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GEN IV International Forum

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GENERATION IV PROLIFERATION RESISTANCE AND PHYSICAL PROTECTION SITING STUDY FOR AMRS AND MICROREACTORS

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Abstract

This document examines various siting options for advanced modular reactors (AMRs) and microreactors and implications for proliferation resistance and physical protection. The report considers the following four siting options for AMRs: remote locations, near population centres, floating or underwater power stations, and civilian marine propulsion. Additionally, it explores five crosscutting considerations: Single versus multi-modules, ultimate heat sink, autonomous and remote operation, high assay low enriched uranium (HALEU) versus low enriched uranium (LEU), and transit of reactors. Each section concludes with key findings and high-level conclusions are consolidated at the end of the report.

List of Authors

Seong-Kyu	AHN	PRPPWG	Korea Atomic Energy Research Institute
Ben	CIPITI	PRPPWG	Sandia National Laboratories
Thomas	DEGUIRE	Intern	Sandia National Laboratories
Logan	SCOTT	PRPPWG	Oak Ridge National Laboratory
Kevin	HESKETH	PRPPWG	National Nuclear Laboratory
Jorge	NAVARRO	PRPPWG	Oak Ridge National Laboratory
Frédéric	NGUYEN	PRPPWG	French Alternative Energies and Atomic Energy Commission
Ty	OTTO	PRPPWG	Pacific Northwest National Laboratory
Guido	RENDA	PRPPWG	European Commission Joint Research Centre
Tomooki	SHIBA	PRPPWG	Japan Atomic Energy Agency
Bryan	VAN DER ENDE	PRPPWG	Canadian Nuclear Laboratories
Ankur	CHAUDHURI	PRPPWG	Canadian Nuclear Laboratories

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List of Acronyms

A/CPPNM	Amendment to the Convention on the Physical Protection of Nuclear Material
AMR	Advanced Modular Reactor
BBRE	Bullet and Blast Resistant Enclosure
CAS	Central Alarm Station
CoK	Continuity of Knowledge
C/S	Containment/Surveillance
EEZ	Exclusive Economic Zone
EPZ	Emergency Planning Zone
FNPP	Floating Nuclear Power Plant
GIF	Generation-IV International Forum
GFR	Gas Fast Reactor
GWD/MT	Gigawatt-Day per Metric Ton
HALEU	High-Assay Low-Enriched Uranium
HTR	High Temperature Reactor
IAEA	International Atomic Energy Agency
LEU	Low Enriched Uranium
LFR	Lead Fast Reactor
LWR	Light Water Reactor
MSR	Molten Salt Reactor
NNWS	Non-Nuclear Weapons State
NPT	Non-Proliferation Treaty
NWS	Nuclear Weapons State
PBR	Pebble Bed Reactor
PIDS	Perimeter Intrusion Detection System
PP	Physical Protection
PPS	Physical Protection System
PR	(Nuclear) Proliferation Resistance
PR&PP	Proliferation Resistance & Physical Protection
PRPPWG	Proliferation Resistance & Physical Protection Working Group
PWR	Pressurized Water Reactor
RHRS	Residual Heat Removal System
SCWR	Supercritical Water Reactor
SeBD	Security by Design
SFR	Sodium Fast Reactor
SMR	Small Modular Reactor
SSC	System Steering Committee
TRISO	Tristructural-Isotropic
UOX	Uranium Oxide
URMS	Unattended Remote Monitoring Systems
VHTR	Very-High-Temperature Reactor

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1. Introduction

The Proliferation Resistance and Physical Protection Working Group (PRPPWG) was established by the Generation-IV International Forum (GIF) to examine PR&PP features of the six GIF technologies: Sodium-Cooled Fast Reactors (SFR), Lead-Cooled Fast Reactors (LFR), Supercritical Water Reactors (SCWR), Gas Cooled Fast Reactors (GFR), Very High Temperature Reactors (VHTR), and Molten Salt Reactors (MSR). One of the GIF goals is to ensure "Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism."

At the 2022 GIF Industry Forum, the PR&PPWG presented its recent work to members of industry for comment and feedback. One of the requests from the Industry Forum was to provide a PR&PP analysis for advanced reactors based on different siting options and locations. The purpose of this paper is to present those results and provide guidance to industry and policy makers on PR&PP aspects based on differences in how advanced reactors may be sited around the world.

Currently, there exists a wide variety of potential siting and use options for small modular and microreactors which were not possible with the previous generation of large light water reactors. These different siting options present new ways for nuclear energy to bring power to new applications, but they also present new challenges in safeguarding and securing these facilities and nuclear fuels. Unique siting options require analysis on physical protection approaches and potential proliferation issues. Additionally, the siting of a large number of smaller reactors around the world may strain the International Atomic Energy Agency (IAEA) safeguards resources.

Since the GIF focuses on advanced reactor designs, the focus of the siting study is based generally on the six GIF reactor designs. However, siting of advanced reactors is not limited to these six designs and may also include light water reactor (LWR) type small modular reactors (SMRs). Many of the conclusions of the work here can apply more generally to any advanced modular reactor (AMR) design unless otherwise noted.

This report provides additional background and context in Section 2. Section 3 discusses the four siting options for AMRs: remote locations, near population centres, floating or underwater nuclear modules, and civilian marine propulsion. Section 4 discusses additional crosscutting considerations: single versus multi-modules, ultimate heat sink, autonomous and remote operation, high assay low enriched uranium (HALEU) versus low enriched uranium (LEU), and transit of reactors. High-level conclusions are consolidated in Section 5. More far-reaching siting options of nuclear including space-based nuclear power are not covered in this report. The goal of this work is to highlight where PR or PP challenges may exist and which industry will need to consider.

2. Background

The PRPPWG was established by the GIF to develop, implement, and foster the use of an evaluation methodology to evaluate Generation IV nuclear energy systems with respect to the GIF PR&PP goal, as described previously.

The PR&PP methodology provides designers and policy makers a technology neutral framework and a formal comprehensive approach to evaluate the proliferation resistance (PR) and physical protection (PP) characteristics of advanced nuclear energy systems using specific measures and metrics. As such, the application of the evaluation methodology offers opportunities to improve the PR&PP robustness of system concepts throughout their development cycle starting from the early design phases according to the PR&PP by design philosophy. The working group released the current version (Revision 6) of the methodology for general distribution in 2011 [1]. The PRPPWG developed the methodology and applied it in a variety of case studies related to the GIF designs [2].

Starting in 2007, the PRPPWG and the six System Steering Committees (SSCs) conducted a series of workshops on the PR&PP characteristics of the respective designs and identified areas for further R&D in each design. The PRPPWG developed a common template to systematically collect GEN IV design information and PR&PP features and issues. This work culminated in white papers on each of the six design technologies, written jointly in 2011 by the PRPPWG and the respective SSC, compiled in an integrated report which included an analysis of crosscutting topics [3].

In 2018-2023, the PRPPWG (in collaboration with the SSCs and Provisional Systems Steering Committees (pSSCs) of the six GIF reactor concepts) completely revised white papers on the PR&PP features of each of the six GIF technologies [4-9]. The intent was to generate updated information about the PR&PP merits of each reactor system and to recommend directions for optimizing their PR&PP performance. Concurrently, the PRPPWG published a crosscutting report on PR&PP aspects that transcend all six GIF systems [10].

The PRPPWG also maintains a bibliography of official reports and publications, applications, and related studies in the PR&PP domain [11].

Proliferation resistance *"is that characteristic of a nuclear system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States in order to acquire nuclear weapons or other nuclear devices. The degree of proliferation resistance results from a combination of, inter alia, technical design features, operational modalities, institutional arrangements and safeguards measures. Intrinsic proliferation resistance features are those features that result from the technical design of nuclear energy systems, including those that facilitate the implementation of extrinsic measures. Extrinsic proliferation resistance measures are those measures that result from States ' decisions and undertakings related to nuclear energy systems."* [12]. Summaries and examples of the intrinsic features and extrinsic measures are reported in Appendix A in the form of tables.

Physical protection refers to characteristics that impede the theft of nuclear materials suitable for nuclear explosives or radiological dispersal devices and the sabotage of facilities and transportation by sub-national entities and other non-State adversaries.

Siting analysis can be an arduous task, especially for nuclear newcomers who may be trying to identify the best siting options for new reactor sites. Early analyses during site selection are crucial to identify site attributes that could enhance or impede safety, security, and safeguards measures for advanced reactors.

A few assumptions are inherent in this report. From an IAEA standpoint, safeguards verification (extrinsic PR measures) will be the same whether in a remote or densely populated area. Likewise, the physical protection of the plant should maintain equal levels of protection whether reactors are in remote or densely populated areas; however the measures taken may be different. Consequences to environment and population should not be weighed differently for different areas.

From a security perspective, potential site options should be analysed for proximity to emergency responders, adequacy of existing security infrastructure, potential transportation routes for nuclear materials, and emergency evacuation options. Other environmental and sociopolitical factors may also need to be taken into consideration as part of a comprehensive siting assessment. The results of a siting analysis can provide insights and valuable information to policymakers, developers, and energy stakeholders during the decision-making process.

3. PR&PP Analysis of Siting Options

3.1. Siting in Remote Locations

New reactor designs, particularly advanced modular reactors (AMRs) are being proposed for deployment in remote locations. The size of reactors proposed for these applications varies, but generally smaller energy output (typically less than 50 MWth) are appropriate for the typical heating and electricity supply needs of remote mining, military, research, and municipal operations, as found in northern regions of Canada and Russia, for example [13,14]. AMRs and LWR-type SMRs also offer other advantages for deployment in remote locations:

1. AMRs can be deployed incrementally, allowing for the addition of more units as power demand grows. This reduces up-front investments for smaller communities with limited resources.
2. AMRs require less land and infrastructure than traditional nuclear power plants, making them well-suited for remote locations with limited access to transportation and construction resources.
3. AMRs can provide a stable, continuous, and affordable power supply to isolated communities that are subject to frequent disruptions and blackouts or are dependent upon the shipment of liquid fuel over long distances. For communities sparsely spread over vast distances, the cost of fuel shipment can be significant [15].

3.1.1. Proliferation Resistance

In proliferation resistance, both intrinsic features within and extrinsic measures applied to a nuclear energy system, can impede the diversion or technology misuse (e.g., undeclared production of nuclear material) by States to acquire nuclear weapons or other nuclear explosive devices.

An intrinsic feature of some smaller AMRs appropriate for deployment in remote locations is their inclusion of an encapsulated core as part of their design. These reactors can be fabricated and fuelled in a factory, encapsulated, transported to sites for power generation, and remain encapsulated until they are safely shipped back to the factory: this feature is a strong intrinsic barrier once the reactor is onsite and can impede technology misuse or nuclear material diversion. Another intrinsic feature of some AMR designs suitable for deployment in remote locations is the long lifetime of their operating cores (up to 20 years in some cases), which will reduce the frequency of transporting reactor cores to their deployment sites and also the frequency for onsite refuelling thus minimizing another potential access to the reactor fuel for diversion.

As part of extrinsic measures, smaller AMRs appropriate for deployment in remote locations can be fabricated and fuelled in a factory, sealed (using a tamper-indicating seal), transported to sites for power generation, and remain sealed until they are safely shipped back to the factory: this feature can impede technology misuse or nuclear material diversion. On the other hand, safeguards inspectors will also need to visit the reactor site on a regular basis. Difficulty to access the site may increase the cost of site visits and reduces the potential of unannounced inspections. Continuity of knowledge must be maintained, and sealed cores can make recovery from loss of continuity of knowledge difficult. Continuity of knowledge is usually maintained with multiple layers of containment and surveillance including quantitative measurements when needed. In the case that many small output AMR sites are sparsely deployed over a vast area, the cost and effort of safeguards inspectors visiting each of these sites on a regular basis can be significant. The burden and/or frequency of such visits could be reduced through the employment of reliable year-round monitoring of redundant authenticated sensors. The IAEA already makes considerable use of unattended remote monitoring systems for safeguarding reactor facilities at other types of siting locations, and such systems can be adapted for use at remote locations. Further development of these types of systems may be needed for their adaptation or to enable more comprehensive monitoring of the facility. The topic of remote monitoring and secure data transmission is discussed further in section 4.3. For such a measure to be reliable in remote locations, reliable communications infrastructure must be implemented in the region in question [16].

3.1.2. Physical Protection

Regarding the physical protection of reactors deployed at remote sites, the difficulty of physical access to the site presents a benefit, in that it will be more difficult for adversaries to reach and access the site for an act of sabotage or theft. All AMRs should be treated the same in terms of physical protection to acknowledge the fact that remote areas of land and people are just as important to protect as dense population centres. One key difference is that remote locations may see less cost associated with an increased site size making larger stand-off distances that will affect consequence.

The smaller size of AMRs in general may allow for physical protection systems designs with smaller numbers of security staff be employed on site, and the site may rely upon off-site response forces to support in the event of a security emergency. However, the difficulty to access the site also serves to impede timely response from the off-site responders. As part of security delay tactics until further off-site response support comes, engineered systems can be included, such as physical barriers, robotics, and unmanned aerial vehicles [17], in addition to human solutions. Development of engineered systems, and tailoring their use by an optimal staff complement, may be required. For offsite monitoring and response to be effective, there is again a need for reliable and secure communications infrastructure to be put in place.

3.2. Siting Near Population Centres (Cities/Universities/Industrial Complexes)

The siting of AMRs and microreactors near population centres may be a more viable option than traditional reactors because of the reduced site and reactor size, flexible operating capabilities, mobility, and projected lower construction costs. Smaller possible source terms can result in reduced emergency planning zone sizes. However, siting near population centres and industrial complexes may introduce new challenges for the physical protection of these facilities against external threats. While most of the reactors are still in the design phase, early consideration of the PR&PP challenges may mitigate some of the associated threats for urban sites, allowing the benefits of these new types of reactor systems to be realized.

The two primary urban applications for AMRs are expected to be 1) for power and heat supply for industrial facilities and 2) for electricity and district heat production. Manufacturing and data processing centres require significant amounts of energy for operations, and having a long-term, clean heat and power supply is an attractive solution for many businesses. Power for data centres in particular is expected to increase demand for nuclear energy, but these energy demands can easily exceed that of a typical small reactor. Strategies for co-locating advanced reactors and industrial systems seek to further improve overall process efficiencies by minimizing heat losses through transmission while also maximizing the energy utilization that can be achieved through shared resources. Some advanced reactor designs can use air cooling further making AMRs and microreactors attractive options for areas with limited space or areas that were previously limited due to water accessibility.

3.2.1. Proliferation Resistance

In terms of proliferation resistance, the discussion might be divided in two broad categories: AMRs deployed in residential areas for electricity production and district heat generation and

AMRs deployed in industrial complexes mainly for non-electrical application of nuclear energy. While these two siting options per se are probably less impactful on PR than on safety and security, the type of reactor designs likely to be deployed in densely populated areas might be influenced by the perceived level of safety and overall performance by the general public. The characteristics of these designs can have practical PR implications in terms of intrinsic and extrinsic (i.e. safeguards) measures. The following paragraphs will highlight some possible desired characteristics that might drive the technology choice in the two above mentioned scenarios, with a brief discussion of the related implications on proliferation resistance.

Regardless of the reactor technology choices, residential and industrial areas generally have very good support infrastructures that safeguards can utilize. Efficient transportation systems enhance site accessibility, facilitate traveling arrangements for safeguards inspectors, and reduce travel time. Residential and industrial areas usually exhibit very good telecom infrastructures, enabling effective and efficient data transmission for remote safeguards monitoring.

The presence of many people near the nuclear facility also means that any non-routine intervention on the site, e.g. extraordinary activities implying transportation of nuclear material or the presence of specialized equipment and transport vehicles, would be readily spotted by many observers and would rapidly become public domain, complicating any attempt of involving the site in a clandestine proliferation strategy.

The existence of very good transportation infrastructure and the presence of a high population density might make the transportation of nuclear material to and from the site more disruptive than in current siting options, especially when closure of the roads affected by the transportation is required.

AMRs deployed in residential and industrial areas for electricity production and district heat generation will most probably exhibit highly enhanced safety performance, including redundant and passive safe designs to minimize or even practically eliminate the need of off-site emergency mitigation measures and to maximize their public acceptance. To limit the complications and implications linked to nuclear material transport in these areas, optimization, and minimization of refuelling cycles should be considered throughout the reactor's operational life.

For AMRs deployed in industrial areas, the selection of design options will typically be influenced by the conventional industrial processes with which the reactor(s) must interface. For instance, a demand for very high temperature process heat would necessitate a different reactor technology compared to a need for electricity production and low to medium temperature process heat. Very good candidates to produce industrial process heat are VHTR or MSR designs: depending on their configuration, VHTR designs might require a substantial nuclear material inventory in either fresh or spent fuel storage, and non-negligible nuclear material transportation requirements to and from the site. For on-load, pebble-bed designs, nuclear material accountancy might be more challenging than that of current LWR designs.

In terms of PR intrinsic features, higher levels of enrichment might increase the material attractiveness of the nuclear material available in the core. On the other hand, the significant or even complete inaccessibility to the nuclear material inventory greatly increases the proliferation technical difficulty associated with a potential diversion strategy. In addition, the need to disrupt the routine maintenance and system improvement services in case of diversion of nuclear material from a single-batch core would make a concealed diversion extremely difficult to succeed.

In terms of PR extrinsic measures, very long irradiation cycles or single batch cores would enable the application of effective and efficient containment and surveillance (C/S) strategies in place, minimizing nuclear material accounting activities and their related burdens. Conversely, a potential loss of continuity of knowledge necessitates a nuclear material inventory reverification, an undertaking that might be extremely challenging.

3.2.2. Physical Protection

Siting AMRs in urban areas may involve additional expenses to develop and demonstrate safety and security plans, particularly for events that might require evacuation of large populations. Additionally, there may be an increased cost for plant physical security because of novel threat vectors that require additional security response resources. These additional challenges can arise due to external structures surrounding the plant site, which may prolong the time required to detect adversaries, diminish the effectiveness of security measures, or lead to increased response times of security personnel. Notably, some of these concerns can be addressed through vendor designs that include additional safety and security features to mitigate threats, and all of them must be considered during the siting process.

Many research reactors throughout the world are successfully located in urban environments with well-established physical protection systems (PPS). However, AMRs and microreactors may have unique design characteristics that should be considered. In addition to the potential increased material attractiveness and quantity of nuclear material used to fuel these advanced reactors, other security implications resulting from the smaller footprint are likely to impact the PPS detection, delay, and response systems. An urban environment will require different fence and sensor arrangements as compared to remote locations.

The PR&PP analysis must consider other less tangible siting constraints. Urban environments may require a novel approach to PPS design to reduce the external security footprint. An example of this is external bullet and blast resistant enclosure (BBRE) towers for responders positioned around the perimeter of the facility. These BBRE towers may not gain public acceptance or support for urban deployment. This may cause the AMR designer or end user to design a PPS where response locations and BBREs are more concealed and less visible to ensure public acceptance. The siting analysis must consider both the physical site attributes as well as other criteria that may impact site safety and security.

An AMR or microreactor sited near major population centres may also need to consider the potential for increased petty crime and theft due to the higher population density. PPS designers and security planners may have to consider how these petty thefts or crimes may cause degradation and damage to security features that are in place to protect the facility. AMR and microreactor facilities sited in urban environments may also have to plan for an increase in protests as compared to facilities located in more rural environments. Depending on the chosen location, there could also be an increase in day-to-day foot traffic around the AMR facility. PPS designers may need to consider this foot traffic and its impact to the perimeter intrusion detection system (PIDS). Extended PIDS technologies that extend the perimeter of an AMR facility may have reduced effectiveness, or even completely ineffective, depending on the time of day. These technologies may generate a significant number of nuisance alarms or frequent alarms, which may hinder central alarm station (CAS) operators from effectively performing their duties. Many densely populated areas are also close to airports, train lines, and highways. These nearby entities could introduce new sabotage pathways and introduce additional considerations in the event of any incident related to the reactor facility, whether it pertains to a safety or security. The very existence of a nuclear reactor in a densely populated area naturally makes it a target of hybrid threats. Potential actions that fall well below the threshold of facility disruption can still serve as significant tools for societal manipulation and/or disturbance.

In industrial complexes, the co-location of conventional industrial processes and a nuclear reactor might represent an attractive target. In scenarios involving hazardous industrial processes in conjunction with a nuclear reactor, an attack on conventional industrial operations could significantly disrupt the reactor's functionality or potentially lead to its shutdown. For instance, site evacuation due to the release of dangerous chemicals could cause such disturbances, with the hybrid component (cascading events) amplifying the impact of the initial event. A nuclear plant integrated with a chemical plant may have unique sabotage targets that need to be assessed for their impact on reactor safety systems as well as the health and safety of the workforce and environment. For example, a chemical incident such as a large plume released into the atmosphere could affect the ability of operators or responders to remain on-site. The use of diversionary attacks like these may need to be considered. A benefit of co-location is that it may also lead to lower net costs for security than if the systems were separate.

The distance between the reactor and the industrial complex will likely depend on the potential consequences resulting from incidents originated in the industrial complex. Likewise, the industrial complex may want some standoff distance depending on the emergency planning zone (EPZ) for the reactor. Due to the smaller sizes, smaller source terms, and improved safety features, recent work has shown that the EPZ for AMRs can be smaller than existing large reactors [18]. The proximity effect of collocating the nuclear reactor and industrial complex should be considered early in the design process.

3.3. Floating or Underwater Nuclear Modules

Floating nuclear power plants (FNPPs) and underwater nuclear modules represent two interesting deployment concepts for marine-based siting considerations. These designs consist of a reactor and the necessary supporting plant infrastructure required for the desired deployment site. For FNPPs, this can be on board a barge or ship with the intention of producing power for on-shore or near-shore transmission. Additionally, these could include reactors on floating platforms in the water, such as on offshore oil rigs or potentially marine-located data centres, to provide either localized or near-shore power transmission. Similarly, the reactor could be anchored to the seabed for underwater power transmission. For current designs, any current or future FNPPs or underwater nuclear modules will be constructed, fuelled, and tested at a shipyard or dedicated service centres prior to commissioning. Once commissioned, the FNPP would be relocated and sited to a pre-approved location to begin power generation. Depending on the deployment model and need, these reactors may be one-time use or redeployed to a new operations site or moved for fuelling, maintenance, or decommissioning, as necessary.

This section outlines how features associated with these types of reactors – such as their operational lifecycle, fuelling characteristics, or siting – could affect PR&PP. Most of the analysis in this section will pertain specifically to FNPPs, as they represent the largest portion of the marine application. However, sub-sections will assess considerations for underwater and platform-based designs as well.[1] Maritime laws and state versus international regulations will play a key role in the potential deployment of these types of reactors; however, this

[1] For simplicity, the nuclear energy system considered here is limited to the *reactor at its deployment location, i.e.,* not including the fuel cycle, construction, transport, or decommissioning phases. Sub-section 4.5 discusses issues relating to transportable or propulsion-based siting considerations.

document will not cover the legal aspects comprehensively. Appendix B provides some more context on maritime laws.

Finally, most of the proposed designs for stationary, marine-based reactors are FNPPs located above the water's surface, rather than anchored below the water's surface. The analyses in this section primarily focus on these above-water designs; however, unique siting considerations for underwater reactor designs are addressed when relevant.

3.3.1. Proliferation Resistance

FNPPs and underwater reactors have a range of characteristics that may enhance some aspects of proliferation resistance, while raising challenges in other aspects. It is noted that some of the elements of proliferation resistance pertain to the specific safeguards agreements of the technology supplier state and the customer state, as well as the bi-lateral relationship between these entities. This discussion will pertain only to the technical elements associated with proliferation resistance features and not the legal or policy implication of various owner-operator and supplier-buyer scenarios.

Key design and operational features of FNPPs and underwater reactors that affect proliferation resistance are described below.

Reactor Size and Layout

Fundamental aspects of reactor design, including the fuel material characteristics and reactor equipment designs, will be similar for FNPPs compared to their land-based counterparts. However, marine-sited reactors should be smaller than conventional land-based reactors, given the deployment model is based on a barge or vessel. This will require the reactor and the auxiliary systems to be highly integrated and spatially efficient within the compact physical layout. The smaller reactor size and power levels associated with FNPPs may increase the time needed to produce significant quantities of nuclear material or increase the fraction of fuel inventory that must be diverted/misused. The compact, smaller designs may also impede certain diversion/misuse scenarios that require reconfiguring reactor equipment for protracted diversion, thus increasing the cost, difficulty, and detection probability for such scenarios. This feature of FNPP could increase detection probability but could also make illicit fuel handling somewhat easier.

Fuelling Strategy

FNPPs may be designed to minimize or streamline the fuel handling activities that occur at the operations site. This may involve longer operational intervals, reduced or no on-site fuel storage, or temporary relocation of the reactor to a centralized service-centre for fuelling. While all intended designs utilize LEU, HALEU, or other non-weapons grade fuels, FNPP fuels may be designed above the conventional fuel initial enrichments or designed for higher burnup. These two factors can impact the conversion time and usability of diverted fuel and affect the practicality of irradiating undeclared targets. Some reactors may have no on-site fuel storage and no equipment for handling refuelling operations, limiting the diversion paths present at the reactor site itself. However, this does not reduce the threat associated with the entire fuel cycle, and it would require secondary storage and handling strategies for receipt of fresh fuel and disposal of spent fuel outside of the primary facility boundary, which differs significantly from land-based reactors. Additionally, for both FNPPs and underwater reactors, some designs plan to replace the entire core at once rather than staggered refuelling schemes. Such strategies may require new safeguards approaches involving IAEA verification at an intermediary location or at a centralized refuelling site with expanded containment and surveillance measures on the reactor during periods of transit and operation.

Reactor Location

For siting considerations, FNPPs may be better suited than conventional land-based reactors for deployment to remote locations based around major waterways or with access to international waters, such as isolated residential sites or remote industrial locations. As discussed earlier, remote siting may be utilized by a state for covert misuse of nuclear technology in a less populated area. Minimal accessibility for remote sites would also increase costs for international safeguards inspections and make certain safeguards activities, such as short-notice verification, less practical. Given any adverse or extreme conditions, reliance on continuous remove verification and knowledge transmission may be a necessity for many of these remote locations. FNPPs may also encounter more turbulent ocean conditions, necessitating the reactor to remain stable under these circumstances. More consequence assessments are needed to fully understand the implications under these conditions.

3.3.2. Physical Protection

Key design and operational features of FNPPs that affect physical protection are described below.

Transport

FNPPs raise important questions surrounding the security of nuclear materials and facilities during transport between sites in the reactor's lifecycle. Because of the nature of maritime jurisdiction and laws of the sea, this can include passage through international waters and evoke situations where States have overlapping jurisdiction. Legal obligations for the transit of nuclear materials are well defined in the Convention on the Physical Protection of Nuclear Material and its Amendment (A/CPPNM) [19], and many of these concerns will be assessed further in sub-section for issues relating to non-fixed transportable reactors, which would be applicable for FNPPs. Developing practices for transport of FNPPs that accord with existing national and international standards, which consider the complex jurisdictional circumstances of maritime deployment, is a topic of ongoing discussion in international forums. As a result, it is not analyzed in this section.

Protection of a Marine Vessel

Another set of physical protection issues arise from operating a reactor on a marine vessel, rather than land. This relates to both the design basis threat and the types of measures a physical protection system employs. Because many land-based reactors are sited immediately next to the ocean, there is substantial experience in addressing the threat of water-borne adversaries.

Conventional application of physical protection may be applicable for marine-sited reactors as stated in the A/CPPNM, which applies to both the nuclear materials and the facility. However, siting on a stationary vessel nevertheless raises novel challenges:

- Absent robust barriers, it could allow for an adversary to approach by water up to the FNPP vessel or barge itself. This could include underwater attacks, ship collision or boarding attacks, or other scenarios that have no analogy for land-based reactors. For FNPPs deployed in ports, excluding marine traffic from the surrounding area may not be a practical option.
- Alternatively, siting on a vessel or barge may impede land-based approaches to the reactor, either for adversaries or for shore-based response forces.
- The vessel or barge itself can be subject to attack, severe damage, or sinking, creating new pathways for sabotage and for dispersing radioactivity into the water.

- The threat of prolonged impediment of the reactors in transit from protest or other forms of civil unrest exists. While the desired adversarial outcome may not be sabotage, this could have both physical security and safety consequences.
- The physical limitations of the vessel or barge might limit the use or the capabilities of physical protection elements (guard forces, fortifications, lines of sight, barriers, containment structures) that could be more easily deployed at a land-based reactor.
- The fact that the reactor physically interfaces with its ultimate heat sink (the ocean) may reduce the feasibility or the consequence of certain sabotage scenarios.

In any case, operators, and regulators of FNPPs will need to take special care to ensure the integration and robustness of the land-based and water-based components of the physical protection system. This includes ensuring that land and/or water-based responders can effectively respond to threats facing the vessel.

The extent to which an FNPP at its operation site would have a physical protection system (including a guard force or engineered barriers) resembling that of a conventional terrestrial reactor is a question that is being examined by industry and regulators. As with other types of small reactors, there has been interest in deploying FNPPs with reduced staffing, highly automated operations, and reduced protective forces, under the assumption that inherent safety attributes or unattended measures can reduce the probability and consequence of adversary attacks. The suitability of these protection plans requires further analysis.

Remote Deployment

As discussed previously, remote deployment locations would make many types of theft or sabotage attempts more costly to undertake or less consequential, while also making some aspects of physical protection (such as hosting a guard force) more costly. A remotely stationed reactor would be less able to rely on assistance from authorities or the use of robust infrastructure (offsite power, roads, communications) than conventional nuclear power plants.

Fresh and Spent Fuel Handling

Fuel handling strategies that greatly reduce the presence of fuel storage or fuel handling equipment would reduce opportunities for theft or certain types of sabotage. Smaller fuel elements associated with FNPPs could be more portable if they could be accessed. Onsite material control and accounting tasks may be minimized if sealed reactor cores or fuel storage vessels are accounted as items with sufficient control and physical security measures in place.

3.3.3. Other Marine Siting Modes

While the previous discussion focuses on FNPPs, it applies in large part to other types of marine-sited reactors. The designation between siting modalities in territorial versus international waters will cause specific challenges, but these must be handled on a case-by-case basis. However, some special distinctions for other marine-sited reactor types are discussed below.

Platform Based Reactors

Platform-based reactors are generally intended as power generation stations sited further from land than FNPPs, which are moored to the shore. The platform-based reactor might be stationed in international waters, introducing additional questions regarding jurisdiction and state responsibility. Intrinsic features of PR likely will not change from other FNPP reactor designs. However, extrinsic PR measures, such as onsite safeguards verification, could be more difficult due to distance and travel complexities. For physical protection, all elements of the physical protection would need to be capable of operating with little support from land. The distance from human populations would affect the consequence analysis for hypothetical sabotage situations in the sense that evacuation plans would likely be simpler. These reactors may be considered to provide power for industrial activities (drilling rigs) which would impose additional considerations as described in the previous section.

New vs. Repurposed Platforms

There are proposed designs to implement platform-based reactors on existing infrastructure for deep-sea drilling rigs. While these platforms are constructed within specific industrial standards and codes, it is unknown at this time whether such standards would be sufficient for a nuclear power plant. Space on the platform will have to be repurposed for nuclear material security and safeguards measures, and this may cause significant siting challenges.

Underwater Reactors

Underwater reactors raise many of the same basic issues as platform-based reactors. For proliferation resistance, novel verification arrangements would be required because of the physical inaccessibility of the operating reactor. For physical protection, undersea threats would be more prominent, although some undersea siting arrangements would be difficult for an adversary to access. The consequences of a sabotage attack could be reduced since the reactor is underwater in a very large heat sink (the ocean) and there would not be airborne radioactivity transport. However, this could be offset by waterborne dispersion, which, although diluted, might be perceived as a greater consequence.

3.4 Civilian Marine Propulsion

Civil uses of nuclear reactor systems for propulsion are not a novel concept. Starting in the 1960s, there are instances of nuclear propelled civilian vessels in both nuclear and non-nuclear weapons states. These vessels were primarily used for either cargo transport or icebreaking purposes, relying on the longer fuel life cycle benefitting from commercially downsized pressurized water reactor designs. While most cargo ships were removed from service or converted to fossil fuel engines by the 1980s, recent development of advanced reactor designs has revived the interest in nuclear-propelled vessels for commercial purposes [30].

Vessels that utilize reactors for propulsion are also generating electrical power for the boat and may be designed to generate power for other vessels or humanitarian efforts. One could imagine that a vessel with a nuclear reactor, while operating at in the high seas, could refuel other dependant vessels in energy (electricity or e-fuel produced on board with the electricity). An example would be a fishing fleet with a factory ship. This means that the vessel with the nuclear reactor is not insulated and is regularly accosted by other vessels. This should be taken into consideration for physical protection and non-proliferation (diversion of nuclear material).

While there may be technical similarities between FNPP reactors and reactors used for civil marine propulsion, propulsion reactors introduce several novel PR&PP considerations. Many new advanced reactor concepts may rely on new fuel forms or novel integrated operations systems that will require significant testing and validation. Most advanced reactor developers are anticipating demonstration of their reactors on land with a primary motivation of meeting safety, security, and nuclear materials safeguards metrics for land-based licensure and assurance.

As stated previously, other studies discussed and analysed the overlap of safety, security, and nuclear material safeguards jurisdiction for maritime-sited reactors; thus, this will not be a focus of this work [20]. However, the overlap for propulsion does present security- and safeguards-based terminology challenges because of the application of the nuclear reactor. If the reactor is only used for civil nuclear propulsion without mechanism to discharge electricity or heat to a land-based station, the vessel that carries it will likely be the responsibility of the State whose flag it bears. Given the mobile nature of propulsion-based vessels, regular transit through or to locations with different authorities could result in multiple States exercising jurisdiction on an actively operating reactor system. At this point, the legal issues surrounding physical protection of a nuclear-powered vessel are more complex or burdensome than for an FNPP because of the greater number of States involved and the possible need to make security-related arrangements on a case-by-case basis.

As noted for FNPPs, there must be significant investment in servicing and supply-chain infrastructure for water-based applications of nuclear reactors, and all these infrastructure investments will require safety, security, and safeguards siting analyses. Whether the proposed solution includes designating select docks for nuclear-propelled vessels or to developing nuclear-specific ports, several different siting considerations will be crucial to ensure the physical protection and safeguards systems meet standards against external adversarial threat and material diversion scenarios. These considerations are complex and require further analysis outside of this report.

3.4.1. Proliferation Resistance

As with more statically located FNPPs, there may be challenges with fuelling or refuelling schedules for civilian propulsion reactors. Fuel handling activities will certainly occur at a specified operations site external to the vessel, and refuelling will rely on longer operational intervals or less fuel loading than FNPPs. These two factors can impact the practicality of irradiating undeclared targets and the usability of diverted fuel. Many of the designs for these types of reactors rely on sealed-core concepts, where the core is loaded with a single-use fuel amount. When the maximum burnup is reached, the entire core would be switched out for a fresh “fuel core.” These designs will require novel verification methods and techniques to meet IAEA safeguards metrics. However, other designs may utilize dynamically fuelled MSRs that require unique servicing and refuelling schemes. Such a fuelling strategy will require an intermediary servicing location or a centralized refuelling site with expanded containment and surveillance measures on the reactor during periods of transit and operation.

All nuclear fuel will likely be stored within the sealed reactor core, and the vessel itself will probably lack the technical infrastructure to open the reactor or make changes to the core. This would essentially preclude diversion, misuse, and theft attempts onboard the ship. The shore-based refuelling facilities would be an important focus for IAEA verification activities, which may rely on containment and surveillance while the ship is at sea. There will need to be strategies and protocol for any nuclear material “lost at sea” due to accidents or adversarial attacks.

Finally, civil propulsion reactors would be subject to IAEA nuclear material safeguards congruent with FNPPs. The provisions for responsibility of nuclear materials in these reactors would be pursuant to either a NWS’s Voluntary Offer Agreement or a NNWS’s Comprehensive Safeguards Agreement. Siting and any planned material transfers should involve the IAEA, the supplier State, and the deployment site State as early as possible to ensure effective deployment scenarios. The location of the vessel is a crucial point for non-proliferation in order to know the location of nuclear material at all times.

3.4.1. Physical Protection

A different set of physical protection issues arise from operating a reactor on a marine vessel intended for constant movement. While the prospect of decreased commercial shipping cost from vessels or barges propelled by nuclear power is a driver of interest and investment, the required cost of personnel and physical protection systems required to ensure material security may greatly increase the operational cost of these designs. Completely new design basis threat scenarios will have to be assessed for this reactor application because the threat response must be included on the vessel while between ports. This also includes strategies for addressing idle times outside of ports waiting for docking stations.

Additionally, while noted that there is experience addressing threat of water-borne adversaries for near-shore land-based reactors, there is limited experience with security approaches for civilian nuclear-propelled vessels. Pirates or other water-borne adversaries may have different motivations for target acquisition than traditional, land-based nuclear facilities. As with other commercial cargo ships, the threat is not for acquisition of nuclear material as much as it is to hold the cargo for ransom. Given the co-location of commercial cargo with a nuclear reactor, these ships may be a desirable (and potentially valuable) target, especially if nuclear propelled vessels had a visibly distinguishable design characteristic. Security strategies will likely be developed from a combination of current commercial cargo approaches, water-based nuclear materials transport approaches, and potentially military propulsion approaches.

Civilian propulsion reactors, like land-based reactors, can establish stationary site boundaries and protected areas around a reactor, while relying on a range of capabilities (sensors, barriers, forces) that are deployed at the site. A marine propulsion reactor will spend much of its lifetime operating while in transit, which greatly changes a variety of physical protection, safety assumptions, and related legal issues.

4. Additional Considerations

A number of topics related to PR&PP of siting AMRs and microreactors crosscut the four siting options considered in the previous section. These additional considerations are described in more detail in the following sub-sections.

4.1. Single vs. Multi Modules

AMRs can be deployed in single module or multiple module installations. Multiple modules power plants best meet the requirement of large electricity networks and with the potential for strong economic benefits from shared facilities and services, as well as shared staffing costs.

AMR designs under development may consider positioning multiple modules in close proximity within a single building. This kind of arrangement gives a compact overall footprint and minimizes construction costs and has the potential for reduced construction times compared with a single large reactor. Some AMR vendors have also cited the potential for early modules to start operating while the other modules are being installed, thereby opening an early revenue stream that might offset the total investment needed during construction.

Installing multiple modules in proximity with each will need to be considered as part of developing the safety case. The Fukushima accident illustrated how accident conditions can propagate between neighbouring units. For example, Unit 4 was in shutdown and defueled at the time of the accident, but nevertheless suffered a hydrogen explosion caused by hydrogen that was vented from Unit 3 to Unit 4. Although Units 3 and 4 were installed in separate buildings, the gas venting installations were interconnected and led to propagation of the accident conditions. In multiple module installations, the potential for interactions between modules will need to be addressed during the licensing process. Ensuring the safety functions in each module are self-contained would help to reduce the possibility of interactions between units. The design of shared emergency systems (such as the supply of water for decay heat removal) would need to be considered to determine whether there is sufficient capacity to manage simultaneous accident conditions in multiple modules. The potential impact on mitigating actions will need to be considered, specifically whether an accident condition in one module might affect access to other modules.

Special consideration is required for the phased deployment of modules. Installing individual AMR modules involves handling large masses (e.g. cranes and earth moving equipment) with potential work site hazards. Nuclear plant construction normally takes place in an inactive environment, where there is limited or no possibility of radiological consequences. Construction activities in close vicinity to an operating module, or near a module which has been operating but is temporarily shut down, raises the possibility of accidents leading to uncontrolled radiological releases.

Phased build of multiple modules may present more of an opportunity for sabotage compared with a single unit. The need to bring heavy lifting gear as used during construction close to operational modules is a new aspect. It raises the possibility of an adversary taking advantage of increased accessibility during construction and the availability of heavy lifting equipment to cause damage to the operational modules. The potential consequences would be most severe if the operational modules were generating at the time. But there could still be consequences from decay heat and radiological inventory of operational modules even if they had been shut down.

With a single unit fresh fuel supply is phased – a delivery once every 18 to 24 months, so fresh fuel is not on site most of the time. With multiple modules there will be fresh fuel present most of the time. Fresh fuel therefore presents as more of a target for theft. With frequent refuelling operations, safeguards may have to treat it more like an on-line refuelled plant.

From an international safeguards perspective, most nuclear power plants today are considered one material balance area. Additional resources may be required for multi-unit sites that will have multiple balance areas. There likely is not a significant proliferation resistance difference with single versus multi-unit sites.

A single unit design is probably more likely for FNPP's or civilian marine propulsion, and if two or more units were considered, they would be built on the vessel at the same time, so aspects of phased construction would not apply. It is unclear at the current time if floating or underwater power stations would consider adding multiple units over time near one another.

4.2. Ultimate Heat Sink

The world's commercial reactor fleet is currently dominated by LWRs. In common with all power reactors, one of the main safety requirements is to manage decay heat from the fuel in planned and emergency shutdown conditions. This is the function of the Residual Heat Removal System (RHRS), which is normally comprised of multiple independent heat removal systems. The RHRS system discharges its heat load to the ultimate heat sink, which for LWRs is an external supply of water. In a shutdown condition, water/steam in the primary or secondary cooling circuits is cooled and steam recondensed by exchanging heat with an external water supply. Ensuring the integrity of this water supply is a key requirement of the safety case.

Some High Temperature Reactors (HTRs) can dissipate decay heat using air as the ultimate heat sink. In this case, air will always be available; thus, scenarios where the ultimate heat sink is lost do not need to be considered. It is always possible to sabotage the heat transfer aspect of the RHRS even if the ultimate heat sink is air.

The ultimate heat sink has few implications on proliferation resistance. Only the siting location itself and choice of reactor technology and fuel will likely impact that. The physical protection implications are more important. Nuclear plants are vulnerable to any loss of the ultimate heat sink or heat transfer mechanisms to the ultimate heat sink. Attack scenarios where water supplies are lost, deliberate destruction of water supply infrastructure, or situations where plant operators are prevented from making interventions to secure the water supply should all be considered in PP design.

The loss of the RHRS function needs to be considered as part of any physical protection assessment. The ultimate heat sink is less important compared to the efficiency of the heat transfer system/mechanism, regardless of whether heat is being rejected ultimately to water or air. Even for FNPPs that are surrounded by ocean, any adversary attempts to stop the heat transfer mechanism needs to be considered. Regardless of siting option, the heat transfer system will need to be considered as an adversary target.

4.3. Autonomous or Remote Operation vs. On-site Staff

Many proposed AMR designs currently consider the use of autonomous or remote operations, which are very different concepts from a cybersecurity perspective. Remote operation is likely to be central to financial viability of AMRs, particularly where AMRs are designed to run in isolated locations, or where there are economic limitations to the number of on-site staff that can be present at a deployed AMR facility. Remote operation can be performed with different degrees of control over facility operation, with a variety of possible operational and organizational boundaries (not necessarily encompassing all facility control functions) that allow for continuous, reliable monitoring and supervising where needed. Remote control of an

AMR requires a trust relationship be established and assured between the AMR facility and the remote connection. There are currently several cybersecurity challenges with remote operations such that regulatory bodies will preclude its use.

Autonomous operations involve control systems that use computer-based tools, using model-based engineering with intelligent systems providing self-governance ability to perform and execute control functions. The degree of autonomy in autonomous operations depends upon the extent to which it can perform forecasting, fault diagnosis, decision-making, and planning. The strategies and control architectures of autonomous operations also require the establishment and assurance of a trust relationship [21]. Since autonomous operations do not require external communication, they're likely to be seen more widely in use before remote operations since there are less cybersecurity challenges. This section explores the proliferation resistance and physical protection implications of deploying autonomous and/or remote operations in an AMR facility.

In the realm of proliferation resistance, the use of unattended remote monitoring systems (URMSs) figures prominently for the purposes of nuclear safeguards. There are four general URMS categories of use: containment systems (e.g., electronic seals), surveillance systems (e.g., surveillance cameras), measurement systems (e.g., gamma- and neutron-based detection), and other systems (e.g., system monitors for assessing facility operations) [22]. The use of URMSs by safeguards regulators for safeguarding AMRs is attractive, as there is the potential for reducing the frequency of safeguards site visits and inspections. Further, the use of reliable monitoring of authenticated sensor data can provide near real-time "virtual access" to AMR reactor cores that are either encapsulated throughout the lifecycle of the reactor core, or where the AMR reactor core has a long operating lifetime [13].

A data collection system is an important component of an URMS, as it serves to receive data from all sensors and detectors at the AMR facility. In doing so, it will monitor the state of health of the said sensors and detectors, store the data received from each sensor or detector, and provide access to safeguards inspectors when on site for data review, system maintenance, and system upgrade. Since the data collection system is a primary database of safeguards-relevant information until the data is transmitted to the safeguards regulator, the data collection system must have functional requirements to ensure that continuity of knowledge is maintained, particularly when there is a delay in data transmission to the safeguards inspectorate, such as in the case of a network failure [22].

The system for transmitting safeguards-relevant information should include facilities for compressing, authenticating, and encrypting the collected data, transmitting the data at a specified interval, and providing the safeguards inspectorate with receive-only remote access to the data. The transmission of data is done securely using a virtual private network over the internet. The access is controlled by the rules set up in the interface system, such as what kind of information can be transmitted and received, and the list of devices that can connect, preventing any unauthorized access. Guiding principles should be followed to ensure a robust and reliable data transmission system [22].

For successful deployment of a URMS, the interfaces the URMS presents to each of the safety, security, and safeguards (3S) aspects of the AMR facility should be considered. As discussed above, a URMS includes systems for data generation, data collection, and data transmission. The 3S interfaces for each of these systems is summarized below [22].

System	Safety	Security	Safeguards
Data Generation	Can help alert about any safety concern, although its related systems (e.g., power supply) can be the cause of a safety concern	Can help alert about any security concern, although this system can also be the target	Supports safeguards implementation
Data Collection	Can help diagnose the cause of a safety event	Can be the target of a security event	Supports safeguards implementation
Data Transmission	Can be the cause of a safety concern	Can be the entry point of a security breach	Supports safeguards implementation

As part of computer-based tools used in autonomous and/or remote operation of an AMR facility, appropriate cyber security measures should be taken to protect the facility from cyber threats. Malicious acts involving digital systems may include information gathering to inform a future attack, attacks disabling or compromising digital assets, or compromise of several systems combined with physical attacks. Computer security of instrumentation and control systems in a nuclear facility is critical since these systems affect the safe operation of the plant. There are four aspects of cybersecurity that have significance with respect to continued advanced reactor development considering improvements in computer technology: cyber risk management, secure architectures, operational transparency, and supply chain assurance. More discussion about this can be found in a previously published white paper [10].

In the realm of physical protection, there is ongoing effort [23,24,25], to modernize the nuclear security regulatory framework for the development and deployment of next generation nuclear energy systems including AMRs. Where traditionally a prescriptive approach prevails to regulating nuclear security, there is now a transition to a graded, performance-based (or combined with prescriptive) approach to meet physical protection requirements. As a result of this regulatory paradigm shift, new physical protection measures can be adopted that protect and adapt to remote and/or autonomous design features of AMRs. These measures would be designed to deter and delay adversary action and improve the effectiveness of response force while reducing the cost to implement and maintain physical protection of the reactor site.

Applicants and licensees of AMRs, particularly those AMRs which will be situated in remote locations, may design a physical protection system with increased reliance on engineered security systems which can be operated autonomously and/or remotely, with the potential to reduce on-site security staffing to save operating costs. The designed physical protection system would need to be capable of timely detection and assessment of unauthorized intruders and provide the necessary delay to facilitate the response by a (on-site or off-site) security force. Use of autonomously and/or remotely operated technologies such as fixed cameras, sensors for intrusion detection, unmanned aerial vehicles etc. have the potential to enhance the overall security of AMRs in a cost-effective manner. Autonomously and/or remotely activated safety barriers can provide necessary delay when unauthorized intrusion is detected and assessed. Examples of active safety barriers are vehicle barriers, and engineered systems to disperse materials such as obscurants (e.g., cold smoke), irritants (e.g., active denial systems), and sticky foams to provide delay [26].

While using autonomous and/or remote cutting-edge technologies to identify and impede hostile activity in the AMR site can be economical, this will also reduce the potential for insider threat due to less human intervention. However, it is crucial to consider their limitations, such as restrictions on their ability to operate in inclement weather and vulnerabilities that could be exploited by cyber-attack. The applicants and licensees of AMRs depending on off-site security forces need to consider that events independent from or outside of the reactor site may hinder the off-site response which can compromise the physical protection of the reactor site. AMRs can therefore be effectively protected with an appropriate balance between the use of off-site security forces and the presence of an on-site security guards. When combined with advanced autonomous/remote technology solutions for physical protection, it is possible that the number of on-site security guards needed for AMRs can be optimized using a Security-by-Design (SeBD) approach [26], however much more work will be required on this in the future. The use of physical security modelling and simulation tools can enhance the SeBD process for new reactors facilities by integrating engineered systems with human-based solutions.

4.4. HALEU versus LEU Fuel

IAEA safeguards considers all uranium with an enrichment below 20% as low enriched, but for the purpose of physical protection there is a distinction of Category III material below 10% and Category II material between 10 and 20% [28]. By convention, LEU fuel is taken to be at a U-235 enrichment no higher than 5.0 wt%. HALEU has a U-235 enrichment above 5.0 wt% and below the IAEA threshold of 20.0 wt% at which the High Enriched Uranium (HEU) category starts. The current generation of LWR power reactors operate with LEU, but AMRs and microreactors may utilize HALEU instead. It is helpful to establish the reasons why HALEU may need to be used in AMRs.

Burnup Rule

A simple burnup rule that applies to any reactor with enriched uranium fuel is a useful starting point. The rule is that the maximum achievable burnup is approximately 10 GWd/tU for uranium at 1.0 wt% initial enrichment and scales linearly with initial uranium concentration. It is valid in both thermal and fast spectrum reactors. The burnup rule can be used to make a rough estimate of the maximum achievable burnup based only on the initial U-235 concentration. This burnup rule is based on the energy output of 200 MeV/fission, with allowances made for the fact that in any realistic reactor design there will always be incomplete fission of the U-235 atoms.

The rule applies to reactors operating with a multi-batch refuelling scheme. Thus, the maximum achievable burnup for natural uranium fuel is approximately 7 GWd/tU, while for LEU at 5.0 wt% it is 50 GWd/tU, consistent with the burnups achieved in current LWRs.

Fast Spectrum Cores

Fast spectrum reactors may use either HALEU fuel or plutonium as the main fissile material. The burnup rule applies to fast spectrum systems equally, with a maximum achievable burnup of approximately 200 GWd/tU expected at the 19.95 wt% upper limit of the HALEU range. This is equivalent to 19.95% burnup and is consistent with the highest fast reactor burnups achieved historically.

End-of-Cycle Reactivity

A reactor requirement is the ability to maintain an effective multiplication k-eff factor of 1.0 to the end of the operating cycle at full power conditions. With optimum moderation LWR cores achieve a mean discharge burnup of 50 GWd/tU with 5.0 wt% initial fuel enrichment. In contrast, VHTR cores are typically under moderated and are unable to achieve an end-of-cycle k-eff of 1.0 without a higher initial U-235 enrichment beyond that indicated by the burnup rule. For a VHTR system with a design discharge burnup of 100 GWd/tHM, the rule indicates an initial enrichment of 10.0 wt%, whereas in practice the under moderation requires VHTR cores to have significantly higher initial enrichments in the region of 15 wt% to reach discharge burnups of 100 GWd/tU. A consequence is that at discharge the residual U-235 content will be high, and the U-235 incompletely burned.

Single-Batch Core

The burnup rule for single-batch core (as proposed in some AMR designs with a lifetime core) needs to be adjusted by halving the achievable burnup. This is obtained from the linear reactivity model which states that the maximum burnup achievable in a batch-loaded core with n batches is Bu-inf x n/(n+1), where Bu-inf is the maximum burnup achievable with an infinite batch core (on-line refuelling). A single-batch core with an initial enrichment of 5 wt% would only be able to achieve a discharge burnup of approximately 25 GWd/tU.

HALEU vs LEU Fresh Fuel Material Attractiveness

The potential attractiveness of just under 20% enriched uranium (HALEU) compared to up to 5% enriched uranium (LEU) in terms of fresh fuel diversion is highly dependent on the state's fuel cycle capabilities and existing infrastructure. The separative work needed to be done to re-enrich HALEU to weapon-grade uranium is much less than the one needed if LEU is the starting material. If the state has an enrichment facility, then HALEU might represent an attractive target, as a hypothetical breakout scenario would see a strongly reduced proliferation time compared to LEU. On the other hand, if the state does not have an existing enrichment facility, the time, difficulty and cost of building such capacity would make the attractiveness difference of the two compositions practically irrelevant.

Proliferation Resistance

To a limited degree, the difference between HALEU and LEU impacts PR in different ways. Fresh fuel will need a higher initial U-235 enrichment than would the equivalent multi-batch core, increasing its Material Attractiveness which will persist during its irradiation. At the end-of-cycle condition there will be a higher residual U-235 concentration compared with a multi-batch core, and it is possible to envisage systems where the fully irradiated fuel would contain enough U-235 to still classify as HALEU.

Some AMRs are designed with a single-batch core that lasts for the entire lifetime of the reactor, perhaps 20 or 30 years. This is achievable if the power density of the fuel is kept very low. As long as the reactor operation is not interrupted early in operation, long irradiation times will reduce the attractiveness of Pu accumulated in the spent fuel. Like any reactor, short irradiation times can yield Pu with attractive isotopics. Monitoring continues to be the key safeguard to ensure reactors are not being misused.

Physical Protection

The main difference with PP strategies between LEU and HALEU fuel is differing levels of protection due to differences in Material Category, for example II (HALEU) and III (LEU). However, the PP of the reactor is the same, since the main threat is sabotage, as opposed to material theft. The differences in protection strategies are seen more in the fuel cycle facilities and transportation of the fuel with HALEU fuel having slightly more protection requirements.

4.5. Transit of Reactors

AMRs and microreactors offer the benefit that many components, perhaps even entire reactor units, are built and assembled at a primary facility prior to shipping to operating site. This reduces the need for on-site construction [29,30]. This section will largely focus on microreactors, with the assumption that these reactors can be assembled nearly in their entirety at a primary manufacturing facility. Many of these reactors are using fuel forms which differ from traditional LWR fuel both in composition and enrichment. Depending on the reactor design and fuel concept, these reactors may be shipped with or without fuel. In considering the transport of these microreactors, there are different considerations based on having fuel versus without fuel. The following two sections discuss PR&PP aspects of both options. Additional considerations may include the form of transport, shipment through remote vs urban environments, and international transport. The additional considerations are discussed in Appendix C.

4.5.1. Shipment of a Microreactor without Fuel

Shipping an unfuelled microreactor is less challenging from both a technical and regulatory perspective compared to shipping a fuelled microreactor. Therefore, many vendors find the unfuelled reactor transport pathway more appealing. Many microreactor designs feature novel fuels in terms of composition and enrichment. Shipment of these fuels, even separate from the reactor, presents new challenges both in terms of their potential appeal to would-be proliferators, thieves, and saboteurs as well as the fact that currently approved shipping containers may not be suitable. Despite these challenges, it is anticipated the transit of microreactor fuel separately from the reactor will resemble current practices for fresh and spent fuel shipments with special considerations being applied on a case-by-case basis [31].

While no nuclear material should be present in shipping an unfuelled microreactor, there is still proprietary and controlled information about the design of the unit that ought to be protected. The reactor also should be accounted for since it would be declared as part of safeguards.

Proliferation Resistance

There are limited intrinsic proliferation features associated with shipping a microreactor without fuel. Assuming the absence of nuclear material has been verified, diversion of such material is not relevant to this situation. Thus, shipping the fuel separately from the reactor increases the intrinsic proliferation resistance of the system as there is no nuclear material to divert; however, a fuel shipment will still need to occur, which poses its own proliferation concerns. Even with the reduced possibility for diversion, the reactor itself still serves as a nuclear technology which could be misused. The small size of the reactor would also enable the covert shipment of the reactor to an undeclared nuclear facility. Reactor designs which make misuse difficult, such as reactors designed to operate with a low power density, or utilize non-traditional fuel elements/coolant could make misuse of the reactor more difficult and therefore more intrinsically proliferation resistant. Likewise, reactors with an easily detectable operating signature would enable for detection of undeclared operations, which would further enhance the intrinsic proliferation resistance of the reactor. Shipping a microreactor without its reactivity controls can prevent unauthorized use.

Thus, safeguards measures should still be implemented in a shipment of this technology. Increasing the proliferation resistance of an unfuelled microreactor in transit will rely largely on extrinsic measures. The application of seals prior to shipment and inspection of them upon receipt can help to maintain continuity of knowledge about the system and ensure the reactor stayed sealed during transit. In addition, providing the IAEA with details regarding the shipment, which should be balanced with security concerns regarding minimizing sharing details which could compromise the security of the shipment, would aid in safeguards verification activities [32]. The same measures to enhance proliferation resistance should also be taken for shipping a used reactor unit.

Physical Protection

Physical protection measures regarding the shipment of an unfuelled microreactor will primarily be concerned with preventing the theft of intellectual property about the reactor design as well as preventing any sabotage to the reactor unit that would render it unusable. The design of the reactor may intrinsically enhance the physical security with regards to these concerns. If any sensitive design choices are not visible on the reactor exterior, proprietary information will be easier to protect. Likewise, design choices made to strengthen the reactor or to enhance the safety characteristics of the reactor may also make it more resistant to physical damage, which would reduce the impact of potential sabotage on the unit while it is being shipped between more hardened facilities.

Additional actions can be taken to extrinsically enhance the physical protection characteristics of the system. Locks placed on the reactor or any external covering can serve to further delay an adversary seeking to gain closer access to the reactor, but only for very small amounts of time to allow on-site security staff to respond. Moreover, consideration should be given to having security forces travel with the reactor to respond immediately to any adversaries. Maintaining communication where possible between the transit convoy, the shipping facility, the receiving facility, and off-site response forces can also help to ensure a rapid response to any potential adversary actions.

The shipment of a reactor that has been operated raises the additional consideration that the reactor unit will be radioactive. This may increase the attractiveness of the shipment as a target for sabotage. As a result of becoming activated over the course of operations, microreactors will need to be shipped in some form of shielded container, as has been done in the case of decommissioned reactor pressure vessels [33]. While these containers are primarily designed with safety in mind, the same design choices which improve their survivability in the event of a transport accident likely also makes them more resistant to damage from sabotage.

4.5.2. Shipment of Fuelled Microreactors

Despite the added difficulty, several proposed microreactors are intended to be shipped already fuelled. These types of reactors are largely associated with deployments in locations that are difficult to securely power in a routine way such as remote villages, mining operations, and areas recently impacted by a disaster. These reactors are typically designed to operate for extended periods without the need for refuelling, and due to the transportable nature of the reactor, it is anticipated refuelling would occur at a central facility as opposed to at the deployment location. In some designs, the reactor vessel is sealed and is not designed to be refuelled; the core lifetime is the planned lifetime of the entire unit.

To achieve the goal of extending operations without a need to refuel, microreactors often rely on HALEU fuel. Unirradiated HALEU based fuel would be categorized by the IAEA as Category II nuclear material, while unirradiated fuel with Pu would likely be Category I or Category II. Irradiated fuel shipments will remain the same category if there is not a significant buildup of activity prior to being shipped again or reduce a category due to the increased core activity (i.e., cores with irradiated fuel are likely to be Category II or Category III) [34,35].

This higher fuel loading increases the attractiveness of the nuclear material present in these reactors both to would-be proliferators and to thieves or saboteurs. Transit of these reactors from the assembly and fuelling facility to the intended operational location may provide increased opportunities to these groups due to the complications of monitoring and protecting a reactor while it is moving.

Proliferation Resistance

There are many intrinsic proliferation resistance features that are likely to apply to any transportable microreactor. Notably, the reactor should not be in operation while in transit; thus, any misuse of the reactor by means of undeclared operations during transport could be detected with relatively few and simple sensors which have the goal of determining if the system were operating or not. Another intrinsic aspect of the reactor which increases proliferation resistance against misuse relates to the level of integration of the reactor and secondary systems. If the reactor unit can be transported within a single container and deployed directly from it without the need for supplementary components, it may present a more appealing option compared to a reactor that necessitates connection to additional systems for proper operation. The convoy transporting the reactor also may not have any means of opening the reactor to access the fuel. To divert nuclear material from the core, the transportation convoy would either include bulky equipment to open the core and move the fuel or divert the convoy to a secondary location where equipment for accessing the fuel was placed in advance. The logistics and concealment challenges of these diversion pathways may increase the likelihood of detection. This process would be even more difficult after the reactor has operated as additional equipment would be needed to handle and transport radioactive materials [36]. If the reactor is designed as a sealed core unit, which is not intended to be refuelled, any diversion attempts will likely result in damage to the reactor. Safeguards inspectors could spot the damage once the transportation of the reactor is finished.

Extrinsic proliferation resistance measures can also be applied to deter a state proliferator, but many traditional methods of surveillance may be challenging to apply during transportation. It is unlikely inspections of the convoy will take place during transit, and as discussed in the previous paragraphs, the means to access the nuclear material directly should not be present with the convoy. Thus, extrinsic proliferation resistance should focus on maintaining continuity of knowledge. Current IAEA safeguards measures regarding the shipment of fresh and spent nuclear fuel focus on sealing the material prior to it being shipped, verifying the integrity of the seals upon receipt, and verifying the nuclear material either prior to applying seals or after the seal is removed [37]. These practices will also apply to the shipment of fuelled microreactors. Redundancy will enhance the robustness of seals against accidental failures as microreactors may be operated for years without the fuel being accessed. Moreover, the tools to do so may not be located at the reactor site, thus making activities to reestablish continuity of knowledge difficult. If the reactor unit is small enough to fit inside of shipping container or shipping cask, additional means of detecting intrusion can be applied to the external container as further means of verifying the nuclear material was not accessed during transit [31,36]. While surveillance devices or sensors meant to detect undeclared operations could be employed to detect diversion and misuse, real-time transmission from these devices may not be possible if the transit route takes the reactor through remote locations. Plans should be established to recover the data from any of these devices such that they can be checked shortly after transit is complete to minimize the time associated with detecting any diversion or misuse. Another extrinsic proliferation resistance characteristic of reactor shipment could include establishing the normative behaviour of sharing relevant shipment details with the IAEA. This would allow the IAEA to confirm the transportation of these reactors is occurring in a timely manner, and that transportation times taking longer than declared may be cause for further investigation. The route may even be able to be confirmed by the Agency after the fact by placing devices on the reactor which log the location as a function of time.

Physical Protection

Reactor units being transported with fuel may present a more appealing target for theft or sabotage to a potential adversary relative to the case where the fuel is shipped separately from the core. An adversary could try to steal a fuelled reactor by gaining control of a single vehicle. Likewise, from a sabotage perspective, the destruction of a full reactor unit may be more attractive than the destruction of nuclear fuel alone. In general, a reactor unit being transported may not have the same level of protection as one located in a fortified installation. In addition, depending on the mode of transportation and the location of transportation, there may be a significant time delay in response from security units not traveling with the reactor,

Many of the intrinsic proliferation resistance characteristics of transportable microreactors also serve as intrinsic physical protection characteristics. The reactor should largely be in motion after leaving its assembly location until it reaches its deployment location. Although transit may restrict the security measures that can be implemented, it also complicates an adversary's ability to plan an attack. Additionally, it increases the likelihood of the reactor evading potential threats if any suspicious activity is detected [34,35]. Extra precaution should be taken by security forces during any planned or unplanned stops [35]. The presumed difficulty in accessing the fuel and lack of tools to do so increases the difficulty of theft just as it does for material diversion. Because the reactor will contain fissile and/or radioactive material, any container designed to ship the reactor, or the reactor unit itself if qualified as its own shipping container for nuclear and radioactive materials, will need to meet current regulatory and safety rules, which include a certain level of resilience to physical damage [34]. Current analysis suggests the reactor itself or an external cask may be required to meet at least the requirements for Type B containers assuming the reactor is fuelled with fuel having an enrichment greater than 5% [39,40]. The resilience these containers are designed to meet for safety reasons should also make the reactor unit resilient to sabotage during transit, for example, since safety features to prevent criticality would also help to prevent sabotage [34]. In addition to sabotage, a thief may try to steal a fuelled microreactor. The motivations for such an action may vary, but if the desire of the thief is to operate the reactor for nefarious purposes, reactors which are easier to deploy and operate may be a more appealing target compared to more complex designs which may require connections to additional systems to operate safely. I

Extrinsic physical protection measures fall into three primary categories: detection, delay, and response. Methods of transportation should be designed to easily enable the inclusion of external devices which increase the probability of detecting an adversary and delaying an adversary. These detection and delay features can include aspects such as locations to add locks to the reactor or the vehicle the reactor is being transported by, means of remotely disabling the transportation vehicle should it be hijacked, locations to place sensors such as motion detectors and other surveillance devices, and ability to deploy delaying devices such as foam [34,35,36,40]. The other category of extrinsic physical protection characteristics is related to response to an adversary event. While it may not always be true, the physical protection system and response force for a reactor in transit should assume an extended period before off-site responders could arrive on the scene. Therefore, the convoy should ensure it has an adequate number of security personnel and other security measures to respond to any design basis threats [34,36]. Communication with off-site responders and relevant authorities should be maintained when practical, but security personnel should also account for the fact that communication to off-site responders may not be guaranteed if they are traveling through locations with poor connection to communication infrastructure [36]. Additionally, off-site responders and relevant authorities should have a means of tracking and locating the nuclear material in the event of theft [34].

Special attention may be warranted in the situation where the reactor is being transported with spent nuclear fuel. Not only will there be a higher activity present compared to the fresh fuel shipment case, but new sabotage pathways could arise if the cooling mechanisms for the spent fuel are compromised [37]. While existing IAEA physical protection recommendations likely remain valid, the relevant authorities may wish to consider how the possibility of new threats impacts the physical protection of such a shipment compared to shipments with fresh or low irradiated fuel [37].

5. Conclusions

This report explored the PR&PP aspects of four siting options for AMRs: remote locations, near population centres, floating or underwater power stations, and civilian marine propulsion, with additional considerations on single versus multi-modules, ultimate heat sinks, autonomous operations, HALEU versus LEU fuel, and transit of reactors.

The following summarizes key observations or trade-offs identified for each deployment option.

Siting in Remote Locations

- Sealed cores will increase the difficulty of access, which is an advantage of proliferation resistance, but they can make inspections more difficult unless transported back to a factory. It is important to maintain continuity of knowledge. Remote monitoring becomes more important to improve efficiency of resource use for international safeguards.
- From a physical protection standpoint, remote siting reduces access for potential adversaries but also increases response time for off-site response.

Siting Near Population Centres

- Proximity to population or industrial centres provides good infrastructure for accessing the site and effective data transmission for remote monitoring. Co-location or the potential for shared resources could be a benefit. Proximity to people provides many observers to spot unusual activity (improves transparency). These factors could improve proliferation resistance.
- On the other hand, proximity to cities can introduce new physical protection threat vectors and challenges in detection and nuisance alarms. Increases in petty crime or protests in urban environments should be considered. Proximity to airports, train lines, and highways could introduce new sabotage pathways. Co-location with industrial processes also introduces additional threats (for example chemical release that could affect safe operations of the reactor.) Public acceptance of security forces may also be a consideration.

Floating or Underwater Power Stations

- Smaller and more compact reactors may be harder to reconfigure for diversion/misuse. Some designs will have no equipment for refuelling since that is expected to occur at a specific refuelling site. Remote siting will lead to the trade-offs identified previously including accessibility issues which could be more of a challenge for siting far offshore or in the case of underwater power stations.
- Designs for physical protection systems should consider potential threats such as approach by water, underwater attacks, ship collisions, or theft of the entire vessel. The physical limitations of the vessel for access delay and response should also be taken into account.

Civilian Marine Propulsion

- Many of the proliferation resistance challenges are similar to floating nuclear power plants, so many of the previous trade-offs and conclusions apply to marine propulsion as well. Different refuelling options are being considered for civilian marine propulsion including both sealed cores and on-line refuelling in the possible case of a molten salt reactor design. Both could have vastly different challenges with regards to proliferation resistance and international safeguards verification.

- There are slightly different challenges with physical protection since the vessel will be traveling and going through different jurisdictions. An adversary may be attracted to nuclear propulsion due to its capabilities and the potential for technology theft.

The following summarizes the key observations for the five additional crosscutting considerations.

Single vs. Multimodules

- Single module sites will have less movement of equipment and fuel, so there is a proliferation resistance advantage, whereas multi-module sites may have more re-fuelling activities which increases the opportunities for diversion.
- Physical protection needs to consider construction of modules in phases and the requirement for compensatory measures and how construction activities, equipment, and personnel can affect the protection strategy.

Ultimate Heat Sink

- There are likely little impacts on proliferation resistance due to the choice of air or water as the ultimate heat sink, but signatures might be different.
- The loss of decay heat removal systems, regardless of ultimate heat sink, needs to be considered as part of sabotage scenarios and must be considered in the physical protection system design.

Autonomous and Remote Operation

- The use of unattended monitoring systems and remote transmission of data will be highly important for international safeguards, and cybersecurity will play a key role in protecting that information.
- Cyber threats will be a key concern for remotely operated or autonomous reactors. There are several challenges with complete remote operation of a reactor from a physical protection standpoint—these reactors would need very robust delay features to prevent access. There is a trade-off in autonomous operation in that it can reduce the potential for insider theft or sabotage, but at the expense of needing more robust cybersecurity.

HALEU vs. LEU

- The desire for less frequent refuelling (which improves proliferation resistance) depends on higher enrichment fuel like HALEU. Fresh HALEU fuel material attractiveness compared to LEU depends on several factors, including the state's fuel cycle and its related capabilities. Irradiated core isotopics will also be different for different fuel enrichments.
- The main difference between LEU and HALEU from a physical protection standpoint is that some countries protect those materials at different security levels. While the protection level at the reactor will be the same, there will be differences in protection strategies in fuel cycle and storage facilities and transportation of the fuel.

Transit of Reactors

- There are a number of tradeoffs regarding proliferation resistance when it comes to reactors shipped with and without fuel. Ultimately there is little difference since either way the fuel and reactor need to be shipped, so other factors will probably be more important for the operator.
- The operator will likely perform a cost-benefit analysis to determine if the additional cost of security for two shipments is better than one. However, the operator should consider whether shipping a fuelled reactor creates a more attractive target for theft or sabotage.

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APPENDIX A: Summary of PR relevant intrinsic design features and extrinsic measures. Adapted from IAEA-STR-332 [12]

Table 1: Summary of PR relevant intrinsic design features, examples. Adapted from IAEA-STR-332. Please refer to IAEA-STR-332, for full explanations and complete definitions of terms and concepts [12].

Features reducing the attractiveness of the technology for nuclear weapons programmes
1. The Reactor Technology eliminates the need of enrichment Fuel Cycle phase
2. The Reactor Technology produces spent fuel with low % of fissile plutonium
3. Fissile material recycling performed without full separation from fission products
Features preventing or inhibiting diversion of nuclear material
4. Fuel assemblies are large & difficult to dismantle
5. Fissile material in fuel is difficult to extract
6. Fuel cycle facilities have few points of access to nuclear material, especially in separated form
7. Fuel cycle facilities can only be operated to process declared feed materials in declared quantities
Features preventing or inhibiting undeclared production of direct-use material
8. No locations in or near the core of a reactor where undeclared target materials could be irradiated
9. The core prevents operation of the reactor with undeclared target materials (e.g. small reactivity margins)
10. Facilities are difficult to modify for undeclared production of nuclear material
11. The core is not accessible during reactor operation
12. Uranium enrichment plants (if needed) cannot be used to produce HEU
Features facilitating verification, including continuity of knowledge
13. The system allows for unambiguous Design Information Verification (DIV) throughout life cycle
14. The inventory and flow of nuclear material can be specified and accounted for in the clearest possible manner
15. Nuclear materials remain accessible for verification the greatest practical extent
16. The system makes the use of operation and safety/related sensors and measurement systems for verification possible, taking in to account the need for data authentication
17. The system provides for the installation of measurement instruments, surveillance equipment and supporting infrastructure likely to be needed for verification

Table 2: Summary of PR relevant extrinsic measures, examples. Quotes from IAEA-STR-332. Please refer to IAEA-STR-332, for full explanations and complete definitions of terms and concepts [12].

States' commitments, obligations and policies with regard to nuclear non-proliferation and disarmament
1. Relevant legal instruments, such as the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) or nuclear-weapon-free zone treaties
2. Safeguards agreements pursuant to the Treaty for the NPT (i.e., as provided for in INFCIRCI153 (Corrected)) [50]
3. Protocols additional to safeguards agreements between a State or States and the IAEA (i.e., as provided for in INFCIRCI540 (Corrected)) [55]
4. National export control legislation and co-operative arrangements, including those that limit nuclear energy use to peaceful purposes
..agreement between exporting and importing States that nuclear energy systems will be used only for agreed purposes and subject to agreed limitations
5. Bilateral arrangements for supply and return of nuclear fuel or other components of a nuclear energy system
6. Bilateral agreements governing the re-export of a nuclear energy system or its components by an importer
7. ..supplies of fresh fuel and waste management services over the life-cycle of the nuclear energy system, reducing the need of the importer to develop indigenous enrichment or reprocessing technologies
..commercial, legal or institutional arrangement that controls access to nuclear material and nuclear energy systems
8. A comprehensive legal framework, including the definition of responsible governmental authorities, to ensure that operators of nuclear energy systems are subject to specific requirements governing the use of those systems and associated materials
9. Common legal provisions to be incorporated into all contracts involving nuclear energy system
10. Multi-national ownership, management or control of nuclear energy systems or any part thereof, perhaps in extra-territorial locations.
..application of IAEA verification and, as appropriate, regional, bilateral and national measures, to ensure that States and facility operators comply with non-proliferation or peaceful-use undertakings
11. Safeguards approaches for the nuclear energy system, capable of detecting diversion or undeclared production of nuclear material
12. State or regional systems for accounting and control of nuclear material
13. An adequately funded and technically competent verification system for a nuclear energy system
15. An adequate number of sensitive and reliable measurement instruments and sensors to support an inspection and verification programme
..legal and institutional arrangements to address violations of nuclear non-proliferation or peaceful-use undertakings
16. A credible system of reporting verification conclusions in a timely manner
17. Reliable institutional arrangements for bringing evidence of violations before the international community
18. An effective international response mechanism

APPENDIX B: International Maritime Definitions and Laws of the Sea

Commercial maritime nuclear applications are not a novel concept. Organizations in several countries, including the United States, Russian, China, the United Kingdom, France, and Denmark, have proposed to design and deploy FNPPs and underwater power plants for civilian power production on a variety of barges, ships, or other marine vessels and platforms [41]. However, only the Russian Federation currently operates an active FNPP, the Akademik Lomonosov, in the Arctic city of Pevek [42]. While most of the marine-based designs are light water reactors, some concepts employ Gen IV designs, including molten salt reactors and metallic fueled fast reactors. The designs vary, and the proposed breadth of designs includes diverse plant designs, fuel types, and fuel management strategies. These design-specific factors will significantly affect a reactor's overall PR&PP attributes, and the issues that are specific to a marine siting arrangement are merely one component of ongoing PR&PP assessments.

Because of their marine nature, these reactors will be subject to international maritime statutes, laws, and regulations. Several studies and presentations have detailed the jurisdictional alignment of these "rules of the sea" for nuclear material security [43,44,45] and safeguards [46,47,48] of FNPPs, but context for this entire design class is necessary to develop holistic understanding of the PR and PP strategies. Regardless of whether the reactor is stationary while in operations, used for commercial propulsion, or tethered to the sea floor, various international laws during the siting process require consideration.

One of the key differences between these designs is their maritime classification. For maritime law, there are different legalities applied to "vessels" and "barges." A vessel is a ship that contains its own form of propulsion, whereas a barge does not. When considering the siting of marine nuclear reactors, the determination of their application could dictate whether vessel or barge laws are required. Jurisdiction of these ships will depend on the use case, its location or docked State, and "flag state jurisdiction".

Finally, more relevant for siting of these designs is their distance from the coastline and the jurisdictional sovereignty associated with coastal zoning. The United Nations Convention of the Law of the Sea defines the various maritime zones that extend from a State's coast to international waters [49]. These zones and jurisdictions include:

- **Coast/Baseline/Port**: A coastal State has absolute jurisdiction over its land territory, including internal waters and its coast. A State may exercise jurisdiction over foreign flagged merchant vessels within its ports and internal waters. Port State jurisdiction extends to foreign commercial ships, but not to vessels owned or operated by another State for non-commercial purposes.
- **Territorial Sea**: A State's jurisdiction in its territorial waters is similar to its jurisdiction over its coast and baseline, i.e., almost absolute. The sovereignty of a coastal State extends to an "adjacent belt of sea, described as the territorial sea" up to a limit not exceeding 12 nautical miles. The sovereignty does not extend in cases of innocent passage by foreign vessels. Defined as "navigation through the territorial sea for the purpose of traversing that sea without internal waters… or proceeding to or from internal waters or a call at such roadstead or port facility," the right of innocent passage allows States free access so long as their journey is "continuous and expeditious," with only incidental pauses, and so long as it is not "prejudicial to the peace, good order or security of the coastal State."
- **Contiguous Zone**: A State's jurisdiction in its contiguous zone (not to extend beyond 24 nautical miles from its baselines) is diminished. The authority is limited to being able to exercise specific national laws relating to customs, taxes, immigration, and sanitation.

- **Exclusive Economic Zone**: A State does not have sovereignty within its exclusive economic zone (EEZ) but enjoys sovereign rights to the management of natural resources and other economic activities, e.g., production of energy. In EEZs, all States, and by extension flagged ships, enjoy the same freedoms of "internationally lawful uses of the sea." [50]

Multi-lateral Jurisdictional Overlap

Given the mobile and marine nature of these reactors, FNPPs may involve multiple jurisdictions or multiple States' international agreements. Currently, there is no agreed international consensus on the status of, and categorization of, FNPPs or seabed nuclear reactors. Various industrial and deployment scenarios could involve both Nuclear Weapons States (NWS) and Non-nuclear Weapons States (NNWS) with overlapping jurisdictional responsibilities. The involvement of multiple States, each subject to different types of safeguards agreements, could increase the legal complexity of safeguards implementation. However, this would not inherently reduce the effectiveness or technical efficiency of IAEA verification activities, assuming effective planning occurs both independently and cooperatively among the IAEA, the supplier State, and the deployment site State. Proactive communication, negotiation, and cooperation are necessary to ensure effective deployment scenarios.

Additionally, there are considerations the safeguards measures required when an NWS transfers an FNPP to a NNWS. Provisions safeguards responsibility, material transfer, and material ownership for Non-proliferation Treaty (NPT) NNWS are found in the Comprehensive Safeguards Agreement (INFCIRC/153) [50], and there are no specific provisions related to jurisdiction or transfer of ownership specifically for NPT NWS (unless specified in a State-specific in the respective Voluntary Offer Agreement) or in INFCIRC/207 (Notification to the Agency of Exports and Imports of Nuclear Material). Some principal provisions include:

- **Basic undertaking of NNWS**: "The (Comprehensive Safeguards) Agreement should contain…an undertaking by the State to accept safeguards, in accordance with the terms of the Agreement, on all source or special fissionable material in all peaceful nuclear activities within its territory, under its jurisdiction or carried out under its control anywhere…" (INFCIRC/153, paragraph 1)
- **Ownership of nuclear material while in transit**: "No State shall be deemed to have such responsibility for nuclear material merely by reason of the fact that the nuclear material is in transit on or over its territory or territorial waters, or that it is being transported under its flag or in its aircraft." (INFCIRC/153, paragraph 91)

Change of responsibility in case of international transfer of nuclear material: "…the States concerned shall make suitable arrangements to determine the point at which the transfer of responsibility will take place." For the importing State, the responsibility from the safeguards point of view is "no later than the time at which the nuclear material reaches its destination." (INFCIRC/153, paragraph 91/(a)). The State receiving the nuclear material must notify the IAEA "At what point of the transfer responsibility for the nuclear material will be assumed by the State for the purposes of the Agreement" (INFCIRC/153, paragraph 95(b)). For the exporting State IAEA safeguards are terminated on nuclear material (transferred out of the State) "…when the recipient State has assumed responsibility…" (INFCIRC/153, paragraph 12).

APPENDIX C: Additional Transportation Considerations

Mode of Transportation

Depending on the size and siting location of an AMR or microreactor, there are four potential modes of transportation: roadway, rail, over water, and by air; all of these are established modes of transportation that have been utilized to transport fresh and spent nuclear fuel previously [51]. Sections 4.5.1 and 4.5.2 discuss proliferation resistance and physical protection for transport largely agnostic to the method of transportation. However, each mode of transportation comes with unique considerations that are worth mentioning.

Roadway

For deployment of reactors inland from the water and in regions without good rail infrastructure, transportation over roadway is the presumed method of moving a microreactor. Roadways typically offer a moderate degree of flexibility in planning a transportation route, as there are likely several different paths which can be selected between the shipper and receiver destinations. This benefits security planners by not requiring the transport convoy to take an easily predictable route [53]. Depending on the distance between the shipping facility and receiving facility, overnight stops may be unavoidable. Protection needs to be maintained during these stops [53]. Special consideration should be given to sections of road along the route which could be easily blocked, provide cover for a hidden adversary (e.g. tall buildings or dense forest), or must be taken due to limited road infrastructure or vehicle weight limits. A particular case is transport via ice road (most likely needed in northern regions of the world) where speed and weight limit can affect adversary event. These sections of road may have an increased probability of an adversary event or may influence how a security force responds. Likewise, the crossing of any bridges should be monitored in advance for signs of sabotage causing a bridge collapse while the reactor is crossing it.

Travel via road also impacts the proliferation resistance of the microreactor. Any attempt to divert or misuse material while moving would be incredibly difficult given limited space and unsteady conditions. However, depending on the length of the route, a convoy may be more likely to make extended stops when traveling by road compared to other modes of transportation. These present a possible opportunity for material to be diverted from the reactor, so attempts should be made to account for the location and duration of these stops if they occur.

Rail

Transit over rail likely reduces the number of viable paths for transportation, but also increases the weight limit of material which can be transported. As a result, an adversary may be more able to predict the transportation route of the reactor to plan an attack, but the additional weight allowance may increase the amount and type of physical protection equipment or the size of the response force in the transportation convoy. Consideration should be given to the trade-off of this scenario and how it compares to other options. Similar to transportation by road, extended stops may be unavoidable. Precautions should be taken to ensure the security of the reactor is maintained during these stops [53].

Similar proliferation resistance concerns arise for transit by rail as they do for roadways. The movement of the train would serve to complicate gaining access to any nuclear material within the core. However, trains also may be required to stop for extended periods. Measures should be taken in advance of transit to account for the duration and location of these stops and to have an ability to survey the reactor during these times to ensure there is no undeclared access to the fuel.

Water

Transportation over water may take several forms including through river systems, near coastlines, and across open water. Each of these options presents different challenges and opportunities. Transportation through rivers or along coastlines will likely yield more waterborne traffic near the transportation vessel compared to in the open water. This increases the ability for a potential adversary to disguise themselves and launch a surprise attack. However, the closer a vessel is to land also increases the ability of the vessel to be tracked by relevant authorities and for off-site response forces to be dispatched more quickly in the event of an attack. Conversely, a vessel in open water will be more able to observe other vessels from a distance and track their movements for any signs of abnormal behaviour, which may provide advanced warning of an adversary. Open water vessels may also be concerned with an underwater attack from a technologically advanced adversary, which increases the scope the PPS of the ship should cover. Another notable category of transportation via water are FNPPs. It is anticipated that a FNPP will be transported on the barge which will serve as its primary site. Thus, this instance of transport by water may be more resistant to theft or sabotage as the reactor can be transported with the physical protection system designed for its long-term siting largely in place.

The security posture over water may also differ compared to land-based transport due to additional concerns posed by ships. A ship can be sunk without the reactor being directly damaged in the attack, which would likely lead to the core sinking with the ship. Damage to the core in addition to sinking may lead to increased criticality concerns, concerns over the dispersion of radioactive material into the water system, and the loss of continuity of knowledge. Thus, the design basis threat and consequences of an attack on a reactor traveling via water are different from a land-based attack, which should be considered in the design of the PPS.

An additional consideration with water-based transit is that it will likely require a transfer of the reactor from road vehicles or train onto the vessel, and then back off again. The reactor and associated nuclear material are more susceptible to diversion during the transfer process [54]. Additional consideration relating to physical protection needs to be given to any transfers which occur because of the chosen method of transportation.

Water based travel also presents a variety of proliferation resistance concerns or enhancements depending on the specifics of the shipment. If the reactor is being shipped on a crowded ship or a ship with other cargo, there will likely be limited space to access the reactor, thus making any attempt to divert material from the core more unlikely. However, ships may also have heavy equipment on board such as shipboard cranes, which could be used to enable access the nuclear material contained within the reactor core. Likewise, if the reactor is transported below the deck of the ship, the visual concealment may serve to increase a proliferators successful chance of diversion of nuclear material or theft of the entire reactor without detection. Therefore, when planning containment and surveillance, careful consideration should be given to the application of cameras and seals to locations and equipment on the vessel which may be utilized by a would-be proliferator.

Air

Transportation via air enforces more restriction on the design of the system to be transported, but it is not ruled out as a means of transit. Transportation via air presents some unique aspects, as the only credible threat comes from an adversary with a high degree of technical competence such that they could mount an attack against an arial target or plant an explosive device on the plane prior to departure. An active escort serving as the ‘response force’ may not be realistic or feasible depending on the parties involved in the shipment and receipt of the reactor; the response force may be limited to personnel in the transport plane carrying the reactor. Thus, a PPS may be more based around features that could fend off or prevent an attack compared to features which could 'fight back.' In contrast to the reduced ability to respond, arial transportation gives the greatest degree of flexibility to set the route. As a result, more coordination with government representatives may be required to ensure they are aware of flight plans and may be able to help respond in the event of an attack.

Special consideration should be given as well to survivability of the reactor unit or any container meant to carry it. An adversary attack which results in the destruction of the transportation airplane would likely result in the reactor crashing into the ground from 1000's of feet in the air. The potential consequences of this event need to be weighed when considering air as a means of transportation. To this end, regulations for the transportation of nuclear material via airplane requires more robust and survivable containers to be used to hold the nuclear material compared to ground transport. Any fueled microreactor traveling via air would likely need to meet these requirements, leading to more intrinsic physical protection of the system [53].

Transport of fueled reactors via airplanes enhances the proliferation resistance of the reactor in transit. Given the probable range of sizes of reactors relative to the holds of cargo aircraft, there is likely to be limited to no space which could be utilized to access the reactor core and divert material. Likewise, compared to the other transportation options, air travel is likely to be the most direct and quickest means of transportation. This would severely limit the number of anticipated, extended stops which could be utilized by a would-be proliferator to divert or misuse the nuclear material in the reactor.

Transportation in Remote vs. Urban Areas

One additional aspect of transportation which warrants discussion is transportation through populated urban areas compared to transportation through more remote locations. Note that this discussion focuses on land-based transportation.

From a proliferation resistance standpoint, transportation via primarily remote options seems to present a higher risk compared to urban areas. Potential disruptions to the shipment, which could serve as cover for moving the nuclear material to a location where diversion could occur, may be more likely in heavily populated and trafficked areas; however, a large population serves to provide many witnesses and possible sources of open-source intelligence which would make any diversion more difficult to conceal. In addition, the communication infrastructure of most urban areas could be utilized to transmit safeguards information in real time or near-real time to detect any potential diversion in a timely manner. In remote locations, less open-source information about the reactor would be generated, and transmission of safeguards relevant data may not be feasible. This may lead to an increased reliance on containment and surveillance methods which can only be reviewed later. Although this approach might not prevent the detection of any deterrence or misuse, it could extend the period before such activities are identified.

From a physical protection standpoint, both options offer different enhancements and challenges. Utilizing remote pathways for transportation provides greater control over the route, permitting the blockade of alternative paths with minimal disruption to other traffic. Additionally, it reduces the likelihood of adversaries blending in with regular traffic. On the other hand, distance from population centres makes it more difficult for additional responders to reach the transportation convoy, and communication from the convoy to a central authority may be disrupted due to lack of telecommunications infrastructure. In a more populated region, a transportation convoy may be less able to control the road due to larger amounts of traffic.

Likewise, the increased expected crowds and tall buildings could offer potential locations for adversaries to hide in advance of an attack. However, local law enforcement would be more able to respond to any event in a prompt manner. Transportation in remote locations and urban locations both may have impacts on the proliferation resistance and physical protection of a microreactor in transport. Any safeguards or physical protection systems will need to be designed with flexibility in mind so that they are able to adapt to whichever method of transport is being used in a specific case.

International Transportation

Another situation which may arise during transportation includes the transportation of nuclear reactors across international borders. While there are many regulatory questions that may be associated with transporting microreactors across borders, this section will focus on proliferation resistance and physical protection concerns. Transportation which involves crossing borders may increase the intrinsic proliferation resistance of the transport. Diverting or misusing nuclear material during international transit would require either the cooperation of a second state or would need to avoid detection from both the IAEA and the transit state. The increased level of coordination or increased level of secrecy needed to pull this off makes any proliferation related activities more difficult to achieve while avoiding detection from another party. However, it also may weaken external proliferation resistance. Depending on the exact procedures associated with crossing another country's borders, there may be opportunity for confusion to arise between the various relevant parties. It is possible that any such confusion could represent opportunities for the diversion of nuclear material. Special care should be taken to ensure proper continuity of knowledge during such situations.

Physical protection of the shipment across international borders becomes more complicated [56]. Intrinsically, more unknowns arise around physical protection because of crossing borders. Gathering information on threats located in a foreign country may be more difficult when compared to gathering domestic threat information. Therefore, there may be uncertainty about which threats need defence. Likewise, this type of transportation would likely require that the shipper state share security related information with the transit state, which increases the number of people aware of said security information and makes it more difficult to control dissemination. The crossing of international borders may also require the material to stop for an extended period to allow for inspections by customs officials. This stoppage period could present itself as an opportunity for an adversary to attack the stationary shipment [54]. However, measures can be implemented to externally bolster the physical security of the shipment, thereby mitigating the effects of intrinsic challenges. An increased level of security measures and forces can be utilized to account for unknown threats which may arise. Effective coordination with other states can facilitate seamless border crossings and clearly define the roles and responsibilities of all involved parties [31,52]. The exact measures taken will depend on the specific details of a given shipment and the parties involved, but careful planning will play a key role in ensuring that extrinsic physical protection actions can account for the intrinsic complications associated with shipments of nuclear reactors that cross international borders.

THE GENERATION IV INTERNATIONAL FORUM

Established in 2001, the Generation IV International Forum (GIF) was created as a co-operative international endeavor seeking to develop the research necessary to test the feasibility and performance of fourth generation nuclear systems, and to make them available for industrial deployment by the 2030s. Under the new 2025 GIF Framework Agreement, GIF brings together countries, as well as Euratom, representing 27 EU member states, to co-ordinate research and develop these systems. GIF has selected six reactor technologies for further research and development: the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), the molten salt reactor (MSR), the sodium-cooled fast reactor (SFR), the supercritical-water-cooled reactor (SCWR) and the very-high-temperature reactor (VHTR).

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