosphere 1939* provides an excellent and detailed description of the different models of the R-1820 and the changes to component parts that allowed the doubling of horsepower.
[36] Hill, H.C.: 'Engineering Aspects of the Single-Row Cyclone G-200 Series Engine', Wright Aeronautical Corporation, (1940), p. 2.
[37] 'Engineering Aspects of the Single-Row Cyclone G-200 Series Engine', p. 4; *G-200 Series Wright Cyclone*, Wright Aeronautical Corporation, (No Date).

also re-designed the intake and exhaust ports to improve their efficiency. The cylinder head was attached to a strengthened forged steel cylinder barrel which, thanks to improved machining techniques, had deeper and more closely spaced cooling fins than the G-100 series, offering 60% more cooling area.[38] The G-200 series incorporated aluminium alloy forged pistons with improved cooling and an additional piston ring for more uniform oil flow.[39]

In the earlier Cyclone 9 R-1820-G-100 series, Wright switched from a forged aluminium to a forged steel two-section crankcase to strengthen the engine as the power output increased. The G-200 series continued with the steel crankcase, but with an improved design to reduce weight and simplify machining operations.[40] To reduce more weight, Wright used a cast magnesium alloy for the front section of the crankcase in place of aluminium. The two-piece crankshaft for the G-200 series was made from a forged chrome-nickel steel alloy and incorporated two Wright Dynamic Dampers to reduce torsional vibration and stress to the propeller shaft.[41] The G-200 used a master rod and eight connecting rods forged from chrome-nickel-molybdenum steel alloy. Wright refined the supercharge design on the G-200 series to improve the flow of air to the intake ports, allowing a greater quantity of air to flow more directly to the impeller, and redesigned the impeller blades for greater efficiency. To save weight on the supercharger and its mounting, Wright again substituted lighter magnesium castings for the mounting and rear housing sections.[42] The propeller shaft, a hollow forging made from a steel alloy, attached to the crankshaft through the reduction gear machined from high-strength, nitralloy steel.

During the 1930s, the Cyclone 9 found wide application in American military and commercial aircraft. As aircraft designers shifted to all-metal aircraft with greater speeds, range and payloads, Wright matched the need for increasing power with its improved models of the Cyclone 9. In the pre-war years, Wright had its greatest success with multi-engine commercial

[38] Hill, 'Engineering Aspects of the Single-Row Cyclone G-200 Series Engine', p. 4; 'Wright G-200 Cyclone, Rated at 1200 H.P., Released for Both Domestic and Export Sale', *Trade Winds*, Vol. 4, No. 10, (Navy Number 1939), p. 7.
[39] *G-200 Series Wright Cyclone*; 'Wright G-200 Cyclone, Rated at 1200 H.P., Released for Both Domestic and Export Sale', p. 8.
[40] Hill, 'Engineering Aspects of the Single-Row Cyclone G-200 Series Engine', p. 5.
[41] *G-200 Series Wright Cyclone*; 'Wright G-200 Cyclone, Rated at 1200 H.P., Released for Both Domestic and Export Sale', p. 8.
[42] *G-200 Series Wright Cyclone*.

airliners. Most airline operators of the Douglas DC-2/DC-3 series chose the Cyclone 9 over Pratt & Whitney's Twin Wasp. The Cyclone 9 helped Wright regain a competitive position versus Pratt & Whitney.[43] Although best known as the engine that powered the Boeing B-17 during World War II, the Cyclone 9 had a remarkably long life after the war. Production of the Cyclone 9 finally ended in 1963 with the final models offering 1,525 hp, nearly three times the output of the first Cyclone 9 engine of the late 1920s. The Grumman S-2 Tracker anti-submarine aircraft, with two Cyclone 9 R-1820-82WA engines, served with the U.S. Navy from the 1950's until the 1970's, while the S-2's carrier on-board delivery aircraft derivative, the C-1 Trader, served until 1988. The Canadian Air Force did not retire its S-2 Trackers until the 1990's, giving the Wright Cyclone 9 some 50 years of continuous service.

The Cyclone 9 had an even longer life in the Soviet Union. In 1933 Wright Aeronautical granted a license to the Soviet Government to build the Cyclone 9 in the Soviet Union as the M-25, completing 13,888 M-25 engines by 1942.[44] A.D. Shvetsov, chief designer at the factory that build the M-25, took on the task of improving the engine, developing the M-62 engine based on the Cyclone 9.[45] Offering 800-1,000 hp in various versions, the M-62 and its later variant the Ash-62 was in production for 60 years with 40,361 engines built in the Soviet Union, with more built in China and Poland.[46] The Ash-62 equipped the Antonov An-2 all-metal single-engine light transport biplane built after the war in great numbers, with over 18,000 built in the Soviet Union, China and Poland.

Cyclone 14

The Cyclone 14 was Wright's first successful double-row air-cooled radial engine. By the mid-1930s, it was clear that airplanes larger than the Douglas twin-engine DC-3 were on the horizon, particularly large, multi-engine flying boats to cross the Atlantic and Pacific, as well as larger bombers and patrol planes for the Army Air Corps and the Navy. To meet this expected need, Wright Aeronautical engineers decided to develop an engine that would provide 30% to

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[43] Eltscher, Louis R., and Edward M. Young: *Curtiss-Wright: Greatness and Decline*, (1998), p. 74.
[44] Kotelnikov, Vladimir: *Russian Piston Aero Engines*, (Marlborough, Wiltshire, 2005), pp.117-19.
[45] Kotelnikov, *Russian Piston Aero Engines*, pp.117-19.
[46] Kotelnikov, *Russian Piston Aero Engines*, p. 120.

40% more power than the Cyclone 9.[47] Initially aiming for 1,500 hp, Wright chose an engine with fourteen cylinders in a double-row configuration, building on Wright's previous experience with two smaller double-row engines built in limited quantities. The new 14-cylinder, double-row engine, designated Cyclone 14, had two and a half times the cooling area of the Cyclone 9. This was made possible through improved casting techniques for the cylinder head and improved machining of longer fins on the cylinder barrel.[48]

Wright began developing the Cyclone 14 in 1935 with the engine receiving its Approved Type Certificate in June 1937.[49] The first Cyclone 14 had a take-off rating of 1,500 H.P., a 50% increase in power output over the Cyclone 9 G-100 series, making it at the time the most powerful aircraft engine in production. By coincidence, the first application of the Cyclone 14, like the Bristol Hercules, was in a flying boat, in this case the Boeing Model 314 Clipper.

Although it differed in its design and construction, the Cyclone 14 was comparable in size and power output to the Hercules, the principal difference being that like all Wright air-cooled radial engines, the Cyclone 14 was a poppet-valve engine while the Hercules used sleeve-valves in its cylinders. From 1937 to 1945, sixteen different versions of the Cyclone 14 went into production for commercial operators, the Army Air Force and the U.S. Navy. The principal war time production models were the Cyclone 14A producing 1,600 H.P., the Cyclone 14BA[50] with 1,700 H.P., and the Cyclone 14BB with 1,900 H.P. There were, of course, several sub-types within each major model, with odd numbers for Army Air Force engines and even numbers for Navy engines.

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[47] Wright Aeronautical Corporation, *Wright Double-Row Cyclone 14 Aircraft Engines*, (No Date).
[48] *Wright Double-Row Cyclone 14 Aircraft Engines*.
[49] *Aerosphere 1939*, (New York, NY, 1939), p. 827.
[50] The first version of the Cyclone 14 became the Cyclone 14A when Wright introduced the more powerful 1,700 hp model as the Cyclone 14B. This became the Cyclone 14BA when the more powerful Cyclone 14BB came into service.

Table A-II-2: Comparative Data: Wright Cyclone 14BA and Bristol Hercules VI

	Wright Cyclone 14BA	Bristol Hercules VI
No. of Cylinders	14	14
Total Cylinder Volume	2603 cu. In.	2360 cu.in.
Diameter	55 in.	52 in.
Dry Weight	1,965 lbs.	1,930 lbs.
Max. Take-off Power	1,700 H.P.	1,615 H.P.

Source: *Jane's All the World's Aircraft 1945-46*, (London, 1946)

The Cyclone 14 drew on many of the design features of the Cyclone 9.[51] The cylinders were basically the same, but with the greater cooling area developed for the Cyclone 9 G-200 series. The engine's fourteen cylinders were arranged in two rows of seven cylinders, with the rear row slightly staggered to improve the flow of cooling air. The diameter of the Cyclone 14 remained the same as the Cyclone 9, and despite having a second row of cylinders, the engine was only a foot longer than the Cyclone 9. The Cyclone 14 was a poppet-valve engine, with one intake valve and one exhaust valve in the cast aluminium cylinder head, as with the Cyclone 9. The crankcase came in three sections, bolted together to hold the two rows of cylinders. In the Cyclone 14A, the crankcase sections were made from aluminium forgings, but as the power output increased Wright switched to using steel forgings for the crankcase. With two rows of cylinders, the Cyclone 14 needed a longer crankshaft with two sections to allow for two master connecting rods for each bank of cylinders. Wright designed a three-section crankshaft with two Wright Dynamic Dampers to reduce torsional vibration. The front section of the crankcase covering the reduction gear and the rear cover housing the supercharger were made from magnesium alloy. As a larger and more complex engine the Cyclone 14 had many more parts than the Cyclone 9, with over 8,000 separate parts. As one would expect, machining, inspecting and assembling an aircraft engine with 8,000 parts was a production challenge of a significantly

[51] 'The Double Row Cyclone 14', *Trade Winds*, Vol. 4, No. 11, (July 1939), p.7; Wright Aeronautical Corporation, *Wright Double-Row Cyclone 14 Aircraft Engines*, (No Date)

greater magnitude than manufacturing the Cyclone 9. Production of the Cyclone 14 ended at the end of World War II.

Cyclone 18

The history of the Wright Cyclone 18 shows that 'engine development is evolutionary—and costly and complex.'[52] The Cyclone 18 came out of Wright's experiments to join two Cyclone 9 engines together in the search for greater engine power. Wright abandoned this early project and instead in 1936 turned to developing a completely new 18-cylinder, two-row engine design with 3,350 cubic inch capacity.[53] This engine had a three-section steel crankcase, incorporating two crankcase sections from the Cyclone 9, nine cylinders per row, the same cylinder design and master and articulated connecting rods, with the same bore and stroke as the Cyclone 14 and a two-throw crankshaft based on work on the Cyclone 14.[54] The first engine ran in April 1937, producing 1,800 hp and soon passed a 50-hour endurance test.[55] Rebuilt to incorporate a two-stage supercharger, the experimental Cyclone 18 (designated the R-3350 by the Army Air Corps) failed its first 150-hour test due to problems with the propeller reduction gear.[56] This was just one of three significant problems that would plague the Cyclone 18 until late in the war. Development of the Cyclone 18 continued with the Army Air Corps purchasing small numbers of experimental engines. By 1939, the Cyclone 18 was producing 2,000 hp, but the engine had developed problems with exhaust valve failures and, more seriously, difficulties cooling the cylinders, a problem that continued even after the engine was introduced into combat operations late in the war.[57] When in April 1941 the Army Air Corps placed an order for the Boeing B-29 long-range bomber powered by four Cyclone 18 engines, now rated at 2,200 hp, the Cyclone 18 was still very much an experimental engine having flown only a limited number of hours and was far from ready for production. After Pearl Harbor, the Army Air Force

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[52] 'From 1700 to 2700 Horsepower in 10 Years', *Aviation Week*, (May 24, 1948), p. 26.
[53] 'From 1700 to 2700 Horsepower in 10 Years', p. 26.
[54] 'From 1700 to 2700 Horsepower in 10 Years', p. 26.
[55] 'Summary of the R-3350 Engine Project', p. 1.
[56] 'Summary of the R-3350 Engine Project', p. 1.
[57] 'Summary of the R-3350 Engine Project', p. 2.

(as it then was) gave the B-29 programme its highest priority and tripled its order for Cyclone 18s.[58]

Table A-II-3: Comparative Data: Wright Cyclone 18BA and Bristol Centaurus

	Wright Cyclone 18BA	Bristol Centaurus XI
No. of Cylinders	18	18
Total Cylinder Volume	3346 cu. In.	3,270 cu.in.
Diameter	55.2 in.	55.3 in.
Dry Weight	2668 lbs.	2,695 lbs.
Max. Take-off Power	2,200 hp	2,520 hp

Source: *Jane's All the World's Aircraft 1945-46*, (London, 1946)

The Cyclone 18 had the same diameter as the Cyclone 9, but with two rows of cylinders and accessories was nearly 30 inches longer.[59] The front section of the crankcase and the rear supercharger housing were magnesium alloy castings, while the crankcase main section comprised three steel forgings, front, centre and rear. The crankcase main section had 18 mounting pads for the two rows of nine cylinders. The Cyclone 18's two-throw crankshaft, to accommodate two master connecting rods, one for each bank of cylinders, was made up of three sections each forged from a chrome nickel steel alloy and machined for accuracy and finish. As in the Cyclone 14, the crankshaft had two Wright Dynamic Dampers to deal with torsional vibration. The Cyclone 18's cylinders were based on the Cyclone 9 cylinder design, with an aluminium cylinder head and steel cylinder barrel. The two rows of cylinders were staggered to improve the flow of cooling air. Each cylinder had one intake and one exhaust valve. The cylinder head had deep and closely-spaced fins for cooling, while the cylinder barrel

[58] Ibid.; McCutcheon, Kimble D.: 'Wright R-3350 "Cyclone 18"', Aviation Engine Historical Society, https://www.enginehistory.org/Piston/Wright/WrightR-3350.pdf, accessed 13 December 2019.
[59] This description of the Cyclone 18 comes from Wright Aeronautical Corporation: *Wright Cyclone 18 Aircraft Engine, Series C18BA, Preliminary Instruction Book*, (November 1942).

had the newer ‘W’ aluminium fins inserted in place of the steel fins cut into the cylinder barrel. The initial models of the Cyclone 18 had a carburetor, while later models switched to fuel injection. The Cyclone 18 had over 13,000 parts.

Problems with the Cyclone 18 continued, leading the Army Air Force to form the R-3350 Engine Committee composed of representatives of the Army Air Force, Wright Aeronautical and Pratt & Whitney to coordinate efforts to address these problems. As previously related, finding solutions delayed production of the Cyclone 18. During 1942 Wright completed only 66 Cyclone 18s and 917 during 1943 at a time when the Army Air Force was trying desperately to ramp up B-29 production; production at the Dodge Chicago factory did not begin until early 1944.[60] Re-designed propeller reduction gears and gear housing helped solve the propeller reduction gear problems, but toward the end of 1943 the Cyclone 18 was still having problems with engine cooling, exhaust valve failures, piston rings and ignition systems.[61] When the B-29 entered combat in May 1944, operating initially from bases in India, the hot temperatures and high humidity made these problems even worse, continuing when the B-29s moved to bases in the Marianas later in the year. In November 1944, 19% of all sorties (one flight by one aircraft) against Japan were ineffective due to mechanical difficulties.[62] Intensive corrective efforts, a more disciplined approach to operating within limits on engine performance and a change in tactics to low level night bombing did much to improve the reliability of the Cyclone 18 in the B-29.

The Cyclone 18 had a long life after World War II, remaining in production until 1961. From the end of the war until it went out of production, Wright built 14,949 Cyclone engines, while Chevrolet built a further 2,591 during the Korean War for the American military.[63] The final military version of the Cyclone 18, the R-3350-42WA, produced 3,800 hp, double the horsepower output of the first Cyclone 18. The Cyclone 18 powered the Lockheed Constellation family which saw widespread service with commercial airlines around the world until the

[60] *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*.
[61] Case History of the R-3350 Engine, P. 126.
[62] Kent, S.R.: ‘Cyclone 18 Performance in Combat Areas”, Society of Automotive Engineers Summer Meeting, June 2-7, 1946, P. 1.
[63] Wright Aeronautical Corporation: Engines Shipped 1920-1964.

advent of the jet airliners, and as military transports for the U.S. Air Force and U.S. Navy. Two Cyclone 18-powered military aircraft, the AC-119 gunship and the EC-121 Airborne Early Warning aircraft, served in the Vietnam War until the mid-1970's, nearly forty years after the first test of the Cyclone 18.

Appendix III: Production Man-hours per Engine

British Engines[1]

Bristol Pegasus III, VI	4,370
Bristol Pegasus XVIII	3,662
Bristol Mercury VIII, IX, XII, XV, XX	5,000
Bristol Taurus	3,700
Bristol Hercules VI, VII, XI	4,457
Bristol Perseus XII	3,600
Bristol Perseus XVI	3,620
Rolls-Royce Merlin II & III	4,174
Rolls-Royce Merlin VIII, X, XX, 21, 30, 47, 60 & 61	4,210
Rolls-Royce Vulture II & V	5,733
Rolls-Royce Griffon	4,960
Napier Sabre I & II	6,200

American Engines[2]

Cyclone 9	2,695
Cyclone 14	2,353
Cyclone 18	
Dodge Chicago	2,855

[1] See un-labelled note of 26.9.41 in AVIA 10/378, NA.

[2] Manpower Office, Management Control, Air Technical Service Command, Army Air Forces: *Labor Statistics for the Aircraft Industry*, November 1944-July 1945, File 218.6-7 Labor Statistics, AFHRA.

Wright Lockland	3,361
Wright Wood-Ridge	3,360
Pratt & Whitney Twin Wasp	1,230
Pratt & Whitney Double Wasp	1,609
Packard Merlin	2,221

Appendix IV: What Happened to the Wartime Aero Engine Factories

Intended to be temporary wartime buildings, many of the aero engine factories in Britain and America had surprisingly long lives. Several are still in use today, seventy-five years after the end of World War II. In the post-war era, the factories built for No. 2 Shadow Group played a significant role in the British motor industry, greatly expanding the industry's production capacity. Several of the firms involved in managing the shadow factories leased the factories from the government and converted them to automobile production.[1]

The Shadow Factories

No. 1 Shadow Group Factories

Austin No. 1 Shadow Factory, Cofton Hackett, Birmingham

After the war, the Austin Motor Company leased and then purchased the combined aero engine and airframe shadow factory to become part of Austin's Longbridge factory complex.[2] The Longbridge East Works, as it was designated, underwent substantial alterations and was converted to building commercial motor vehicles and later vehicles for the British military. The Longbridge East Works lasted until 2006 when it was demolished to make room for a housing estate.

Bristol No. 2 Shadow Factory

The Bristol Aeroplane Company took over its No. 2 Shadow Factory at the end of the war and incorporated the building into the Aero Engine Department complex as No. 2 Engine Factory in what became Bristol's East Works at Filton. After Rolls-Royce acquired the merged Bristol-Siddeley company, Rolls built a new aero engine factory across from the old Bristol East Works

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[1] Thoms, David, and Tom Donnelly: *The Motor Car Industry in Coventry since the 1890's*, (Abingdon, Oxon, 2018), p. 153.

[2] *British Car Factories from 1896*, P. 191; http://www.austinmemories.com/styled-12/index.html accessed 4 June 2020.

at Patchway which was later demolished. In 2015 the St. Francis Group acquired the former East Works site for a mixed-use industrial development as the Horizon 38 Scheme.

Daimler No. 1 Shadow Factory, Capmartin Road, Coventry

In March 1946, the Board of Trade allocated the Daimler No. 1 Shadow Factory, located next to the Company's Radford Works, to the Daimler Company.[3] Daimler repaired and extended the factory building and converted it to automobile production. In 1957 the Standard Motor Company leased the old shadow factory buildings to manufacture transmissions. Jaguar, who took over the Daimler Company in 1960, used the Radford Works to build engines for its automobiles until 1997. The factory complex was demolished in 1997 to make way for housing.[4]

Rootes No. 1 Shadow Factory, Aldermoor Lane, Coventry

In May 1945, the Rootes Securities Company announced that it had reached an agreement with the Government to take over its wartime shadow factories for automobile production, the transaction being completed in December that year.[5] The No. 1 Shadow Factory building manufactured engines and gear boxes for Hillman-Humber cars and later the Talbot Motor Company and Peugeot-Talbot Motor Company. The building served as the headquarters of Peugeot UK until 2008.[6]

Rover No. 1 Shadow Factory, Acocks Green, Birmingham

Rover took over its No. 1 Shadow Factory after the end of the war as part of a consolidation of its automobile production facilities. The Acocks Green factory built automobile engines for the former No. 2 Shadow Factory at Solihull until it was later closed down.

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3 *British Car Factories from 1896*, pp. 214-15; *Financial Times*, March 4, 1946, p. 3.
4 https://en.wikipedia.org/wiki/Daimler_Green accessed 4 June 2020.
5 *Financial Times*, May 26, December 10, 1945
6 *British Car Factories from 1896*, p. 218; https://en.wikipedia.org/wiki/Stoke_Aldermoor accessed 4 June 2020.

Standard No. 1 Shadow Factory, Fletchampsted, Coventry

Like Rootes and Rover, the Standard Motor Company took over its No. 1 Shadow Factory for its own automobile production after the end of the war. Known after the war as the Fletchampstead South factory, Standard used the building to build and assemble engines for its Standard and Triumph automobiles.[7] After 1959 the building was converted to administrative offices for the Standard-Triumph Company and after subsequent consolidations within the motor industry, for the Rover Company.[8] The entire Canley factory site was demolished in 1997.[9]

The No. 2 Shadow Group Factories

Daimler No. 2 Shadow Factory

In July 1945, the Daimler Company arranged with the Ministry of Aircraft Production and the Board of Trade a five-year lease of the Daimler No. 2 Shadow Factory.[10] The lease would allow Daimler to resume automobile production while the company repaired its war-damaged Radford Works. In 1951, the Government allocated the factory to Jaguar Cars Ltd. for automobile production. Jaguar built luxury sedans at the Brown's Lane factory until 2004 when the Ford Motor Company, Jaguar's parent, announced the closure of the factory as a cost-cutting measure.[11] In March 2006, Jaguar sold the Brown's Lane site to a property development company and the factory buildings were demolished to make way for a technology park.[12]

Rootes No. 2 Shadow Factory, Ryton-on-Dunsmore, Coventry

In May 1945, the Rootes Group announced that its Hillman and Humber factories would take over its No.1 and No. 2 Shadow Factories.[13] That August the Board of Trade formally allocated the No. 2 Shadow Factory at Ryton-on-Dunsmore, covering 583,100 square feet, to the Rootes

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[7] *British Car Factories from 1896*, p. 229.
[8] *British Car Factories from 1896*, p. 230.
[9] https://www.standardmotorclub.org.uk/page508.html accessed 4 June 2020.
[10] NA, BT 177/1470, H.R. Camp, Ministry of Aircraft Production, to Sir Philip Warter, Board of Trade, 11 July 1945.
[11] *Financial Times*, September 17, 2004, p. 2; *British Car Factories from 1896*, pp. 220-21.
[12] *Financial Times*, March 23, 2006, p. 5
[13] *Financial Times*, May 26, 1945, p. 3.

Group.[14] The combination of the two factories doubled the company's pre-war factory space.[15] The Ryton-on-Dunsmore factory became the main source for the Hillman, Humber and Sunbeam-Talbot brands and later, after Peugeot acquired Rootes, Peugeot's models.[16] In 2006, however, Peugeot announced that it was closing the Ryton-on-Dunsmore factory and on January 8, 2007 the factory shut down, to be demolished later that year.[17]

Rover No. 2 Shadow Factory, Lode Lane, Solihull, Coventry

The Solihull factory is the only war-time shadow factory that is still in use for automobile production. As production of Hercules engines ended in the summer of 1945, the Rover Group decided to take over the factory and transfer automobile production from its Coventry factories to Solihull.[18] At the end of the year, the Rover Group leased the factory from the Government and sold its New Meteor factory, completing the re-equipping and new layout of the factory by the end of 1946.[19] In a speech to the company's shareholders, the Rover chairman said, in the opinion of your directors the Solihull factory will be one of the finest car body and assembly works in the country capable of producing cars of a high quality on the most up-to-date and economical lines.'[20] Production of Rover automobiles at Solihull has continued to the present day, under various corporate identities.[21] The factory complex at Solihull has been greatly expanded, but the original No. 2 Shadow Factory remains.

Standard Motor No. 2 Shadow Factory, Banner Lane, Coventry

In February 1945, the Board of Trade announced that it had leased the Banner Lane shadow factory, Coventry's largest shadow factory with one million square feet of floor space, to the

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[14] *Financial Times*, August 13, 1945, p. 5
[15] *Financial Times*, May 26, 1945, p. 3.
[16] *British Car Factories from 1896*, pp. 218-19.
[17] *Financial Times*, April 20, 2006, p. 2; January 9, 2007, p. 3; Ryton Plant https://en.wikipedia.org/wiki/Ryton_plant#:~:text=Coordinates%3A52.370%C2%B0N%201.449,the%20headquarters%20of%20the%20group. Accessed 5 June 2020.
[18] *Financial Times*, June 16, 1945, p. 3.
[19] *Financial Times*, December 20, 1945, p. 6, January 1, 1947, p. 3
[20] *Financial Times*, December 20, 1945, p. 6
[21] *British Car Factories from 1896*, pp. 231-32.

Standard Motor Company for motor vehicle production.[22] Instead of cars, however, Standard entered into an agreement with Harry Ferguson Ltd, later Massey-Ferguson, to build agricultural tractors.[23] The Standard Motor Company withdrew from the arrangement in 1959, but Massey-Ferguson continued building tractors at Banner Lane until AGCO, who bought Massey-Ferguson in 1994, closed down the factory in 2002.[24] By 2005, the original shadow factory had been demolished.

Bristol No. 3 Shadow Factory, Clayton-le-Moors, Accrington, Lancashire

When the Bristol Aeroplane Company decided that the Bristol No. 3 Shadow Factory was surplus to its post-war requirements, the Ministry of Aircraft Production allocated the factory to Courtaulds Ltd. for production of textile machinery and yarn.[25] Courtaulds used the factory for several years before selling it to English Electric, possibly in 1948, who used it from then on for manufacturing parts for English Electric aircraft. In 1968, English Electric merged with the General Electric Corporation (GEC) who continued manufacturing operations at the Accrington Factory until 1989. From then on, the factory site, little changed from its wartime configuration, went through a number of owners and became an industrial estate, with space in the factories rented out to various small companies.[26] Today it is known as Junction 7 Business Park, and is probably the last remaining shadow factory in its approximate original condition.

The Wright and Wright-licensee Factories

The Wright Paterson Factories

Since the Defense Plant Corporation (DPC) had financed Wright's Plant 3 and Plant 4, at the end of the war Wright returned these plants to the DPC for sale or lease to others. Plant No. 3 was

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[22] *Financial Times*, February 24, 1945, p. 2.
[23] Robson, Graham: *The Book of the Standard Motor Company*, (Dorset, England, 2011), p.79.
[24] *The Book of the Standard Motor Company*, p. 79.
[25] *Financial Times*, September 1, 1945, p. 1.
[26] My thanks to Mick Donnelly, property manager at the Junction 7 Business Park, for this information.

sold to a group of five industrial firms in November 1947 after having been idle for two years.[27] After the war, Wright Aeronautical had decided to close down its other Paterson factories and consolidated its production at the larger Wright factory in Wood-Ridge, New Jersey.[28] Wright offered its original building, Plant 1, and the nearby Plant 2 for auction in April 1947, and sold these two buildings to a New York realty company for $3.2 million.[29] The factories went through a number of owners during the years. Plant 1 still exists, though in a derelict state.[30]

The Wright Lockland, Ohio Factory

At the end of the war, the Army Air Force requested that the Wright Lockland factory be designated a stand-by facility, to be re-opened in an emergency.[31] The factory was shut down but maintained in serviceable condition. In 1948, the General Electric Corporation began leasing space in the factory from the then U.S. Air Force for jet engine production.[32] The machine shop and assembly building at Lockland became what is now the much expanded headquarters of GE Aviation, which builds all of GE's military and commercial jet engines. This building has been involved in aero engine production for nearly 80 years.

The Wright Wood-Ridge, New Jersey Factory

Toward the end of 1945, Wright Aeronautical arranged to lease the Wood-Ridge factory from the Government for five years and moved all its aero engine production from its Paterson factories to Wood-Ridge.[33] Wright continued building aero engines at Wood-Ridge until the early 1960's, ending production of the Cyclone 18 in 1961, the Cyclone 9 in 1963 and the J-65

[27] *The New York Times*, November 9, 1947, p. R1.
[28] *The New York Times*, May 24, 1946, p. 30.
[29] *The New York Times*, April 13, 1947, P. 251; June 18, 1947, p. 43.
[30] https://www.patersonnj.gov/egov/apps/document/center.egov?view=item;id=896 Accessed 5 June 2020.
[31] Surplus Property Administration: *Aircraft Plants and Facilities: Report of the Surplus Property Administration to the Congress, January 14, 1946*, (Washington, D.C., 1946), p. 51.
[32] 'How GE Aviation's headquarters relates to the Wright Brothers', *Dayton Daily News*, April 13, 2004, https://www.daytondailynews.com/news/how-aviation-headquarters-relates-the-wright-brothers/yIDYMgGCgCwPYan8HzALIM/ accessed 5 June 2020.
[33] *Aircraft Plants and Facilities: Report of the Surplus Property Administration to the Congress, January 14, 1946*, p. 53.

jet engine, the Armstrong Siddeley Sapphire engine built under license, in 1958.[34] Unable to compete with General Electric and Pratt & Whitney in the jet engine business, the re-named Wright Aeronautical Division of Curtiss-Wright exited the aero engine business, but retained the Wood-Ridge factory to make parts for other business lines as Curtiss-Wright diversified into industrial gas generators and nuclear propulsion.[35] Curtiss-Wright shut down the Wood-Ridge factory in the late 1970's, but retained the property until it was sold to a developer in 2001.[36] The factory now serves as an industrial warehouse and distribution facility, looking much as it did in 1945.[37]

The Dodge Chicago Factory

At the end of the war the Dodge Chicago factory returned to the Government. In July 1946, the Tucker Corporation acquired a five year lease on the factory with the intention of using it to produce a newly designed automobile.[38] Unable to secure financing, the Tucker Corporation's venture failed and in November 1949 the Dodge Chicago factory returned to the War Assets Administration.[39] The factory returned to aero engine production in 1950 when the Ford Motor Company acquired a lease after receiving a contract from the U.S. Air Force to build the Pratt & Whitney R-4360 air-cooled radial aero engine under license.[40] As the Ford Aviation Division, the factory later converted to building the Pratt & Whitney J-57 jet engine. After aero engine production ended, Ford retained the factory until 1967 when it was sold to Tootsie Roll Industries, a maker of American candies.[41] At some point the foundries and forges were demolished and replaced with a shopping mall. The main machine shop and assembly building, however, continues as the Tootsie Roll factory, remarkably unchanged since 1945. The engine

[34] *Engines Shipped by Wright Aeronautical Division and its Licensees 1920 to January 1, 1964*, p. 5.
[35] *The Wall Street Journal*, December 3, 1977, p. 16.
[36] See Lost in Jersey Blog, https://lostinjersey.wordpress.com/2009/03/05/curtis-wright-aircraft-facility/ accessed 7 June 2020.
[37] See https://www.commercialcafe.com/commercial-property/us/nj/wood-ridge/wood-ridge-industrial-complex/, accessed 7 June 2020.
[38] *The Wall Street Journal*, July 6, 1946, p. 8.
[39] *The Wall Street Journal*, November 26, 1949, p. 1.
[40] Based on an advertisement in *Air Force Magazine*, Vol. 41, No. 9, (September 1958), p. 50; *The Wall Street Journal*, September 17, 1953, p. 3.
[41] Taken from the Wikpedia entry for the Dodge Chicago factory, https://en.wikipedia.org/wiki/Dodge_Chicago_Plant, accessed 7 June 2020.

test cells remain in place. There is a small exhibit just inside explaining the factory's contribution in World War II, with a Dodge-build Cyclone 18 engine mounted on a stand nearby.

The Studebaker Factories

In September 1945, the Western Electric Company, the manufacturing arm of the Bell Telephone system, negotiated a lease for the Studebaker Chicago factory to add to its extensive manufacturing facilities in Chicago.[42] This factory apparently lasted until the early 1980s when Western Electric closed down its facilities. The factory sites were later demolished and turned into a shopping centre.[43] U.S. Rubber Corporation purchased the Studebaker Ft. Wayne, Indiana factory in September 1946.[44] Sometime later the International Harvester Corporation, a maker of agricultural equipment and trucks with substantial facilities in Ft. Wayne, took over the factory and operated it until 1983 when the company closed down its truck manufacturing operations.[45]

The Army Air Force initially designated the Studebaker aero engine factory on Chippewa Street in South Bend, Indiana, as a stand-by facility, but in November 1947 Studebaker purchased the factory for truck production.[46] Studebaker continued truck production at the factory until December 1963 when the Corporation, in severe financial difficulties, closed all its American factories and moved production to Canada.[47] The Kaiser Jeep Corporation purchased the factory in February 1964, and under various corporate identities reflecting the merger and acquisition craze of the 1980's and 1990's, continued building trucks at the factory until February 1990 when the Chippewa plant closed down.[48] For the past twenty years the Chippewa factory has served as an industrial park, with the factory still much the same as it was

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[42] *The Wall Street Journal*, September 25, 1945, p. 9.
[43] See https://en.wikipedia.org/wiki/Hawthorne_Works, accessed 7 June 2020.
[44] Young, Jan: *Studebaker and the Railroads*, Vol. 1, 2nd Ed., (2016), p. 179.
[45] See https://www.journalgazette.net/features/20170629/international-harvester-truck-plant-closes-july-15-1983, accessed 7 June 2020.
[46] *Aircraft Plants and Facilities: Report of the Surplus Property Administration to the Congress, January 14, 1946*, P. 51; *Studebaker and the Railroads*, Vol. 1, p. 179.
[47] *The Wall Street Journal*, December 11, P. 69; December 16, 1963, p. 66.
[48] See www.lynchhummer.com/agmhistory.html accessed 7 June 2020.

in 1945. As with the Wood-Ridge and Dodge Chicago factories, the engine test cells remain at the north end of the factory building, the only reminder of its wartime activity.

Bibliography

Primary Sources

Archives

Aerospace Bristol Museum

Records of the Bristol Aeroplane Company

Albert Kahn Associates, Detroit, MI

Air Force Historical Research Agency, Maxwell AFB, AL

A2070: Case Study of the R-2600 Aircraft Engine Project

N0875: Case Study of the R-3350 Aircraft Engine Project

A2095: History of Dodge-Chicago

A2171: Report of Conditions at Wright Aeronautical New Jersey Plants

Aviation Hall of Fame & Museum of New Jersey, Teteboro, NJ

Papers relating to the Wright Aeronautical Corporation

Baker Library Special Collections, Harvard Business School, Cambridge, MA

British Motor Museum, Coventry

Records of the Rover Company, Ltd. (Aero Engines)

City of Coventry Archives, Herbert Art Museum, Coventry

Chicago History Museum, Chicago, IL

Detroit Public Library, Rose & Robert Skillman Branch Library, Detroit, MI

National Automotive History Collection: Records of the Automotive Council for War Production

Franklin D. Roosevelt Presidential Library and Museum

Harry Hopkins Papers

Diaries of Henry Morgenthau, Jr., April 27, 1933-July 27, 1945

Library of Congress, Washington, DC

Papers of General Henry H. Arnold

Papers of Robert P. Patterson

Modern Records Centre, University of Warwick

Records of the Rover Company, Ltd. (Aero Engines) and the Standard Motor Company.

National Archives, Kew, London UK

AIR 2. Air Ministry registered files:

Piece numbers 629, 1738, 1821, 1822, 1823, 1842, 2015, 2194, 2324, 2325, 2326, 2366, 2577, 2873, 3355, 3683, 3684, 3685.

AIR 6. Records of meetings of the Air Board and Air Council:

Piece numbers 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60.

AIR 10. Air Ministry Air Publications and Reports:

Piece numbers 310, 1544, 1545, 1546, 1547, 1548, 1549, 1550, 1551.

AIR 19. Air Ministry Private Office papers:

Piece numbers3, 4, 5, 6, 7, 9, 73, 74, 282.

AIR 20. Air Ministry unregistered papers:

Piece numbers 3065, 3066, 3554.

AIR 41. Air Ministry and Ministry of Defence: Air Historical Branch: Narratives and Monographs: Piece number 8.

AVIA 9. Ministry of Aircraft Production Private Office papers.

Piece numbers 5, 9, 21, 44, 45, 70.

AVIA 10. Ministry of Aircraft Production unregistered papers:

Piece numbers 5, 6, 7, 14, 15, 18, 20, 32, 41, 94, 99, 104, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 174, 175, 176, 177, 178, 179, 180 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198 199, 200, 201, 202, 203, 204, 205, 206, 207, 214, 230, 231, 232, 262, 264, 267, 268, 269, 276, 284, 311, 315, 316, 317, 318, 327, 332, 378, 382, 383, 384, 393, 616, 617, 621.

AVIA 15. Ministry of Aircraft Production files:

Piece numbers 414, 423, 724, 907, 1344, 1390, 1583, 1852, 2102, 2346, 2349, 2485, 2537, 2538, 2576, 2910, 3746, 3765, 3825.

AVIA 22. Ministry of Supply registered files:

Piece numbers 2661, 2684, 2685.

AVIA 38. Ministry of Supply and Ministry of Aircraft Production: North American Supply Missions, Second World War:

Piece numbers 81, 314, 421, 423, 426, 442, 450, 455, 485, 489, 532, 611, 623, 639, 664, 738, 781, 790, 803, 868.

AVIA 46. Ministry of Supply files series I (Establishments):

Piece numbers 35, 65, 70, 71, 72, 73, 82, 88, 91, 95, 97, 98, 106, 112, 118, 121, 159, 160, 179, 261, 306, 307.

AVIA 53. Ministry of Supply: Contracts, registered files:

Piece number 554.

BT 87. Ministry of Aircraft Production: Ministers' and Officials' papers:

Piece numbers 93, 177.

CAB 64. Minister for the Co-ordination of Defence: Registered Files (CD series):

Piece number 17.

CAB 68. War Cabinet Memoranda (WP(R) series):
Piece number 2.
CAB 102. Cabinet Office historical section: official war histories (Second World War), civil:
Piece numbers 45, 53, 274, 275, 332.
CAB 140. War Cabinet and Cabinet Office: Historical Section:
Piece number 32.
CAB 141. War Cabinet and Cabinet Office: Central Statistical Section: Working Papers:
Piece number 87.
FO 115. Foreign Office: Embassies and Consulates, United States of America. General Correspondence. North American Supplies:
Piece number 3771.
SUPP 3. Principal Supply Officers Committee:
Piece number 44.

National Archives and Records Administration, Chicago, IL
Record Group 270: War Assets Administration: Real Property Disposal Case Files 1947-1951, Dodge-Chrysler, Studebaker, Wright Aeronautical.

National Archives and Records Administration, College Park, MD
Record Group 18: Records of the Army Air Force, Entry 219, Material Command, Col. A.J. Lyons Project Files 1939-1941; Entry 290, Central Decimal File, General Correspondence 1939-1942; Entry 292, Central Decimal File, General Correspondence 1942-44.
Record Group 107: Office of the Under Secretary of War.
Record Group 169: Entry 322, Foreign Economic Administration, Bureau of Supplies.
Record Group 179: War Production Board, Policy Documentation Files, Entry 1; Select Document Files, Entry 3.
Record Group 234: Reconstruction Finance Corporation: Defense Plant Corporation, Entry 146, Engineers' Reports and Appendices.
Record Group 342: Records of the United States Air Force Commands, Activities, and Organizations, Entry P-26, 'Sarah Clark' Correspondence Files.

Royal Air Force Museum, Hendon, London, UK
X003-8876/066: Bristol Aeroplane Company: *History of Production of Bristol Aero Engines by the Shadow Industry Operating Under the Joint Aero Engine Committee in Conjunction with the Bristol Aeroplane Company Limited.*

Rolls-Royce Heritage Trust-Bristol Branch, Filton, UK
Records of the Bristol Aeroplane Company

Studebaker Museum, South Bend, IN

Magazines and Yearbooks

Aero Digest

Aeronautical Engineering Review

Aeroplane

Aerosphere

Air Annual of the British Empire

Aircraft Engineering

Aircraft Production

Aircraft Yearbook

American Aviation

American Machinist

Architectural Forum

Architectural Record

Automotive Industries

Automotive and Aviation Industries

Aviation

Chicago Tribune

Engineering News-Record

Factory Management and Maintenance

Flight

Foundry

Journal of the Society of Automotive Engineers

Machinery (Lon)

Machinery (NY)

Mechanical Engineering

Mill & Factory

New York Times

Steel

Studebaker Spotlight

The "Bristol" Review

The Iron Age

The Tool Engineer

Wall Street Journal

Wright Trade Winds

Wright at the Moment

Government Documents

Air Service Command, Army Air Force: Technical Order No. 02-35JA-2: *Handbook of Service Instructions: R-3350-13, -21, -23, -35 Aircraft Engines*, (February 15, 1943).

------: AN 02-35JA-2: *Service Instructions: R-3350-13, -18, -19, -21, -23, -35, -41 Aircraft Engines*, (25 September 1944, Revised 1 November 1944).

Civilian Production Administration: *Industrial Mobilization for War: History of the War Production Board and Predecessor Agencies, 1940-1945*, (Washington, D.C., 1946).

Civilian Production Administration: *Minutes of the Advisory Commission to the Council of National Defense, June 12, 1940 to October 22, 1941*, Historical Reports on War Administration, War Production Board, Documentary Publication No. 1, (Washington, D.C., 1946).

Civilian Production Administration: *Minutes of the Council of the Office of Production Management, December 21, 1941 to January 14, 1942*, Historical Reports on War Administration, War Production Board, Documentary Publication No. 2, (Washington, D.C., 1946).

Civilian Production Administration: *Minutes of the War Production Board, January 20, 1942 to October 9, 1945*, Historical Reports on War Administration, War Production Board, Documentary Publication No. 4, (Washington, D.C., 1946).

Civilian Production Administration: Industrial Statistics Division: *Alphabetic Listing of Major War Supply Contracts, Cumulative June 1940 through September 1945*, Vol. 1 A-C, Vol. 2 D-j, Vol. 3 K-Rex, Vol. 4 Rey-Z, (Washington, D.C., 1946).

Defense Plant Corporation: *Advance Listing of Industrial Plants and Plant Sites to be Disposed of by Defense Plant Corporation, Oct. 14, 1944*, (Washington, D.C., 1944).

Surplus Property Administration: *Aircraft Plants and Facilities: Report of the Surplus Property Administration to the Congress, January 14, 1946*, (Washington, D.C., 1946).

U.S. Department of Commerce, Bureau of the Census: *Statistical Abstract of the United States 1941*, (Washington, D.C., 1942).

U.S. Department of Commerce, Civil Aeronautics Administration, Office of Aviation Information, Division of Aircraft Statistics: *U.S. Military Acceptances 1940-1945: Aircraft, Engines and Propeller Production*, (Washington, D.C. 1946).

War Production Board: Historical Reports on War Administration: Special Studies No. 21, *Aircraft Production Policies under the National Defense Advisory Commission and Office of Production Management, May 1940 to December 1941*, (Washington, D.C., 1946).

Articles and Books

’40 Years of Machine Tool Progress’, *Automotive Industries*, Vol. 81, No. 7, (October 1, 1939), pp. 52-53, 352, 354, 356, 358, 360, 362, 364.

’30,000 Workers in 6 Wright Plants to Build 3,780,000 h.p. Monthly’, *Trade Winds*, (April 1941, pp. 3-5.

‘A Huge Plant for Engine Assembly’, *Aircraft Production*, (December 1941), pp. 111-13.

‘Aero Engine Manufacture II: Methods Employed by the Bristol Aeroplane Co., Ltd., Filton, Bristol, on the Mark VI. Jupiter Engine’, *Machinery (Lon)*, Vol. 28, No. 725, (September 2, 1926), pp. 637-41.

‘Aero Engine Manufacture III: Methods Employed by the Bristol Aeroplane Co., Ltd., Filton, Bristol, on the Mark VI. Jupiter Engine’, *Machinery (Lon)*, Vol. 28, No. 726, (September 9, 1926), pp. 669-73.

‘Aero Engine Manufacture IV: Methods Employed by the Bristol Aeroplane Co., Ltd., Filton, Bristol, on the Mark VI. Jupiter Engine’, *Machinery (Lon)*, Vol. 28, No. 727, (September 16, 1926), pp. 711-15.

‘Aero Engine Manufacture V: Methods Employed by the Bristol Aeroplane Co., Ltd., Filton, Bristol, on the Mark VI. Jupiter Engine’, *Machinery (Lon)*, Vol. 28, No. 728, (September 23, 1926), pp. 733-38.

‘Aero Engine Manufacture VI: Methods Employed by the Bristol Aeroplane Co., Ltd., Filton, Bristol, on the Mark VI. Jupiter Engine’, *Machinery (Lon)*, Vol. 28, No. 729, (September 30, 1926), pp. 780-83.

‘Aero Engine Manufacture VII: Methods Employed by the Bristol Aeroplane Co., Ltd., Filton, Bristol, on the Mark VI. Jupiter Engine’, *Machinery (Lon)*, Vol. 29, No. 730, (October 7, 1926), pp. 1-5.

Aircraft Division, National Defense Advisory Council, 'Report on a Study of Aircraft Engine Manufacturing Capacity', July 22, 1940, (Report 7), Record Group 179, Records of the War Production Board, Entry 1, War Production Board Policy Documentation File, Box 1125, File 315.30421, National Archives and Records Administration (NARA), Washington, D.C.

Aircraft Industries Association of America, Inc.: *Aviation Facts and Figures 1945*, (New York, NY, 1945).

'Albert Kahn', *Architectural Forum*, Vol. 69, No. 2, (August 1938), pp. 87-101.

Alford, L.P.: *Cost and Production Handbook*, (New York, 1940).

'Aluminum Fins Rolled on Aircraft Engine Cylinders', *The Iron Age*, (February 22, 1945), pp. 66-70.

Anderson, Arthur G.: *Industrial Engineering and Factory Management*, (New York, 1928).

'Austin Production Methods: An Improved Layout of the Engine Shop', *The Automobile Engineer*, Vol. XXV, No. 329, (February 1935), pp. 43-47.

'Automatic Bore-Finishing Machines', *Aircraft Engineering*, Vol. 8, Issue 7, (July 1936), pp. 201-02.

AuWerter, Jay P.: 'Pratt & Whitney Expands', *Aviation*, Vol. 139, No. 7, (July 1940), pp. 38-41, 116, 118.

Banks, F.R.: 'The Art of the Aviation Engine', *Journal of the Royal Aeronautical Society*, Vol. 52, Issue 453, (September 1948), pp. 527-50.

Bastian, Paul J.: 'Production Control in Aircraft-Engine Manufacture', *Machinery (NY)*, (March 1944), pp. 205-07.

Berghell, A.B.: *Production Engineering In the Aircraft Industry*, (New York, 1944).

Berlin, Don R. and Peter F. Rossmann: 'Applying Automotive Methods to Aircraft Production', *Aviation*, Vol. 40, No. 1, (January 1941), pp. 42-43, 122, 144; Vol. 40, No. 3, (March 1941), pp. 46-47, 122.

Biermann, Arnold E.: 'The Design of Metal Fins for Air-Cooled Engines', *Society of Automotive Engineers Journal (Transactions)*, Vol. 41, No. 3, (September 1937), pp. 388-92.

Blank, H.E. Jr.: 'Precision is the watchword in the Pratt & Whitney aircraft engine plant. Exacting requirements prompt a technique unique in production methods', *Automotive Industries*, Vol. 77, No. 1, (July 3, 1937), pp. 10-19, 37.

Bristol Aeroplane Co. Ltd.: *"Bristol" Hercules VI-XI-XVI-XVII-XVIII Operator's Handbook*, (Filton, UK, August 1945).

Bristol Aeroplane Co. Ltd.: *The "Bristol" Pegasus Aircooled Radial Engines*, Vol. III, Types XVII and XVIII, (Filton, UK, March 1940).

Bristol Aeroplane Co. Ltd.: 'History of the Production of Bristol Aero Engines by the Shadow Industry Operating under the Joint Aero Engine Committee in Conjunction with the Bristol Aeroplane Company Limited', (January 1945), X003-887/066, Royal Air Force Museum.

Bristol Aeroplane Co. Ltd.: *The Power Behind Their Wings: An account of the part played by the Bristol Aeroplane Company in the development of the air-cooled radial aero-engine in Great Britain*, (No Date).

'Bristol Built: The Evolution of Bristol Aero-Motors', *The Aeroplane*, (March 13, 1942), pp. 296-300.

'Bristol Fashion II: The Rise of the Radial', *Flight*, (March 9, 1939), pp. 236-44.

'Bristol Pegasus Engine', *The Automobile Engineer*, Vol. XXVI, No. 346, (June 1936), pp. 221-24.

'Bristol Sleeve Valve Engines', *Aircraft Engineering*, Vol. 9, No. 102, (August 1937), pp. 218-22.

Brown, P.W.: 'Wright Cyclone Production Speeded up by Special Methods', *Machinery (NY)*, Vol 49., No. 12, (August 1943), pp. 172-76.

------: 'Wright Turns to Line Production', *American Machinist*, vol. 85, No. 13, (June 25, 1941), pp. 595-607.

Brown, P.W. and H.E. Linsley: 'Engines from the Ground Up', *American Machinist*, Vol. 84, No. 11, (May 29, 1940), pp. 371-74.

------: 'More Horsepower for National Defense', *Aero Digest*, Vol. 39, No. 4, (October 1941), pp. 176-82, 305.

'Buick's Cylinder Head Foundry', *Aero Digest*, Vol. 42, No. 2, (January 1943), pp. 192-93, 195-96, 199.

'Build the Plant Around the Process', *Factory Management and Maintenance*, Vol. 97, No.4, (April 1939), P. B-35.

‘Building Types: Factories’, *Architectural Record*, Vol. 82, No. 2, (February 1938), pp. 99-139.

‘Building Types: Factory Design’, *Architectural Record*, Vol. 89, No. 1, (January 1941), pp. 138-154.

Burghardt, Henry D.: *Machine Tool Operation*: Part I: *Lathe, Bench, Forge*, (New York, 1936); Part II: *Drilling, Planing, Milling, Grinding,* (New York, 1937).

Campbell, Kenneth: ‘Cylinder Cooling and Drag of Radial Engine Installations’, *Society of Automotive Engineers Journal (Transactions)*, Vol. 43, No. 6, (December 1938), pp.515-27.

‘Canley Works Extensions: Improved Methods and New Machines at the Standard Motor Co., Ltd.’, *The Automobile Engineer*, Vol. XXVII, No. 354, (January 1937), pp. 2-9.

Chatfield, Charles Hugh and Charles Fayette Taylor: *The Airplane and its Engine*, (New York, 1928).

Chatfield, C.H., C. Fayette Taylor, and Shatswell Ober: *The Airplane and its Engine*, 5th Ed., (New York, 1949).

Clinton, Arnold C.: ‘Machining Operations on the Bristol “Mercury” Engine’, in Nelson, W/C H.: *Aero Engineering*, Vol. II, Part 1: Production, (London, 1939), pp. 342-90.

------: ‘Mercury and Pegasus Engines’, in Nelson, W/C H.: *Aero Engineering*, Vol. I, Part 2: Principles and Construction, (London, 1939), pp. 573-638.

------: ‘Short Survey of Aero-engine Production’, in Nelson, W/C H.: *Aero Engineering*, Vol. II, Part 1: Production, (London, 1939), pp. 287-324.

Collison, Thomas: *Flying Fortress: The Story of the Boeing Bomber*, (New York, NY, 1943).

------: *The Superfortress is Born: The Story of the Boeing B-29*, (New York, NY, 1945).

Connery, Robert H.: *The Navy and Industrial Mobilization in World War II*, (Princeton, NJ, 1951).

‘Cornfield to Mass Production in A Single Year-That’s the Story of Wright’s Cincinnati Division’, *Trade Winds*, (November 1941), pp. 7-9.

‘Crankcases by Otis Elevator’, *Trade Winds*, Vol. 6, No. 11, (April 1943), pp. 6-7, 18.

‘Crankshaft by Ohio’, *Trade Winds*, Vol. 6, No. 10, (February 1943), pp. 8-9, 18.

De Leeuw, A.L.: ‘Machine Tools of the Present and the Future’, *The Iron Age*, Vol. 136, No. 10, (September 5, 1935), pp. 50-54, 215-20.

Devons, Ely: *Planning in Practice: Essays in Aircraft Planning in War-time*, (Cambridge, 1950).

Diemer, Hugo: *Factory Organization and Administration*, 2nd Ed., (New York, NY, 1914).

'Dodge Chicago Division of Chrysler Corporation', *Factory Management and Maintenance*, Industrial Plant Section, Vol. 102, (April 1944), pp. B-72-76.

'Dodge Chicago Plant Division of Chrysler Corp.', *Architectural Forum*, Vol. 73, No. 6, (December 1943), pp. 50-58.

'Dodge Chicago Plant Makes Own Forgings for Army B-29 Super-Fortress Plane Engines', *Industrial Heating*, Vol. XI, No. 10, (October 1944), pp. 1581-94.

'Drilling Operations on the Vauxhall Cylinder Block', *Machinery (London)*, Vol. 43, No. 1120, (March 29, 1934), P. 769-771.

Duston, Freeman C.: 'Airplane Engine Plant Uses Carbide Tools in Small-lot Production', *Machinery* (NY), Vol. 40, No. 11, (July 1934), pp. 673-4.

Engelbach, C.F.R.: 'Some Notes on Re-organizing a Works to Increase Production', *Proceedings of the Institute of Automobile Engineers*, Vol. XXII, (1927-28), pp.496-544.

'Engine-Testing Equipment: New Electrical Installation at Longbridge Works', *The Automobile Engineer*, Vol. XXV, No. 332, (May 1935), pp. 177-78.

'Engines for the Air Force', *American Machinist*, Vol. 83, No. 11, (May 31, 1939), pp. 369-376.

'Engines from Line Production', *Aviation*, (July 1941), pp. 54-55.

Evans, W.D.: 'Recent Productivity Trends and Their Implications', *Journal of the American Statistical Association*, Vol. 42, No. 238 (June 1947), pp. 211-223.

Fairbrother, E.: 'Aero-Engine Production', *Aircraft Engineering*, Vol. 16, Issue 7, (July 1944) pp. 209-10.

Faurote, Fay Leone: 'Aeronautical Aluminum Foundry', *The Iron Age*, Vol. 124, No. 14, (December 12, 1929), pp. 1587-1592.

------: 'Assembling an Airplane Engine', *The Iron Age*, Vol. 124, No.10, (September 5, 1929), P. 597.

------: 'Layout of a Manufacturing Plant', *The Iron Age*, Vol. 124, No. 16, (December 26, 1929), pp. 1730-31.

------: ‘Machining Airplane Cylinders’, *The Iron Age*, Vol. 124, No.8, (August 22, 1929), pp. 462-64.

------: ‘Machining the Wright Crankshaft’, *The Iron Age*, Vol. 124, No. 7, (August 15, 1929), pp. 402-03.

------: ‘Machining Two Connecting Rods’, *The Iron Age*, Vol. 124, No. 6, (August 8, 1929), pp.337-40.

------: ‘Making Aluminum Aircraft Castings’, ‘Layout of a Manufacturing Plant’, *The Iron Age*, Vol. 124, No. 15, (December 19, 1929), pp. 1650-54.

------: ‘Making a Whirlwind Crankcase’, *The Iron Age*, Vol. 124, No.9, (August 29, 1929), pp. 525-28.

------: ‘New Wright Aeronautical Engines’, *The Iron Age*, Vol. 124, No. 3, (July 18, 1929), pp. 148-52.

Fedden, A.H. Roy: ‘Aircraft Power Plant Past and Future’, Thirty-Second Wilbur Wright Memorial Lecture, *Royal Aeronautical Society Journal*, Vol. XLVIII, (1944), P. 337-459.

------: ‘Next Decade’s Aero Engines Will Be Advanced But Not Radical’, *Society of Automotive Engineers Journal (Transactions)*, Vol. 33, No. 6, (December 1933), pp. 377-400.

------: ‘Trend of Air-Cooled Aero-Engines-The Next Five Years’, *Society of Automotive Engineers Journal (Transactions)*, Vol. 41, No. 4, (October 1937), pp. 437-67.

‘Fifteen Curtiss-Wright Factories Speed Defense Output’, *Aero Digest*, Vol. 39, No. 4, (October 1941), pp. 160, 164, 166, 168.

Finney, Burnham: *Arsenal of Democracy: How Industry Builds Our Defense*, (New York, NY, 1941).

‘Ford Airplane Engine Plant Has Many Distinctive Features’, *Mill & Factory*, Vol. XXIX, No. 4, (October 1941), pp. 59-66.

‘Ford Methods in Rolls-Royce Merlin Engine Production’, *Machinery (London)*, Vol. 62, No. 1579, (January 14, 1943), pp. 29-33.

‘Forged Cylinder Heads Require New Technique’, *Aviation*, Vol. 43, No. 6, (June 1944), pp. 142-45, 248, 251.

Frass, Arthur P.: *Aircraft Power Plants*, (New York, 1943).

‘From 1700 to 2700 Horsepower in 10 Years’, *Aviation Week*, (May 24, 1948), pp. 26-27, 31.

Fuller, Curtis: 'Superfort Power Plant', *Flying*, Vol. 35, No. 1, (July 1944), pp. 70-23, 170.

'G-200 Cyclone', *Aviation*, Vol. 38, No, 7, (July 1939), pp. 56, 90, 95.

Gadd, E.R.: 'Metallurgical Problems of Aero Engine Manufacture', *Royal Aeronautical Society Journal*, Vol. XXL, (1936), pp. 622-30.

Gagg, R.F.: 'Current Problems in Airline Engines', *Society of Automotive Engineers Journal (Transactions)*, Vol. 36, No. 2, (February 1935), pp. 50-57.

------: 'New Production Lines for Aircraft Engines', *Mechanical Engineering*, Vol. 63, No. 3, (March,1941), pp. 177-79.

Geschelin, Joseph: 'Advanced Tooling Produces Newest Studebakers', *Automotive Industries*, Vol. 80, No. 13, (April 1, 1939).

------: 'Buick's Know How Speeds Production of Airplane Engine Parts', *Automotive and Aviation Industries*, Vol. 87, No. 10, (November 15, 1942), pp. 20-25, 80, 82.

------: 'Buick's Warplane Engine Plant', *Automotive and Aviation Industries*, Vol. 86, No. 11, (June 1, 1942), pp. 20-27, 82;

------: 'Chevrolet's Unique Setup for Airplane Engine Production', *Automotive and Aviation Industries*, Vol. 88, No. 11, (June 1, 1943), pp. 24—28, 42.

------: 'Conversion Almost Complete', *Automotive and Aviation Industries*, Vol. 87, No. 7, (October 1, 1942), pp. 52-55, 266, 228.

------: 'Conversion for War: Influence of Automotive Mass-Production Methods', *SAE Transactions*, Vol. 50, No. 7, (July 1942), pp. 278-83.

------: 'Dodge Spent $6,000,000 and Got a Model Truck Plant', *Automotive Industries*, Vol. 80, No. 5, (February 4, 1939), pp. 130-41.

------: 'Ford War Plant Facilitates Straight-Line Production", *Automotive and Aviation Industries*, Vol. 86, No. 11, (June 1, 1942), pp.18-24, 102, 104.

------: 'Production at Chrysler Plant, Windsor, Ontario Multi-Model Engine Assembly Adapted to Mass Production at Chrysler Plant, Windsor, Ontario', *Automotive Industries*, Vol. 79, No. 7, (August 6, 1938), pp. 164-72, 180-81.

------: 'Sixty-three Parts and Assemblies from Studebaker to Cyclones', *Automotive and Aviation Industries*, Vol. 88, No. 12, (June 15, 1943), pp. 32-35, 67-68, 70

------: ‘Studebaker Know-how Speeds Flying Fortress Engine Output’, *Automotive and Aviation Industries*, Vol. 88, No. 7, (April 1, 1943), pp. 18-22, 70, 72, 74.

------: ‘Wright Ready to Power Bombers’, *Automotive and Aviation Industries*, Vol., No., (February 1, 1942), pp. 22-29, 74, 76.

Gough, H.J.: ‘Materials of Aircraft Construction’, Twenty-Sixth Wilbur Wright Memorial Lecture, *Royal Aeronautical Society Journal*, Vol. XLII, (October 1938), pp. 921-1032.

‘The Government Aircraft “Shadow” Scheme’, *Machinery (London)*, Vol. 51, No. 1308, (November 4, 1937), pp. 133-36.

Gude, William G.: ‘Aluminum Castings by Dodge Chicago Plant’, *The Foundry*, Vol. 72, No. 9, (September 1944), pp. 80-83, 198-200.

------: ‘Magnesium Castings by Dodge Chicago Plant’, *The Foundry*, Vol. 72, No. 8, (August 1944), pp. 78-81, 178-80.

Hall, Herbert D. Foundation: *The Machine Tool Primer*, (Newark, NJ, 1943).

Heldt, P.M.: *High-Speed Combustion Engines: Design: Production: Tests*, 13th Ed., (New York, 1946).

Herb, Charles O.: ‘Buick Now Manufactures Bomber Engines’, *Machinery (NY)*, Vol. 48, No.11, (July 1942), pp. 161-66.

------: ‘Buick Manufactures Bomber Engine’, *Machinery (NY)*, Vol. 49, No.5, (January 1943), pp. 149-53.

------: *Machine Tools at Work*, (New York, 1942).

‘Herculean Development’, *Aeronautical Engineering, The Aeroplane*, (November 28, 1941), pp. 599-601.

‘Hercules Engine Components: Machining Operations on the Crankcase, Impeller, Sleeve, Cylinder Barrel and Connecting Rods’, *Aircraft Production*, (July 1944), pp. 309-19.

‘Hercules Progress’, *Flight*, (November 11, 1943), pp. 528-30.

‘Hercules Sleeve Valve Engine Production’, *Machinery (Lon)*, Vol. 65, No. 1678, (December 7, 1944), pp. 617-625.

Hesse, Herman C.: *Engineering Tools and Processes: A Study of Production Technique*, (New York, 1941).

Hill, Henry C.: ‘Design Problems in the Quantity Production of Aircraft Engines’, *SAE Journal (Transactions)*, Vol. 46, No. 1, (January 1940), pp. 18-24.

------: ‘Engineering Aspects of the Single-Row Cyclone G-200 Series Engine’, Wright Aeronautical Corporation, (1940), pp. 1-11.

------: ‘More Aircraft Engines for National Defense’, Paper presented at the National Aeronautic Meeting of the Society of Automotive Engineers, March 13-14, 1941, pp. 1-7.

Hirsch, Werner Z.: ‘Manufacturing Progress Functions’, *The Review of Economics and Statistics*, Vol. 34, No. 2 (May 1952), pp. 143-55.

Holben, Martin M.: ‘Some Aircraft-Engine Production Methods’, *SAE Journal (Transactions)*, Vol. 52, No. 10, (October 1944), pp. 492-500.

‘Hudson Builds Cyclone Parts’, *Trade Winds*, Vol. 6, No. 9, (October 1942), pp. 6-7.

Humphrey, William V.: ‘Aircraft Engine Forging Operations’, *Industrial Aviation*, Vol. 1, No. 2, (July 1944), pp. 58-59.

Immer, John R.: *Layout Planning Techniques*, (New York, 1950).

‘Increase in Production Capacity of Machine Tools in Ten Years’, *Machinery (NY)*, Vol. 43, No. 5, (July 1937), pp. 325-27.

‘Inspection: Routine Employed by the Bristol Aeroplane Co., Ltd., to Ensure Quality and Accuracy’, *The Automobile Engineer*, Vol. XXIII, No. 306, (May 1933), pp. 169-70.

James, Thurstan: ‘Getting Going at the Shadow Factories’, *The Aeroplane*, (November 3, 1937), pp. 529-39.

Johnson, J.B.: ‘Aircraft-Engine Materials’, *Society of Automotive Engineers Journal (Transactions)*, Vol. 40, No. 4, (April 1937), pp. 153-64.

Jones, E.J.H.: *Production Engineering: Jig and Tool Design*, (New York, 1941).

Jones, H.A.: *The War in the Air*, Vol. VI, (Oxford, 1937).

Judge, A.W.: *Aircraft Engines*, Vol. One, (London, 1941), Vol. Two, (London, 1942).

------: *Motor Manuals: Volume I: Automobile Engines in Theory, Design, Construction, Operation, Testing & Maintenance*, (London, 1942).

Kahn, Albert: 'Design of Plants for Mass Production', *Aero Digest*, Vol. 39, No. 4, (October 1941), pp. 156-59, 305.

'Keeping the Record Straight', *Automotive and Aviation Industries*, Vol. 86, No. 4, (February 15, 1942), pp. 17-19, 60.

Kimball, Dexter S.: *Principles of Industrial Organization*, 4th Ed., (New York, NY, 1933).

Klemin, Alexander: 'A Miracle of Production', *Scientific American*, (December 1944), pp. 256-58.

Kudlich, Donald U.: 'Engineering Liaison and Production Control', *SAE Journal (Transactions)*, Vol. 50, No. 5, (May 1942), pp. 169-76.

Leak, A.H.: 'Coordinating Aircraft-Engine Design and Production', *SAE Journal (Transactions)*, Vol. 44, No. 2, (February 1939), pp. 85-92.

------: 'Problems Co-ordinating Engine Design and Production', (Wright Aeronautical Corporation, 1940), pp. 1-19.

LeGrand, H.R.: 'Right Gears for Wright Engines', *American Machinist*, Vol. 80, No.1, (January 1, 1936), pp. 4-6

Lilley, Tom, et al: *Problems of Accelerating Aircraft Production During World War II*, (Cambridge, MA, 1947).

Linsley, H.E.: 'A Preview of Plant Layout', *American Machinist*, Vol. 85, No. 10, (May 14, 1941), pp. 419-20.

------: 'Aircraft Engines on the Production Line', *Mechanical Engineering*, Vol. 65, No. 7, (July 1943), pp. 493-96.

------: 'Automatic Tooling Speeds Production in the New Wright Aero Plant', *Machinery (NY)*, Vol. 48, No. 6, (February 1942), pp. 109-18.

------: 'Cyclone Engines Mass Produced', *The Iron Age*, (October 9, 1941), pp. 53-61.

------: 'Forged Cylinder Heads Increase Power of Cyclone Engine', *Aero Digest's Aviation Engineering,* Vol. 40, No. 6, (June 1942), pp. 141-42.

------: 'Machining the Wright Cyclone Forged Cylinder Head', *The Iron Age*, (January 13, 1944), pp. 47-53.

------: 'Mass Production for the Aircraft-Engine Industry', *Mechanical Engineering*, Vol. 64, No. 2, (February 1942), pp. 100-05.

‘Line Production of the Rolls-Royce Merlin Engine’, *Machinery (London)*, Vol. 61, No. 1567, (October 22, 1942), pp. 449-56.

Liston, Joseph: *Aircraft Engine Design*, (New York, 1942).

Lucato, C.R.: ‘At Cowley To-day’, *The Morris Owner*, (August 1934), pp. 556-58.

‘Machine Tool Developments’, *Machinery (Lon)*, Vol. 49, No. 1261, (December 10, 1936), pp. 301-17.

‘Machine Tool Developments in 1935’, *Machinery (Lon)*, Vol. 47, No. 1209, (December 12, 1935), pp. 312-33.

‘Machining Aero-engine Crankcase Castings’, *Machinery (London)*, Vol. 61, No. 1471, (November 19, 1942), pp. 561-65.

‘Machining Aero-Engine Crankshafts and Airscrew Shafts’, *Machinery* (London), Vol. 49, No. 1252, (October 8, 1936), pp. 33-38.

‘Machining Aero-engine Crankshafts and Camshafts’, *Machinery (London)*, Vol. 61, No. 1572, (November 26, 1942), pp. 589-96.

‘The Manufacture of Aero-engine Connecting Rods’, *Machinery (London)*, Vol. 61, No. 1573, (December 3, 1942), pp. 617-23.

‘The Manufacture of Aero-engine Pistons’, *Machinery (London)*, Vol. 61, No. 1574, (December 10, 1942), pp. 645-49.

‘Machining Aero-Engine Cylinder Barrels’, *Machinery (Lon)*, Vol. 65, No. 1679, (December 14, 1944), pp. 645-53.

‘Machining Aero-Engine Cylinder Blocks’, *Machinery (London)*, Vol. 61, No. 1570, (November 12, 1942), pp. 533-38.

‘Machining Aero Engine Cylinders’, *Machinery (Lon)*, Vol. 41, No. 1057, (January 12, 1933), pp. 425-

‘Machining Airplane Engine Cylinder Heads’, *Machinery (Lon)*, Vol. 65, No. 1681, (December 28, 1944), pp. 701-705.

‘Machining Airplane Engine Propeller Shafts’, *Machinery (Lon)*, Vol. 65, No. 1682, (January 4, 1944), pp. 1-6.

‘Machining Bristol Engine Parts’, *Aircraft Engineering*, Vol. 6, No. 2, (February 1934), pp. 40-43.

‘Machining “Bristol” Hercules Connecting Rods’, *Machinery (Lon)*, Vol. 65, No. 1686, (February 1, 1944), pp. 109-14.

‘Machining the Bristol Mercury and Pegasus Cylinder Heads’, *Machinery (Lon)*, Vol. 41, No. 1058, (January 19, 1933), pp. 453-

Machining Cast Crankshafts and Camshafts’, *Machinery (London)*, vol. 47, No. 1208, (December 5, 1935), pp. 269-74.

‘Machining Cylinder Heads for the Merlin Engine’, *Machinery (London)*, Vol. 65, No. 1672, (October 26, 1944), pp. 449-56.

‘Machining Cylinder Fins’, *Aircraft Production*, Vol. VI, No. 66, (April 1944), pp. 155-56.

‘Machining Cylinder Skirts and Liners for the Merlin Engine’, *Machinery (London)*, Vol. 65, No. 1673, (November 2, 1944), pp. 477-81.

‘Machining Ford 8-h.p. Cylinder Blocks’, *Machinery (London)*, vol. 41, No. 1045, (October 20, 1932), pp. 69-71.

‘Machining Light-alloy Castings for the Merlin Engine’, *Machinery (London)*, Vol. 65, No. 1676, (November 23, 1944), pp. 561-65.

‘Machining Methods on Wright Aero-Engines’, *Machinery (London)*, Vol. 59, No. 1516, (October 30, 1940), P. 113-19.

‘Machining a Gear Bank’, *Aircraft Production*, Vol. III, No. 27, (January 1941), pp. 5-6.

‘Machining Master Connecting Rods for Radial Aero Engines’, *Machinery* (London), Vol. 49, No. 1253, (October 15, 1936), pp. 61-65.

Mansfield, J.H.: ‘Production Robots Cut Machining Costs’, *Society of Automobile Engineers Journal*, Vol. 55, (February 1947), pp. 42-44.

‘Manufacturing the Cyclone, Part I’, *Aircraft Production*, Vol. II, No. 4, (April 1940), pp. 109-15.

‘Manufacturing the Cyclone, Part II’, *Aircraft Production*, Vol. II, No. 5, (May 1940), pp. 151-58.

‘Manufacturing the Ford V-Eight’, *The Automobile Engineer*, Vol. XXVI, No. 343, (March 1936), pp. 95-101.

‘Manufacturing the Rolls-Royce Merlin XX, Part I’, *Aircraft Production*, Vol. IV, No.45, (July 1942), pp. 433-44.

‘Manufacturing the Rolls-Royce Merlin XX, Part II’, *Aircraft Production*, Vol. IV, No.46, (August 1942), pp. 486-97.

'Manufacturing the Rolls-Royce Merlin XX, Part III', *Aircraft Production*, Vol. IV, No.47, (September 1942), pp. 548-58.

'Manufacturing the Rolls-Royce Merlin XX, Part IV', *Aircraft Production*, Vol. IV, No.48, (October 1942), pp. 592-601.

'Mass Production Brings Mass Inspection', *Western Flying*, Vol. XXII, No. 8, (get date), pp. 64-65.

'Mass Production Methods for Building Wright Cyclones', *Aeronautical Engineering Review*, (August 1942), pp. 13-17.

Mead, George J.: 'Aircraft Powerplant Trends', *Society of Automotive Engineers Journal (Transactions)*, Vol. 41, No. 4, (October 1937), pp. 455-67.

Miller, R.E.: 'Machine Tools Developed to Meet Lower-Cost Production', *The Iron Age*, Vol. 133, No. 1, (January 4, 1934), pp. 119-28.

'Milling Operations on the Wright "Cyclone", *American Machinist*, Vol. 78, No.7, (March 28, 1934), pp.245-48.

Ministry of Labour and National Service: *Women in Engineering*, (London, No Date).

------: *Women in Industry*, (London, 1945).

'Modern Plant Insures Clouds of Planes', *Mill & Factory*, Vol. XXVII, No. 1, (July 1940), pp. 55-59.

Modley, Rudolf, ed.: *Aviation Facts and Figures 1945*, (New York, 1945).

Molloy, E.: *Aircraft Production*, (London, 1941).

------: The 'Complete Engineer' Series, Volume 2: *Aircraft Production*, (London, 1941).

'Motor Cars to Munitions: Chrysler: Didn't Wait for New Machines; Revamped the Ones They Had', *American Machinist*, Vol. 86, No. 12, (June 1942), pp. 549-61.

'Multi-Tooling for Aero-Engine Production', *Aircraft Engineering*, Vol. 11, Issue 5, (May 1939), pp. 217-9.

'Multiple-Arch Concrete Roof Saves Steel', *Engineering News-Record*, Vol. 130, No. 2, (January 14, 1943), pp. 99-100, 121-22.

Muther, Richard: *Production Line Technique*, (New York, 1944).

'New Heat-treatment Department at Bristol Aeroplane Co., Ltd.', *Machinery (London)*, Vol. 52, No. 1350, (August 25, 1938), pp. 637-39.

'New Wright Line-production Foundry Features Company's Plant No. 3 in Fair Lawn, New Jersey', *Trade Winds*, Vol. 5, No. 7, (November 1940), pp. 6-7.

'Nickel Steels and Alloys in Aircraft Engines', *Aero Digest*, Vol. 29, No. 1, (July 1936), pp. 38-39.

Nixon, Frank: 'Design of Aero-Engines for Production', *Aircraft Engineering*, Vol. 11, issue 3, (March 1939), pp. 127-131.

Nutt, Arthur: 'A Survey of Engine Development', *Journal of the Aeronautical Sciences*, Vol. 3, No. 4, (February 1936), pp. 137-41.

------: 'Aviation Faces Biggest Production Problem', *Automotive Industries*, Vol. 83, No. 7, (October 1, 1940), pp. 321-42, 413.

Oates, J. A.: 'The Bristol Hercules: Part I. Sleeve Valve Design and Operation: Manufacturing the Cylinder and Sleeve', *Aircraft Production*, Vol. IV, No. 40, (February 1942), pp. 176-186.

------: 'The Bristol Hercules: Part II. Production of the Master Connecting Rod, Airscrew Shaft and Cylinder Head: the Sleeve Ball and Housing', *Aircraft Production*, Vol. IV, No. 41, (March 1942), pp. 176-186.

------: 'The Bristol Hercules: Part III. The Gear Department: Engine Assembly and Testing: Heat Treatment and Process Sections: Laboratories and Standards Room', *Aircraft Production*, Vol. IV, No. 42, (April 1942), pp. 303-09.

------: 'The Hercules Crankshaft: Design Features: Machining and Assembly Operations at a Shadow Factory', *Aircraft Production*, Vol. VI, No. 64, (February 1944), pp. 59-66.

------: 'Hercules Engine Components: Machining Operations on the Crankcase, Impellor, Sleeve, Cylinder Barrel and Connecting Rods', *Aircraft* Production, Vol. VI, No. 69, (July 1944), pp. 309-19.

------: 'Manufacturing the Hercules Piston: Part I. Design Details: Press Forging Methods Employed by Specialloid Ltd.: Machining Sequence; Milling the Pockets', *Aircraft Production*, Vol. XI, No. 77, (March 1945), pp. 128-39.

------: 'Manufacturing the Hercules Piston: Part II. Fettling and Heat Treatment: Later Stages of Machining: Diamond Turning and Boring: Final Inspection', *Aircraft Production*, Vol. XI, No. 78, (April 1945), pp. 176-83.

'Only the Productive Can Be Strong-Only the Strong Can Be Free: A Report of the 1940 SAE National Aircraft Production Meeting, held in Los Angeles', *Aviation*, Vol. 39, No. 12, (December 1940), pp. 64-65, 144, 148.

‘Operations in the Production of the “Bristol” Hercules Engine’, *Machinery (Lon)*, Vol. 65, No. 1687, (February 8, 1944), pp. 137-40.

‘Over 900 Wright Employees Are Cited For Long Service; 52 Receive 15-year Awards’, *Trade Winds*, Vol. Two, No. Seven, (October-November 1935), P. 2.

‘Over 36,500 Operations are Required in the Production of the Wright Cyclone’, *Trade Winds*, Vol. Two, No. Six, (September 1935), P. 2.

‘P &W Engine Production’, *Aero Digest*, Vol. 34, No. 1, (January 1939), pp. 57-59.

‘Packard Production of the Merlin Engine’, *Machinery (London)*, Vol. 65, No. 1676, (August 17, 1944), pp. 177-82.

Pagé, Victor W.: *The Ford Models V8, B and A Cars: Construction-Operation-Repair*, (New York, 1933).

Phair, W.A.: ‘In-line Machining of Aircraft Cylinder Heads’, *The Iron Age*, (August 12, 1943), pp. 66-73.

‘Power at the Salon’, *Flight*, (November 26, 1936), pp. 575-79.

‘Precision is the watchword in the Pratt & Whitney aircraft engine plant. Exacting requirements prompt a technique unique in production methods’, *Automotive Industries*, vol. 77, No. 1, (July 3, 1937), pp. 10-19, 37.

‘Producer of Production Lines’, *Architectural Record*, Vol. 91, No. 6, (June 1942), P. 39-43.

‘Producing Aero-Engine Parts on Automatic Machines’, *Machinery (Lon)*, Vol. 49, No. 1251, (October 1, 1936), pp. 1-4.

‘Producing Morris Eight Engines; The Foundry and Machine Methods at the Coventry Works’, *The Automobile Engineer*, Vol. XXV, No. 335, (August,1935), pp. 291-296.

‘Production of the Merlin Engine’, *Machinery (London)*, Vol. 65, No. 1675, (November 16, 1944), pp. 533-37.

‘Progressive Assembly of Wright Engines’, *Aero Digest*, Vol. 39, No. 4, (October 1941), pp. 192, 194, 305.

Pye, D.R.: *The Internal Combustion Engine*, Volume II: *the Aero-Engine*, (London, 1934).

Rautenstrauch, Walter: *The Design of Manufacturing Enterprises: A Study in Applied Industrial Economics*, (New York, NY, 1941).

Ray, Samuel: ‘Quality Control of Wright Engine Parts’, *Automotive Industries*, Vol. 85, No. 4, (August 15, 1941), pp. 14-17, 60-62.

Ross, Donald: *An Appraisal of Prospects for the Aircraft Manufacturing Industry, Aviation: Manufacturing-Transportation*, White, Weld & Co., (New York, NY, May 1940).

Rothbarth, E.: ‘Causes of the Superior Efficiency of U.S.A. Industry as Compared with British Industry’, *The Economic Journal*, Vol. 56, No. 223 (September 1946), pp. 383-390.

‘SAE Talks Production’, *Aviation*, Vol. 38, No. 11, (November 1939), pp. 32-33, 84, 86, 108.

‘Single-story Concrete Factory-A War-inspired Innovation’, *Engineering News-Record*, Vol. 129, No. 17, (October 22, 1942), pp. 117-212

‘Shadow Factories in Being’, *Flight*, (4 November 1937), pp. 445-449.

Smith, G. Geoffrey: ‘The Bristol Hercules’, *Flight*, (November 27, 1941), pp. 379-83.

‘Some Machining Operations in the Manufacture of Bristol Air-cooled Aero Engines’, *The Machine Tool Review*, Vol. 22, No. 139, (March-April 1934), pp.33-37.

‘Sometimes It’s “The Little Things That Count’ Even in Aircraft Engines; Studs, For Example’, *Trade Winds*, Vol. Three, No. Four, (January 1937), pp. 7, 18.

‘Special Equipment in the Production of the Merlin Engine’, *Machinery (London)*, Vol. 62, No. 1582, (February 4, 1943), pp. 113-17.

‘Special Machine Tools Boost Engine Production’, *The Tool Engineer*, (November 1943), pp. 76-78, 81.

Stout, Wesley W.: *Great Engines and Great Planes*, (Detroit, MI, 1947).

‘Surface Hardening of Engine Parts by the Nitriding Process’, *Aero Digest*, Vol. 38, No. 1, (January 1941), pp.114, 235.

Sutton, Kenneth E.: ‘Production and Quality’, Wright Aeronautical Corporation (1941).

------: ‘Progressive Assembly of Wright Engines’, *Aero Digest*, Vol. 39, No. 4, (October 1941), pp. 192, 194, 305.

Swan, Andrew: *Handbook of Aeronautics*, Volume II: *Aero-engine Design and Practice*, (London, 1938).

‘The Bristol Centaurus’, *The Aeroplane*, (July 6, 1945), pp. 11-17.

‘The “Bristol” Engine Inspection Department’, *The “Bristol” Review*, Engine Issue No. 11, (November 1936), pp. 30-35.

‘The Bristol Hercules’, *Flight*, (November 27, 1941), pp. 379-83.

‘The Coming of the Sleeve Valve’, *Aircraft Engineering*, Vol. 9, No. 102, (August 1937), pp. 203-04.

‘The Design of Industrial Buildings’, *Architectural Record*, Vol. 81, No. 2, (February 1937), pp. BT3-BT40.

‘The Engine Fitting, Stripping and Re-Building Department’, *The “Bristol” Review*, Engine Issue No. 10, (June 1936), pp. 35-38.

‘The Government Aircraft “Shadow” Scheme: Progress at the Factories’, *Machinery (London)*, Vol. 51, No., (November 4, 1937), pp.133-36.

‘The Government Shadow Factories’, *Engineering*, (November 5, 1937), pp. 511-514.

‘The Hercules Crankshaft: Design Features; Machining and Assembly Operations at a Shadow Factory’, *Aircraft Production*, Vol. VI, No. 64, (February 1944), pp. 59-66.

‘The Industry’s Largest Engine Factory’, *Aero Digest’s Aviation Engineering*, Vol. 39, No. 1, (July 1941), pp. 156, 159-60, 205.

‘The Making of Reduction Gears for Wright Aircraft Engines’, *Automotive Industries*, Vol. 84, No. 4, (February 15, 1941), pp. 151-54,

‘The Manufacture of “Bristol” Aero Engine Components’, *The “Bristol” Review*, Engine Issue No. 8, (November 1934), pp. 23-26.

‘The Manufacture of High Performance Aero Engines’, *Machinery* (London), Vol. 48, No. 1249, (September 17, 1936), pp. 737-56.

‘The Manufacture of Rolls-Royce Aero-engines’, *Machinery (London)*, Vol. 55, No. 1427, (February 15, 1940), pp. 525-44.

‘The Manufacture of Motor-car Engine Components’, *Machinery (London)*, vol. 47, No. 1215, (January 23, 1936), pp. 489-92.

‘The New Engine Building Department’, *The “Bristol” Review*, Engine Issue No. 13, (June,1938), P. 35.

‘The New Double-Bank Sleeve-Valve Engine’, *The “Bristol” Review*, Engine Issue No. 12, (June 1937), pp. 15-16.

‘The Ohio Plant Today’, *Trade Winds*, Vol. 6, No. 11, (April 1943), pp. 12-13, 16.

‘The Packard-Built Merlin’, *Aircraft Production,* Vol. VI, No. 70, (August 1944), pp. 389-94

‘The Production of Aero-engine Crankcases and Superchargers’, *Machinery* (London), Vol. 48, No. 1250, (September 24, 1936), pp. 774-78.

‘The Production of Aero-engine Crankshafts: Methods Employed at a Government “Shadow” Factory in the Manufacture of the Bristol Hercules Engine’, *Machinery (London)*, Vol. 60, No. 1534, (March 5, 1942), pp.145-47, 149-51.

‘The Production of the Merlin Engine’, *Machinery (London)*, Vol. 65, No. 1671, (October 19, 1944), pp. 421-27.

‘The Production of the Rolls-Royce Merlin Engine’, *Machinery (London)*, Vol. 62, No. 1580, (January 21, 1943), pp. 57-60.

‘The Production of Supercharger Impellers’, *Machinery (Lon)*, Vol. 60, No. 1535, (March 12, 1942), pp. 169-73.

‘The Shadow Factories: A Preliminary Survey of Plant and Methods’, *The Automobile Engineer*, Vol. XXVII, No. 3645, (November 1937), pp. 444-46.

‘The Standard Shadow Factory: Specialized Production Methods for Bristol Mercury Cylinder Units’, *The Automobile Engineer*, Vol. XXVIII, No. 370, (April 1938), pp. 123-30.

‘The Standard Shadow Factory Specialized Production Methods for Bristol Mercury Cylinder Units’, Part II, *The Automobile Engineer*, Vol. XXVIII, No. 371, (May 1938), pp. 154-156.

The Times: *British War Production 1939-1945: A Record*, (London 1945).

‘The Wright Aeronautical Corporation Plant at Paterson, N.J.’, *Mill & Factory*, Vol. XXIV, No. 6, (June 1939), pp. 143-50, 300-01.

‘Transfer Machines Speed Engine Output’, *The Tool Engineer*, (November 1943), pp. 82-84.

‘Traveling Form System as Used for Longer Spans’, *Architectural Record*, Vol. 92, No. 6, (December 1942), pp. 54-55.

Tumser, A.A.: ‘Quality Control: Checking and Inspection Procedure in the Production of Wright Engines’, *Aero Digest’s Aviation Engineering*, Vol. 39, No. 5, (November 1941), pp. 152, 155-56, 159-60.

Turner, A.A.: ‘Quality Control’, *Aero Digest’s Aviation Engineering*, Vol. 39, No. 5, (November 1941), pp. 152-55.

'Turret Lathe Operations on the Hercules Crank Case', *Machine Tool Review*, Vol. 31, No. 184, (March-April 1943), pp. 26-28.

Tuttle, W. Gerard: 'Production Changes Necessary for Women Workers', *Automotive and Aviation Industries*, Vol. 88, No. 8, (April 15, 1943), pp. 24-26, 74, 76.

United Aircraft Corporation: *The Pratt & Whitney Story*, (1950).

United States Air Force: United States Air Force Numbered Historical Studies, No. 40: *Expansion of Industrial Facilities under Army Air Force Auspices 1940-1945*, (No Date).

------: United States Air Force Numbered Historical Studies, No. 106: *Distribution of Air Material to the Allies, 1940-1944* (No Date).

'Valve Spring Manufacture', *Machinery (London)*, Vol. 62, No. 1581, (January 28, 1943), pp. 85-89

Waddington, J.L.: 'American Methods and Modes-II', *Flight*, Vol. XXXVI, No. 1605, (September 28, 1939), pp. 269-71.

Walton, Francis: *Miracle of World War II: How American Industry Made Victory Possible*, (New York, NY, 1956).

Ward, J. Carlton, Jr.: 'Plant Layout and Production Methods for Modern Aircraft Engines', *Society of Automotive Engineers Journal (Transactions)*, Vol. 40, No. 5, (May 1937), pp. 178-89.

------: 'Machine Tools in the Aero-engine Industry', *Machinery (London)*, Vol. 55, No. 1418, (December 14, 1939), P. 275.

Ware, B.T.: *Production Flow at the Austin Works*, *Machinery*, Vol. 44, (June 7, 1934), pp. 178-89.

'"Warspeed" System of Construction in Concrete', *Architectural Record*, Vol. 92, No. 6, (December 1942), P. 52.

'Wartime Construction of Factory Buildings…Building Type Study No. 72', *Architectural Record*, Vol. 92, No. 6, (December 1942), pp. 51-57.

'What the Manufacturer Wants from His Architect', *Architectural Forum*, Vol. 69, No. 2, (August 1938), pp. 96-97.

'What's Happening and What's Ahead in Industrial Plant Development', *Factory Management and Maintenance*, Vol. 99, No. 4, (April 1941), pp. B-37-52, 76.

Wilkinson, Paul H.: *Aircraft Engines of the World 1941*, (New York, 1941).

------: *Aircraft Engines of the World 1945*, (New York, 1945).

Wilson, Eugene E.: *Slipstream: The Autobiography of an Air Craftsman*, (New York, 1950).

Winter, O.W.: 'Unskilled Labor Creates New Tooling Problems', *American Machinist*, Vol. 87, No. 6, (March 18, 1943), pp. 95-96.

Woollard, Frank G.: 'Some Notes on British Methods of Continuous Production', *Proceedings of the Institute of Automobile Engineers*, Vol. XIX, (1924-25), pp. 419-74, 885-90.

Wright, I.H.: 'Developments in Machine Tools', *Machinery (Lon)*, Vol. 49, (February 11, 18, 1937), pp. 607-11, 625-26.

'Wright Aero Produces Engines for the B-29 Superfortress', *Machinery (New York)*, Vol. 50, No. 12, (August 1944), pp. 134-44.

'Wright Aero Will Expend $1,350,000 for Extensions to Factory and New Equipment', *Trade Winds*, Vol. 3, No. 7, (May 1937), pp. 2-3.

'Wright Aero's Electro-plating Equipment Among Most Modern and Versatile in Industry', *Trade Winds*, Vol. 5, No. 7, (November 1940), pp. 10-11.

'Wright Aeronautical's Line Conveyor Technique Speeds Painting of Cyclone and Whirlwind Parts', *Trade Winds*, Vol. 5, No. 7, (November 1940), pp. 14-15.

'Wright G-200 Cyclone, Rated at 1200 H.P., Released for Both Domestic and Export Sale', *Trade Winds*, Vol. 4, No. 10, (Navy Number 1939), pp. 6-8.

'Wright G-200 Series Cyclone Engines', *Aero Digest*, Vol. 35, No. 1, (July 1939), pp. 113-14.

'Wright Plant Sets New Size Record', *Engineering News-Record*, Vol. 127, No. 1, (July 3, 1941), pp. 52-54.

Wright Aeronautical Corporation: *Application of High Production Machine Tools*, (No date).

------: *The G-100 Series 1100 H.P. Wright Cyclone*, (No Date).

------*: G-200 Series Wright Cyclone 1200 Horsepower*, (No Date).

------: *Wright Double-Row Cyclone 14 Aircraft Engines*, (No Date).

------: *Preliminary Instruction Book: Wright Cyclone 14 Aircraft Engine: Series C14-BB*, (Paterson, NJ, 1943).

------: *Preliminary Instruction Book: Wright Cyclone 18 Aircraft Engine: Series C18BA*, (Paterson, NJ, 1942).

------: *Service Manual: Wright Cyclone 9GC Aircraft Engines,* 3rd Edition, (Paterson, NJ, 1944).

------: *Service Manual: Wright Cyclone 14BA Aircraft Engines,* 3rd Edition, (Paterson, NJ, 1944).

------: *Service Manual: Wright Cyclone 14BB Aircraft Engines,* 2nd Edition, (Paterson, NJ, 1944).

------: *Service Manual: Wright Cyclone 18BA Aircraft Engines,* 2nd Edition, (Paterson, NJ, 1944).

------: *Wright Cyclone Engines: Series 18BA Service Manual*, 4th Edition, (Paterson, NJ, 1947).

------: *Wright Cyclone Engines: Series 18BD Service Manual*, 1st Edition, (Paterson, NJ, 1946).

------: *Wright Double-Row Cyclone 14 Aircraft Engines*, (No Date).

Wright, T.P.: 'America's Answer: Gearing Our Aviation Industry to the National Defense', *Aviation*, Vol. 38, No. 6, (June 1939), pp. 26-29, 78, 80, 82, 84.

------: 'Factors Affecting the Cost of Airplanes', *Journal of Aeronautical Sciences*, Vol. 3, No. 4, (February 1936), pp. 122-128.

------: 'U.S. Aircraft Production Mission to England, October 6 to November 11, 1942: Report on Personal Observations of the Chairman', *Articles and Addresses of Theodore P. Wright*, Vol. II: Aircraft Production, Uses of Aviation, (Buffalo, NY, 1961).

Contemporary Films

Chevrolet Motor Company: 'Master Hands', (1936), available on YouTube at https://www.youtube.com/watch?v=Pr8rCNaASlc, accessed 21 February 2020.

Ford Motor Company: 'Trip Through the River Rouge', (circa late 1930's), available on YouTube at https://www.youtube.com/watch?v=Xa0PAg7FfMk, accessed 21 February 2020.

Rolls-Royce, 'Contribution to Victory', (circa 1946), available on YouTube at https://www.youtube.com/watch?v=-fo7SmNuUU4, accessed 25 November 2019.

War Department Official Training Film 1-135, 'Aircraft Engines', (1940), available on YouTube at https://www.youtube.com/watch?v=4vBPlcquAD8 accessed 3 March 2020

Wilding Picture Productions, Inc., 'Engines for Super Bombers', (1945), available on YouTube at https://www.youtube.com/watch?v=_t3akMEm9bI, accessed 25 November 2019.

Wright Aeronautical Corporation, 'Wright Builds for Air Supremacy', (1941), available on YouTube at https://www.youtube.com/watch?v=sBfFpcdyd5Q, accessed 25 November 2019.

Secondary Sources

Articles and Books

Alchian, Armen: 'Reliability and Progress Curves in Airframe Production', *Econometrica*, Col. 31, No. 4, (October 1963), pp. 679-693

Aldcroft, Derek H.: 'The Performance of the British Machine Tool Industry in the Interwar Years', *Business History Review*, Vol. 40, No. 3, (Autumn 1966), pp. 281-296.

Anderson, John D., Jr.: *The Aeroplane: A History of its Technology*, (Reston, VA, 2002).

Andrews, C. F., and E.B. Morgan: *Vickers Aircraft Since 1908*, New Edition, (London, 1988).

Bailey, Gavin J.: *The Arsenal of Democracy: Aircraft Supply and the Anglo-American Alliance, 1938-1942*, (Edinburgh, 2013).

Baloff, Nicholas: 'The Learning Curve-Some Controversial Issues', *The Journal of Industrial Economics*, Vol. 14, No. 3, (June 1966), pp. 275-82.

Barnett, Correlli: *The Audit of War: The Illusion and Reality of Britain as a Great Nation*, (London, 1986).

Barnes, C.H.: *Handley Page Aircraft Since 1907*, (London, 1976).

------: *Shorts Aircraft Since 1900*, James, Derek N. Rev. Ed. (London, 1989).

Bergeron, Louis and Maria Teresa Maicellori-Pontois: *Industry, Architecture, and Engineering*, (New York, NY, 2000).

Bilstein, Roger E.: *The American Aerospace Industry: From Workshop to Global Enterprise*, (New York, 1996).

Bingham, Victor: *Major Piston Aero Engines of World War II*, (Shrewsbury, UK, 1998).

Bitran, Gabriel R., and Li Chang: 'Productivity Measurement at the Firm Level', *Interfaces*, Vol. 14, No.3, (May-June 1984), P. 29.

Blaine, A.J.: *The Arsenal of Democracy: FDR. Detroit, and an Epic Quest to Arm an America at War*, (New York, NY, 2014).

Blaszczyk, Regina Lee: “Reign of the Robots”: The Homer Laughlin China Company and Flexible Mass Production’, *Technology and Culture*, Vol. 36, No. 4, (October 1995), pp. 863-911.

Botticelli, Peter: ‘The British Engineering Press During the Second Industrial Revolution: Responses to Corporate Capitalism’, *Business History Review*, Vol. 71, (Summer 1997),

Bowden, Sue and David M. Higgins: ‘British Industry in the Interwar Years’, in *Cambridge Economic History of Modern Britain*, Volume 2: *Economic Maturity 1860-1939*, (Cambridge, 2004), pp. 374-402.

Bowyer, Michael J.F.: *The Stirling Bomber*, (London, 1980).

Bradley, Betsy Hunter: *The Works: The Industrial Architecture of the United States*, (New York, NY, 1999).

Breer, Carl: *The Birth of the Chrysler Corporation and its Engineering Legacy*, Edited by Anthony J. Yanik, (Warrendale, PA, 1995).

Bresnahan, Timothy F. and Daniel M.G. Raff: ‘Intra-Industry Heterogeneity and the Great Depression: The American Motor Vehicles Industry, 1919-1935’, *Journal of Economic History*, Vol. 51, No. 2 (June 1991) pp. 317-31.

Broadberry, Stephen N.: ‘How Did the United States and Germany Overtake Britain? A Sectorial Analysis of Comparative Productivity Levels, 1870-1990’, *The Journal of Economic History*, Vol. 58, No. 2, (June 1998), pp. 375-407.

------: ‘Technological Leadership and Productivity Leadership Since the Industrial Revolution: Implications for the Convergence Debate’, *The Economic Journal*, Vol. 104, No. 453 (March 1994), P.291-302.

------: *The Productivity Race: British Manufacturing in International Perspective, 1850-1990*, (Cambridge, 1997).

Broadberry, Stephen and Carsten Burhop: ‘Comparative Productivity in British and German Manufacturing before World War II: Reconciling Direct Benchmark Estimates and Time Series Projections’, *The Journal of Economic History*, Vol. 67, No. 2, (June 2007), pp. 315-49.

Broadberry, Stephen and Mary O’Mahony: ‘Britain’s Productivity Gap with the United States and Europe: A Historical Perspective’, *National Institute Economic Review*, No. 189, (July 2004), pp. 72-85.

Brooks, Peter W.: *The Modern Airliner: Its Origin and Development*, (London 1961).

Bryan, Ford R.: *Rouge Pictured in its Prime*, (Dearborn, MI, 2003).

Bucci, Frederico: *Albert Kahn: Architect of Ford*, (New York, NY, 1993).

Burnham, Rayner: *A Concrete Atlantis: U.S. Industrial Building and European Modern Architecture 1900-1925*, (Cambridge, MA, 1989).

Butler, Phil and Dan Hagedorn: *North American Arsenal: Aircraft for the Allies 1938-1945 Purchases and Lend-Lease*, (Hinckley, UK, 2004)

Cairncross, Sir Alec: *Planning in Wartime: Aircraft Production in Britain, Germany and the USA*, (Basingstoke, UK, 1990).

Carew, Michael G.: *Becoming the Arsenal: The American Industrial Mobilization for World War II, 1938-1942*, (New York, NY, 2010)

Carlsson, Bo: 'The Development and Use of Machine Tools in Historical Perspective', *Journal of Economic Behaviour and Organization*, Vol. 5, (1984), pp. 91-114.

Carstensen, Fred V.: Review of *From the American System to Mass Production, 1800-1932: The Development of Manufacturing Technology in the United States*, *The Business History Review*, Vol. 59, No. 2 (Summer, 1985).

Chandler, Alfred D., Jr.: *Scale and Scope: The Dynamics of Industrial Capitalism*, (Cambridge, MA, 1990).

Church, Roy: *Herbert Austin: The British Motor Car Industry to 1941*, (London, 1979).

------: *The Rise and Decline of the British Motor Industry*, (London 1994).

Church, Roy, and Michael Miller: 'The Big Three: Competition, Management and Marketing in the British Motor Industry, 1922-1939' in Supple, Barry ed.: *Essays in British Business History*, (Oxford 1979).

Collins, Paul, and Michael Stratton: *British Car Factories from 1896: A Complete Historical, Geographic, Architectural & Technological Survey*, (Goodmanstone, Dorset, 1993).

Connors, Jack: *The Engines of Pratt & Whitney: A Technical History*, (Reston, VA, 2010).

Constant, Edward W., II: *The Origins of the Turbojet Revolution*, (Baltimore, 1980).

Craven, Wesley Frank and James Lea Cate, eds.: *The Army Air Forces in World War II,* Volume Six: *Men and Planes*, (Chicago, IL, 1955).

Cunningham, William Glenn: *The Aircraft Industry: A Study in Industrial Location*, (Los Angeles, CA, 1951).

Crouch, Tom: *Wings: A History of Aviation from Kites to the Space Age*, (New York, 2003).

Darley, Gillian: *Factory*, (London, 2003).

DeGarmo, Paul, J.T. Black, Ronald A. Kosher, and Barney E. Klamecki: *Materials and Processes in Manufacturing*, 9th Ed., (Hoboken, NJ, 2003).

De Jong, Herman and Pieter Woltjer: 'Depression dynamics: a new estimate of the Anglo-American manufacturing productivity gap in the interwar period', *The Economic History Review*, Vol. 64, No. 2 (May 2011), pp. 472-492

de Syon, Guillaume: 'What the Wrights Wrought: The Centennial of Flight in Recent Literature', *Technology and Culture*, Vol. 45, No. 2, (April 2004), pp. 350-357.

Dunbabin, J.P.D.: 'British Rearmament in the 1930s: A Chronology and Review', *The Historical Journal*, Vol. XVIII, No. 3, (1975), pp. 587-609.

Edgerton, David: *England and the Aeroplane: Militarism, Modernity and Machines*, Revised Edition, (London, 2013).

------: *Britain's War Machine: Weapons, Resources and Experts in the Second World War*, (London, 2011).

------: 'Eléments pour une nouvelle histoire global de la production du XXème siècle'. in *Le monde du génie industriel au XXe siècle: Autour de Pierre Bézier et des machines-outils, (2016).*

------: 'From Innovation to Use: Ten Eclectic Theses on the Historiography of Technology', *History and Technology*, Vol. 16, (1999), pp. 111-36.

------: *Warfare State: Britain, 1920-1970*, (Cambridge, 2006).

Elphick, Peter: *Liberty: The Ships that Won the War*, (Annapolis, MD, 2001).

Eltscher, Louis R., and Edward M. Young: *Curtiss-Wright: Greatness and Decline*, (1998).

Emerson, Howard P. and Douglas C.E. Naebring: *Origins of Industrial Engineering: The Early Years of a Profession*, (Atlanta, GA, 1988).

Emiliani, M. and P.J. Seymour: 'Frank George Woollard: forgotten pioneer of flow production', *Journal of Management History*, Vol. 17, Iss. 1, pp. 66-87.

Fear, Jeffrey: 'War of the Factories', in Geyer, Michael and Adam Tooze, eds.: *The Second World War*, Volume III, *Total War: Economy, Society and Culture*, (Cambridge, 2015).

Fearon, Peter: ‘Aircraft Manufacturing’, in Buxton, Neil K and Derek H. Aldcroft, eds.: *British Industry Between the Wars: Instability and industrial development 1919-1939*, (London, 1979), pp. 216-40.

------: The British Airframe Industry and the State, 1918-1935’, *The Economic History Review*, Vol. 27, No. 2, (May 1974), pp. 236-51.

------: ‘The Formative Years of the British Aircraft Industry, 1913-1924’, *The Business History Review*, Vol. 43, No. 4, (Winter, 1969), pp. 476-95.

Fenton, John, ed.: *Gasoline Engine Analysis for Computer Aided Design*, (London, 1986).

Ferguson, Robert G.: ‘One Thousand Planes a Day: Ford, Grumman, General Motors and the Arsenal of Democracy’, *History and Technology*, Vol. 21, No. 2, (June 2005), pp. 149-75.

Ferry, W. Hawkins: *The Legacy of Albert Kahn*, (Detroit, MI, 1970).

Field, Alexander J.: *A Great Leap Forward: 1930s Depression and U.S. Economic Growth*, (New Haven, CT, 2011).

------: ‘The Impact of the Second World War on US Productivity Growth’, *The Economic History Review*, New Series, Vol. 61, No. 3 (August 2008), pp. 672-94.

Flamming, James M.: *Chrysler Chronicle: An Illustrated History of Desoto-Dodge-Imperial-Plymouth*, (Lincolnwood, IL, 1995).

Foreman-Peck, James, Sue Bowden and Adam McKinlay: *The British Motor Industry*, (Manchester 1995).

Freeman, Joshua B.: *Behemoth: A History of the Factory and the Making of the Modern World*, (New York, NY, 2018).

Furse, Anthony: *Wilfrid Freeman: The Genius Behind Allied Survival and Air Supremacy 1939 to 1945*, (Staplehurst, Kent, 2000).

Gibbs-Smith, Charles H.: *Aviation: An Historical Survey from its Origins to the end of World War II*, (London, 1970).

Giffard, Hermione: ‘A Hard Sell: Factors Influencing the Interwar Adoption of Tungsten Carbide Cutting Tools in Germany, Britain, and the United States’, *Technology and Culture*, Vol. 56, No. 4, (October 2015), pp. 895-927.

------: *Making Jet Engines in World War II: Britain, Germany, and the United States*, (Chicago, IL, 2016).

Gowing, Margaret: ‘The Organization of Manpower in Britain During the Second World War’, *Journal of Contemporary History*, Vol. 7, No. ½, (January-April 1972), pp. 147-67.

Gregor, Neil: *Daimler-Benz in the Third Reich*, (New Haven, CT, 1998).

Gropman, Alan L.: *Mobilizing U.S. Industry in World War II*, McNair Paper 50, (Washington, D.C., 1996).

Gunston, Bill: *The Development of Piston Aero Engines*, Reprinted, (Sparkford, Somerset, UK, 1994).

------: *Fedden: The life of Sir Roy Fedden*, (Derby, UK, 1998).

------: *Rolls-Royce Aero Engines*, (London, 1989).

Haight, John McVickar: *American Aid to France 1938-1940*, (New York, NY, 1970).

Hall, Hessel D.: *History of the Second World War, United Kingdom Civil Series, War Production Series: North American Supply*, (London, 1955).

Hallion, Richard P.: *Taking Flight: Inventing the Aerial Age from Antiquity Through the First World War*, (Oxford, 2003).

Hannah, Leslie: ‘Strategic Games, Scale, and Efficiency, or Chandler Goes to Hollywood’, in Coopey, Richard and Peter Lyth: *Business in Britain in the Twentieth Century: Decline and Renaissance?* (Oxford, 2009).

Hansen, James R.: “Aviation History in the Wider View’, *Technology and Culture*, Vol. 30, No. 3 (July 1989), pp. 643-656.

Harrison, Mark, ed.: *The Economics of World War II: Six great powers in international comparison*, (Cambridge, 1998).

Hartley, K.: ‘The Learning Curve and Its Application to the Aircraft Industry’, *The Journal of Industrial Economics*, Vol. 13, No. 2, (March 1965), pp. 122-28.

Hassell, Patrick: ‘The Bristol Sleeve Valve Aero Engines’, in Starr, Fred, Edward L. Marshall, and Bryan Lawton: *The Piston Engine Revolution: Papers from a Conference on the History of the Reciprocating Internal Combustion Engines Held at the Museum of Science and Industry, Manchester, 14-17 April 2011*, (Manchester, UK, 2012).

Heaven, John: *Bristol Piston Engines Since 1914*, unpublished manuscript, copy in the possession of the Rolls-Royce Heritage Trust, Filton.

Heinrich, Thomas B.: 'Jack of All Trades: Cramp Shipbuilding, Mixed Production, and the Limits of Flexible Specialization in American Warship Construction, 1940-1945', *Enterprise and Society*, Vol. 11, No. 2, (June 2010), pp. 275-315.

Herman, Arthur: *Freedom's Forge: How American Business Produced Victory in World War II*, (New York, 2012).

Heron, S.D.: *History of Aircraft Piston Engines*, (Detroit, MI, 1961).

Heywood, John B.: *Internal Combustion Engine Fundamentals*, (New York, 1988).

Hildebrand, Grant: *Designing for Industry: The Architecture of Albert Kahn*, (Cambridge, MA, 1974).

Hirst, Paul and Jonathan Zeitlin: 'Flexible Specialization versus post-Fordism: theory, evidence and policy implications', *Economics and Society*, Vol. 10, No. 1, (February 1991), pp.1-56.

Hoke, Donald R.: *Ingenious Yankees: The Rise of the American System of Manufacture in the Private Sector*, (New York, 1990).

Holley, Irving Brinton, Jr.: *Buying Aircraft: Material Procurement for the Army Air Forces, United States Army in World War II: Special Studies* (Washington, D.C. 1964).

------: 'A Detroit Dream of Mass-Produced Fighter Aircraft: The XP-75 Fiasco', *Technology and Culture*, vol. 28, No. 3, (July 1987), pp. 578-93.

Hooks, Gregory: *Forging the Military Industrial Complex: World War II's Battle of the Potomac*, (Chicago, IL, 1991).

Hornby, W.: *History of the Second World War, United Kingdom Civil Series, War Production Series: Factories and Plant*, (London, 1958).

Hounshell, David A.: 'Automation, Transfer Machinery and Mass Production in the U.S. Automobile Industry in the Post-World War II Era', *Enterprise & Society*, Vol. 1, No.1, (2000), pp. 100-38.

------: 'Ford Eagle Boats and Mass Production During World War I', in Smith, Merrett Roe, Ed.: *Military Enterprise and Technological Change: Perspectives on the American Experience*, (Cambridge, MA, 1985), pp. 175-201.

------*: From the American System to Mass Production: The Development of Manufacturing Technology in the United States*, (Baltimore, MD, 1984).

Howlett, Peter, ed.: *Fighting with Figures: Statistical Digest of the Second World War*, (London, 1995).

Hughes, Thomas P.: *American Genesis: A Century of Invention and Technological Enthusiasm, 1870-1970*, (Chicago, 2004).

Hyde, Charles K.: *Arsenal of Democracy: The American Automobile Industry in World War II* (Detroit, 2013).

------: 'Assembly-Line Architecture: Albert Kahn and the Evolution of the U.S. Auto Factory, 1905-1940', *The Journal of the Society for Industrial Archeology*, Vol. 22, No. 2 (1996), pp. 5-24.

------: *Riding the Roller Coaster: A History of the Chrysler Corporation*, (Detroit, MI, 2003).

Hyde, H. Montgomery: *British Air Policy Between the Wars 1918-1939*, (London, 1976).

Immer, John R.: *Layout Planning Techniques*, (New York, NY, 1950).

Inman, P.: *History of the Second World War, United Kingdom Civil Series, War Production Series: Labour in the Munitions Industry*, (London 1957).

Jarret, Philip, ed.: *Aircraft of the Second World War: The Development of the Warplane 1939-1945*, (London, 1997).

------: *Biplane to Monoplane: Aircraft Development 1919-1939*, (London, 1997).

Jolly, Michael: 'Employment Variability and Mass Production Technology in the British Automobile Industry during the Interwar Period', *Journal of European Economic History*, Vol. 25, No. 2, (Fall 1996), pp. 425-40.

Kennedy, David M.: The Oxford History of the United States, Volume IX: *Freedom from Fear: The American People in Depression and War, 1929-1945*, (Oxford, 1999).

Klein, Maury: *A Call to Arms: Mobilizing America for World War II* (New York, 2013).

Koistinen, Paul A.C.: *Arsenal of World War II: The Political Economy of American Warfare 1940-1945*, (Lawrence, KS, 2004).

------: *Planning War, Pursuing Peace: The Political Economy of American Warfare 1920-1939*, (Lawrence, KS, 1998).

Koham, C.M.: *Works and Buildings*, History of the Second World War, United Kingdom Civil Series, (London, 1952).

Lacey, Jim: *Keep From All Thoughtful Men: How U.S. Economists Won World War II*, (Annapolis, MD, 2011).

Lane, Frederic C., with Blanche D. Coll, Gerald J. Fischer, & David B. Tyler: *Ships for Victory: A History of Shipbuilding under the U.S. Maritime Commission in World War II*, (Baltimore, MD, 1951).

Launius, Roger D. Ed.: *Innovation and the Development of Flight*, (College Station, TX, 1999).

------: 'Introduction: Patterns of Innovation in Aeronautical Technology', in Launius, Roger D. Ed.: *Innovation and the Development of Flight*, (College Station, TX, 1999),

Leviton, Sar A., and Diane Werneke: *Productivity: Problems, Prospects, and Policies*, (Baltimore, MD, 1984),

Lewchuk, Wayne: *American Technology and the British Vehicle Industry*, (Cambridge, 1987).

------: 'Fordist Technology and Britain: the diffusion of labour speed-up', in Jeremy, David ed.: *The International Diffusion of Technology*, (London, 1992).

Lewis, Robert: 'Redesigning the Workplace: The North American Factory in the Interwar Period', *Technology and Culture*, Vol. 42, No. 4, (October 2001), pp. 665-84.

Little, Stephen E. and Margaret Grieco: 'Shadow factories, shallow skills? An analysis of work organization in the aircraft industry in the Second World War', *Labour History*, Vol. 52, No. 2, (May 2011), pp. 193-216.

Lloyd, Ian: *Rolls-Royce: The Merlin at War*, (London, 1978).

Lloyd-Jones, Roger and M.L. Lewis: *Alfred Herbert Ltd. and the British Machine Tool Industry, 1887-1983*, (Aldershot, UK, 2006).

Loften, Laurence K., Jr.: *Quest for Performance: The Evolution of Modern Aircraft*, (Washington, D.C., 1985)

Lombardi, Pino: *Short Stirling: The First of the RAF Heavy Bombers*, (Croydon, UK, 2015).

Lumsden, Alec: *British Piston Aero-Engines and Their Aircraft*, reprint of 1994 edition, (Ramsbury, Marlborough, UK, 2003).

Lund, Eric: 'The Industrial History of Strategy: Reevaluating the Wartime Record of the British Aviation Industry in Comparative Perspective, 1919-1945', *The Journal of Military History*, Vol. 62, No. 1, (January 1998).

Lyddon, Dave: 'The Myth of Mass Production and the Mass Production of Myth', *Historical Studies of Industrial Relations*, Vol. 1, (March 1996), pp.77-105.

Mandel, Ernest: *Late Capitalism*, Verso Edition, (Oxfordshire, 1980).

Marshal, E.L.: 'A Lifelong Love Affair—Sir Harry Ricardo and the Sleeve Valve', *The International Journal for the History of Engineering and Technology*, Vol. 83, No. 1, (January 2013), pp. 62-95.

Marshall, Ed and Bryan Lawton, eds.: *The Piston Engine Revolution: Papers from a Conference on the History of Reciprocating Internal Combustion Engines held at the Museum of Science and Industry, Manchester, 14-17 April 2011*, (London, 2012), pp. 401-20

Mason, Francis K.: *The British Bomber Since 1914*, (London, 1994).

------: *The British Fighter Since 1912*, (London, 1992).

McFarland, Keith D. and David L. Roll: *Louis Johnson and the Arming of America*, (Bloomington, IN, 2005).

McPherson, Thomas A.: *The Dodge Story*, (Glen Ellyn, IL, 1975).

Melnikova-Raich, Sonia: 'The Soviet Problem of Two 'Unknowns': How an American Architect and a Soviet Negotiator Jump-Started the Industrialization of Russia, Part I: Albert Kahn', *The Journal of the Society for Industrial Archeology*, Vol. 36, No. 2, (2010), pp. 57-80.

Meredith, Richard: *Phoenix: A Complete History of the Luftwaffe 1918-1945*, Volume 2: *The Genesis of Air Power*, (Solihull, UK, 2017).

Meyer, Stephen: 'The Persistence of Fordism: Workers and Technology in the American Automobile Industry, 1900-1960', in Lichtenstein, Nelson, and Stephen Meyer, eds.: *On the Line: Essays in the History of Autowork*, (Urbana, IL 1989), pp.73-99.

Midwest Regional Office, National Park Service, U.S. Department of Interior: Historic American Engineering Record: Pratt & Whitney Plant (Kansas City Plant), 1500 & 2000 East Bannister Road, Kansas City, MO, Written Historical and Descriptive Data, Field Records, HAER MO-118, (2012).

Miller, M., and R.A. Church: 'Motor Manufacturing', in Buxton, Neil K and Derek H. Aldcroft, eds.: *British Industry Between the Wars: Instability and industrial development 1919-1939*, (London, 1979), pp. 179-215.

Miller, Ronald and David Sawers: *The Technical Development of Modern Aviation*, (New York, 1970).

Mills, Edward D.: *The Modern Factory*, (London, 1951).

Milward, Alan S. : *War, Economy and Society 1939-1945*, (London, 1977)

Neale, M.C., ed.: *An Account of a Partnership-Industry, Government and the Aero Engine: The Memoirs of George Purvis Bulman,* Rolls-Royce Heritage Trust Historical Series No. 31, (Darby, UK, 2002).

Nelson, Daniel: 'Mass Production and the U.S. Tire Industry', *Journal of Economic History*, Vol. XLVII, No. 2, (June 1987), pp. 329-39.

Nixon, Frank: 'Aircraft Engine Developments During the Past Half Century', *Journal of the Royal Aeronautical Society*, Vol. 70, (January 1966), pp. 150-67.

Nuwer, Michael: 'From Batch to Flow: Production Technology and Work-Force Skills in the Steel Industry, 1880-1920', *Technology and Culture*, Vol. 29, No. 4, (October 1988), pp. 808-838.

Nye, David E.: *America's Assembly Line*, (Cambridge, MA, 2013).

O'Brien, Phillips Payson: *How the War Was Won: Allied Air-Sea Power and Allied Victory in World War II* (Cambridge, 2015)

O'Callaghan, Timothy J.: *Ford in Service to America: Mass Production for the Military in World War II*, (Jefferson, NC, 2009).

Olsen, Byron and Joseph Cabadas: *The American Automobile Factory*, (St. Paul, MN, 2002).

Overy, Richard: *William Morris, Viscount Nuffield*, (London 1976).

Pattillo, Donald M.: *Pushing the Envelope: The American Aircraft Industry*, (Ann Arbor, MI, 1998).

Pedden, G.C.: *Arms, Economics and British Strategy: From Dreadnaughts to Hydrogen Bombs*, (Cambridge, UK, 2007)

Piore, Michael J. and Charles F. Sabel: *The Second Industrial Divide: Possibilities for Prosperity*, (New York, 1984).

Postan, M. M.: *History of the Second World War, United Kingdom Civil Series, War Production Series: British War Production*, (London, 1952).

Postan, M.M., D. Hay, and J.D. Scott: *History of the Second World War, United Kingdom Civil Series, War Production Series: Design and Development of Weapons*: *Studies in Government and Industrial Organization*, (London, 1964).

Pratten, C.F.: *Economies of Scale in Manufacturing Industry*, (Cambridge, 1971).

Price, Brian: 'Developments of Aero-Engine in War 1915 to 1950: Impacts of Knowledge Management and Heuristics in the Configuration of Aero-Engine Architecture', in Starr, Fred, Ed Marshall, and Bryan Lawton, eds.: *The Piston Engine Revolution: Papers from a Conference on the History of Reciprocating Internal Combustion Engines held at the Museum of Science and Industry, Manchester, 14-17 April 2011*, (London, 2012), pp. 401-20.

Price, Brian: 'Developments of Aero-Engine in War 1915 to 1950: Impacts of Knowledge Management and Heuristics in the Configuration of Aero-Engine Architecture', in Starr, Fred, Ed Marshall, and Bryan Lawton, eds.: *The Piston Engine Revolution: Papers from a Conference on the History of Reciprocating Internal Combustion Engines held at the Museum of Science and Industry, Manchester, 14-17 April 2011*, (London, 2012), pp. 401-20.

Pugh, Peter: *The Magic of a Name: The Rolls-Royce Story: The First Forty Years*, (Duxford, Cambridge, UK, 2000).

Rae, John B.: *American Automobile Manufacturers: The First Forty Years*, (Philadelphia, PA, 1969).

------: *The American Automobile Industry*, (Boston, MA, 1984).

------: *Climb to Greatness: The American Aircraft Industry, 1920-1960*, (Cambridge, MA, 1968).

------: 'Financial Problems of the American Aviation Industry, 1906-1940', *Business History Review*, Vol. 39, No. 1, (Spring, 1965), pp.99-114.

Raff, Daniel M. G.: 'Making Cars and Making Money in the Interwar Automobile Industry: Economies of Scale and Scope and the Manufacturing behind the Marketing', *Business History Review*, Vol. 65, No. 4 (Winter 1991), pp. 721-753.

------: *What Happened at Highland Park?* National Bureau of Economic Research, (Washington, D.C. 2003).

Ricardo, Harry R.: *The High Speed Internal Combustion Engine*, 5th Ed., (London, 1968)

Richardson, Keith: *The British Motor Industry*, (London 1977).

Riddle, Donald H.: *The Truman Committee: A Study in Congressional Responsibility*, (New Brunswick, NJ, 1964).

Ristuccia, Cristiano Andrea, and J. Adam Tooze: 'Machine tools and mass production in the armaments boom: Germany and the United States, 1929-44', *The Economic History Review*, Vol. 66, No. 4, (2013), pp. 953-74.

------: 'The Cutting Edge of Modernity: Machine Tools in the United States and Germany 1930-1945', *Cambridge Working Papers in Economics*, CWPE 0342, (September 2003).

Ritchie, Sebastian: 'A New Audit of War: The Productivity of Britain's Wartime Aircraft Industry', *War and Society*, Vol. 12, No. 1, (May 1994), pp. 125-47.

------: *Industry and Air Power: The Expansion of British Aircraft Production, 1935-1941*, (London, 1997).

Robertson, A.J.: 'The British Airframe Industry and the State in the Interwar Period: A Comment', *The Economic History Review*, New Series, Vol. 28, No. 4, (November 1975), pp. 648-657.

Rosenberg, Nathan: 'Technological Change in the Machine Tool Industry, 1840-1910', *Journal of Economic History*, vol. 23, No.4, (December 1963), P. 414-43.

------: *Inside the Black Box: Technology and Economics*, (Cambridge, 1982).

Rubenstein, James M.: *Making and Selling Cars: Innovation and Change in the U.S. Automotive Industry*, (Baltimore, MD, 2001).

Ryden, A.J.: 'Flow Production', *Work Study*, Vol. 2, Iss. 12, (December 1953), pp. 26-31.

Sabel, Charles F. and Jonathan Zeitlin: 'Historical Alternatives to Mass Production: Politics, Markets, and Technology in Nineteenth-Century Industrialization', *Past and Present*, vol. 108 (August 1985), pp. 133-176.

Sabel, Charles F. and Jonathan Zeitlin, eds.: *World of Possibilities: Flexibility and Mass Production in Western Industrialization*, (Cambridge, 1997).

Schlaifer, Robert: *Development of Aircraft Engines*, Heron, S.D.: *Development of Aviation Fuels*: *Two Studies of Relations Between Government and Business*, (Cambridge, MA, 1950)
Scott, J. and R. Hughes: *The Administration of War Production*, (London, 1955).

Scranton, Philip: Endless Novelty: Specialty Production and American Industrialization, 1865-1925, (Princeton, NJ, 1997).

------: 'Diversity in Diversity: Flexible Production and American Industrialization, 1880-1930', The Business History Review, vol. 65, No. 1, (Spring, 1991), pp. 27-90.

------: 'From Depression to Globalization: Reconfiguring 20th Century American Machinery and Machine Tool Building', Practical Machinist: 06-14-2003.

Seymour, Peter: Wolseley Radial Aero Engines: Lord Nuffield's Thwarted Venture, (Stroud, UK, 2006).

Sherrard, Peter: Rolls-Royce Hillington: Portrait of a Shadow Factory, Rolls-Royce Heritage Trust Historical Series No. 44, (Derby, UK, 2011).

Simonson, G.R.: 'The Demand for Aircraft and the Aircraft Industry', Journal of Economic History, vol. XX, No. 3, (September 1960).

Smith, Herschel: *Aircraft Piston Engines: From the Manly Baltzer to the Continental Tiara*, (New York, 1981).

Smith, Merritt Roe: *Harpers Ferry Armory and the New Technology: The Challenge of Change*, (Ithaca, NY, 1980).

Smith, Merrett Roe, Ed.: *Military Enterprise and Technological Change: Perspectives on the American Experience*, (Cambridge, MA, 1985).

Smith, R. Elberton: *The Army and Economic Mobilization, United States Army in World War II: The War Department*, (Washington, D.C., 1959).

Smith, Richard K.: 'The Intercontinental Airliner and the Essence of Airplane Performance, 1929-1939', *Technology and Culture*, Vol. 24, No. 3, (July 1983), pp. 428-449.

Society of Motor Manufacturers and Traders Limited: *The Motor Industry of Britain Centenary Book 1896-1996*, (London, 1996).

Stoughton, Bradley: *History of the Tools Division War Production Board*, (New York, 1949).

Stratton, Michael: 'Skating Rinks to Shadow Factories: the Evolution of British Aircraft Manufacturing Complexes', *Industrial Archeology Review*, Vol. 18, No. 2, (Spring 1996), pp. 223-244.

Sullivan, Mark P.: *Dependable Engines: The Story of Pratt & Whitney*, (Reston, VA, 2008).

Tapper, Oliver: *Armstrong Whitworth Aircraft since 1913*, (London, 1988).

Taylor, Charles Fayette: *Aircraft Propulsion: A Review of the Evolution of Aircraft Piston Engines*, (Washington, D.C., 1971).

------: 'Engine Design in 1936', *Aviation*, Vol. 36, No. 1, (January 1937), pp. 21, 67.

------: *The Internal Combustion Engine in Theory and Practice,* Volume 1*: Thermodynamics, Fluid Flow, Performance*, 2nd Ed. Revised, (Cambridge, MA, 1985).

------: *The Internal Combustion Engine in Theory and Practice,* Volume 2: *Combustion, Fuels, Materials, Design*, 2nd Ed. Revised, (Cambridge, MA, 1985).

Thoms, David: *War, Industry and Society: The Midlands 1939-45*, (London, 1989).

Thoms, David, and Tom Donnelly: *The Motor Car Industry in Coventry Since the 1890's*, (Abingdon, Oxon., 2018).

Thomson, Ross: *Eras of Technological Convergence: Machine Tools and Mechanization in the United States, 1820-1929*, Paper Prepared for the Economic History Association Meetings, September 2010.

Tolliday, Steven: *The Rise and Fall of Mass Production*, Volume I, The International Library of Critical Writings in Business History, (Cheltenham, UK, 1998).

------: 'Transferring Fordism: The First Phase of the Overseas Diffusion and Adaptation of Ford Methods, 1911-1939', Actes du GERPISA No. 11.

Tooze, J. Adam: 'Endless Possibilities? Historical alternatives to mass production fifteen years on', available at www.adamtooze.com/wp-content/uploads/2016/03/Tooze-Alternatives-to-Mass-Production-Review-Sabel-Zeitlin-Herrigel-and-Scranton-2000.pdf, accessed 30/6/2017

------: Review of World of Possibilities. Flexibility and Mass Production in Western Industrialization by Charles Sabel and Jonathan Zeitlin; Industrial Constructions. The Sources of German Industrial Power by Gary Herrigel; Endless Novelty. Specialty Production and American Industrialization 1865-1925 by Philip Scranton, *Social History*, Vol. 25, No. 2 (May 2000).

------: *The Wages of Destruction: The Making and Breaking of the Nazi War Economy*, (London, 2006).

Underwood, Jeffrey S.: *The Wings of Democracy: The Influence of Air Power on the Roosevelt Administration*, (College Station, TX, 1991).

Vander Meulen, Jacob: *The Politics of Aircraft: Building an American Military Industry*, (Lawrence, KS, 1991.)

------: *Building the B-29*, (Washington, D.C., 1995).

Vetter, Harold G.: *The U.S. Economy in World War II*, (New York, NY, 1985).

Vincenti, Walter G.: 'Technological Knowledge without Science: The Innovation of Flush Riveting in American Airplanes, ca. 1930-ca.1950', *Technology and Culture*, vol. 25, No. 3, (July 1984), pp. 540-576.

------: *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*, (Baltimore, MD, 1990).

Wagner, Ray: *American Combat Planes of the 20th Century: A Comprehensive Reference*, (Reno, NV, 2004).

Wagoner, Harless D.: *The U.S. Machine Tool Industry from 1900-1950*, (Cambridge, MA, 1968).

Warner, Graham: *The Bristol Blenheim: A Complete History*, (Manchester, UK, 2002).

White, Gerald T.: *Billions for Defense: Government Financing by the Defense Plant Corporation during World War II*, (Birmingham, AL, 1980).

White, Graham: *Allied Piston Engines of World War II*, (Shrewsbury, UK, 1995).

------: *R-2800: Pratt & Whitney's Dependable Masterpiece*, (Shrewsbury, UK, 2001).

Whitney, Daniel D.: *V for Victory: The Story of the Allison V-1710 Aircraft Engine 1929-1948*, (Atglen, PA, 1998).

Williams, Karel, Tony Cutler, John Williams, and Colin Haslem: 'The End of Mass Production?' *Economy and Society*, Vol. 16, No. 3, (August 1987), pp. 405-39.

Williams, Karel, Colin Haslem, and John Williams: 'Ford versus 'Fordism': The Beginning of Mass Production?' *Work, Employment & Society*, Vol. 6, No. 4, (December 1992), pp. 517-55.

Williams, Karel, Colin Haslem, John Williams, Andy Adcroft & Sukhdeve Johal: 'The Myth of the Line: Ford's Production of the Model T at Highland Park, 1909-16' *Business History*, Vol. 35, No. 3, (1993), pp. 66-87.

Williams, Raymond: *Key Words: A Vocabulary of Culture and Society*, New Edition, (Oxford 2015).

Williamson, Oliver E.: *Markets and Hierarchies: Analysis and Antitrust Implications: A Study in the Economics of Internal Organization*, (New York, NY, 1975).

Wilson, James M. and Alan McKinlay: 'Rethinking the Assembly Line: Organization, performance and productivity in Ford Motor Company, c. 1908-27', *Business History*, Vol. 52, No. 5 (August 2010), pp. 760-78.

Winter, John: *Industrial Architecture: A Survey of Factory Building*, (London, 1970).

Woltjer, Pieter: *The Great Escape: Technological Lock-in vs Appropriate Technology in Early Twentieth Century British Manufacturing*, GGDC Research Memorandum 141, (University of Groningen, 2013)

Womack, James, P., Daniel T. Jones, and Daniel Roos: *The Machine that Changed the World*, (New York, 1990).

Woodbury, Robert S.: *Studies in the History of Machine Tools*, (Cambridge, MA, 1972).

Woollard, Frank G.: *Principles of Mass and Flow Production*, 55th Anniversary Special Reprint Edition, (2009).

Zeitlin, Jonathan: 'Flexibility and Mass Production at War: Aircraft Manufacture in Britain, the United States, and Germany, 1939-1945', *Technology and Culture*. Vol. 36, No. 1, (January 1995), pp. 46-79.

------: 'The Historical Alternatives Approach', in Jones, Geoffrey G. and Jonathan Zeitlin, eds.: *The Oxford Handbook of Business History*, (Oxford, 2008), pp. 120-40.