Assessing a Proliferation Resistance Methodology: Sodium-Cooled Fast Reactor (SFR) Case Study

Case studies of SFR and other advanced reactor designs for developing a proliferation resistance optimization methodology

August 18-21, 2025

IAEA Technical Meeting on Proliferation Resistance Features of Fast Reactors and Associated Fuel Cycles

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Presentation Overview

PRO-AR&FC Methodology Review

Case Study Goal and Execution

- Goal
- Assumptions
- Advanced Burner Test Reactor (ABTR)
  - A Sodium-cooled Fast Reactor (SFR) Proliferation Resistance (PR) Case Study
  - Modified SFR (M-SFR) for Preliminary Optimization Study

Future Work

Methodology Review: Attributes Group 1

Group 1 Attributes: Reactor Design Features

Attribute	Description
1	Fissile material production capacity of the reactor in kilograms (kg) per year per thermal power (MWth)
2	Cumulative amount of all types of fissionable nuclear material (Pu, U, Th) in SQs present at the reactor facility for a given year. Evaluated in three-sub categories: ▪ **2a:** Maximum amount of all types of fissionable nuclear material present at the reactor facility (outside the core) as fresh fuel at the end of each year for ten years ▪ **2b:**Maximum amount of all types of fissionable nuclear material present at the reactor core at the end of each year for ten years ▪ **2c:** Maximum amount of all types of fissionable nuclear material present at the reactor facility as spent fuel at the end of each year for ten years
3	Total mass (kg) of removed material that contains one SQ of nuclear material estimated separately for fresh fuel, short-cycled fuel, and spent fuel
4	Volume of the total removed material in cubic meter (m^3) that contains one SQ of nuclear material estimated separately for fresh fuel, short-cycled fuel, and spent fuel
5	Number of items to be removed to obtain one SQ of nuclear material (number of fuel assemblies, or storage containers for bulk material, etc.) estimated separately for fresh fuel, short cycled fuel, and spent fuel

Methodology Review: Attributes Group 2

Group 2 Attributes: Fresh and Irradiated Nuclear Fuel After Removal from

Attribute #	Description
6	Time needed in days for converting the removed material (fresh fuel, short-cycled fuel, spent fuel) from the reactor facility to its pure (U or Pu) metallic form
7	What steps are required to convert removed material from the reactor facility to its pure (U or Pu) metallic form?
8	Bare-sphere critical mass (BCM) in kg, estimated separately for the corresponding fresh fuel, short-cycled fuel, and spent fuel removed, and converted into its pure (U or Pu) metallic form
9	Radiation level (gamma and neutron radiation) in Sv/h at 1 meter (m) from the surface of aBCM sphere, estimated separately for the corresponding fresh fuel, short-cycled fuel, and spent fuel removed and converted into its pure (U or Pu) metallic form
10	Spontaneous fission neutron rate in seconds per BCM, estimated separately for the corresponding fresh fuel, short-cycled fuel, and spent fuel removed and converted into its pure (U or Pu) metallic form
11	Thermal power in W per BCM, estimated separately for the corresponding fresh fuel, short-cycled fuel, and spent fuel removed and converted into its pure (U or Pu) metallic form

Methodology Review: Attributes Group 3

Group 3 Attributes: Reactor Facility Features

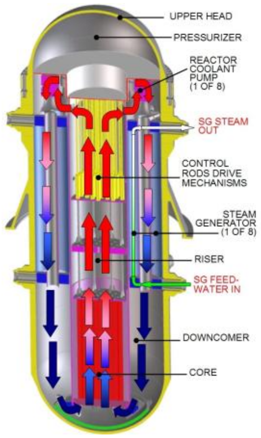
Attribute #	Description
12	Presence of operational modes of reactor design features that could enable proliferation. Evaluated in three sub-categories: • **12a:** Is there online refueling provision in the reactor design? (Yes/No) *If the answer is "Yes", what is the frequency of refueling?* • **12b:** Are there specialized remote tools int eh reactor facility to help the operator access and transfer nuclear material? (Yes/No) *If the answer is "Yes", what is the frequency of using such tools (e.g., heavy load cranes), spaces (e.g., hot cells), etc.?* • 12c: Is there additional space for target irradiation in the reactor? (Yes/No) *If the answer is "Yes", how many target irradiation locations are present and what is the total volume available for target irradiation?*

Goal of the Case Studies

Approach:

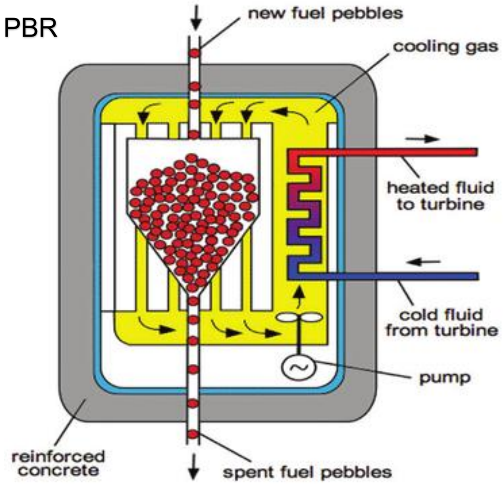
- Stress test the methodology for a broad range of advanced reactors:
  - ➢ Do the attributes adequately capture proliferation resistance (PR)?
  - ➢ Is the methodology reproducible?
- Calculate the PR attributes
- Identify areas of improvement
- Consider how well the draft methodology achieves the program's goals

iPWR



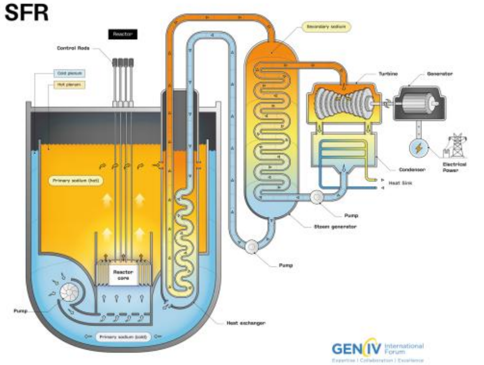
Integral Pressurized Water Reactor

PBR



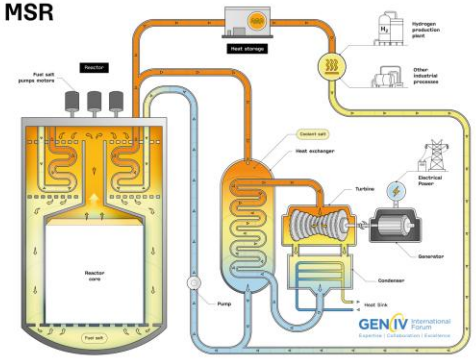
Pebble Bed Reactor

SFR



Sodium-cooled Fast Reactor

MSR

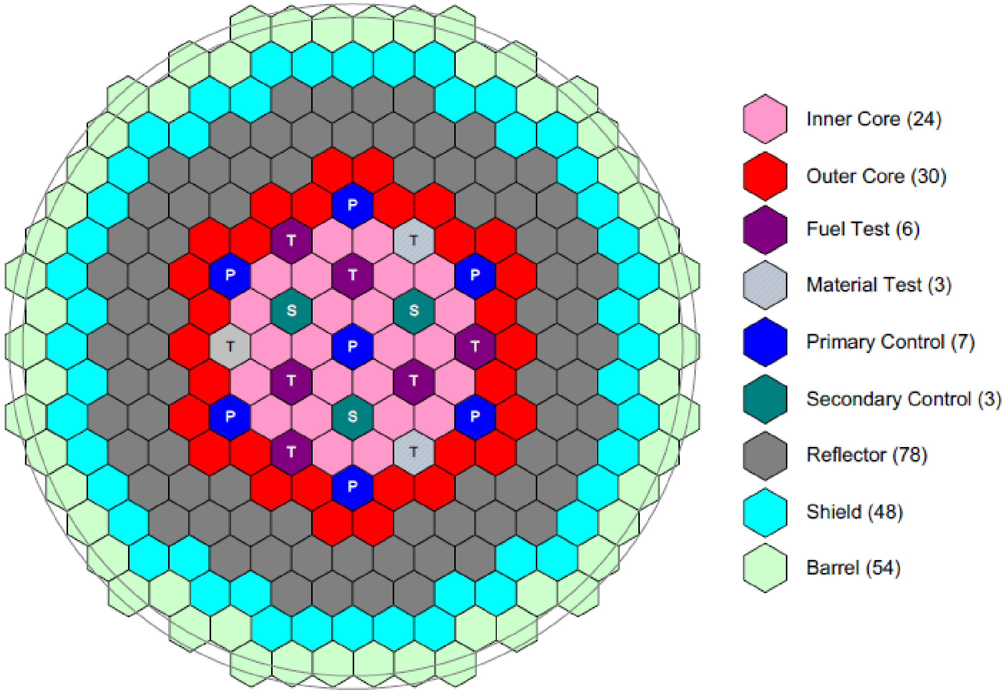


Molten Salt Reactor

MSR: https://www.gen-4.org/generation-iv-criteria-and-technologies/molten-salt-reactors-msr
SFR: https://www.gen-4.org/generation-iv-criteria-and-technologies/sodium-fast-reactor-sfr
PBR: https://www.researchgate.net/figure/Schematics-of-a-pebble-bed-reactor-left-and-of-a-molten-salt-reactor-right-Pebble_fig3_282446783
iPWR: https://www.researchgate.net/figure/Diagram-of-integral-primary-system-reactor-design_fig2_236538819

PRO-AR&FC PR Assessment Steps

- Develop reactor physics models to generate Quantitative Values
- Perform simulations to calculate Attribute Values for:
  - Normal operations
  - Misuse cases
  - Design changes

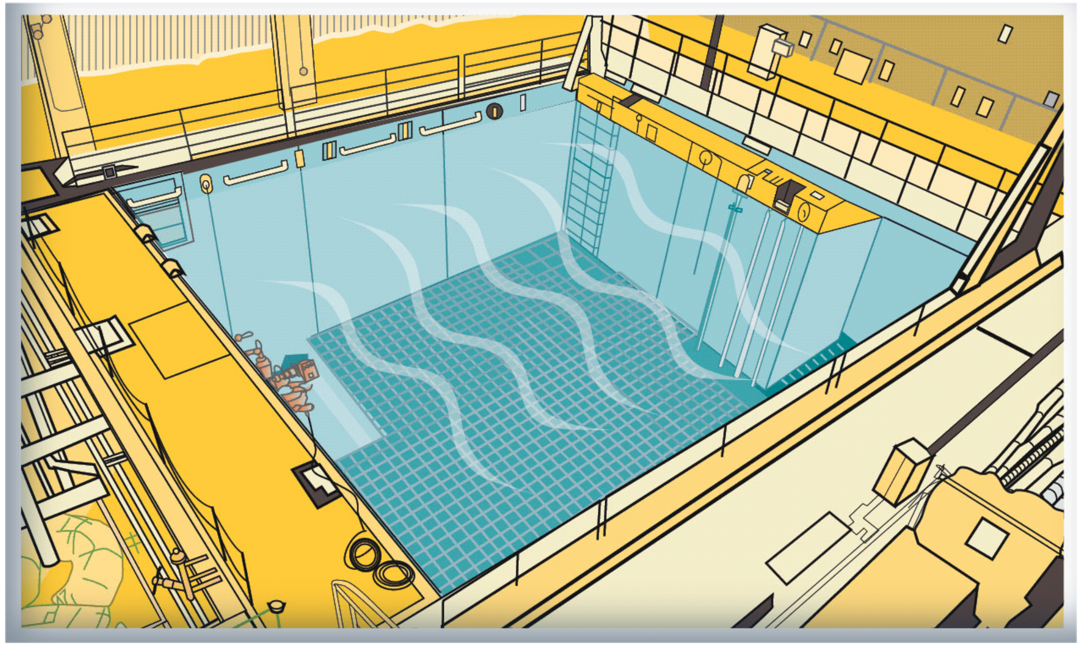


Taek K. Kim, "Benchmark Specification of Advanced Burner Test Reactor," ANL/NSE-20/65, Nuclear Science and Engineering Division, ANL, December 16, 2020

Initial Assumptions

- Focused on the reactor facility and associated fuel cycle design choices
  - On-site fresh fuel storage
  - Analysing evolution of fuel burn-up

- Spent fuel is cooled at the reactor facility for five (5) years



https://www.nrc.gov/images/waste/spent-fuel-storage/generation-storage.gif

Why an SFR Case Study?

- **SFRs are one of the six Generation IV candidates selected by the Generation IV International Forum**
  - SFRs have higher burn-up, passive safety, etc.
  - Flexibility in fuel cycle
  - Close the fuel cycle
  - Burn transuranics (TRU)

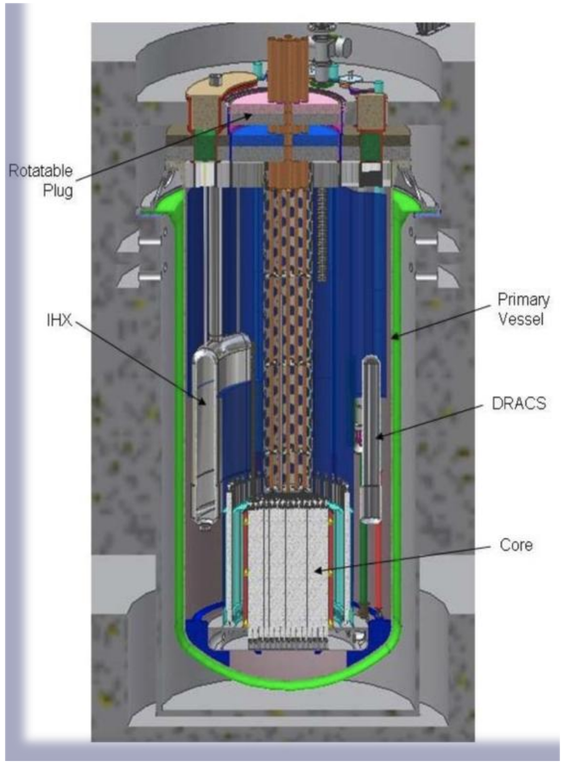
- **High SFR Technology Readiness Level (TRL)**
  - Extensive experiments and prototyping conducted in test SFRs (e.g., EBR-II, FBTR, FFTF, Joyo, Monju, Phenix)
  - Demonstrated operation (e.g., BN600, CFR600, Super Phenix)
  - Ongoing development in the U.S.

Superphénix (Image: Areva/D. Robcis)

https://www.world-nuclear-news.org/Articles/Areva-to-remove-Superphenix-internals

Advanced Burner Test Reactor (ABTR)

- **The ABTR is an Argonne National Laboratory design of an SFR intended to demonstrate transmutation technologies:**
  - Reduce LWR transuranics (TRU) without necessitating Pu separation
  - Incorporates design features that improve safety, efficiency, reliability
  - Key features: pool-type; TRU burner; passive heat rejection via DRACS; SCO_2 Brayton PCS; in-vessel fuel storage
- **Detailed conceptual reactor design is publicly available**
  - Well-developed technical basis and facility design, regularly used in other benchmark activities
  - Efficiency – readily available computational models
- **Expecting TRU fuel cycle to be unique test of methodology**



Y.I. Chang, P.J. Finck, and C. Grandy. “Advanced Burner Test Reactor Preconceptual Design Report.” ANL-ABR-1 (ANL-AFCI-173). ANL. September 5, 2006.

ABTR Parameters

Parameter	Value
Reactor Power	250 MWth
Coolant	Sodium
Driver Fuel	Metallic rods: U-TRU-10% Zr (U:TRU 80:20) in hexagonal assemblies
Cladding	HT9 stainless steel
Design Life	30 years
Refueling Cycle	Four months
Power Conversion Cycle	SCO_2 Brayton
Thermal Efficiency	38%

Developing an Optimization Methodology

- Calculated intrinsic PR attribute values for ABTR (SFR Case Study)
- Modified the intrinsic design features to determine if they impacted the PR attribute values for:
  - Normal operations
  - Selection of misuse cases (in progress)

Tested using 4 Advanced Reactors + 1 Large LWR Non-Proprietary Case Studies

PR Optimization

Optimization Methodology of Advanced Reactor Design

As-Designed Initial Reactor Facility Design

PR Optimization Recommendations

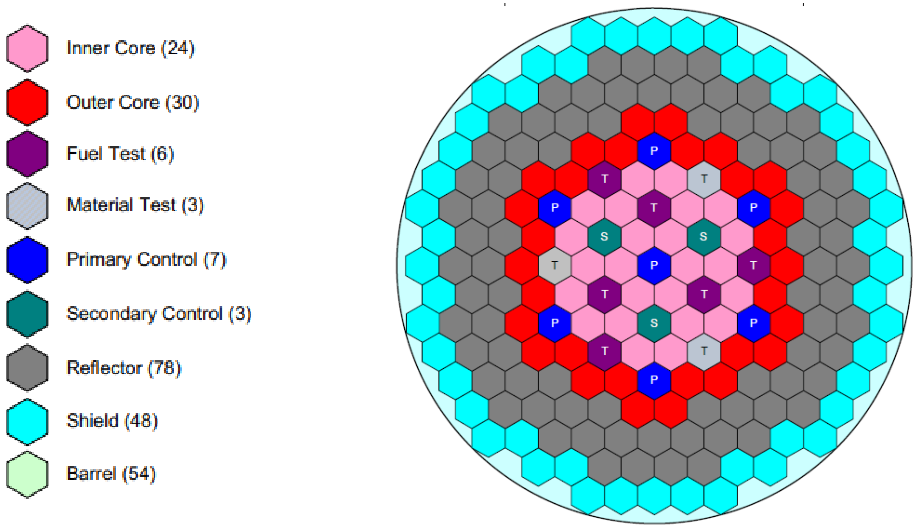
Optimize PR w/other design aspects

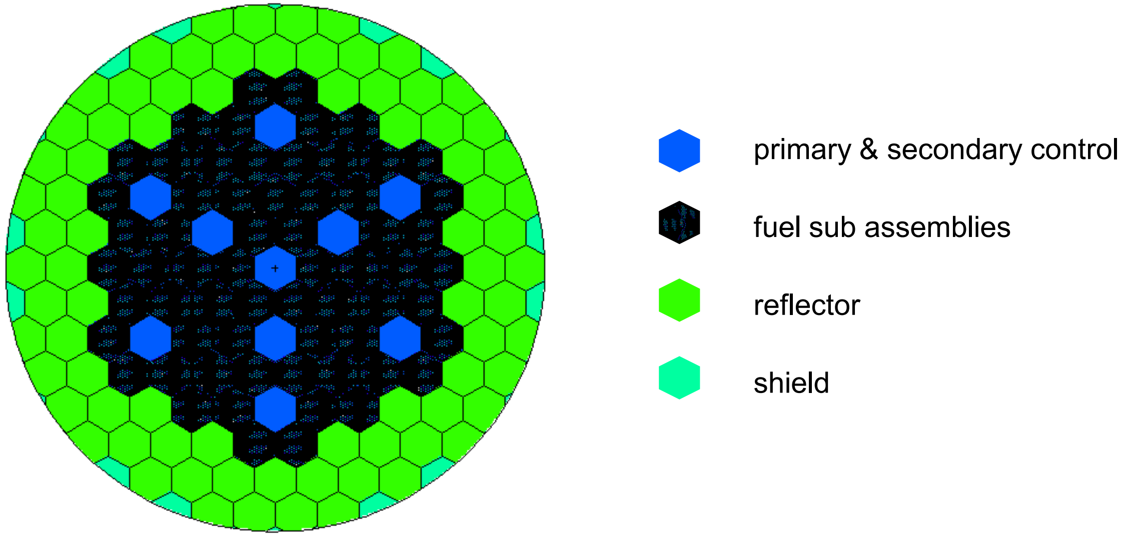
Show design recommendations to increase intrinsic PR

Phase II: Develop and Test Methodology for Optimization

Modified Advanced Burner Test Reactor (M-ABTR)

- ABTR (an SFR used for the PR case study) was modified (M-SFR) by changing the TRU fuel into HALEU fuel at 19.75 ^{235}U wt. %
- Burned ~ 4.5 years to a burn-up of ~72 GWd/MTU
- No test or transmuter sub-assemblies in M-SFR





Taek K. Kim, "Benchmark Specification of Advanced Burner Test Reactor," ANL/NSE-20/65, Nuclear Science and Engineering Division, ANL, December 16, 2020

Modified SFR (M-SFR) Parameters

Parameter	Value
Reactor Power	250 MWth
Coolant	Sodium
Driver Fuel	Metallic rods (90% HALEU, 10% Zr) in hexagonal assemblies
Cladding	HT9 stainless steel
Design Life	30 years
Refueling Cycle	Six (6) months
Power Conversion Cycle	SCO_2 Brayton
Thermal Efficiency	38%

PR Optimization Analysis

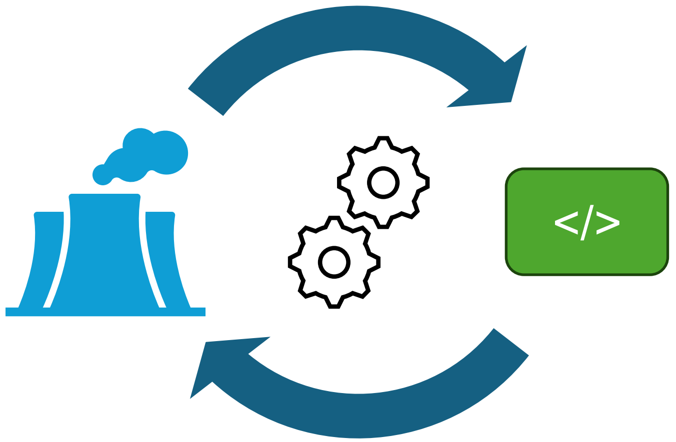
- Rigorous plant layout and safety analysis done for ABTR
  - These have not been done for the M-SFR
- Method used for calculating ABTR's neutronics was DIF-3D, REBUS, ORIGEN-S
- Method used for calculating M-SFR's neutronics was MCNP6.3 with CINDER90 module

Initial M-SFR Attribute Examples

Select Attributes	M-SFR Compared to ABTR for Normal Operations	
	HALEU Fresh Fuel	Spent Fuel Pu
Group 1: Attribute 5	Increased by a factor of 5	Increased by a factor of 4
Group 2: Attribute 8	Increased by a factor of 73	Approximately the same

Future Work

- Calculate all 12 attributes to comprehensively stress test the PR Assessment Methodology for select misuse cases for non-proprietary designs.
- Modify the PR Assessment Methodology, if needed, as identified by the stress tests.
- Develop a PR Optimization Methodology to recommend changes to vendor designs to improve PR.



Thank you!