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National Nuclear Security Administration

Sandia National Laboratories

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Proliferation Resistance Insights for Fast Reactors: A U.S. and International Perspective

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and on behalf of the GIF PR&PP Working Group

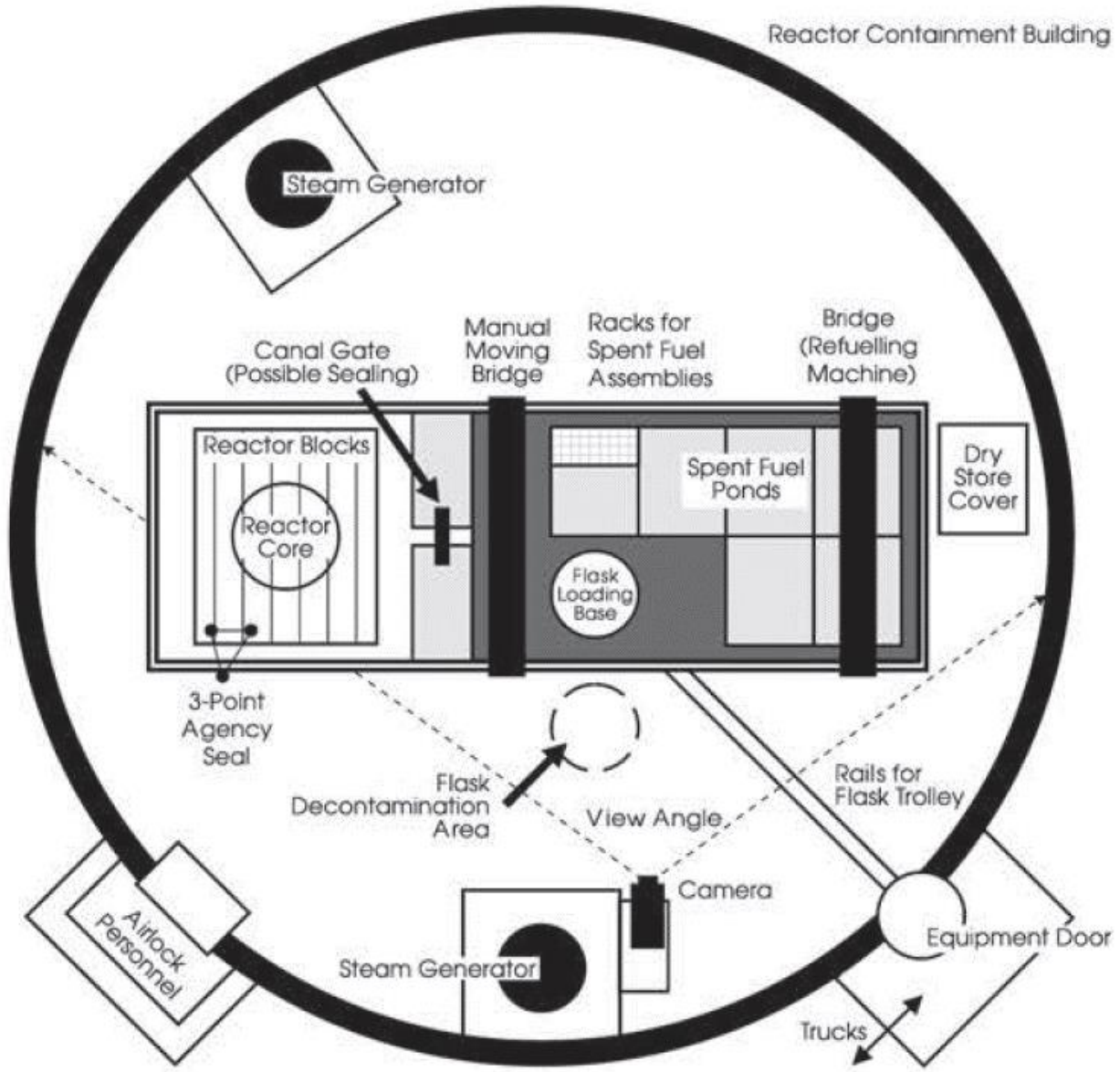
IAEA Technical Meeting on
Proliferation Resistance Features of
Fast Reactors and Associated Fuel Cycles
18-21 August 2025

U.S. Domestic vs. International Perspectives

- U.S. domestic 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.
  - Material Control and Accounting (MC&A) is achieved through item accounting and the use of burnup codes to declare actinide inventories.
  - Also, existing large reactors must protect the plant against the Design Basis Threat for sabotage which is bounding.
- International safeguards requirements for large light water reactors are well-established and additionally rely on continuity of knowledge through containment and surveillance (including access control, tags/seals, cameras, and possibly reactor power or temperature monitoring).
- Generally, advanced reactors that utilize solid fuel assemblies are going to follow the same requirements to meet both U.S. domestic and international safeguards requirements. There are some minor differences due to different coolants and handling requirements.

International Safeguards at Existing Reactors

- Surveillance cameras on reactor, spent fuel pools, and fuel transfer areas.
- Seals on containment penetrations and fuel transfer channels.
- NDA measurements on fresh and irradiated fuel.
- Item accounting and verification of assemblies in storage areas.
- Power monitoring, spent fuel discharge monitors, and fuel bundle counters protect against misuse scenarios.



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"International Safeguards in the Design of Nuclear Reactors," IAEA Nuclear Energy Series, No. NP-T-2.9 (2014).

U.S. Domestic Research and Development

- U.S. research on domestic MC&A for advanced reactors has focused on pebble bed and liquid-fueled molten salt reactors since the bulk or semi-bulk nature of the fuel requires a different approach to MC&A.
- Solid-fueled fast reactor designs will be following the U.S. MC&A approach outlined in ANSI Standard N15.8-2009, which is used for existing nuclear power plants.
- Some work will be required to improve burnup codes for the inventory declarations.

- However, there are differences in how international safeguards are applied to fast reactors
  - more broadly, there are also unique proliferation resistance features of these designs.

PR&PP White Papers

- The Gen-IV International Forum has recently updated six white papers to foster PR&PP by design for each of the six Gen-IV reactor technologies.
- All six reactor technologies white papers on PR&PP are available along with a companion crosscut report.

https://www.gen-4.org/gif-activities/working-groups/gif-proliferation-resistance-and-physical-protection-working-group

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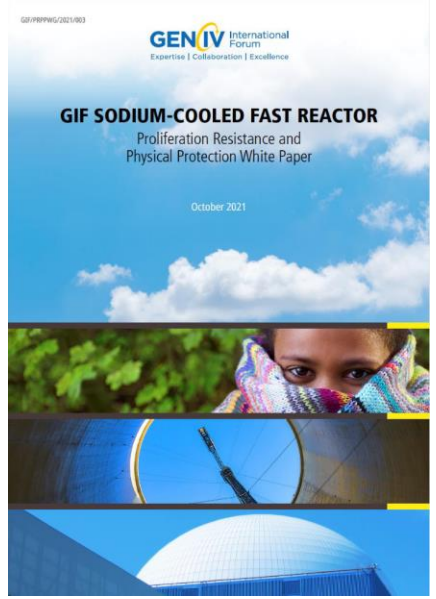
PR&PP Key Points

- PR&PP considers both intrinsic features and extrinsic measures.
- Intrinsic features are typically more associated with the fuel design and unique performance of the reactor system.
- Extrinsic measures include technologies for materials accountancy, international safeguards, and physical protection and may include monitoring, surveillance, or measurements.
- So when we talk about materials accountancy or international safeguards, those aspects are part of extrinsic measures so only one part of Proliferation Resistance, but the required measures depend on the intrinsic features.
- PR&PP by Design is mainly about understanding where advanced nuclear energy systems have advantages or challenges that will affect how extrinsic measures need to be used.
- The PR&PP working group does not perform evaluations to pick winners, but rather to better inform designers and regulators on threats and ways to mitigate those threats.

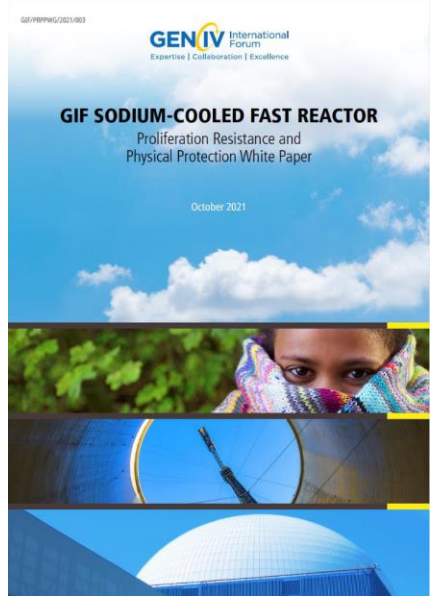
Sodium Fast Reactor (SFR) PR&PP White Paper

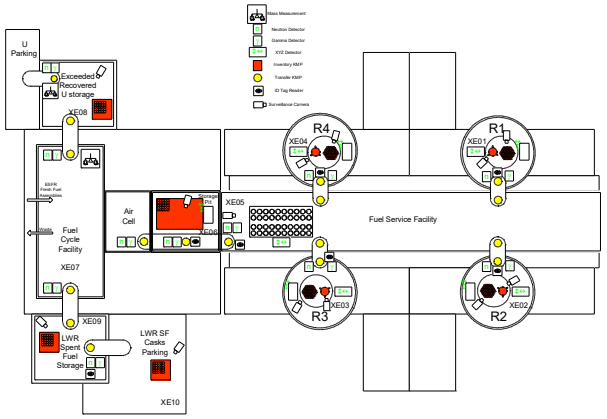


- Five reference designs: Japan SFR (compact loop), KALIMER-600 (pool configuration), European SFR (pool configuration), BN-1200 (pool configuration), AFR-100 (small modular).
- All designs utilize solid fuel and most are contained in steel cladding with assembly weights between 53 and 219 kg. Most use some type of Pu or mixed oxide fuel with fissile content from 13.5 to 25% Pu.
- The fuel assemblies have a higher percentage of fissile content and smaller weight (as compared to LWRs), but item accounting, containment, and surveillance will still be used at the reactor site.
- Both fresh and spent fuel have high activity which requires remote handling and operations under sodium. *PR tradeoff:* PR advantage due to difficulty of access, but also complicates material tracking and verification.

Sodium Fast Reactor PR&PP White Paper (cont.)

- The use of blankets could present a PR challenge, but extrinsic measures to detect blanket misuse/diversion scenarios are fairly mature.
- The potential use of long-lived or sealed cores was also considered: *PR tradeoff:* PR advantage with much less fuel movement, but the amount of fissionable material moved each time is larger.
- Previous work (see reference below) found no credible pathway for concealed diversion of SFR assemblies since it would be detected by the safeguards system. Several steps needed for concealed production, and specialized equipment and infrastructure for liquid metal coolants deters clandestine use.

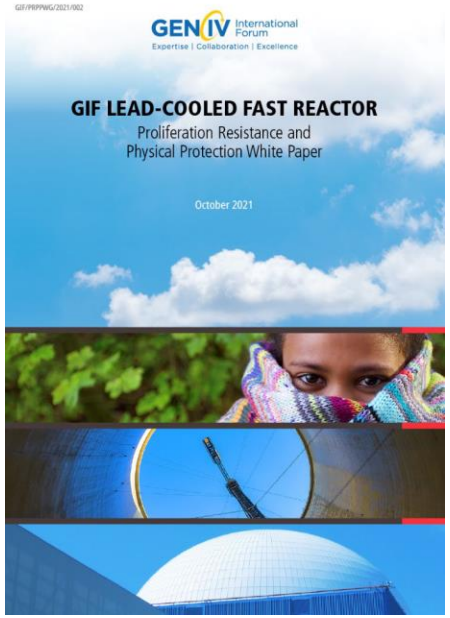




Example Sodium Fast Reactor (ESFR) PR&PP Case Study:

GIF PRPP Working Group, "PR&PP Evaluation: ESFR Full System Case Study," Final Report, GIF/PRPPWG/2009/002, Gen-IV International Forum, (October 2009).

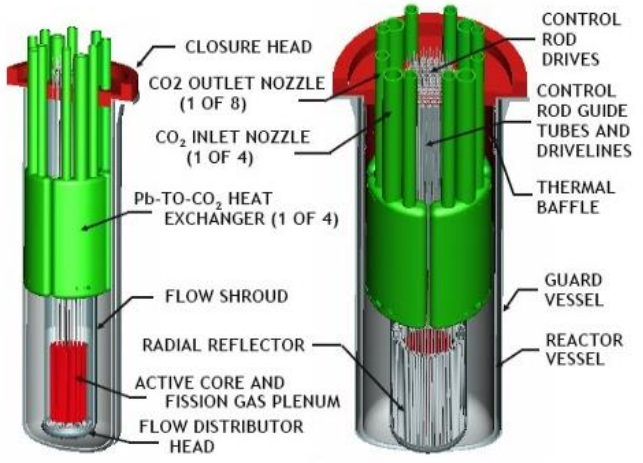
Lead Fast Reactor (LFR) PR&PP White Paper



- Three reference designs: European LFR (600 MW_e), BREST-OD-300 (300 MW_e), SSTAR (SMR).
- These designs also use solid fuel assemblies with either mixed oxide or nitride fuel and lead coolant.
- Many of the insights from the SFR also apply to the LFR designs.
- More detail was provided about pin removal on-site, but this equipment generally doesn't exist at the reactor site.
- The LFR white paper went into more detail on routes for concealed undeclared production, but also highlighted how international safeguards make such activities readily detectable.

SSTAR (one of three reference systems):

J. J. Sienicki, A. Moisseytsev, D. C. Wade and A. Nikiforova, "Status of development of the Small Secure Transportable Autonomous reactor (SSTAR) for Worldwide Sustainable Nuclear Energy Supply," in *Proceedings of the International Congress on Advances in Nuclear Power Plants (ICAPP)*, Nice (F), 2007.



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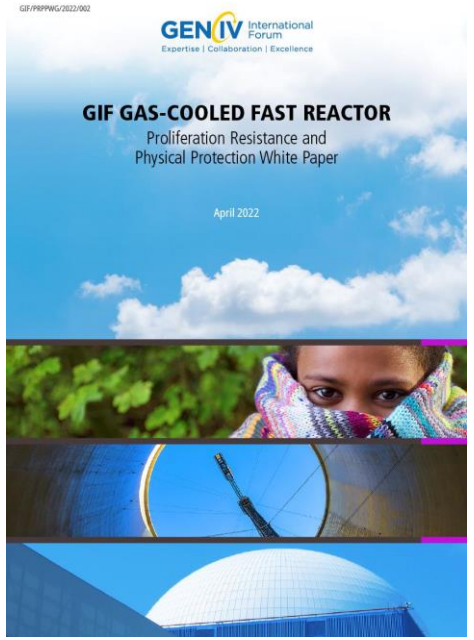
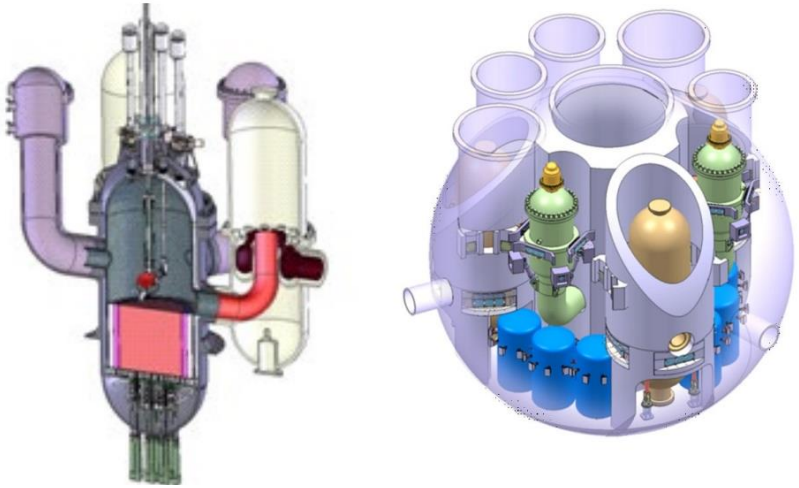
Gas Fast Reactor (GFR) PR&PP White Paper

- One design track considered: 2400MW$_{th}$ GFR reference design, but other designs like ALLEGRO and EM2 are discussed.
- System assumes a closed fuel cycle with mixed carbide pins in a ceramic hex tube. The fuel contains Pu with minor actinides.
- PR features: fissile material is diluted with minor actinides, contain low-grade reactor Pu, and fuel pins are not separated from fuel assemblies on site.
- Implementation of international safeguards makes diversion or misuse difficult to accomplish.
- High radiation levels for both fresh and spent fuel hinder theft.





2400 MWt GFR
Reference System

Summary

- From both a U.S. domestic MC&A perspective and an international safeguards perspective, advanced reactors designs that utilize solid fuel assemblies largely take advantage of MC&A and international safeguards approaches that already exist.
- 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 fueling intervals may reduce opportunities for diversion.
- Some of the difficulties for accounting of assemblies under different coolants also makes clandestine operation unlikely since a considerable amount of expertise and specialized equipment would be required (which is well above and beyond other ways to acquire fissionable material).

Thank You!

Open reports from the DOE NE Advanced Reactor Safeguards and Security program are posted to the program website:
https://energy.sandia.gov/arss

All current Gen-IV PR&PP reports can be obtained at:
https://www.gen-4.org/gif-activities/working-groups/gif-proliferation-resistance-and-physical-protection-working-group

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