Advancing Nuclear Innovation: Responding to Climate Change and Strengthening Global Security[1]

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I. Overview

Advanced nuclear reactors, the smaller, flexible, and innovative nuclear technologies of the future, are rising in importance as the global community grapples with the vital challenges of cutting carbon emissions, supporting the global demand for electric power, and ensuring the continued peaceful use of nuclear power in the 21st century.

The Global Nexus Initiative is a leader in analyzing the intersection of nuclear power, climate change, and global security. It determined that advanced reactors offer sufficient potential value in providing zero carbon energy and supporting global economic growth, and that further study was needed of the nuclear safeguards and security requirements for the three major types of advanced reactors – molten salt fuel, TRISO-based fuel, and fast-spectrum neutron reactors.

The assessment was conducted from 2018-2019. One result was the acceptance of a paper based on the GNI safeguards analysis, *Identifying Preliminary Criteria for Safeguarding Advanced Nuclear Reactors*, by the International Atomic Energy Agency (IAEA). It was presented at the *2018 Symposium on International Safeguards: Building Future Safeguards Capabilities*. GNI supplemented that core safeguards assessment and analyzed the nuclear security impacts and geopolitical implications of advanced reactors.

The results of these assessments are presented in this document. The findings are preliminary because there are a number of different reactor designs within the three major technology categories and the GNI analysis did not examine each unique reactor design. The different sizes and design features of individual reactors may influence and change these preliminary findings.

There are five primary results of these assessments are:

- Advanced reactors are an important component of the global strategy to reduce carbon emissions to zero. The evolution and application of the nuclear non-proliferation and security regimes for these reactors need to be further developed. This is best done through

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[1] This analysis was produced by Anita Nilsson, Caroline Jorant, Kenneth Luongo, and Everett Redmond with contributions from Ashley Finan. It is a final draft and is subject to revision.

the interaction of the reactor design community, the International Atomic Energy Agency (IAEA), and other key stakeholders. This interaction will result in the adaptation of the international safeguards and security systems for advanced reactors and facilitate increased effectiveness to support their deployment on a timely basis. This intensified dialogue must be initiated at an early date.

- There is high confidence that any of the advanced reactor concepts can be safeguarded to prevent nuclear weapons proliferation[i]. The question is how easily and at what cost. The current international safeguards system has been effectively and efficiently implemented for the global fleet of Light Water Reactors (LWRs). The IAEA will need to consider how to best accommodate the unique characteristics of advanced reactor technologies and designs. The reactor designers must, from the early concept stage, be focused on "safeguards by design", identifying reactor features that will facilitate effective international safeguards and ensure a high level of proliferation prevention and security comparable to LWRs.
- There are characteristics of advanced reactors that can support improved nuclear security and prevent unauthorized radioactive release, including below-ground placement, passive safety features, low operating pressures, and decreased external power dependence. Emerging technologies like artificial intelligence and blockchain, potentially may assist with security and safeguards. There are questions regarding the implications of remote location of these reactors (because they can support industrial as well as electric power operations), including how that siting may impact physical security and the effectiveness of local infrastructure, including timely response in the case of a security event.
- Advanced reactors must be thoroughly evaluated with respect to both safety and security, as part of an evolved nuclear governance structure. Traditionally, the dominant suppliers of a nuclear technology have had significant influence on these issues. It is not clear at this point which advanced reactors, or which countries, will lead the market competition. Therefore, the international community must ensure from an early point that any race for market share among key geopolitical competitors strengthens nuclear governance rather than weakens it.
- There must be political and public confidence in this new class of reactors if they are to effectively contribute to the climate and security challenges the word faces in this century. Nations that are interested in the deployment of these reactors must commit, and be offered adequate international assistance, to increase their capability to safely, securely and effectively operate them.

II. Importance of Nuclear Power for Climate Change

In order to meet the Paris Climate Change Agreement, analysis by the Intergovernmental Panel on Climate Change (IPCC) and others experts indicates the need for a near-zero carbon electricity system soon after mid-century.[ii] The most recent report by the IPCC[iii] states that limiting the global temperature increase to 1.5^0 Celsius will avoid the worst impacts of climate change, but will require, “rapid, far-reaching and unprecedented” action on decarbonization. Reductions of this magnitude require significant and rapid technological advances including in the four key elements of a climate change response strategy – energy efficiency, renewable energy, carbon capture and storage, and nuclear power.

At present, nuclear power is making a very significant contribution to the Paris goal and most studies by the IPCC and others suggest that nuclear capacity will need to grow.[iv] But, the recent IPCC report also noted that the significant deployment of nuclear power faces headwinds primarily from public opinion. And several prominent new nuclear projects in the U.S., U.K., Finland, and France have faced financial challenges. But there is a growing chorus of expert opinion noting that nuclear power remains an important element of the global decarbonization strategy.[v]

The existing nuclear reactor fleet is facing a potential cliff of retirements in mid-century. Fifty-three percent of the current global reactor fleet is over 30 years old, and by 2050, those plants will be over 60 years old. It is estimated that by 2050, 357 of the current 454 operating reactor units[vi] could be retired. Yet, very few nations have included nuclear power as a part of their approach to reducing carbon emissions as outlined in their national commitments at the Paris meeting.[vii]

In comparison with LWRs, Advanced Reactors offer the following: coolant systems that can enhance efficiency and safety; reduced construction time and costs; fuel cycles that can reduce environmental impacts; a wider variety of sizes and outputs for different locations and applications. Beyond electricity generation, there may be a role for next generation reactors in the desalination of sea water, which would provide a new source of fresh water to countries and regions that need it, and military power applications are also being seriously evaluated.

All of these attributes, plus the value of producing emission free electricity in a carbon-constrained world, make advanced reactors attractive energy sources. However, in order to make a timely contribution to meet the energy and climate challenges that the world faces, advanced reactors must move to deployment in the 2025-2030 timeframe. The construction and operating costs of these reactors will need to be more competitive with other energy options, particularly coal, renewables with battery storage and natural gas and this reduced cost is not yet proven.

If the clean energy benefits that are contributed by the existing reactor fleet decline significantly, there is a considerable risk in assuming that renewable or other zero carbon energy options will be able to substantially compensate for this reduction by mid-century.[viii] In addition to replacing the carbon benefits produced by the reactor fleet, these sources also will need to displace the remaining 60% of the world’s electricity that today comes from fossil fuels as well as all future energy growth. It is at a minimum uncertain at this point if, in the future, renewables with storage alone or combined with fossil fuel carbon capture and sequestration (CCS) and energy efficiency can meet these goals. In recent cases where nuclear plants have been shut down in the U.S, carbon emissions have grown as the substitute power came primarily from natural gas, while in Germany, lignite and now imported coal, has accounted for the major replacement source.[ix]

If non-nuclear zero carbon energy sources and related technologies cannot meet carbon reduction objectives, then falling back on carbon emitting sources of power including natural gas or coal without capture and sequestration, will inevitably mean that aggressive climate targets will be unmet, with the attendant global consequences.[x]

III. Advanced Nuclear Technologies

Advanced reactors are gaining attention due to their potential ability to meet energy demands in underserved areas, provide zero carbon-emission energy, address fuel cycle and proliferation concerns, operate safely, and provide lower cost production and operational flexibility. Compared to large, LWRs, these reactors are smaller, operated at lower power, and not water-cooled. They are designed to provide electricity and support industrial and desalination processes. Because of their reduced profile and coolants, these reactors can be used for distributed energy including in arid landscapes. Because about 14% of the global population lacks access to reliable electricity, these reactors can help to reduce the global deficit of reliable electricity.

For the purposes of this report, Advanced reactors have been grouped into three main categories: i) the Molten Salt Fueled Reactors; ii) the TRISO-Fueled reactors; and iii) Fast Reactors.

i. Molten Salt-Fueled Reactors (MSRs)

In molten salt-fueled reactors, the fuel consists of fissile materials dissolved in a salt, a mixture that becomes liquid during operation. In general, the design has no fuel units such as fuel rods or assemblies, the fissile element (uranium, or thorium) is mixed with the coolant. MSRs operate with a fuel uranium enrichment up to 20% or thorium-based fuel. In a reactor with thorium-based fuel, ^{232}Th in the initial fuel inventory is converted during operation to the fissile isotope ^{233}U which is then consumed as fuel. Some of these designs have two fluid zones in the core: one center region where the power production takes place and one in a surrounding 'blanket' region where ^{232}Th is converted to ^{233}U. Some MSRs use graphite as moderator.

The molten-salt reactor is typically refueled online, allowing for extended reactor operation. MSR designs can range in size from 10s of MWe to 100s of MWe. Removal of unwanted fission by-products and the addition of fresh fuel enables the reactor to run for long periods without major refueling outages. MSRs can be either thermal reactors, burning the fuel, or fast reactors which may, but does not have to, produce more new fissile material than they consume in operation. The salt is solid in room temperature, but a molten liquid during the operation of the reactor.

These reactors operate at or near atmospheric pressure, with temperatures from 500^{o}C to 900^{o}C. MSRs make use of passive safety systems and have safety features that will work in a loss-of-power situation[xi]. The potential for fuel melting (e.g. as in LWRs) is eliminated by using already molten fuel. MSR designs typically do not require offsite power during emergencies to ensure safety shutdown and cooling.

ii. TRISO-Fueled Reactors

Tristructural-**iso**tropic (TRISO)-fueled reactors operate at high temperature, using small uniform microspheres of uranium oxycarbide coated with several layers of pyro carbon and silicon carbide that are dispersed into a) graphite pebbles (e.g., billiard-ball sized) or b) prismatic, hexagonal graphite fuel blocks in which the TRISO fuel particles are dispersed into a graphite block matrix. The reactor uses graphite as moderator. The fuel is designed not to crack due to the stresses from very high temperatures, which will prevent release of fission products or actinides during accident conditions - an improved safety feature versus current LWR fuel designs. The ^{235}U-enrichment is specified to be up to 20%. Some designs are helium-cooled, and some are molten fluoride salt-cooled designs. Triso-fueled reactors can range in size from 10s of MWe to 100s of MWe.

Pebble-bed TRISO-fueled reactors are refueled online. Used pebbles are taken out of the core and unirradiated pebbles that have not reached the desired burnup are added to the core. The reactor is shut down periodically (about every 6-10 years) for replacement of in-core graphite structures. Prismatic designs will require regular refueling outages every 1 to 3 years.

TRISO-fueled reactors use extensive passive safety features and do not require offsite power or any pumping capacity during accident conditions because the fuel can be cooled through natural heat transfer.

iii. Fast Reactors

Fast reactors use a fast neutron spectrum that can enable high fuel utilization, operational flexibility, and fuel recycling. Fast reactors can use liquid metal, gas coolants[xii] or salt coolants. Liquid metal reactors are typically designed to operate at low, near-atmospheric, pressure and high temperature (~500-800 ^{o}C).

Lead-cooled fast reactors utilize either molten lead or a lead-bismuth mixture as the coolant, which are relatively inert in relation to water or air but are highly corrosive, requiring more robust piping or vessel materials. Lead-cooled designs typically use uranium metal or nitride fuels.

Sodium-cooled fast reactors have several hundred reactor-years of operational experience and the benefit of oxygen-free/low-corrosion operation. However, the chemical volatility of sodium requires a sealed coolant system. Sodium cooled reactors typically use uranium oxide or metal fuel.

There are several varieties of fast reactors. One specific type is a *Gas Fast Reactor (GFR)*, which is helium-cooled, with the coolant under high pressure and high temperature, about 850^{o}C. It uses uranium fuel in silicon carbide fuel rods. Some fast reactors are being designed to operate for an estimated period of 10 to 40 years without refueling

Preliminary Assessment of Safeguarding Advanced Nuclear Reactors

The peaceful use of nuclear energy has been an important global energy source for over 60 years. It has resulted in 452 nuclear reactor units in 32 countries, most of them in Europe, North America, East Asia and South Asia. Most of them are Light Water Reactors (LWR), units that may produce up to 1650 MW-electricity. This has significantly contributed to, and accelerated, economic development in a number of States. But nuclear technology can be dual use – peaceful or weaponized - and an extensive and effective international safeguards regime, implemented by the International Atomic Energy Agency, has been established to contain the proliferation of nuclear weapons. Because of their unique features, advanced reactors do not easily fit into the existing national regulatory or international governance regimes and, in particular, they pose new challenges for the safeguards system.

IAEA Safeguards and Advanced Reactors

The IAEA safeguards system has carefully evolved over almost 50 years. It is well understood and accepted as effective. The methodology used in this analysis is to assess the new advanced reactor technology from a safeguards perspective by using IAEA Safeguards as implemented for light water reactors as the beginning reference point.

The primary elements of IAEA safeguards at operational LWRs are:

- The reactor is regarded as an “item facility”; i.e. all nuclear material is available as an encapsulated item, e.g. in a closed fuel which is then assembled into a fuel assembly. Accountancy at such a facility is, in principle, based on counting and identification. Source data provide full information of inter alia the nuclear material content, its chemical and physical form and where the item is placed. The integrity of these items remains unchanged, although the fissile content of the items changes as a result of irradiation.

Post-irradiation source data provide information of burn-up and post-irradiation composition of the nuclear material.
- The fresh fuel contains low enriched uranium, around 5%, the lower part of the enrichment range of LEU. This is below 20% ^{235}U, which is the demarcation between low enriched and high enriched uranium.
- Source data will provide detailed information on the unirradiated fuel and will be available after irradiation including burn-up and post-irradiation isotopic composition, assigned to each fuel assembly.
- LWRs are refueled during outage periods during which the inventory of nuclear material in the reactor and storage areas can be verified.
- All nuclear material is accessible for inspection through visual, non-destructive assay (NDA) measurements and through containment and surveillance (C&S).
- There are no obvious parts of the reactor where clandestine irradiation of undeclared material may take place.

Without any indication that there is clandestine enrichment or reprocessing in the country, i.e. the IAEA has issued a broader safeguards statement, the timeliness for verification of spent LWR fuel is set to one year. Detection quantity is set to 75 kg ^{235}U.

Non-proliferation and Advanced Reactors

The IAEA can apply safeguards at any type of nuclear facility, however, the effort required, and the expense, would depend on the type of facility and whether the nuclear material is available in bulk form or as items. There is a direct relationship between non-proliferation and the ease of applying effective safeguards. The evaluation of the safeguarding of advanced reactors is based on a comparison with the safeguards processes and approaches used by the IAEA for safeguarding existing LWRs.

A principle used in this evaluation is that safeguards for advanced reactors that are similar to those employed for LWRs would be less costly and time consuming to implement, fit well within the IAEA's current abilities and processes, and reduce the potential for diversion of nuclear materials. It needs to be underscored that the IAEA will be able to safeguard all advanced reactor designs, the question is only at what expense.

The application of safeguards is much more complex in a facility processing nuclear material in bulk form than in a facility where nuclear material is available in well-defined items. At a bulk-handling nuclear facility, nuclear material may be able to be removed in small quantities, which increases the complexity of the verification.

For the assessment of advanced reactor technology, this paper uses a two-part analysis:

1. Compare elements of "LWR safeguards" with the relevant characteristics of each type of advanced reactor technology
2. Assess whether safeguarding the advanced technology is likely to require the same, somewhat more, or significantly more safeguards effort compared with the application of IAEA safeguards at LWRs.

It assumes that (all) countries with advanced technology reactors will have:

- A comprehensive safeguards agreement and be party to the Additional Protocol
- Received a broader IAEA statement of correctness and completeness, i.e. no-diversion of any nuclear material, that all material has been declared, and there is no indication of undeclared activities.

The following evaluation is relevant for the three design-groups, recognizing that there are variations among them in the specific designs that are being developed around the world.

Evaluation Results

Overall, this initial assessment indicates that all of the advanced reactor groups can be adequately safeguarded. However, none of the design groups are exactly equivalent in safeguards effort and background criteria when compared to LWRs. Each group has weaknesses and challenges that either require an adaptation or new safeguards approach or design alterations that will address the weaknesses.

Molten-Salt Fueled Reactor Group

In the liquid fuel designs, the molten-salt-fueled reactor group shows the following characteristics in common with and different from LWRs:

- The fuel, during reactor operation, is in the form of a fluid, not as individual fuel items.
- The incoming fresh fuel is well known to its composition, chemical and physical form, uranium and/or thorium weight and Uranium enrichment.
- The post-irradiation fuel likely will have to use calculation or measurement to determine its content of uranium or thorium, including isotopes. This may be more challenging if the post-irradiation fuel is removed in batches.
- In principle, there is a possibility of diversion of small quantities.
- It is assumed that all parts of the reactor, the flow of fuel and potential extract possibilities, can be monitored with C&S methods.

Based on this analysis, the molten-salt type of reactor design could not be safeguarded as an item facility. Because of the possibility to extract a fluid containing uranium and plutonium, the facility may need to be subject to safeguards consistent with a bulk material handling facility like a spent fuel reprocessing plant. But expert opinions vary on this.

The safeguards efforts required, will depend on the technical solutions for the flow of fuel, the size of the reactor, and its fuel loading and unloading system. It is a reasonable assumption that safeguards of the molten-salt-reactor will require significantly more efforts than an LWR**.**

A more detailed study of the molten-salt reactor group will be required for a more precise evaluation of how IAEA safeguards may be applied. Further study of the various design models will be required, particularly to understand the size of the individual reactor, its need for refueling, the duration of its operating cycle, and whether the reactor could become more like an item-facility.

The Triso-Fueled Reactor Group

In its present design, the Triso-fueled reactor group shows the following characteristics in common with and different from LWRs:

- The fuel consists of unidentifiable fuel particles, the microspheres which are dispersed in either graphite pebbles or prisms.
- The pebbles will be identical, but it may not be possible to identify when moving into or out of the reactor during online refueling.
- Source data after irradiation may not be possible to be assigned to an individual pebble.
- The unirradiated nuclear material is specified in source data obtained from the fuel manufacturer.
- It is assumed that the number of pebbles may be counted at critical points, e.g. entry into the reactor or exit from the reactor.
- The design-use of hexagonal prisms may offer a fuel design that is more similar to identifiable items, such as a fuel assembly.
- It is assumed that all points in the flow of pebbles will be possible to monitor with C&S methods.
- Variation in the size of the reactor core may have important impact on the ability to safeguard the reactor, e.g. a Triso-SMR.

This analysis indicates that this group of reactors - operating with fuel designed with solid units, microspheres dispersed into pebbles, or prisms – will present safeguards difficulties because the reactor type may not conform with an item-facility and may require a more intense safeguards effort and potentially the development of new and improved safeguards methods.

However, if Triso-fueled reactors can solve the problem with fuel items and their identification, or if innovative approaches and technologies can result in a satisfactory assurance of non-diversion, the reactor appears to be possible to safeguard without major additional effort by the IAEA.

Advanced containment and surveillance methods, possibly requiring further development than those available today, will play a major role in creating an effective safeguards approach for this reactor type. Further analysis with access to more detailed information on the fuel for specific reactor designs will be required (e.g. regarding variation of nuclear material content in individual pebbles post-irradiation and of the detailed information related to the feed of pebbles during online refueling and how this flow may be measured). Further, difference in the size of the reactor cores may also impact the safeguards system implementation (e.g. a small reactor based on Triso-fuel technology may offer solutions that are not possible with a larger reactor).

A more detailed study of the Triso-fueled reactor group will be required for a more precise evaluation of how IAEA safeguards may be applied.

The Fast Reactor Group.

Advanced reactors in this group, other than molten-salt fueled varieties, have several characteristics in common with LWRs:

- Item fuel, individually identified, the same identification follows the fuel assembly through the reactor cycle.
- The unirradiated nuclear material is specified in source data obtained from the fuel manufacturer.
- Some unirradiated fuel may contain plutonium, in a mix with uranium. The plutonium can be obtained from a reprocessing facility in the State, or from another country. Once it is loaded into the reactor, it becomes irradiated.
- Refueling is performed during outage, which can be monitored.
- Long operation periods will influence the frequency of inspection.
- It is assumed that C&S measures can be applied throughout the entire fuel cycle at the reactor site.

This analysis indicates that IAEA safeguards at this type of reactor can be performed in a manner very similar to LWRs, assuming that the fuel is accessible for and that C&S measures can be applied. However, the potential presence of separated plutonium in fresh, unirradiated fuel is a higher proliferation risk factor than for fresh fuel containing only LEU. Once the fresh fast reactor fuel is loaded into the reactor and irradiated, it will change category and become spent fuel, and be treated as spent LWR-fuel.

This reactor group has the technical potential to breed plutonium which, in some designs, is used to extend the operating period without refueling. If the plutonium is to be separated from the spent fuel, e.g. in a reprocessing process, the reactor is associated with a fuel cycle step that is proliferation sensitive. Separated plutonium, if stored in any form at the facility, presents a distinct set of potential proliferation risks and challenges, and require additional verification compared with LEU fuel alone.

A more detailed study of the individual reactor designs contained in the fast reactor group will be required e.g. to obtain clarification regarding quantities of fresh fuel normally in storage, size of reactor core and individual fuel elements in the various designs.

Safeguards Conclusions and Recommendations

In the light of the rising demand for electrical capacity in the world and the need to deeply reduce carbon emissions, the development of advanced nuclear power technologies is timely and necessary. This initial evaluation has demonstrated with clarity the novelty of the technologies. Although there is some experience in operating fast reactors and in developing demonstration facilities of pebble-bed reactors, the potential broad use of these reactors is a global challenge.

The IAEA can perform safeguards on all kinds of facilities, including these advanced reactors. However, the resources required will be a measure for the ease with which it is carried out. The following four conclusions and recommendations are drawn from the evaluation:

- **All** of the advanced reactor types can be safeguarded, but those techniques will differ from LWRs and both the IAEA and reactor designers will need to work together to ensure cost efficient and operationally effective "safeguards by design".
- **None** of the advanced reactor design categories can be safeguarded in the same manner as a LWR. Pebble bed and molten-salt reactors offer new challenges in verifying items in the reactor and fuel cycle. Fast reactors are closer to the LWR model but present some unique problems and have the added complication of the potential for separated plutonium.
- **The IAEA and the designers** of advanced technology reactors should initiate at an early date, an interactive process in which the safeguards system can be explained, and safeguards-challenging elements of the technology be identified. Steps should be taken to facilitate international safeguards in the design phase of the reactor.
- **The reactor designers** should review their designs considering the efficient, well established IAEA safeguards system for LWR reactors. Such review should focus on the possibility to turn the advanced reactor into an item-facility, recognizing that the definition of an item may be needing to evolve in new and untraditional ways.
- **The IAEA** should recognize that advanced reactor technologies represent new safeguards challenges and that it is important to accelerate its work to identify potential technical problems that may impact safeguards implementation. The Agency should identify whether more effective verification tools will be required and start working on new safeguards approaches that could be implemented for the new types of reactors including those with long life cores. These could include new C&S techniques and non-destructive measurement of enrichment and

nuclear material quantities in process-related circumstances, such as online refueling of a reactor.

IV. Nuclear Security and Advanced Reactors

Advanced nuclear reactors will be subject to security measures that are defined in the international legal framework, including IAEA recommendations and guidelines, and by the regulations of individual nations. There are a number of nuclear security challenges that are applicable to all nuclear reactors and some that are specific to advanced reactors.

- A primary concern for all reactors is the physical protection of all nuclear materials, unirradiated and irradiated in storage and in transport.
- Nuclear security also extends to protection of facilities from acts of sabotage, including insider and outsider threats, terrorism and cyber-attack and the potential security threats posed by new and emerging technologies.
- For advanced reactors, specific challenges may include the specific location and siting of the reactor, including how remote the area is where it is deployed, whether it is built above or below ground, and how prepared the nation in which it is deployed is for nuclear operations and emergencies.

Aside from an attack on a nuclear facility, a major nuclear terrorism threat can come from potential access to nuclear weapons materials. A nuclear terrorist attack is considered either insider sabotage or outside attack. It has been considered a high-level concern since the 9/11 attacks and it was the subject of four global Nuclear Security Summits (NSS) from 2010-16.

Physical Protection

The primary physical protection document is the IAEA *Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities*[xiii]. The recommendations identify *categories* of nuclear material based on its attractiveness for weapons purposes and outlines the protections recommended for each category. The strongest protection is given to Category 1 nuclear material; >5kg of highly enriched uranium (>20% ^{235}U, referred to as HEU) or > 3 kg of separated plutonium because of the attractiveness of the material for weapons purposes. Normal LEU fuel (with an enrichment around 4-5%) is Category 3 material and spent fuel of all kind is in Category 2.

Advanced reactors of the three types addressed in this document, typically contain uranium-based fuel with an enrichment up to 20%, which would be Category 2 or 3 according to the IAEA definition. This would also apply to designs that use thorium-based fuel. After irradiation, the spent fuel will be treated as Category 2.

The Fast reactor group is the only type of advanced reactor design that presents a Category 1 nuclear material concern if the reactor uses separated plutonium in the fresh fuel. The risk of theft of weapons-usable material directly depend on the quantity of material, which will vary with the size of the reactor and the operating cycle. Therefore, the specific technical characteristics of individual reactors and the operational approach to their fuel supply will be important in assessing and addressing this concern. According to the IAEA recommendations, with a period between refueling of several years, the time during which unirradiated plutonium is available for potential theft will be short and can be covered with additional physical protection. For the operating cycle the fast reactor group will be operating with fuel that is of Category 2 or 3, material which is associated with considerably lower risk and can be protected at a suitably lower level.

For some types of advanced reactors, particularly those that are sodium cooled, there are long intervals between refueling, sometimes decades, and therefore, the challenge is to ensure that none of the fuel is surreptitiously extracted during operation. This is primarily a safeguards challenge, but it would have significant nuclear security implications if that threat was supported by insider access or facilitation of the act.

Facility Sabotage and Nuclear Terrorism

Nuclear facilities are required to be protected against acts of sabotage that may result in unacceptable radiological consequences, with particular concern centered on the vital areas which would be critical for reactor safety. Historically, the threat has been an attack from outside the facility. But, in recent years, there has been significant concern about the potential for insiders or employees of the facility alone or supporting outsiders, to sabotage the operation.

Advanced reactors offer the potential of limiting the impacts of facility sabotage or attack and the resulting radiation release concerns because they are designed with characteristics that are likely to reduce the risk of the dispersal of radioactivity:

- *Passive safety features* that automatically respond and move the reactor into safe state.
- *No external power dependence*, which would reduce the risk of cutting the power supply for the circulation of the reactor coolant.
- *Low operating pressure* that can reduce the dispersal of radioactivity in most designs.

All three primary groups of advanced reactor design have passive safety systems, which significantly lowers the risk of accident, caused by a safety failure or acts of sabotage. The non-dependence on external power during emergency supports both safety and security. Operation under atmospheric pressure will result in the decreased dispersal of actinides or fission products during an accident or as a result of an act of sabotage.

Cyber and Emerging Technologies

The advanced reactors are being introduced into an environment where emerging technologies are creating new security challenges. Cyber security is a major challenge of the existing global nuclear reactor fleet and may cause problems for advanced reactors. Some small reactors may be used in off-grid applications and therefore may be less vulnerable to grid-related cyber-attacks. But there is not a global approach to cyber security in the civil nuclear sector. The IAEA has made recommendations, but, like nuclear security, this is an issue that nations primarily are addressing inside their borders and with their domestic regulatory systems. There is not much discussion outside of borders among nuclear regulators or reactor cyber security professionals.

Rapidly advancing technologies include artificial intelligence, additive manufacturing and blockchain. The benefits and challenges of each of these technologies needs to be explored in more detail, and there is not a definitive assessment yet, but there is the potential that some may contribute to greater nuclear security. For example, artificial intelligence may be configured to prevent insider threats through surveillance and may help with the physical protection of facilities without requiring excessive security personnel. Blockchain holds the promise of potentially being applicable in cataloguing small and numerous fuel pellets as they enter and exit a reactor, as is the case for Triso fuelled reactors.

Reactor Location and Siting

The three major advanced reactor designs can be deployed in remote and arid locations. They may be sited below or above ground or at sea. These unique characteristics may have some inherent security value but also can raise questions. For example, below ground deployment can contain the radiation should a problem arise. This may also be true for sea-based siting, but such a deployment can also raise questions about the vulnerability of the reactor to attack by hostile vessels and be a challenge for applying safeguards to the reactors.

A small, remotely located reactor would have to have a level of protection from outside attack and a rigorous vetting process for the operations staff to minimize the potential for insider sabotage. It, therefore, will be important to consider how a particular reactor would be sited and then to develop various options for physical protection of the plant and its fuel.

A further concern is that any country considering the deployment of an advanced reactor develop an effective nuclear and governance infrastructure, including an educational system, workforce, and regulatory capacity to safety and effectively operate the reactor. While there is some sense that these reactors could be set down virtually anywhere and operated with little oversight, neighboring countries and the international community more broadly may have concerns if nuclear technologies are operated in nations not well equipped to maintain the infrastructure and effectively address the potential consequences of problems. If advanced reactors are to be widely deployed, the IAEA and more experienced nuclear nations may have to provide more long-term and predictable support to the newcomer nuclear nations.

Security Conclusions and Recommendations

Further analysis of the security vulnerabilities for which additional updated and technical information is required to determine with clarity the specific security challenges posed. The different technologies, size of the cores, and location for the reactor are examples of parameters that may shed further clarity on the assessment. However, as a preliminary assessment, the following points are relevant:

- ***Molten-Salt Fueled Reactor** designs* presents a technology that appears to be the least vulnerable from the nuclear security perspective, with a low risk for theft of nuclear material and low risk of dispersal of radioactivity. It must be noted, however, that the size of the reactor is a critical consideration and may impact this initial assessment.
- ***Triso-fueled Reactors*** use extensive passive safety features including no dependency on offsite power or any pumping capacity during accident conditions. During accident conditions, cooling is achieved passively through the graphite and the vessel. It has been demonstrated that the microspheres in the pebbles or prisms are extremely resistant to change under high temperatures and will contain the nuclear material and fission products, reducing the risk of the dispersal of actinides or fission products. There are several reactor designs with Triso fuel, and the potential security impact of the different designs will require additional evaluation.
- ***Fast Reactors*** can be cooled by liquid metal or helium gas. While the metal-cooled reactors will operate around atmospheric pressure, the helium-cooled reactor will require high operating pressure. The size of the reactors can vary considerably, which makes an overall group assessment more complex. The overall assessment in such a case could point to having a relatively low risk of accident, with low risk of dispersal of radioactivity. However, fast reactors may have fresh fuel containing separated plutonium, a category 1 material that requires strong physical protection and other security measures during transport and storage. Category 1 material is a potential security risk, being attractive for theft for weapons purposes. This risk disappears when the fuel is loaded into the reactor.
- **Below ground deployment** - a reactor that installed below ground can pose a lower security risk.
- **Sabotage** - Further information will be required, both regarding the general reactor design and the technical specifications, to reliably assess the vulnerability of specific advanced reactors to an act of sabotage with radiological consequences.
- **Cyber Security** - Confidential discussions should be encouraged and organized among key nuclear nations, regulators, and cyber security professionals. While there are national security and sensitivity concerns at the national level, the consequences of a serious nuclear cyber-attack would reverberate globally and negatively.

- **Emerging Technologies** - A more thorough evaluation of the benefits, challenges, and implications of rapidly emerging technologies including artificial intelligence, additive manufacturing and blockchain, need to be conducted in relation to advanced reactors, and the civil nuclear sector more generally. Similar to cyber security, this is an assessment that may be done at the national level but that would also benefit from circumscribed international collaboration.
- **Working Group** - Representatives from the reactor designer community, IAEA, and other experts and authorities should be assembled to further assess security challenges and benefits of advanced reactors.

TEXT BOX: Physical Protection Evaluation

The evaluation of security robustness is reflected in the table below in which each type of advanced reactor design is compared with the design features that are important for security robustness;

Characteristic *Reactor type*	*Molten Salt Reactor:*	*Triso-type Reactor*	*Fast Reactors*
Fuel; Category of nuclear material	Unirradiated: Cat 2 or 3 Irradiated: Cat 2	Unirradiated: Cat 2 or 3 Irradiated: Cat 2	Unirradiated: Cat 2 or 1 Irradiated: Cat 2
Passive safety features	Yes	Yes	Yes
Dependence on external power	No	No	Some designs do not depend on external power during emergency.
*Operating pressure**	Atmospheric pressure	He-cooled reactors require high operating pressure	Some operate under atmospheric pressure. He-cooled reactors require high operating pressure.

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*More relevant to nuclear safety but still a security-related issue

V. Nuclear Geopolitics, Governance and Advanced Reactor Innovation

The future of advanced reactors cannot be divorced from the critical issues of the intensifying geopolitical competition among large powers, particularly the U.S., Russia and China and their allies, the evolution of nuclear supplier arrangements, and the future of nuclear governance.

Innovation Competition

A critical element of the geopolitical competition is the race for technological dominance and global influence in the 21st Century. Advanced reactors cut across both of those key challenges. Several countries are focused on developing advanced reactors, including the U.S., Canada, South Korea, U.K, France, Russia and China. While many of the underlying advanced reactor technologies are not new and have been tested over the past 70 years, the deployment of these technologies has not been wide spread and the specific designs of the new reactors are different than in the past. There are several challenges that result from this[xiv].

The lack of a developed regulatory system and regulator experience for advanced reactors is a challenge for all nations. Individual countries are in the process of developing regulatory regimes for these reactors. In the U.S., the Nuclear Regulatory Commission is working to accelerate the consideration of these reactors and the Congress has passed legislation to support the development and deployment of these reactors.[xv] Canada has developed a roadmap for small modular reactors (SMRs)[xvi] that clearly identifies the opportunity and benefits of that technology from an energy and climate perspective but also underscores the importance of developing policy, standards and regulatory infrastructure and institutions. This roadmap has applicability to advanced reactors as well.

As these reactors move through the design and development phase it will be important to have well developed test beds to demonstrate the technology. In this area, Russia and China have shown an advantage. Russia is primarily focused on fast neutron reactors and sea-based reactors. Fast reactors have operated in Russia for decades and the testing of these technologies is not in question on its territory. China also has an interest in fast reactors and is moving toward the deployment of a small high-temperature gas cooled pebble bed reactor. But it also is focused on molten salt technologies, committing $3.3 billion to a molten salt demonstration facility in the Gobi Desert. China also is exploring the application of molten salt technology for military purposes.

China has been viewed as a potential test bed for some U.S.-developed advanced technologies. But in late 2018, the US government significantly restricted the transfer of U.S. advanced reactor technologies to China based on concerns that it was acquiring intellectual property and applying it to military systems[xvii]. This has increased the pressure on the U.S. to provide testing facilities for these new reactors.

The potential market for advanced reactors is also a key issue. Their small size and unique cooling systems make them attractive for developing countries that need zero carbon electricity and that may also see the reactors as essential to provide fresh water by powering desalination. The supply of reactors entails considerably more than just the transfer of technology. The relationship between supplier and recipient nation can last up to a century through the contract and decommissioning stages. This offers the supplier nation significant influence over the purchasing country and influence in the region. It also offers the opportunity to sell other products including infrastructure to the recipient nation.

Geopolitical Competitiveness

Both Russia and China have intimately tied their nuclear export strategy to their geopolitical ambitions and objectives and their companies are state-financed. OECD countries face restrictions on using financing as an incentive for reactor sales and limits on the repayment of credit. Companies in OECD countries also must comply with strict export control laws.

At present Russia controls 50% of the reactor construction and fuel market.[xviii] Russia offers a build, own, operate model that will lend nations funds for the reactor, operate it for them, and take back the spent fuel from it. That is a very attractive deal for a newcomer nuclear nation. Russia's ROSATOM has a presence in 44 countries and is building reactors in half a dozen of them, including Turkey, Bangladesh and India.

China is using its One Belt One Road initiative to influence Eurasia's economics and trade and 65 nations are engaged with the program. China also has a "Made in China 2025" initiative that is designed to dominate new technologies including robotics, artificial intelligence, aviation and energy. By the mid-2020's China is projected to be the largest domestic nuclear fleet operator in the world, surpassing the U.S. China is also deeply involved in the nuclear modernization efforts in the U.K. It is providing significant financing for a new plant at Hinckley Point, and with Japan's Hitachi and Toshiba having bowed out of two additional new plants at Bradwell and Sizewell, the China National Nuclear Corporation (CNNC) is set to build its reactors and operate them. This will provide China with a strategic nuclear foothold in Europe, provide additional construction and operating experience outside its borders in a high-regulation, mature nuclear country, sustain a hot production line for its nuclear industry, and improve its positioning a dominant nuclear supplier.

While other countries have semi-nationalized nuclear industries, like KEPCO in South Korea and EDF in France, neither alone have the international nuclear market reach to counter Russia's aggressive marketing or the deep pockets to match China's methodical effort to become the major nuclear supplier of the 21st Century. The U.S. has very weak ties between the government and the nuclear industry and while efforts have been taken to create a "Team

America” approach to nuclear market opportunities, the major nuclear corporations are not government backed and do not have the depth of financing offered by sovereign nations.

An uneven playing field has now developed between state-backed nuclear suppliers and those private sector companies that are mostly independent of government. Recent examples of large LWR sales have demonstrated that the purchasing nations value a government-backed supply deal. The sale of three reactors from South Korea to the United Arab Emirates is one example. The decision of the Japanese companies Toshiba and Hitachi to pull back from building new reactors in the U.K. is another example where the cost of the project outran the capability of the company to support it, despite the willingness of the U.K. to contribute significant funds to the projects. These reactors may now be built by China.

The advanced reactor market will be different from LWRs as they will be smaller and less costly. But the question remains whether state-backed companies and technologies will have an advantage in the competition because of the full range of financing and value that they can contribute to the project. The domination of one or two countries in the advanced reactor market would have real geopolitical impacts and will influence how the governance structure for these reactors will be structured.

Nuclear Governance

It is important to note that during the history of the nuclear era, the nation’s dominating nuclear supply have exercised an outsized influence on the nuclear governance regime. The U.S., once the world’s dominant nuclear supplier used four main approaches to strengthen nuclear governance and global security.[xix]

The first and most influential means was through the inclusion of bilateral safeguards and related requirements in its nuclear export agreements. Many other nations do not have this requirement. The second method was through the manipulation of supply and demand and, in particular, the withholding of sensitive nuclear technologies like uranium enrichment and spent fuel reprocessing. The third approach was consensus building within the Nuclear Suppliers Group, an organization that defines and influences nuclear supply practices. The fourth approach is through a policy of denial - some examples include South Africa, Turkey, China, and Iran.

It is unclear in the current nuclear power market, whether nuclear suppliers will replicate the practices of the U.S. and continue evolving the IAEA safeguards and security systems to adapt to new technical challenges and political situations. As the advanced reactor competition plays out in this century, it is essential to keep competitive supplier states from boosting their marketability by racing to the bottom on nuclear safeguards and security.

Geopolitics and Governance Conclusions and Recommendations

Advanced reactors are not yet ready for deployment, but likely will be within a decade. This will be a major technological competition among large and powerful geopolitical competitors. It is essential that an effective governance structure for these reactors be developed in advance of their deployment and that it be subject to continuous improvement.

Achieving this goal will be challenging because the U.S. and some key allies are in competition with one another in the nuclear supply market and they collectively are facing significant geopolitical and commercial pressure from the state-backed nuclear companies of Russia and China. Therefore, it does not seem that the U.S., along with its traditional nuclear allies will be able to impose its influence on the nuclear governance structure the way it did when it was the dominant nuclear supplier of the 20th Century. A diminishing of nuclear governance standards cannot be allowed to occur. Supplier nations must strengthen proliferation prevention and security for advanced nuclear reactors. A lack of public confidence in the safety, security and safeguarding of advanced reactors will significantly impact public acceptance and the willingness of nations and companies to invest in and deploy these technologies to support carbon reduction and climate change mitigation. There are two suggestions for steps that can be taken in these areas:

- **Support Nuclear Newcomers** – There is a need to significantly strengthen the support that is provided to countries considering nuclear power for the first time. The IAEA has a number of programs in place to assist nations with preparation for the deployment of LWRs, but even with that support there is a need to further develop and sustain the educational, training, regulatory, and emergency response capabilities in these nations. With the consideration of advanced reactors, the situation becomes even more complex because not even advanced nuclear nations have deployed or operated these reactors as part of their nuclear fleet. This argues for an IAEA Plus process that would bring supplier nations, the purchasing countries and the Agency into a deeper discussion of how to ensure the long-term safety, security and proliferation resistance of these reactors.

- **Create a New Nuclear Alliance** – The evolution of nuclear technology supply is beginning to tilt heavily in the direction of state-backed companies in Russia and China. If they become the dominant suppliers of the 21st Century, it will have a number of potentially significant implications. It may relegate the U.S. and its allies like France, Japan and South Korea to subcontractor status or may effectively knock them out of the nuclear supply business.

  Historically, the U.S. as a dominant nuclear supplier has prized nuclear non-proliferation, security and safety in their commercial dealings. It is not clear that geopolitical competitor nations will have a similar priority.

One option is for traditional nuclear allied nations to band together to create a Next Generation Nuclear Alliance. As a first order of business U.S. and its allies have to think about how to collaborate rather than compete against one another in the global nuclear market. This will be a difficult, complex process but a necessary one. One way to think about it is that some nations are better at the hardware of nuclear power – hot production and supply lines - and others are better at the software – design, governance, operations, regulation, and education. But this combination of attributes will be very attractive to nations seeking nuclear power. This new alliance does not need to exclude Russia and China but how it could incorporate them will be a major challenge for all sides.

This alliance could take the following actions:

- Develop the nuclear governance and regulatory regime for advanced reactors within the next 3 to 5 years and present it to the IAEA for consideration.
- Collaborate on advanced reactor design, development and demonstrations.
- Support and supplement the IAEA’s work to prepare newcomer nuclear nations by providing funding and experts for education and training to prepare the market and support advanced reactor deployment and operations
- Consider pooling contributions from national export financing institutions to support alliance member and third country nuclear projects.
- Expand outreach to the investment community to draw together private and public funding for technology innovation and development and projects.
- Focus on the socially responsible contributions that nuclear power can make in the 21st century and ensure that the governance system is continuously improved to support those objectives.

ANNEX I

Global Nuclear Governance Regime

Nuclear activities have been subject to strict control since nuclear technology was made accessible to all countries for peaceful purposes. The international legal framework has evolved over time and it establishes the rules and principles that are relevant for any State that wishes to implement a nuclear energy programme.

Any new, advanced reactor technology will have to be implemented within the framework of obligations and policies established. At a minimum, the principles, obligations and cooperation requirements of the treaties and conventions included in the legal framework for peaceful nuclear programmes will have to be fulfilled.

I. The International Legal Framework

The building blocks of the international legal framework to govern nuclear activities are;

- *The Non-Proliferation Treaty (NPT)* (1970)
- *The Convention on the Early Warning of a Nuclear Accident* (1986)
- *The Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency*, (1986)
- *The Nuclear Safety Convention (1996)*
- *The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management* (1997)
- *The Convention on the Physical Protection of Nuclear Material and Nuclear Facilities* (1980, amended 2016).
- *The International Convention on the Suppression of Acts of Nuclear Terrorism* (2007).

The international legal framework is solid and useful for States in building policy and regulatory systems. Although it has gaps and weaknesses, it is likely to remain the legal foundation in the foreseeable future.

II. The Establishment of the IAEA

The IAEA is the one international organization with responsibilities in the nuclear field. The IAEA has three main responsibilities; to implement its safeguards system, to develop and establish nuclear safety standards and security guidance and to facilitate the use of nuclear energy and other applications using radioactive materials.

III. IAEA Safeguards system

The term, *international nuclear "safeguards*", usually refers to a set of technical and accounting measures that the IAEA designed to verify that no sensitive nuclear materials are diverted from peaceful to non-peaceful uses, or that no facility committed to peaceful activities is misused for undeclared purposes. The IAEA safeguards system, which is based on comprehensive safeguards agreements and additional protocol declarations of States, technical measures and surveillance techniques that are applied to physically control the declared use of nuclear material or technology, combined with inspections carried out by IAEA inspectors. *Conclusions* are reported once every year to the IAEA General Conference as a *Safeguards Statement. Non-compliance* of the undertakings made in the safeguards agreement is reported to the United Nation Security Council (UNSCR) which may decide on *sanctions*, documented in UNSC resolutions.

Responsibilities and obligations of States and the IAEA

Under the IAEA safeguards system, individual States and the Agency have specific responsibilities.

States responsibilities include:

- Establishing a *State System of Accountancy and Control (SSAC)* that will maintain records with updated knowledge of all nuclear material and its use, for accounting purposes, with identified source data and records of all movements.
- Reporting at specified intervals, the inventory of nuclear material, inventory changes and import/exports of nuclear materials, as well as provide advance notifications of international transports.
- Providing a technical description of all nuclear facilities well in advance of the construction, and subsequently when there is a change in design.
- Accepting inspections and making arrangements to ensure access to safeguarded facilities by IAEA inspectors, including for the IAEA to apply the technical measures IAEA uses for verification purposes.
- Providing additional information, as specified in the Additional Protocol to the Safeguards Agreement, regarding past, present and planned future nuclear activities, including R&D, and provide access to additional locations upon the request of the IAEA, within and outside of nuclear facilities on the state's territory.

The IAEA *responsibilities include:*

- *Implementing its safeguards system* in an effective and efficient manner to verify that there is no diversion of declared nuclear material from peaceful activities and that there is no indication of undeclared nuclear material or activities. Based on such verification results, the IAEA may conclude that there is no diversion of declared nuclear material to non-peaceful activities and that *all* nuclear material in the country remains in peaceful activities;
- Developing State-level safeguards approaches using a structured, technical method to analyze the plausible paths by which nuclear material suitable for use in a nuclear weapon or other nuclear explosive device could be acquired;

- Establishing the safeguards approach for each facility, in line with the Facility Attachment to the Safeguards Agreement and considering early notifications by the State;
- Verifying the information received regarding facilities, through verification of the facility design information and updates as well as in relation to inventory change reports, physical inventory reports and advance notifications;
- Carrying out, as necessary, complementary access at nuclear facilities, and at locations outside nuclear facilities to assure the absence of undeclared nuclear material or to resolve questions or inconsistencies regarding material or activities in the information provided by the State.
- Performing continuous analysis of accounting reports, notifications, inspection results and other safeguards relevant information, as the basis for the annual safeguards statement issued by the IAEA;
- Issuing the Safeguards Statement on an annual basis.

The IAEA has *the right to* use various tools as part of the safeguards system, including but not limited to:

- **Access to all nuclear material** at a facility, including its **source data** *inter alia* related to its chemical and physical form.
- **Non-destructive testing and measurement** of any nuclear material or storage unit in the facility; as applicable, weighing, determination of substance and enrichment of uranium.
- **Sample nuclear material** in bulk form, seal the sample and submit it for destructive analysis.
- **Containment and surveillance techniques**, such as seals, cameras and detectors installed at the facility, may be used to provide continuity of knowledge over nuclear material and facilities between inspections by preventing undetected access to nuclear material or undeclared operation of the facility. Containment and surveillance measures, which are essential to maintain efficiency of verification over time, may also be carried out remotely.
- **Environmental samples, including swipe samples,** may be taken to verify that the facility is used as declared. The advanced analysis allows the discovery of very minor traces of materials and specific isotopes that can bring objective information about nuclear material or activities (e.g. separation of plutonium or enrichment), information that will allow consistency analysis vis-à-vis declarations made of past activities at the facility.

The IAEA may carry out different types of on-site inspections and visits under comprehensive safeguards agreements and additional protocols.

- ***Ad hoc* inspections** to verify a State´s initial report according to the concluded safeguards agreement, and to verify the nuclear material in international transfers.

- ***Routine inspections*** - the type most frequently used – are mostly carried out according to a prior planned schedule but may also be of an unannounced or short-notice character. The Agency´s right to carry out routine inspections under comprehensive safeguards agreements is limited to those locations within a nuclear facility, or other locations containing nuclear material, through which nuclear material is expected to flow.
- ***Special inspections*** may be carried out in circumstances according to defined procedures. The IAEA may carry out such inspections if it considers that information made available by the State concerned, including explanations from the State and information obtained from routine inspections, is not adequate for the Agency to fulfil its responsibilities under the safeguards agreement.
- ***Complementary access*** may be carried out (Additional Protocol provision) both at the premises of a nuclear facility, without notice, and outside of facilities as requested by the IAEA, with a minimum notice of 24 hours.

In recent years, the IAEA has both strengthened and streamlined its safeguards system. The State Level Consideration allows the IAEA to profile the verification effort in an individual State, thereby considering its programmes, history and future plans. States with a comprehensive safeguards agreement[xx]and an additional protocol in force are subject to a much more in-depth and complete verification of its commitment to non-proliferation and peaceful nuclear activities.

The Safeguards Statement

For countries with both a safeguards agreement and an additional protocol in place and in which the IAEA has not found any indication on diversion of nuclear material or indication of undeclared activities, the statement may read

…the (IAEA) Secretariat found no indication of the diversion of declared nuclear material from peaceful nuclear activities and no indication of undeclared nuclear material or activities. On this basis, the Secretariat concluded that, for [State], all nuclear material remained in peaceful activities…

A conclusion by the Agency of the absence of undeclared nuclear material and activities in a State reflects confidence by the IAEA that the State meets its safeguards undertakings, all material is declared correctly and completely, and there are no undeclared activities. This broader statement has enabled a redefinition of the safeguards implementation criteria, particularly for less sensitive nuclear material such as depleted, natural and low enriched uranium and irradiated fuel, with corresponding reductions in the level of safeguards verification effort on such declared nuclear material, so called integrated safeguards. This change has been made with the understanding that that the safeguards statement remains equally valid also under the regime of integrated safeguards.

The timeliness goal for irradiated fuel was extended from three (3) months to one year, based on the conclusion that *all material* has been declared, and that there are *no undeclared activities* in the State, such as clandestine reprocessing, conversion and manufacturing facilities to recover plutonium from irradiated fuel. It is estimated that clandestine enrichment and/or reprocessing cannot be developed in less time than one year, and thus it is sufficient to detect diversion within one year. This assumption is carefully evaluated by the IAEA. Accordingly, an increase in the timeliness verification goal for irradiated fuel to one year has taken place for all countries with the Additional Protocol in force and which has qualified for the statement above.

This development is essential for the assessment of compliance of new advanced reactor technology with States undertakings in Safeguards Agreements and Additional Protocols and whether IAEA safeguards of these new reactors will be possible to carry out effectively and efficiently.

The International Nuclear Security Regime

Unlike nuclear safeguards, the nuclear security regime lacks uniformity, transparency in its implementation and strict enforcement. Individual nations determine their security threats and design their own nuclear practices to respond to them. There are three pillars of the nuclear security regime.

I. IAEA Recommendations and Services

The IAEA has been assisting countries with their nuclear security since the 1970s and is widely considered to be the foremost international authority on nuclear issues in many countries. Since 2003, the IAEA defines nuclear security as "*the prevention and detection of, and response to, theft, sabotage, unauthorized access, illegal transfer, or other malicious acts involving nuclear material, other radioactive substances or their associated facilities*."

However, the IAEA is only allowed to produce recommendations and other guidance to encourage states to take action on nuclear security matters. At present, it evaluates state performance in implementing or complying with its recommendations only when there is a *national request* for such an evaluation.

The most developed set of recommendations and guidance that the IAEA offers on the physical protection of nuclear materials and facilities can be found in Information Circular (INFCIRC) 225/Revision 5. The fifth revision of INFCIRC 225 was released in early 2011 as IAEA Nuclear Security Series No. 13. It addresses the post-9/11 threat environment, as the previous revision was completed in 1999. The most recent version updates how to protect the different categories of nuclear material and clarifies site access and control areas. Other changes involve new licensing requirements, protection against acts of sabotage, interface with safety, interface with material accounting and control systems, and response to a malicious act.

The IAEA also has a Division of Nuclear Security with several responsibilities. It plays the leading role in planning, implementing, and evaluating the agency's nuclear security activities. It also produces Nuclear Security Series documents (15 of which have been published to date) and manages the Nuclear Security Fund which is used to prevent, detect, and respond to nuclear terrorism. This fund is largely reliant upon extra-budgetary contributions from member states and organizations. In addition, a small part of the IAEA regular budget is devoted to nuclear security.

In addition to the documents that the IAEA produces, member states can augment their domestic security protections by seeking in-country assistance. The IAEA's nuclear security advisory services include: International Nuclear Security Advisory Service (INNServ) missions which help identify a country's broad nuclear security status and measures needed for meeting them; International Physical Protection Advisory Service (IPPAS) missions which evaluate a country's existing physical protection arrangements; and IAEA State Systems for Accountancy and Control Advisory Services which provides recommendations for improving a country's nuclear material accountancy and control systems.

II. International Agreements

There are several international agreements related to nuclear security that cover important elements of the international nuclear security regime. However, the regime has gaps, most importantly the lack of a recurring review mechanism and feedback on achievements, or difficulties, in the implementation of the agreements. This stands in contrast with the legal framework for nuclear safety and the Convention on Nuclear Safety. As a result, there are no common international standards for nuclear security. The objectives and essential elements of a nuclear security regime are largely drawn from the CPPNMNF[xxi]and after approval by the IAEA Board of Governors, published in the IAEA Nuclear Security Series. The implementation is entirely the responsibility of individual nations that control their own specific nuclear facilities and materials. There is little transparency associated with these national practices and only voluntary and rather limited peer review of them.

The **Convention on the Physical Protection of Nuclear Material and Nuclear Facilities (CPPNMNF)**, a legally binding agreement originally agreed in 1980[xxii], to protect civilian nuclear materials, was amended in 2005, requiring states to protect their civilian nuclear facilities and materials wherever they are used, stored or transported, and expanding its obligations to prevent and respond to nuclear smuggling. The Amendment entered into force 2016, after 10 years plus.

The CPPNMNF requires that states establish and maintain a legislative and regulatory framework to govern physical protection, establish or designate an enforcing body to implement such a framework, and take other actions as necessary to protect material and facilities. It includes an initial review conference after five years (i.e. 2021). Thereafter, a review can be requested by a majority of State Parties. This ad hoc mechanism was used to initiate the negotiation of the 2005 amendment but has otherwise not been used. The IAEA Director General is the Depositary of the convention.

The **International Convention for the Suppression of Acts of Nuclear Terrorism (Nuclear Terrorism Convention or ICSANT)** was adopted by the United Nations (UN) General Assembly in April 2005, entered into force 2007, to ensure that states would criminalize the illicit possession or use of nuclear material or devices by non-state actors. Under the Nuclear Terrorism Convention, states must enact laws to investigate possible offenses and to arrest, prosecute, or extradite offenders. Countries are also called upon to cooperate and share information on nuclear terrorism investigations and prosecutions, make every effort to protect radioactive material within their borders, and receive instruction on how to proceed if an illicit device or material is recovered from non-state actors. Unlike the CPPNMNF, the Nuclear Terrorism Convention applies to civilian and military material.

Several **UN Security Council resolutions (UNSCR)**, including Resolutions 1373, 1540 and 1887, passed in 2001, 2004, 2009, respectively, are aimed at preventing WMD terrorism.

In the weeks following the terrorist attacks of September 11, 2001, the UN Security Council unanimously passed UNSCR 1373. Though it focused on wide-ranging counterterrorism mechanisms such as the suppression of financing and improving international cooperation it specifically notes with concern "*the threat posed by the possession of weapons of mass destruction by terrorist groups*" and "*illegal movement of nuclear, chemical, biological and other deadly materials*." [13] Because the resolution was passed under the UNSC's Chapter VII authority, action is not voluntary. It requires members to take measures to combat terrorism. Despite its mandate for action, the resolution has gaps, and its shortcomings were highlighted by the discovery of an international nuclear proliferation network run by the Pakistani scientist A.Q. Khan.

A more universal approach to WMD security, including fissile materials, was approved in 2004 in UNSCR 1540. For the first time, UN member states were bound to take and enforce measures against WMD, i.e. nuclear, chemical and biological weapons proliferation and were required develop and maintain effective measures to account for, secure, protect as well as having effective border control for related materials. States were also required to report on their implementation of the resolution to the Security Council 1540 Committee. The resolution was primarily aimed at preventing WMD terrorism by non-state actors. Compliance with the reporting requirement has been inconsistent and irregular.

In September 2009, UNSCR 1887 was unanimously adopted. UNSCR 1887 reaffirmed the threat of nuclear proliferation to global security and the need for multilateral actions to prevent it. The resolution highlighted the need for improving the security of nuclear materials to reduce the risk of nuclear terrorism and expressed support for the goal of securing all vulnerable nuclear materials around the world within four years, minimizing as far as feasible the civil use of HEU, and multilateral initiatives such as the Global Partnership and the Global Initiative to Combat Nuclear Terrorism.

III. National Regulation and Law

Nuclear security addresses nuclear sensitive materials, facilities, and authorized personnel. Governments have responsibility for developing the regulations and legal foundations necessary for maintaining a high level of safety, security and peaceful uses of nuclear material and facilities. Countries with new nuclear projects must ensure that their legislation is appropriate and in place prior to the construction phase. If fissile material were to leak from a nation and/or make its way into the hands of terrorists, an international crisis would emerge, transcending domestic concerns. Therefore, the domestic political requirements need to be balanced against the need for international stability.

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[i] The purpose of nuclear safeguards is to detect any diversion or misuse of nuclear material for weapons purposes. Effective safeguards are a key element in preventing nuclear weapons proliferation.

[ii] Fuss, Sabine, et al. "Betting on Negative Emissions." Nature Climate Change 4 (September 21, 2014): pp. 850-853. Accessed March 29, 2019. https://www.nature.com/articles/nclimate2392; Fawcett, Allen A., et al. "Can Paris Pledges Avert Severe Climate Change?" Science 350, no . 6265 (December 4, 2015): pp. 1168-169 Accessed March 29, 2019. http://science.sciencemag.org/content/350/6265/1168.

[iii] "SPECIAL REPORT Global Warming of 1.5 ºC." The Intergovernmental Panel on Climate Change. Accessed March 29, 2019. https://www.ipcc.ch/sr15/.

[iv] See, e.g., "AR5 Climate Change 2014: Mitigation of Climate Change", Intergovernmental Panel on Climate Change, Working Group III, Presentation, pp. 32-33, http://www.ipcc.ch/report/ar5/wg3/; "World Energy Outlook 2014", International Energy Agency, pp. 396, https://www.iea.org/publications/freepublications/publication/WEO2014.pdf; "Pathways to Deep Decarbonization", UN Sustainable Solutions Network (2014): pp. 33, http://unsdsn.org/wp-content/uploads/2014/09/DDPP_Digit.pdf; "Better Growth, Better Climate: The New Climate Economy Report", Global Commission on the Economy and Climate, Figure 5 (September 2014): pp. 26, http://static.newclimateeconomy.report/wp-content/uploads/2014/08/BetterGrowth-BetterClimate_NCE_Synthesis-Report_web.pdf; "Energy and Technology Needs to Deliver the NDCS and 2 Degrees", Joint Global Change Research Institute/Pacific Northwest National Laboratory, Presentation, Implications of Paris 1st Workshop (College Park, Md, May 4, 2016)

[v] "The Future of Nuclear Energy in a Carbon-Constrained World." Accessed March 29, 2019. http://energy.mit.edu/research/future-nuclearenergy-carbon-constrained-world/.

[vi] Number of Nuclear Reactors Operable and Under Construction, World Nuclear Association, Accessed March 29, 2019. http://www.world-nuclear.org/nuclear-basics/global-number-of-nuclear-reactors.aspx

[vii] The countries most prominently identifying nuclear power as part of their Paris commitment were China and India.

[viii] The following projects highlight differing opinions on the subject - "The Solutions Project." The Solutions Project. Accessed March 29, 2019. https://thesolutionsproject.org/ ; Jacobson, Mark Z., et al. "100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World." Joule 1, no. 1 (September 6, 2017): pp. 108-21. Accessed March 29, 2019. https://www.cell.com/joule/fulltext/S2542-4351(17)30012-0; POWERING EARTH 2050: Is California's 100% Renewable Strategy Globally Viable? Directed by UCLA IoES. YouTube. February 24, 2016. Accessed March 29, 2019. https://www.youtube.com/channel/UC_iW_KvXMd7-hJb8yrDgI3A.

[ix] This includes Wisconsin, California, and Vermont. Shellenberger, Michael. "How Not to Deal With Climate Change." The New York Times, June 30, 2016. Accessed March 29, 2019. https://www.nytimes.com/2016/06/30/opinion/how-not-to-dealwith-climate-change.html.

[x] "Climate Change Threatens Irreversible and Dangerous Impacts, But Options Exist to Limit Its Effects." UN Environment. Accessed March 29, 2019. https://www.unenvironment.org/pt-br/node/6589.

[xi] A common safety feature in case of power-loss, is a "freeze plug": In the fluoride salt/fuel loop, there is a drain that is closed by a fluoride salt "plug." The fluoride plug is actively cooled to keep it frozen, but if power to the plant is lost or the fuel salt temperature exceeds a maximum allowable level, the plug will melt, releasing the fuel through the drain and into storage tanks below. The storage tanks are designed to arrange the fuel salt in a non-critical configuration that stops the fission chain reaction. The tanks are also designed so that the fuel salt can be passively cooled by the surrounding air while it is stored there, without a need for offsite power.

[xii] Some molten-salt fuelled reactors are also fast-spectrum reactors, but those are included in the MSR category, not in the fast reactor category, for the purposes of this paper.

[xiii] IAEA Nuclear Security Series No. 13: Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities, (equivalent with INFCIRC/225/Rev.5.) https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1481_web.pdf

[xiv] Ford, Michael J., et al. Advanced Nuclear Energy Need, Characteristics, Projected Costs, and Opportunities. Report. Clean Air Task Force. p. 21. https://www.catf.us/wp-content/uploads/2018/04/Advanced_Nuclear_Energy.pdf.

[xv] The Nuclear Energy Innovation and Modernization Act became Public Law No: 115-439. on January 14, 2019, https://www.congress.gov/bill/115th-congress/senate-bill/512

[xvi] A Call to Action: A Canadian Roadmap for Small Modular Reactors, Summary of Key Findings, November 2018, Accessed March 29, 2019, https://smrroadmap.ca/wp-content/uploads/2018/11/SMRroadmap_EN_nov6_Web-1.pdf

[xvii] DOE Announces Measures to Prevent China's Illegal Diversion of U.S. Civil Nuclear Technology for Military or Other Unauthorized Purposes, United States Department of Energy Press Release, October 11, 2018, Accessed March 29, 2019. https://www.energy.gov/articles/doe-announces-measures-prevent-china-s-illegal-diversion-us-civil-nuclear-technology

[xviii] Jewell, Jessica, et al. "The International Technological Nuclear Cooperation Landscape: A New Dataset and Network Analysis." Energy Policy 128 (May 2019): pp. 838-52. Accessed March 29, 2019. https://www.sciencedirect.com/science/article/pii/S0301421518308231?dgcid=author.

[xix] McGoldrick, Fred. "Nuclear Exporters' Influence on Governance: Who Makes the Rules." Lecture, Nuclear Geopolitics in an Evolving Environment: Global Responsibility, Influence and Innovation in the 21st Century, Carnegie Endowment for International Peace, Washington, DC, May 30, 2018.

[xx] Comprehensive safeguards agreements, consistent with the model agreement published in INFCIRC/153, Corr.

[xxi] After the amendment of the CPPNM entered into force in 2016, the amended Convention was renamed to: Convention on the Physical Protection of Nuclear Material and Nuclear Facilities (CPPNMNF).

[xxii] The original title was the Convention on the Physical Protection of Nuclear Material.