IDENTIFYING PRELIMINARY CRITERIA FOR SAFEGUARDING ADVANCED NUCLEAR REACTORS

A. NILSSON
AN & Associates
Uppsala, Sweden
anitanilsson.swe@gmail.com

C. JORANT
SDRI Consulting
Paris, France
c.jorant@orange.fr

A. FINAN
Nuclear Innovation Alliance
Cambridge, MA, USA
ashley@nuclearinnovationalliance.org

E. REDMOND
Nuclear Energy Institute
Washington, DC, USA
elr@nei.org

K. LUONGO
Partnership for Global Security
Washington, DC, USA
kluongo@partnershipforglobalsecurity.org

Abstract

Climate change and the urgent need to reduce carbon emission globally forecast a significant rise in the interest of advanced nuclear reactors. The contributed paper presents the results of a dedicated study of proliferation resistance of the main technologies for advanced nuclear reactors. Much of the current safeguards system has been developed and implemented for the water-cooled reactors that dominate the nuclear energy landscape. Advanced nuclear reactors are distinctly different compared with light-water reactors, with the use of different coolants and a broader spectrum of fuel compositions. Some advanced reactor designs employ a fast neutron spectrum, often associated with an ability to create plutonium. The variety of advanced reactor designs and their coolants present challenges to the existing safeguards regime. Some of the designs allow for on-line fuel processing and unique refuelling schemes. These features may require updated or new tools for nuclear accountancy and control as well as built-in technological features to prevent malicious use of the facility. The paper communicates the results of an overview of the most prominent advanced nuclear reactor designs, in which their proliferation resistance is assessed in comparison with the implementation of IAEA safeguards at a light water-cooled reactor (LWR) fuelled with low enriched Uranium, as established in States with comprehensive safeguards agreements and additional protocols. Advanced nuclear reactor technology is presently being developed in several countries, with prototype reactors being projected and, in some cases, constructed.

1. INTRODUCTION

The peaceful use of nuclear energy has been an important global energy source for over 70 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 1400 MW-electricity. This has significantly contributed to, and accelerated, economic development in a number of States. But the technology can be dual use – peaceful or weaponized - and an extensive and effective international safeguards regime, implemented by the International Atomic Energy Agency (IAEA), has been established to contain the proliferation of nuclear weapons.

In the last decade, significant attention has been focused on a new class of advanced reactors that have very different characteristics from traditional LWRs. They are typically smaller, 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. This can help to reduce the huge deficit of electricity because about 14% of the global population lacks access to reliable electricity.

However, because of their unique features, advanced reactors do not easily fit into the existing national regulatory regimes and they pose new challenges for the safeguards system. This paper will provide a preliminary overview of the potential of these technologies to meet established non-proliferation requirements as defined by the international legal framework, safeguards agreements and international control systems.

It offers a comparison of the various technologies (in principle but not specific to particular reactors or companies) with the prevailing requirements for operationally effective IAEA safeguards. These preliminary results may provide valuable insights for reactor designers as well as input to the IAEA, on how a safeguards system for these advanced reactor designs can be effectively implemented and cost-effective.

The final findings of this work will be published by the Global Nexus Initiative in early 2019.

2. ADVANCED NUCLEAR TECHNOLOGIES

Advanced reactors are gaining attention due to their potential ability to meet energy demands in underserved areas, provide zero carbon energy, address fuel cycle and proliferation concerns, offer inherent passive safety features, and provide lower cost production and operational flexibility. Advanced reactors can be grouped in three main categories: i) the Molten Salt Reactors; ii) the TRISO-based reactors; and iii) Fast Reactors.

2.1. Molten Salt-Fuelled Reactors (MSRs)

In molten salt-fuelled 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. However, there is at least one molten salt design that has solid fuel assemblies or units. MSRs operate with a fuel uranium enrichment from 3% 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 centre 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 refuelled online, allowing for extended, continuous reactor operation. MSR designs 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 refuelling 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 it consumes in operation.

The salt is solid in room temperature, but a molten liquid during the operation of the reactor. The weight of the fuel depends on the specific design but may in the order of several tons.

These reactors operate at or near atmospheric pressure, with temperatures from 500ºC to 900ºC. MSRs make use of passive safety systems and have safety features that will work in a loss-of-power situation[1]. The potential for fuel melting in some designs is eliminated by using already molten fuel. MSR designs typically do not require offsite power during emergencies to ensure safety shutdown and cooling.

2.2. TRISO-Fueled Reactors

Tristructural-**iso**tropic (TRISO)-fuelled 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 (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 pebbles are designed not to crack due to the stresses from processes with 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 235U-enrichment is specified to be in the 8-20% range. Some designs are helium-cooled, and some are molten fluoride salt-cooled designs. Triso-fuelled reactors can range in size from 10s of MWe to 100s of MWe.

[1] 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.

TRISO-fuelled reactors are refuelled online, robotically handled; used pebbles are dropped out from the bottom of the core and unirradiated, or recycled pebbles dropped into the core from the top. The reactor is shut down periodically (about every 6-10 years) for replacement of in-core graphite structures. Prismatic designs will require regular refuelling outages every 1 to 3 years. The spent fuel will be placed in canisters and stored for final disposal in a geologic repository.

TRISO-fuelled 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 methods.

2.3. 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[2] 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. The fuel assemblies are roughly size of LWR assemblies, (4-5m high, around 20cm on side) depending on size of reactor.

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 (or used LWR fuel) in silicon carbide fuel rods. The reactor is sited in a below-grade sealed containment and can run for 30-years without refuelling.

Other liquid metal cooled reactors are being designed to for an estimated period of operation without refuelling spanning 40 to 60 years. These reactor designs seek very high burnup to achieve high utilization and avoid spent fuel reprocessing.

The fast reactors use passive safety approaches and the high-heat capacity coolants allows their cooling through natural heat transfer under accident conditions.

3. IAEA SAFEGUARDS SYSTEM 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 because 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, i.e. which is below 20% ^{235}U, which is considered the baseline enrichment threshold for potential nuclear weapon use.
- *Source data* will provide detailed information of the unirradiated fuel and will be available after irradiation including burn-up and post-irradiation isotopic composition, assigned to each fuel assembly.
- LWRs are *refuelled 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; visual, non-destructive assay (NDA)measurements and for containment and surveillance.
- There are no obvious parts of the reactor where *clandestine irradiation* of undeclared material may take place.

[2] 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.

Without any indication that there is clandestine enrichment or reprocessing in the country, i.e. there is 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.

4. EVALUATION OF NON-PROLIFERATION OF ADVANCED REACTORS

The authors believe that 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, its fuel 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 authors have evaluated the safeguarding of advanced reactors based on a comparison with the processes and approaches for safeguarding traditional 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 to implement, fit well within the IAEA's current abilities and processes, and reduce weapons proliferation concerns. 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 can 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:

a) Compare elements of "LWR safeguards" with the relevant characteristics of each type of advanced reactor technology.

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

- a comprehensive safeguards agreement *and* be party to the Additional Protocol, and

- 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 analysis below 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.

4.1. Evaluation results

Overall, this initial assessment indicates that *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 a new safeguards approach or design alterations that would address the weaknesses.

4.2.1. The Fast Reactor Group.

Advanced reactors in this group, other than salt cooled 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 contains 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, as any other uranium-plutonium mixed fuel.
- Refuelling is performed during outage, which can be monitored.
- Long operation periods will influence the frequency of inspection.
- It is assumed that containment & surveillance (C&S) measures can be applied throughout the entire fuel cycle at the reactor site.

Evaluation result

The analysis indicates that IAEA safeguards at this type of reactor can be performed in a very similar manner as an LWR. However, the potential presence of separated plutonium in fresh, unirradiated fuel is a higher proliferation risk factor than for fresh fuel containing LEU but can be compared with mixed oxide (Uranium and Plutonium) LWR fuel. 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.

However, this reactor group has the technical potential to breed plutonium which, in some designs, is used to extend the operating period without refuelling. reactors. 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. Some of the designs do not intend to reprocess the contained plutonium, but rather utilize the breeding capacity for longer operation without refuelling. In that case, the proliferation sensitivity may be diminished.

Assuming that the fuel is accessible for verification in a manner that is similar to a LEU-fuel LWR, and that C&S measures can be applied, this evaluation indicates that this group of reactors can be safeguarded with similar efforts to LEU reactors. 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.

Recommendations

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. The IAEA should perform a “type-study” of this group of reactors and confirm, or otherwise, the conclusions drawn in this study. The reactor designers should take the opportunity to review the design to ensure that all fuel assemblies may be verified throughout the operating cycle and that C&S measures are possible to apply at any time. This will strengthen the safeguards process and potentially reduce the time and cost involved in it.

4.2.2. The Triso-Fuelled Reactor Group

In its present design, the Triso-fuelled 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 and prisms are not planned to be individually identifiable with an individual number and content.
- The pebbles will be identical but not possible to identify when moving into or out of the reactor during online refuelling.
- Source data after irradiation may not be possible to be assigned to an individual pebble.
- 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.

Evaluation result

This evaluation indicates that this group of reactors - operating with fuel designed with solid units, microspheres dispersed into pebbles, or prisms without identification – will present safeguards difficulties because the reactor type may not conform with an item-facility. The onload refuelling of unidentified pebbles, with a possible flow of microspheres, will create difficulty in matching the feed of unirradiated, fresh fuel with discharged irradiated fuel.

Advanced C&S 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 of 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 refuelling 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).

This evaluation indicates that the TRISO reactor-group, as presently presented, will not allow safeguards to be implemented as a traditional item-facility, but rather require more a more intense safeguards effort and potentially the development of new and improved safeguards methods or tools.

Recommendations

A more detailed study of the technical details connected with refuelling, the movement of pebbles and the various sizes of a reactor core will be required.

The IAEA should initiate interaction with the designers of these types of reactors to learn about the technology, prepare a safeguards approach for a new type of facility, one that is neither an item or a bulk facility. The IAEA also should discuss with the designers how the design can be made more safeguards appropriate. The key question that needs to be answered is how to identity the individual fuel units. If Triso-fuelled reactors can solve the problem with fuel items and their identification, the reactor appears to be possible to verify without major additional effort by the IAEA.

4.2.3. Molten-Salt Fuelled Reactor Group

In the liquid fuel designs, the molten-salt-fuelled 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 will have to be determined, through calculation or measurement to its content of Uranium or Thorium, including isotopes.
- 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.

Evaluation results

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 is likely to be subject to safeguards as a bulk material handling facility like a spent fuel reprocessing plant.

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 a LEU-fuelled LWR. Further study of the various design models will be required, particularly to understand the size of the individual reactor, its need for refuelling, and the duration of its operating cycle. Further information also will be required regarding the isotopic composition of the fuel mass, including how the contained uranium and mixed thorium will change with radiation.

Recommendations

A more detailed study of the technical process of the molten-salt reactor group will be required for a more precise evaluation of how IAEA safeguards may be applied. It is necessary to understand the parameters associated with the chemical composition of the fuel, in solid form at room temperature, in liquid form in the reactor, and when the fuel is unloaded from the reactor.

- *The IAEA* should initiate interaction with the designers of molten-salt-reactors to obtain the information required to formulate a safeguards approach of this type of facility.
- *The designers* should review their design with the question of how the reactor could become more like an item-facility. Designers should also consider the possibilities to apply C&S measures at all parts of the fuel movement into the reactor and out of it.

5. CONCLUSIONS AND RECOMMENDATIONS

In the light of the huge demand for additional electrical capacity in the world, the development of advanced nuclear power technologies is timely and necessary. Advanced nuclear technologies are new power sources that, in principle, can be deployed broadly in many countries and for different purposes. An advanced nuclear reactor could significantly contribute to the base-load need of electrical power, provided it meets established requirements for safety, security and peaceful uses.

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. However, the resources required will be a measure for the ease with which it is carried out. As of today, the following 4 conclusions and recommendations are drawn from the evaluation:

- **None** of the advanced reactor design categories can be safeguarded in the same manner as a LEU-fuelled LWR. Pebble bed and molten-salt reactors offer significant 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 LEU reactors. Such review should be comprehensive, with 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 opportunities and that it is reasonable to review present safeguards system to identify technical problems for safeguards implementation and whether more effective verification tools will be required. The agency also should start working on new safeguards approaches, possibly with new criteria, that could be implemented for the new types of reactors and ensure availability of effective tools, such as new C&S techniques, remote monitoring and non-destructive measurement of enrichment and nuclear material quantities in process-related circumstances, such as online refuelling of a reactor.