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# TRANSPORTATION SECURITY CONSIDERATIONS OF SMALL MODULAR AND MOBILE REACTORS

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## Abstract

An often-cited characteristic of small modular reactors (SMR) is that they can be transported as complete reactor systems, either for installation at nuclear sites or to remain mobile as transportable nuclear power plants. Various designs of smaller reactors will be transported in a fuelled state. Under some scenarios, the number and distribution of SMRs globally means that the number of transport operations required to support them will be considerable. However, the security challenges associated with moving nuclear material, in any configuration, are distinct to that of a nuclear site. Furthermore, many of these reactors are seeking to use non-standard fuels, some of which will increase the potential consequences should a radiological release occur. Taken together, the novelty of these factors may increase the attractiveness of nuclear transport operations to threat actors who might seek to sabotage or steal highly valuable, sensitive nuclear equipment and/or materials. This paper explores these challenges and suggests a range of potential approaches to delivering enhanced transport security through novel, cost-effective solutions. The paper recommends that reactor developers ensure to consider the transport phase in security planning and do so early enough in the design process to incorporate innovative solutions against current and future adversary capabilities.

## 1. Introduction

It is anticipated that in the coming years there will likely be a significant increase in the number of nuclear power reactors [1, 2]. This will include an expansion of nuclear power to a much wider range of countries, including many which have hitherto not used nuclear as part of their energy generation mix. Due to a range of potential benefits, it is anticipated that a significant proportion of new nuclear power plants (NPP) will be either small modular reactors (SMR) or advanced modular reactors (AMR), as defined in Table 1. It has been estimated that the global installed capacity of SMR technology will be 65-85 GW by 2035 [3], suggesting that over 200 individual reactors will be deployed globally within the next 15 years.

Within this paper, the term small modular reactor (SMR) is used in a broad sense to include evolutionary designs based on the miniaturisation of Generation III+ reactor technology, micro-reactors, and transportable nuclear power plants (TNPP). However, many of the discussed considerations will also be relevant to innovative, Generation IV advanced reactor designs, given they will likely need to address some of the challenges below as they seek to compete within the global nuclear technology marketplace, particularly with regards to advanced and novel fuel materials.

The transition to modular NPPs will have a wide range of impacts, including on supply chains, export controls implementation, plant construction timelines, investment risk, and many more. This paper focusses on one area in particular – nuclear equipment and materials transportation and the associated security considerations.

**Table 1: Typology of evolutionary and innovative nuclear power plant designs, based on technology Generation [4] and net electrical power rating [1]. Many new designs with ratings greater than 300 MWe (net) are planning to use modular approaches [5].**

<table>
<tr><th></th><th>≤10 MWe</th><th>>10 – 300 MWe</th><th>>300 MWe</th></tr>
<tr><td>Gen II or III</td><td>N/A</td><td>N/A</td><td rowspan="2">Large conventional Nuclear Power Plant (NPP).<br>Possibly with modular approaches for Gen III+.</td></tr>
<tr><td>Gen III+</td><td>Micro-reactors</td><td>Small Modular Reactor (SMR)</td></tr>
<tr><td>Gen IV</td><td>Advanced micro-reactors</td><td colspan="2">Advanced (modular) reactor (AMR)</td></tr>
</table>

## 2. Nuclear Transport Security Fundamentals

Nuclear security may be defined as "the prevention and detection of, and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear material, other radioactive substances or their associated facilities" [6]. Its objective is to reduce, eliminate or otherwise manage the risks posed by malicious actors external to and within nuclear organisations and facilities. This is achieved by considering a wide range of realistic, worst-case scenarios of potential nuclear security incidents affecting a given target, based on a Design Basis Threat (DBT) or Representative Threat Statement (RTS) as supplied by a state's Competent Authority (CA) [7]. In the context of nuclear transport, one might consider, for example, a ship carrying spent nuclear fuel in international waters, and then implementing suitable measures to reduce the risk to acceptable levels, either by reducing the severity of the potential consequences or reducing the probability of the incident occurring.

Nuclear security considers the intersection of three factors:

1. Threat – the nature, strength, capabilities, and willingness to act of the ill-intentioned actors who wish to carry out the attack, which might be, e.g., an armed physical attack by a terror group, an incursion by peaceful protestors to prevent normal operations, a cyber-attack perpetrated by hostile foreign state, an act of sabotage carried out by a disgruntled employee, and so on. This is primarily driven by the actors themselves and the context within which they exist. The threat can be countered through the collection and analysis of intelligence information and through deterrence to reduce willingness to act, for instance by presenting an image of insurmountable security. Threat information is prepared by state governments and communicated confidentially to relevant organisations in the form of the DBT or RTS [8].

2. Consequences – the potential outcome should the attack scenario play out to its conclusion without any intervention by security personnel or systems. This is a function of the asset

which may be attacked, be it nuclear material, equipment, information, personnel or other. Consequences can be reduced by, for instance, minimising the amount of nuclear material in a given location or transport operation, or converting it into a less readily stolen/sabotaged form.

3. Vulnerabilities – the weaknesses or features of the target that the malicious actors might seek to exploit to bring about the consequences. Vulnerabilities can be common between similar systems but should always be assessed on a case-by-case basis as they are often unique to a given situation. For instance, for a nuclear site, they may include access control points or safety critical facilities. For transport operations, vulnerability assessments must also consider proper analysis of the transport route, accounting for potential pinch points and any intermodal/loading activity included. The increased range of variables which influence nuclear transport compared to nuclear facilities mean that in practice, a broader scope of assessment may need to be conducted for transport operations.

Transport forms a crucial part of the nuclear fuel cycle and site construction, with security during this time being naturally of great importance. The challenges associated with moving nuclear material and nuclear technology through different threat environments are recognised as distinct from those faced by licensed nuclear sites. Further, utilising different modalities (road, rail, sea, or air) will require bespoke approaches for each when designing the appropriate PPS for the transport operations. The approach to security in transport is underpinned by key areas of analysis regarding categorisation of the nuclear material being transported for theft and sabotage, vulnerability assessments of the transport mode and route and relevant threat assessments. Layers of security can then be developed to account for the specific variables (such as route, mode, and threat) and to design a PPS to meet the security requirements.

Fundamental principles within nuclear security are applicable to transport just as they would be at a licensed nuclear site. Following the appropriate analysis upfront, the application of a graded approach will see a PPS designed that is proportionate to the categorisation and threat assessment of the transport. The application of security arrangements in transport sees multiple *layers* of security applied to an operation, supporting the principle of defence in depth (i.e., the use of several redundant, diverse security measures in series). Operations requiring lower levels of security will see arrangements such as staff background checks and access control arrangements. Common transport security requirements include:

- Minimizing the number and duration of transports
- Using the shortest possible route with minimum stops/transfers
- Avoiding areas of known conflict or disorder
- Avoiding regular schedules, where possible
- Restricting knowledge of movement information
- Establishing & agreeing handover of security responsibility
- Predetermination of trustworthiness
- Security being commensurate with the threat
- Ensuring packages or conveyances are not left unattended

These generic principles are still applicable to the systems in the scope of this paper. It is worth noting that in these are only guiding principles. In practice it is not always the correct approach for security to meet these principles, hence why a case-by-case approach is always appropriate. The interested reader is invited to consult the IAEA Nuclear Security Series of publications for more detailed information on the above [9], particularly the volume on transport security [10].

## 3. Legal and Regulatory Frameworks in Transport Security

The only legally binding international instruments regarding the physical protection of nuclear material are the Convention on the Physical Protection of Nuclear Material (CPPNM) and its Amendment (A/CPPNM). The original CPPNM was signed in 1980, and in 2005 States Parties to the Convention achieved consensus for an Amendment which came into force in 2016 [11]. The original Convention established physical protection arrangements only for the international transport of nuclear material, whilst the more recent Amendment extended its application to nuclear materials in domestic use, storage, and transport. Several legal obligations are placed on States Parties to protect nuclear material in transport. The high-level nature of the convention allows States Parties to develop their own regulatory requirements regarding the physical protection of nuclear material in transport. This means that there is an element of interpretation where individual states are enabled to apply security measures according to their own assessments and preferences, subject to the scope of the obligations in the Convention and its Amendment.

Annex I and II of the Convention set out the levels of protection to be afforded to nuclear material in transport, based on material type and the associated mass. These tables underpin the approach to nuclear materials categorisation, which is typically the starting point for designing a PPS for transport of nuclear material and allows for a commensurate and graded approach to be implemented, whereby the nature and level of security measures are matched to the level of risk [12]. In the context of this paper, the new fuel forms and general increased use of HALEU pose an interesting area when considering categorisation and subsequent security arrangements.

## 4. Unique Features of SMR leading to transport security considerations

SMRs differ from large conventional NPPs in several ways. Those differences which create transport security considerations are addressed below, firstly in terms of how the SMR might be deployed and used, secondly in terms of the nuclear equipment, and thirdly in terms of nuclear materials. The range of equipment and fuels proposed by SMR developers is very broad, with almost 40 SMR designs of ≤300 MWe (net) within the IAEA's public Advanced Reactor Information System (ARIS) database and many more known to the authors which are not held within ARIS [5]. It is unlikely that all these designs will make it to market. It is probable that elements of the threat, consequences and vulnerabilities will be common across many or all designs, and so it follows that similar broad security approaches will be applicable across numerous designs, even if they differ in the details, although detailed consideration of each individual SMR and fuel will, of course, be required as part of security design activities. The security implications of the differences presented here are addressed in Section 4.3 below.

### 4.1. Application Differences – Geographical, Regulatory

A key proposed benefit of SMRs is their greater flexibility in terms of siting. Many are designed to be operable in isolated locations with little to no requirement for resources such as large cooling water supplies or access to offsite power, whilst some are designed for completely remote or autonomous operation with no permanent presence of staff at the site. TNPPs take this even further, being able to operate effectively anywhere they can reach. Many developers are also seeking to reduce emergency planning zones, allowing the site footprint to shrink significantly. This allows for installation and operation of small local NPPs to provide power to specific users, such as remote communities, industrial facilities, or seawater desalination plants. Finally, the modular nature of these NPPs allows for the installation of many units at a single site, replacing the capacity of a large power plant with many SMRs.

As stated in section 1, it is expected that SMRs will be deployed into states which have not previously operated nuclear power reactors. Whilst some of these may have operated research reactors previously, there are questions over whether all these states are ready to accept SMRs as part of their energy mix; their nuclear regulatory and wider industry organisations may be immature, or lack the capability or capacity required to adequately manage SMR transport or deployment security risks.

### 4.2. Nuclear Equipment Differences – Transport of Complete Reactors

The large conventional NPPs in operation and under construction today are constructed at their final site locations from many individual, relatively simple components over a prolonged period. In contrast, SMRs are generally expected to be factory-manufactured as complete, integrated nuclear steam supply systems and then transported for installation at sites, in some cases with nuclear fuel already loaded. This will almost certainly be the case for mobile, transportable nuclear power plants (TNPP), which are permanently in an at least semi-transportable state. Within ten years, complete, fuelled and ready-to-operate nuclear power plants may be transported by road, rail, river, air, and sea, both intra- and internationally. Currently, air transport of large quantities of nuclear material and large items of nuclear equipment is not carried out, in part due to the package design requirements for air transport, the type of aircraft that would be required, and the mass of the equipment. However, this may change in future, particularly given the objective to be able to site EIDs in isolated locations in future.

As an additional difference compared to large conventional NPPs, SMRs are planning to operate with a much wider range of potential fuel cycle lengths, meaning that the refuelling may take place much more or less regularly. Some designs, such as molten salt reactors and pebble bed reactors, may be refuelled continuously whilst operating at full power. Other designs will operate for several months or years without refuelling, whilst at the extreme end some designs are expected to operate for decades without refuelling, allowing for completely sealed cores which operate for their full life without refuelling. For those which are refuelled regularly, some designers are planning to use factory sealed cores of fuel, which would be loaded with nuclear material by the manufacturer and transported for installation into the reactor on site.

### 4.3. Nuclear Materials Differences – Higher Enrichment, Use of Plutonium

The range of nuclear materials to be transported for SMR is potentially much wider than for large conventional NPPs. The latter are fuelled almost exclusively with fuel assemblies or bundles containing natural uranium oxide or low enriched uranium oxide with <5% $^{235}$U. Conversely, the range of potential fuels planned for use in SMR is much broader, including higher uranium enrichments of up to <20% for evolutionary designs and potentially fuels incorporating plutonium and other materials [5] (see Table 2). Furthermore, novel physical and chemical fuel forms are under consideration, including metallic, novel ceramic and cermet fuel materials within assemblies and bundles, as well as non-fixed fuels such as molten salt fuels and pebble bed reactor fuels where the fuel will likely be accounted for as a bulk material rather than as individual items.

**Table 2: Number of NPP concepts within the Advanced Reactor Information System Database using higher enrichments of uranium fuel [13]. Materials categories are taken from IAEA guidance, based on likely mass required for an SMR core [14].**

| **Fuel material in each entry** | **Likely fuel material category** | **Number of entries** |
|---|---|---|
| U enrichment listed < 10% | III | 24 |
| U enrichment listed ≥ 10% but < 20% | II | 35 |
| MOX or Pu, or U enrichment ≥20% | I | 8 |
| Total entries | III + II + I | 67 |

The figures in Table 2 indicate that several future designs have potentially higher categorisations of transport security associated with their respective fuel cycles in line with the CPPNM Annex II. Therefore, future transports associated with SMRs and their expected fuel cycles have the potential to attract a higher level of security provision under the arrangements currently in place.

## 5. Transport Security Considerations for SMR

### 5.1. Increased need for nuclear transport operations

It is expected that SMRs will become increasingly common during the coming years, displacing large conventional NPPs from future market share and spreading into additional countries [3]. This will lead to a need for a greater number of secure nuclear transport operations per year, to transport both equipment and materials. However, this is challenging to project due to many additional factors which must be considered.

This raises questions over the impact of transitioning towards SMR. Firstly, will there be a significant change in the number of secure transport operations required? Secondly, will nuclear transport of SMRs and materials affect the average risk associated with nuclear transport operations, e.g., will there be a change in the proportion of high-risk vs low-risk operations?

Generally, more deployable smaller reactors being used to meet energy demands are going to see an increase in global nuclear transport operations, some of which will involve novel concepts such as moving loaded cores or transportable reactor systems as well as involving advanced fuel types. However, this is challenging to project due to many additional factors that must be considered. These factors include:

- The number and distribution of countries that wish to make use of nuclear energy in the coming years. This is generally expected to increase, with several newcomer states wishing to construct or otherwise acquire their first nuclear power plant.
- The number of NPPs being installed in each country. This will be driven by a combination of the total nuclear installed capacity that each country seeks to achieve, and the technology

selections that the country makes. As countries seek to decarbonise energy generation and make use of nuclear energy, it is likely that the number of NPP per country will increase.

- The installed capacity and number of reactors at each nuclear site. As described in section 4.3, sites may have a single SMR or multiple SMR units to achieve different site capacities according to energy needs. In general, the option to use SMR to supply nuclear-derived electricity in smaller quantities closer to consumers suggests that the average installed capacity per site will likely decrease while the total number of sites increases.
- The types of SMR being deployed. This directly influences the frequency of refuelling operations and quantity and form of fuel required. Whilst sufficient material may be held at the site for more than one refuelling operation and sufficient material for multiple refuels may be delivered together, it should be borne in mind that this increases site security risk. Some designs do offer much longer refuelling intervals, although these are in the minority. Future decisions on technology selection and the resulting impact on fuel delivery requirements are difficult to predict.
- Spent nuclear fuel management approaches. Different SMR designs produce and discharge UNF at different rates and have different approaches to storage. Some plants are designed with sufficient on-site interim storage to allow for UNF to be held at the plant location for the plants entire operating life, allowing for removal as a single operation at end of life. Others require periodic removal during life to an off-site storage or disposal facility, thus requiring host countries to provide this. As with the previous point, this heavily depends on individual country technology selection over the coming decades and thus is highly challenging to assess.

The learning curve in this area is further compounded for emerging nuclear states that are yet to develop any practical experience in nuclear transports. The IAEA and member states will play a pivotal role in assisting developing states in efforts to capitalise on the benefits of SMR and transportable reactor technology.

As can be seen from the above, predicting the changing demand for nuclear transport operations is highly complex and beyond the scope of this paper, though a merited research activity. However, of the five factors presented, the first three suggest that there will likely be an increase in the number of nuclear sites globally, and these will be more highly distributed. Whilst the demand for nuclear materials at each of those sites is dependent on largely as-yet unmade technology choices, the authors believe it to be reasonable to assume that the overall demand for nuclear transport operations will increase due to the adoption and use of SMRs over the coming years.

### 5.2. Transport of higher risk materials becoming more common

In addition to an increased number of nuclear transport operations, the average security categorization per operation could increase.

As stated in section 4.3, SMRs are looking to adopt a wider range of nuclear fuel materials, including higher uranium enrichments and plutonium-containing or plutonium-based fuels. This will increase the associated threat due to the increased attractiveness of these materials to malicious actors. The IAEA categorises nuclear materials for security purposes for theft, with transport sabotage analysis also concerning the details of the nuclear material in transport (such as form and dispersibility). The lowest risk materials (e.g., uranium enriched to <10% $^{235}U$) or lower quantities of higher risk materials falling into the lowest risk group, Category III. However, as shown in

Table 2 and given the wider range of nuclear materials under consideration as SMR fuels, higher categories will likely apply. In quantities of greater than 5-10 kg, uranium enriched to 10 – <20% $^{235}$U is classed as Category II, and uranium of ≥20% $^{235}$U is classed as Category I. Plutonium in quantities ≥2 kg always falls into Category I [15]. As a result, under the IAEA guidance the nuclear materials associated with SMR designs may attract a greater requirement based on the categorisation for theft in accordance with the CPPNM and associated IAEA guidance. International Category I moves already take place routinely today, the frequency of these will likely see an increase in line with the wider deployment of the systems within the scope of this paper.

Annex II of the CPPNM sees a graded approach applied based on the categorisation of the bulk amount of fissile material within the fuel. Additional analysis of the chemical and physical form of new advanced fuels may better establish the security provision attached to transports when compared to the fuel types in transport today. For example, proliferation resistant and less dispersible advanced fuel types may have similar or higher $^{235}$U content but prove to be less attractive for unauthorised removal or less dispersible when considering sabotage scenarios. This means the categorisation process will remain the same however the security afforded may be less onerous. TRISO fuel is a good example of a fuel type that is less dispersible and considered too large and dense to travel in the atmosphere except under extreme conditions [16]. Conversely, the use of novel physical and chemical fuel forms may also have the potential to lead to increased radiological consequences, as these materials may be more readily dispersed by threat actors. The broad range of fuel types paired with their influence on security reiterates the need for case-by-case analysis in transport.

The concept of factory-sealed cores raises questions as to whether there is an increased risk of the core becoming critical during transport operations. If a saboteur could, for instance, somehow place the core into a critical configuration this could greatly increase the risks of radiological consequences, for instance, through a criticality event. However, even if this did not result in radiological consequences, it could still destroy the credibility of nuclear security and deal a major blow to the reputation of the nuclear power industry in general.

Vital Area Identification of the cores / TNPPs in transport would aid in establishing what systems, structures or components would need to be accessed to make the transportable plant or loaded core go critical or lead to an event resulting in unacceptable radiological consequences. This anti-sabotage methodology widely used on nuclear sites uses logic models to identify key areas for protection when considering sabotage events that could lead to unacceptable radiological consequences. Data from this form of analysis could underpin the approach to designing anti-sabotage elements of the transport PPS for more complete reactor systems. It is expected that for TNPPs or FNPPs, this analysis will already have been undertaken Further, work to establish the difference between the critical state and the transportable non-critical state of the core would identify where the security efforts could be focussed.

When considering the transport of systems containing nuclear material, either as cargo, within a sealed core or in a TNPP configuration, holistic assessment of the security credit of the core / reactor would give useful data to measure against the relevant threat or DBT. One approach may be to consider what type of licensed package would typically be used for the same amount of nuclear material as cargo, and then what security credit and delay time would this package provide? Licensed packages undergo specific safety testing to ensure robustness, it is expected that this testing will also be required for TNPP and loaded core modules. This robustness also serves a security function, which can be further identified through field testing. The additional transport security arrangements required to meet the security outcome could then be applied to the cores or TNPPs in transport. This could see the use of overpacks for smaller designs, or increased escort provision for the larger. Engineered approaches could also be used, such as flooding the core with borated water during transport.

The average cost of transport operations is impacted by the Category of the material under transport, with Category II and I material incurring much greater costs, largely due to the potential need of armed escort forces. As such, an increase in the average per-transport security Category will drive an increase in overall transportation costs for SMR compared to large conventional NPP unless an alternative approach can be found, such as the use of novel solutions to deliver equivalent security through alternative means (see section 6) or a redrafting of the IAEA guidance on categorisation (see above in this section). The other factor driving security requirements and thus costs is the threat, and measures to reduce this, for instance through deterrence, can be an effective approach to control security costs.

### 5.3. Impacts of moving towards more remote siting

A key advantage of SMRs and TNPPs is their ability to be sited remotely to supply power in locations with poor grid connectivity. This will lead to the use of new and less established transport routes, which can place facilities and nuclear material at greater distances from response arrangements unless appropriate assessment and contingency planning is undertaken. Analysis of the transport route options, in conjunction with the DBT or RTS, will inform decisions regarding routes to the facility destination.

Larger facilities using fuel cycles with Category I and II nuclear material would typically require response forces close to the facility or in escort of the transport, creating significant additional cost. For Category I and II transports, IAEA NSS 26-G advises that consideration should be given to the security situation along the entire route for transport [10]. When considering response force capability and associated times in remote settings, this has potential add complexities to transporting nuclear material to and from these locations. However, where one area of security cannot be supplied at the required, then others must be increased to compensate. The uplift in security to cover remote siting should target increase in effectiveness of the detect and delay functions, both of which could be included as design features. In remote environments, this could see a large cost increase attached to the transports as remote areas would have little additional support from local police or other security support that is often available in more populated areas. Security contingency arrangements must ensure that the detect and delay functions allow for response times in a security event.

In addition, the mode of transport will be influenced by local infrastructure and geographical features. Therefore, the transport security arrangements will be cognisant of these elements to ensure security of the nuclear material and nuclear technology is never diminished. The availability of safe haven and contingency route arrangements are desirable transport security options that may be hindered by remote siting.

Intermodal and loading points are key areas for a transport and infrastructure availability should be considered during the site selection process, as the characteristics of the location may determine the chosen transport mode. When siting, consideration should be given to incorporating intermodal points within the site boundary to minimise the time at risk for any transport and increase operational efficiency with regards to transport.

### 5.4. Legal and Regulatory Frameworks in Transport Security

The IAEA and member states will play a key role in developing the additional requirements and regulatory frameworks regarding transport security of SMRs and TNPPs. Typical transport for SMRs (i.e., nuclear material as cargo) would see the same or similar approaches as are currently in practice for the transport security elements associated with these designs. For the more novel concepts of TNPPs or moving cores containing nuclear material, collaboration between the member states will be key in developing technical guidance and best practice.

It is expected that being signatory to and ratifying the CPPNM and A/CPPNM will form a key element of new nuclear states adopting the SMR systems. The ratification of the convention will give assurances to the IAEA that the appropriate legislative instruments are in place for a state to securely manage the nuclear material it intends to transport, use, and store. Regulatory development is paramount to using nuclear technology, and this remains the case for SMRs and TNPPs.

Article 4 of the CPPNM addresses the scenario of nuclear material in transport involving States that are not party to the Convention. Paragraphs 2 obligates party states not to import, or authorise the import of, nuclear material from a State not party to the Convention without receiving the relevant assurances regarding the physical protection levels set out in Annex I. Similarly, paragraph 3 of Article 4 states the same requirement for permitting transit of a party state between states that are not party to the Convention. This extends the application of the Convention to cover non-party state international transports, seeing these states subject to the same assurance requirements regarding physical protection as party states.

The application of the CPPNM remains pertinent to the evolving designs within the scope of this paper and the IAEA guidance and current approaches will apply to the transport of nuclear material used in these reactors. However, certain operational approaches may need to be adapted to account for novel aspects of the reactor designs, mainly associated with the size of loads (where reactors are moved with fuel in the core) and routes (such as remoteness of sites). Further, for developing nuclear states, much work will need to be done to guide the states through the requirements of the CPPNM and the A/CPPNM.

## 6. Novel approaches to transport security for SMRs

For conventional transports associated with these reactor systems, even in remote settings, the current approaches and principles in use for transport security are still applicable. Through proper assessment of threat, route and the material in transit, security arrangements can be designed to ensure the security of material is consistent throughout the duration of the transport.

When considering novel fuels and moving nuclear material within loaded cores TNPPs, additional security analysis of the material would provide useful data. This would aid in establishing the characteristics of the material in an attack or sabotage scenario for example. The same analysis would also prove useful for any reactors that are considered TNPPs or module cores being transported containing nuclear material. If it is possible to establish the security credit of the reactors or cores in transport, then the appropriate transport security arrangements can be designed with this in mind. Measuring the systems that are intended to be transported against the DBTs would provide valuable insight into security incident conditions. Baseline security requirements for reactors and core modules that are going to be transported containing nuclear material will be underpinned by this type of analysis.

For international transport of fuelled modules or transportable systems, appropriate engagement with the origin state, the destination and any state being transited remains an imperative part of operational preparation. Engagement with the relevant CA in each state will ensure the transport is carried out in a manner agreeable for the states on the transport route. As the responsibility for nuclear security within a state rest entirely with that state, for any international transport involving Category I material, engagement at the government-to-government level will be required in a series of Records of Discussion (RODs). The RODs confirm security responsibility of the material being transported is accounted for and agreed upon for the entirety of the transport, which is common practice for conventional Category I transport undertaken with licensed packages.

## 7. Specific Challenges for Transportable Nuclear Power Plants

The transport security considerations explored above apply both to TNPPs and fixed land based SMR. However, TNPP systems are subject to additional factors worthy of consideration, which are briefly outlined here. TNPP systems exist at the intersection of licensed fixed nuclear sites and nuclear transport. Therefore, it is expected that a hybrid approach drawing lessons and regulatory insight from both areas will be required. There are four key elements which have security considerations, both as individual elements and at their interfaces:

- Nuclear materials transport, in the form of a sealed core or module
- Nuclear equipment transport, in a state of being ready to operate
- A non-fixed platform, such as a ship, barge, road, or rail vehicle, capable of moving the materials and equipment through various jurisdictions and zones of control.
- The intent to operate the nuclear power plant from the non-fixed platform. In addition, there is a possibility that the platform may be self-propelled, potentially by energy derived from operation of its nuclear power plant.

Compared to the movement of nuclear power plants, which must be installed at site locations with other supporting equipment, TNPPs will be self-contained units, likely capable of operating using only equipment that is on the platform. This makes them a more attractive target for hijacking, whilst at the same time reducing the ability to use PPS measures to keep potential attackers at a distance – it may be that attackers can approach the platform itself before being treated as a threat. As such, the PPS will need to be more compact than for fixed SMRs which can control an owned area of land around secure facilities. As with all nuclear facilities, many of the potential vulnerabilities of TNPP will be created during the design phase. It is crucial that physical protection during TNPP transportation be addressed as early as possible during the design process, such that vulnerabilities can be eliminated or protected, and security features can be built into guard against attackers.

Considerations for these systems when in transport would be their lack of manoeuverability and expected slow speed, making them vulnerable to more agile attackers. However, being transportable does have an advantage in that they can be potentially deployed to states or areas with less stable political or security environments, allowing for the benefits of nuclear energy to be realised in times of acceptably low threat, but for the TNPP to withdraw in case of a deteriorating threat situation when the potential for attack beyond the DBT becomes a possibility.

One key aspect for consideration concerns floating nuclear power plants, as these are subject not only to nuclear law and regulation, but also maritime law, licencing requirements, and so on. The intersection of nuclear and maritime considerations creates numerous potential areas for overlap and potential conflict, and designers should consider early how these can be identified and resolved as part of the design process. Several developers of floating NPP concepts, e.g., Seaborg Technologies, are already working to acquire approvals from maritime authorities for their designs [17].

Legal and regulatory considerations for TNPP have already been addressed in previous publications from the IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) [18], although this work had clear gaps and insufficient coverage. In response to the numerous unknowns and challenges of applying security to TNPPs, as well as safety, the IAEA is developing a new technical document (TECDOC), which will cover design safety and security considerations for TNPP in transportation [19]. The authors understand that this document is likely to be published during 2022 or 2023.

## 8. Conclusions and Recommendations

This paper has explored the security considerations associated with the transportation requirements for novel SMRs and associated nuclear materials. Transport will be a major requirement in support these new nuclear technologies, given their anticipated greater number, geographical distribution, and use of higher Category nuclear materials.

Current international legislation, such as the CPPNM and its Amendment, and national legislation and regulations derived from this, are likely sufficient for these systems. However, specific security analyses of the new fuels, equipment and planned transport operations will be required, and this should be performed at an early stage of the design process such that conflicts can be avoided which would necessitate costly redesign work later during the design process. Under no circumstances should transport security considerations be left by designers to other stakeholders, as this will result in transport operations which could require significant expenditure on escort forces to be secured. Detailed security analyses will serve as one of the initial steps in the design of an effective yet proportionate PPS for transport.

SMR developers and transporters should work together to identify and mitigate security risks that are unique to or magnified during transport operations. Novel technological approaches may be used to achieve transport security. Where possible, designers should seek to eliminate the possibility of security incidents leading to theft or sabotage through engineering means. Whilst it is certainly possible to achieve security performance through the application of current and historical approaches, e.g., large armed escorts, this is unlikely to be cost-effective for facility operators. Utilities selecting technologies to build should consider these costs as part of their economic case when making decisions. Instead, the use of a secure-by-design approach to transport is recommended, where features are built into the module, core, or other item under transport to detect and prevent theft or sabotage. These measures need not be specific to the transport phase – features which give security throughout all parts of the SMR's life will give the greatest cost efficiencies for security. Transporters and developers should co-develop approaches to deter threat actors, ensure early detection attacks and timely communication with responders, impose delay upon attackers until response forces can arrive and neutralise the threat, and ensure tracking of stolen equipment and materials to facilitate recovery as swiftly as possible.

Beyond security, developers should also consider safety, safeguards, and operations, how security decisions may interface with these other areas, and how there may be synergies and conflicts between them. Decisions taken for security reasons, such as complete sealing of the module, may have repercussions for safety and/or safeguards, and so security should not be considered in isolation.

Finally, beyond the transport security of standard SMR, additional considerations will apply to TNPP. The upcoming IAEA TECDOC mentioned in section 7 will TNPP security and safety considerations in detail. Interested readers are encouraged to examine this once published.

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