PROLIFERATION RESISTANCE INSIGHTS FOR FAST REACTORS: A U.S. AND INTERNATIONAL PERSPECTIVE

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INTRODUCTION: Many fast reactor designs, including sodium-cooled fast reactors, lead-cooled fast reactors, and gas-cooled fast reactors, utilize solid fuel assemblies. Both domestic Material Control and Accounting (MC&A) and international safeguards measures will follow similar requirements as those used for existing large light water reactors—for which there is a large body of experience. This paper discusses proliferation resistance of fast reactors based on insights from the U.S. domestic MC&A approach as well as insights for international safeguards based on work in the Generation-IV International Forum.

1. BACKGROUND

Proliferation Resistance (PR) "*is that characteristic of a nuclear system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States in order to acquire nuclear weapons or other nuclear devices. The degree of proliferation resistance results from a combination of, inter alia, technical design features, operational modalities, institutional arrangements and safeguards measures. Intrinsic proliferation resistance features are those features that result from the technical design of nuclear energy systems, including those that facilitate the implementation of extrinsic measures. Extrinsic proliferation resistance measures are those measures that result from States decisions and undertakings related to nuclear energy systems*" [1]. A key aspect of this definition is the distinction between intrinsic features that are more inherent to those design aspects that makes a system or its nuclear material difficult to exploit in a proliferation strategy as compared to extrinsic measures that may include measurements, monitoring, or control technologies as performed by inspectorates. As such, domestic MC&A and international safeguards measures are both extrinsic measures and so important to consider as part of PR.

U.S. domestic MC&A regulatory requirements are built around large light water reactors which consider the bulk and weight of fuel assemblies as a deterrent to theft or misuse. Therefore, MC&A is achieved through item accounting of assemblies and the use of burnup codes to declare actinide inventories [2].

International safeguards requirements for large light water reactors are well-established and additionally rely on continuity of knowledge through containment and surveillance techniques including access control, tags/seals, and possibly reactor power or temperature monitoring to ensure that the nuclear material is not diverted and the nuclear processes are not being misused [3,4].

Advanced reactors (including most fast reactors) that utilize solid fuel assemblies are generally going to follow the same requirements as outlined above, so both domestic MC&A and international safeguards verification are relatively straight-forward. There are differences in the coolant, operating and handling of the fuel, fuel enrichment, and the potential for breeding that can influence the international safeguards approach. These aspects and their effect on proliferation resistance are described in this paper.

2. U.S. DOMESTIC MC&A RESEARCH AND DEVELOPMENT

The U.S. support R&D on advanced reactors through a number of research program areas. The Department of Energy Office of Nuclear Energy's Advanced Reactor Safeguards and Security (ARSS) program area funds research on domestic MC&A, physical protection, and cybersecurity for advanced reactors. The ARSS program work is coordinated with related work on international safeguards and security in the National Nuclear Security Administration.

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The ARSS program support for MC&A has centered around those areas where the nuclear industry has requested assistance. In the case of advanced reactors, only the pebble bed reactors and liquid-fueled molten salt reactors have been spaces where there are MC&A challenges. Fast reactors, most of which utilize solid fuel assemblies, are not seen as having domestic MC&A challenges. The only aspect of domestic MC&A which does require more work is to improve reactor physics or burnup codes for these unique designs to help improve both modelling of reactor operation and the declarations the operator transmits to the regulatory body.

3. GENERATION-IV PROLIFERATION RESISTANCE AND PHYSICAL PROTECTION

A large body of work related to PR exists within the Generation-IV International Forum (GIF), which has been providing research and develop support for advanced reactors for over 25 years. A key value of GIF is that it brings together experts from around the world to provide different perspectives on the development and deployment of advanced nuclear reactors. The Proliferation Resistance and Physical Protection Working Group (PRPPWG) was established by the GIF to develop, implement, and foster the use of an evaluation methodology to assess Generation IV nuclear energy systems with respect to the GIF PR&PP goal, "*Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism*." [5].

In 2018-2023, the PRPPWG (in collaboration with the Systems Steering Committees (SSCs) and Provisional SSCs of the six GIF reactor concepts) revised previously developed white papers on the PR&PP features of each of the six GIF technologies [5,6,7,8,9,10]. The intent was to generate updated information about the PR&PP merits of each reactor system and to recommend directions for optimizing their PR&PP performance. Three of those white papers in particular focus on fast reactor systems (sodium-cooled, lead-cooled, and gas-cooled).

4. SODIUM-COOLED FAST REACTOR

The Sodium-Cooled Fast Reactor (SFR) PR&PP White Paper [5] considered three types of reactor designs: compact loop configuration (1500 MW_e), pool configuration (1000-1500 MW_e), and a small modular design (100 MW_e). All of these designs utilize solid fuel and most are contained in steel cladding with assembly weights between 53 and 219 kg. Most use some type of Pu or mixed-oxide fuel with fissile content from 13.5 to 25% Pu. The system elements containing nuclear material are shown in Figure 1.

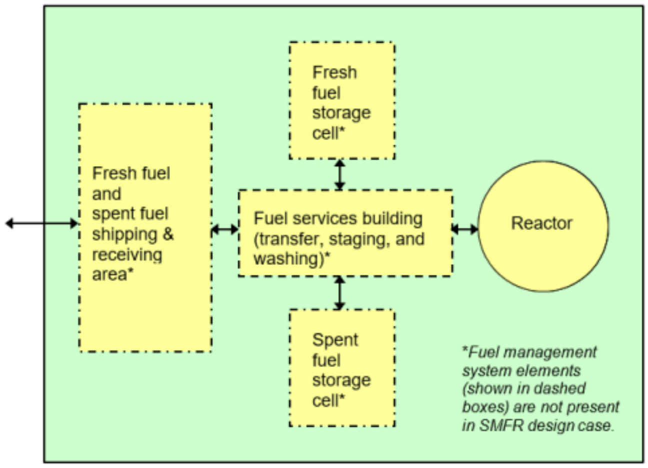

FIG. 1. SFR system elements containing nuclear material [5]

From a PR standpoint, there are some key differences from large light water reactors. The fuel assembly has a higher percentage of fissile inventory and the assemblies are smaller. However, SFR designs will still use item accounting, containment, and surveillance of all assemblies at the reactor site. The fresh and spent fuel have high activity and dose which requires remote handling, and operations occur under sodium—this can be a PR advantage due to difficulty of access. However, it may complicate material tracking and verification. Since breeding configurations are possible, safeguards verification techniques aimed at detecting clandestine Pu production will be implemented.

The potential use of long-lived or sealed cores was also considered. These designs lead to much less frequent fuel movement, which creates fewer opportunities for PR, but the amount of material moved each time is larger.

Previous work had found no credible pathways for the concealed diversion of SFR assemblies since it would be detected by the safeguards system [11]. A host state would also need to accomplish several steps for concealed production of material that would be difficult to accomplish under international safeguards. The SFR technology was not found to lend itself well to clandestine use due to the specialized equipment and infrastructure of liquid metal coolants. In short there are easier ways to produce fissile material.

5. LEAD-COOLED FAST REACTOR

The Lead-Cooled Fast Reactor (LFR) PR&PP White Paper [6] also considered three types of reactor designs: a large system rated at 600 MW_e, a medium system rated at 300 MW_e, and a small transportable system. These designs use either MOX or mixed nitride fuel with solid fuel assemblies and lead coolant. The two larger designs assume standard refuelling operations from time to time while the small transportable design assumes replacement of the entire core.

Many of the insights outlined above for the SFR apply for the LFR as well. The LFR white paper went into more detail on routes for possible concealed undeclared production but also highlighted how international safeguards measures make such activities readily detectable. More detail was also provided about pin replacement in an assembly and the challenges of carrying that out at the fuel fabrication facility. Also, potential replacement of assemblies with depleted uranium would cause changes to reactor power and temperature that would be detected. Small replacements would make the proliferation time very long. The LFR technology also was not found to lend itself well to clandestine use due to the specialized equipment and infrastructure.

6. GAS-COOLED FAST REACTOR

The Gas-Cooled Fast Reactor (GFR) PR&PP White Paper [7] considered one large (2400 MW_{th}) reference design but did mention potential small modular reactor designs. The reference design uses mixed carbide fuel pins contained in a ceramic hex tube. The system elements containing nuclear material are shown in Figure 2.

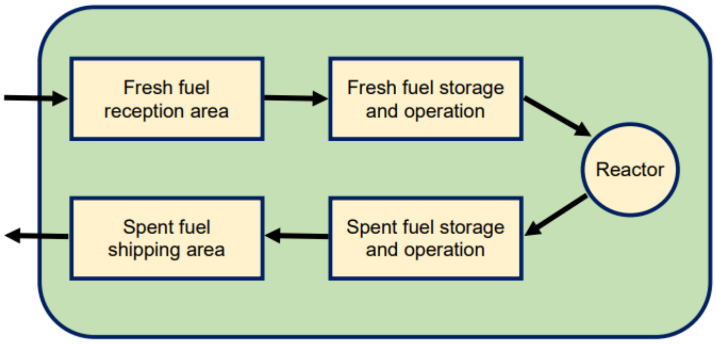

FIG. **2**. GFR system elements containing nuclear material [7]

The PR features outlined include the fact that fissile materials are diluted with minor actinides, contain low-grade reactor Pu, and fuel elements are not separated from their assemblies on the reactor site (same as for the other reactor types considered here). Once again, implementation of international safeguards makes diversion or misuse difficult to accomplish. Concealing production in large enough amounts, even if it is possible to substitute material in fuel fabrication, would lead to changes in reactor power or temperature monitoring. The white paper raised the possibility of incorporating minor actinides in any blanket assemblies to lower the quality of material produced.

7. CONCLUSIONS

From both a U.S. domestic MC&A perspective and an international safeguards perspective, advanced reactor designs that utilize solid fuel assemblies largely take advantage of MC&A and international safeguards approaches that already exist and were developed for large light water reactors. Domestic MC&A focuses on item accounting of assemblies and use of burnup codes for declarations to the state's regulatory body. International safeguards focus on nuclear material accounting complemented by containment & surveillance to ensure continuity of knowledge on the nuclear material inventory evolution.

The use of fuel with higher fissile material content could potentially increase attractiveness but does not change the fact that accounting of all assemblies is required. Different than usual fuel forms can make U and Pu characterization difficult compared to convention LWRs. Different fuelling intervals may reduce opportunities for diversion. Some of the difficulties of accounting for assemblies under different coolants also makes clandestine operation unlikely since a considerable amount of expertise and specialized equipment would be required well above and beyond other ways to acquire fissionable material.

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