Proliferation Resistance and Physical Protection (PR&PP) of GEN IV Systems

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U.S. DEPARTMENT OF ENERGY

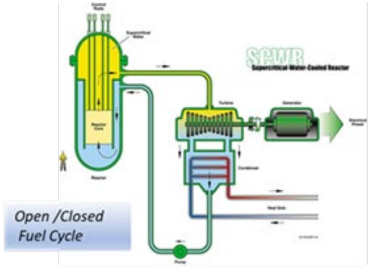
GEN IV International Forum

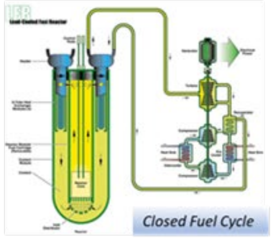
Proliferation Resistance and Physical Protection (PR&PP) Working Group

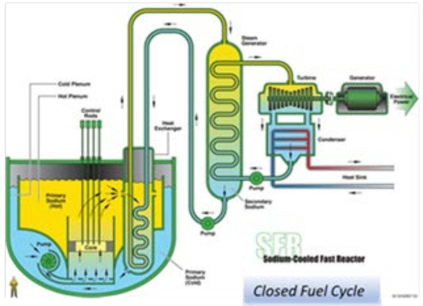
GEN IV International Forum[SM]

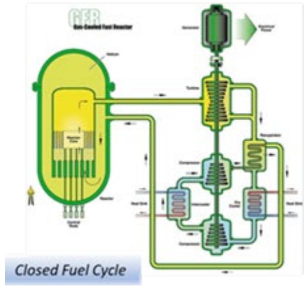
Expertise | Collaboration | Excellence

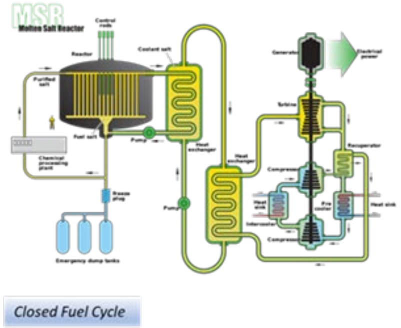
A framework for international co-operation in research and development for the next generation of nuclear energy systems

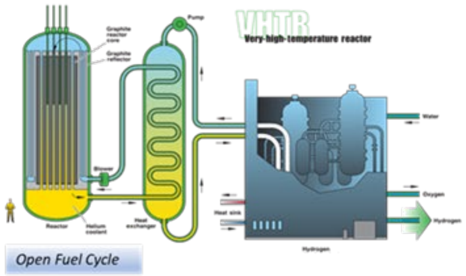












Technology Goals for GEN IV Systems:

Sustainability - source of long-term clean energy

Economics - life-cycle cost advantage and competitive financial risk

Safe and Reliability - excel in operation with low likelihood of core damage and low consequence, negating need for offsite emergency response

Proliferation Resistance and Physical Protection - least desirable target for diversion, misuse, theft and sabotage

PR&PP Working Group

Objectives

- Facilitate introduction of PRPP features into the design process at the earliest possible stage of concept development

  → PRPP by design

- Develop methodology to assess PRPP characteristics of nuclear energy system and provide results to inform designers and policy makers
- Support GIF technology goal for PRPP,

“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.”

- Current Co-Chairs:
  - G.G.M. Cojazzi (EC-JRC), L. Cheng (BNL-US)
  - G. Renda (EC-JRC), Interim Co-Chair
- B. Cipiti (SNL –US), member of core group

- Canada
- China
- Euratom
- France
- IAEA - Observer
- Japan
- NEA - Secretariat
- Republic of Korea
- Russian Federation
- South Africa
- United Kingdom
- USA

PR&PPWG Major Accomplishments

- The Methodology: developed through a succession of revisions – currently in Revision 6
- The "Case Study" approach: an example sodium-cooled fast reactor system with co-located fuel cycle facility was chosen to develop and demonstrate the methodology – resulted in major report
- Joint Efforts with six GIF design areas (System Steering Committees or SSCs,) - resulted in major report including white papers on the six systems -> being updated
- PRPP Bibliography – annual update of reference citations.

All reports can be obtained at public WEB site:

https://www.gen-4.org/gif/jcms/c_9365/prpp

GIF webinar – presentation by R. Bari on PR&PP of GEN IV reactor systems:

https://www.gen-4.org/gif/jcms/c_82831/webinars

Demonstration of GIF PR&PP Methodology

PR&PP Assessment Paradigm

CHALLENGES → SYSTEM RESPONSE → OUTCOMES

Threats

PR
- Diversion/misuse
- Breakout
- Clandestine facility

PP
- Theft
- Sabotage

PR & PP

Intrinsic
- Physical & technical design features

Extrinsic
- Institutional arrangements

Assessment

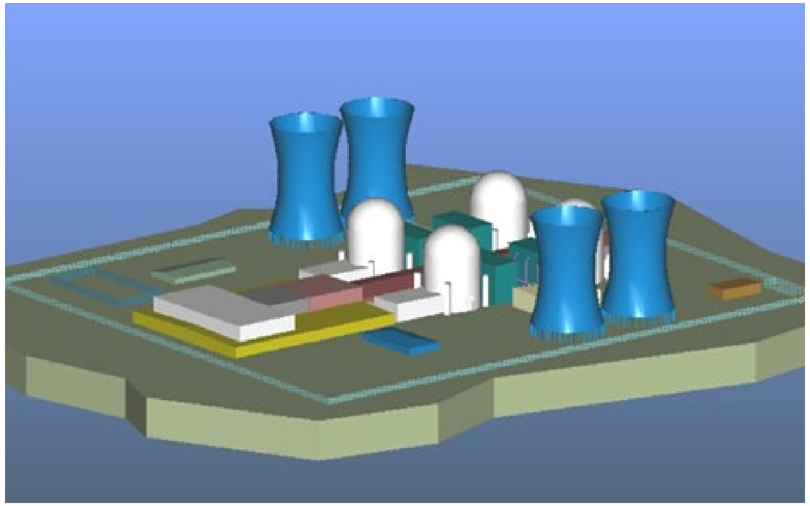
Measures and Metrics

PR
- Technical Difficulty
- Detection Probability
- Material Type
- Proliferation Cost
- Proliferation Time
- Safeguards Cost

PP
- Adversary Success
- Consequence
- Security Cost

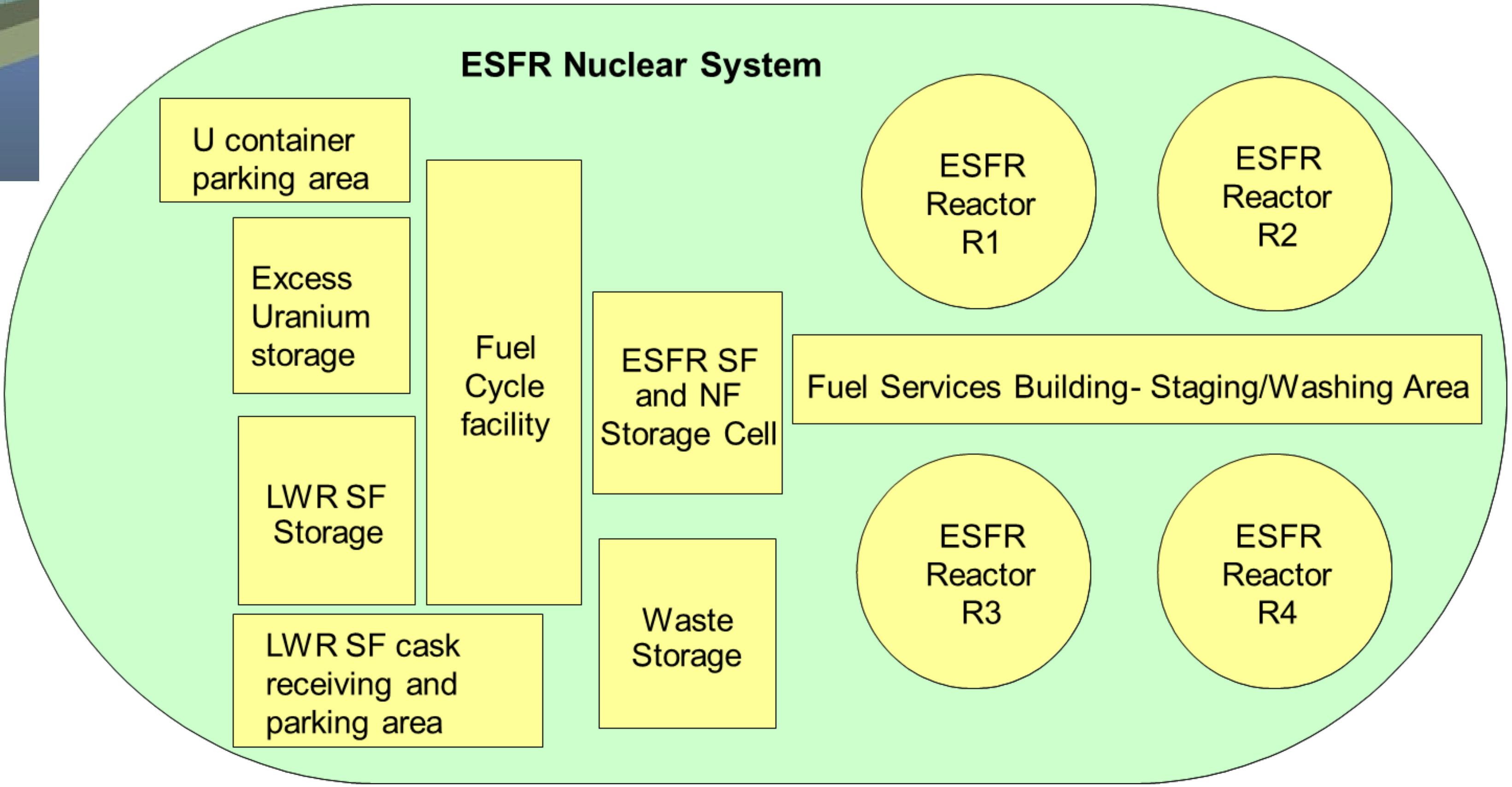
Proliferation, theft and sabotage involve **competing actors**.
Important to recognize actors' perspectives and the human interplay.

Example Sodium Fast Reactor -System Elements

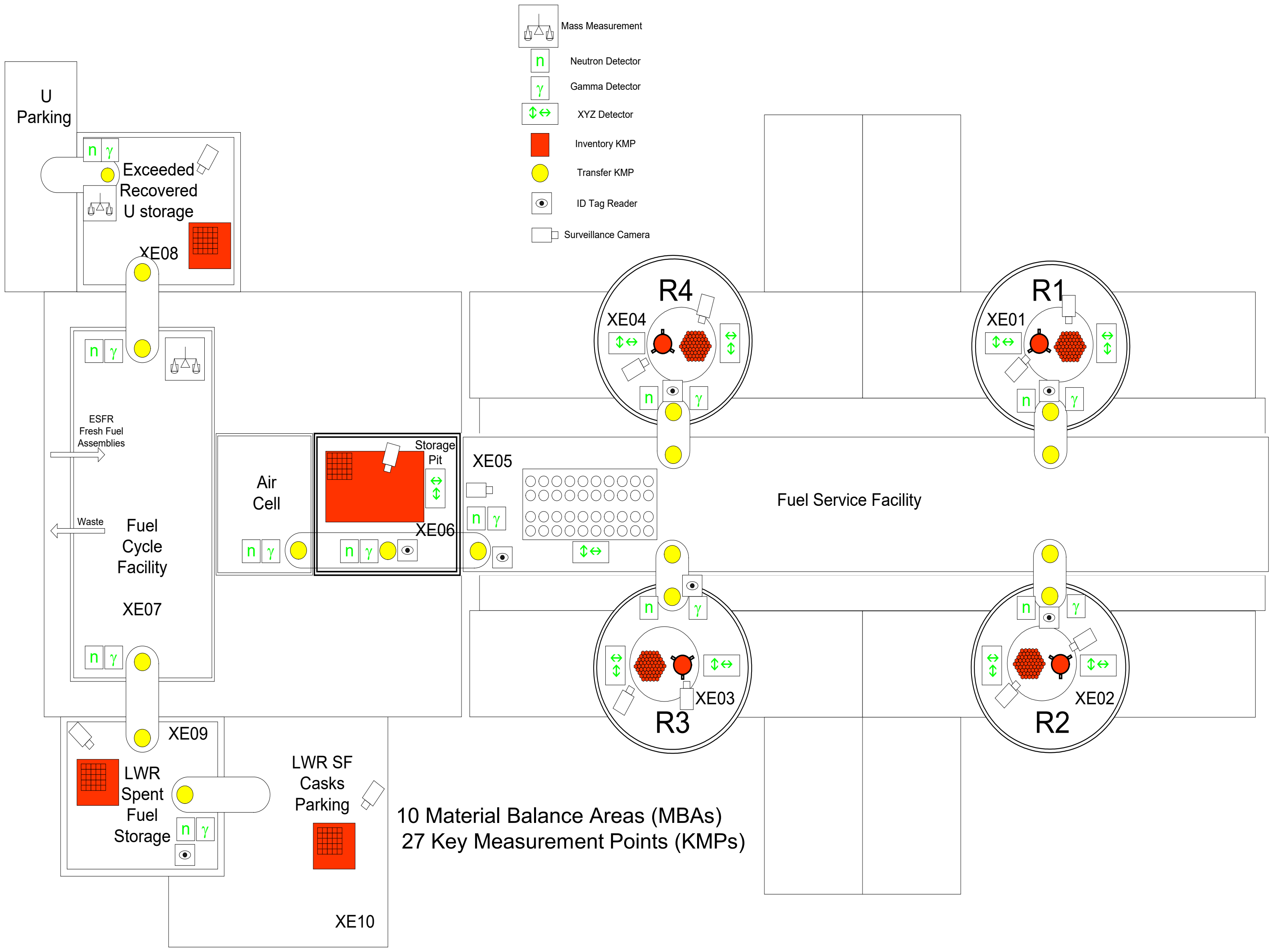


Example Sodium Fast Reactor (ESFR) – a hypothetical system developed by the PR&PP Working Group for the methodology development and demonstration.

- Each plant system consists of four small modular sodium-cooled fast reactors
- Co-located with a dry fuel storage facility and a pyrochemical spent-fuel reprocessing facility.



ESFR Safeguards System

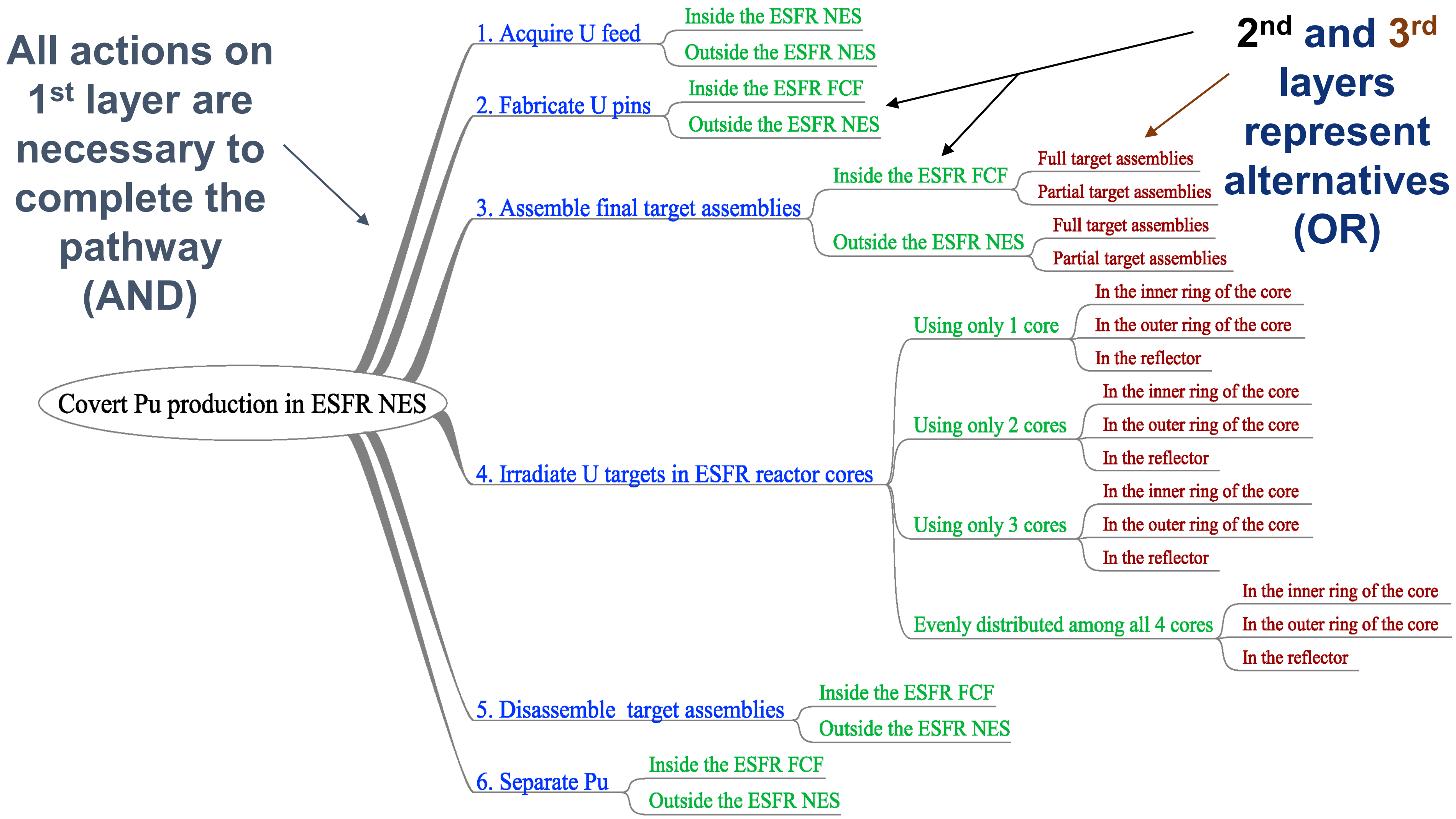


Primary Objectives:
Deter and timely detection of diversion and misuse of facilities for concealed production.

Primary Safeguards Measures:

- Material accounting (records and inventory)
- Design information verification
- Containment and surveillance
- Inspection and sampling

Sample of ESFR Misuse Pathway Segments



The figure embeds up to 5184 misuse pathways…

Insights from Study of Breakout Threat

- Until point of breakout, safeguards, supplier-group controls, national intelligence agencies, and technical means will play a role in detecting the intent to break out. Detection Probability and Detection Resource Efficiency are important measures during the pre-breakout period but play no role post-breakout

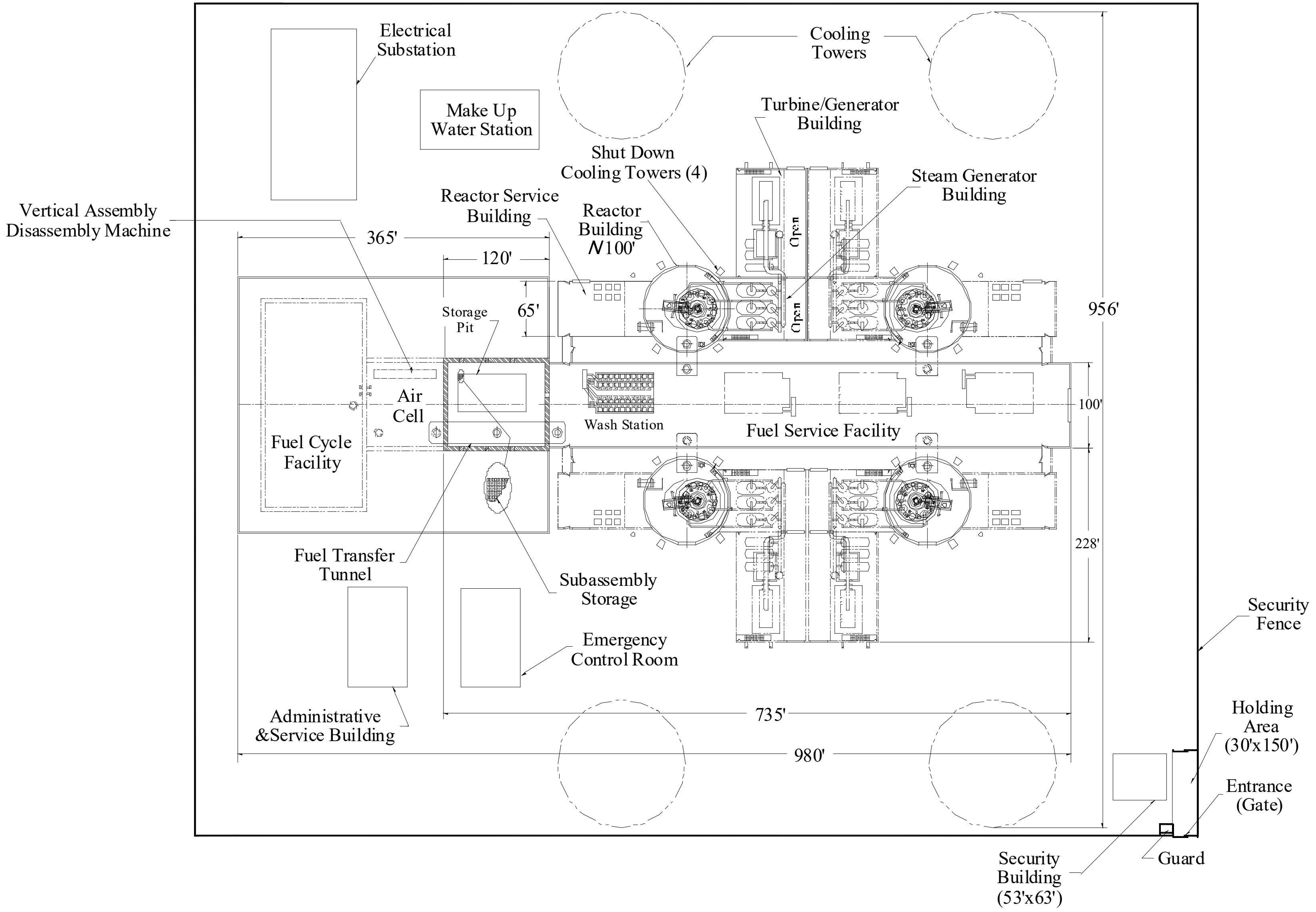
- Breakout is possibly not a stand-alone strategy but the "end game."

- As a "Strategy modifier" the timing of breakout will shape the misuse or diversion threat via Proliferation Time (pre- or post-breakout).

- A key issue in assessing the breakout pathways is the definition of the proliferant state's strategy around detection, and how the state's aversion to detection risk changes as it progresses closer to the end of the pathway. Such "dynamic strategy" considerations add another level of complexity to the analysis of Proliferation Time.

- Most attractive Breakout strategy is non-intuitive: depends on political factors not included in PR&PP analysis (e.g. Material Type measure may not have same impact, as political gains may be met with faster weaponization using lower-grade material)

Physical Protection System Elements and Theft Targets



System Elements:

- LWR spent-fuel cask parking area
- LWR spent-fuel storage
- Fuel cycle facility
  - Air cell (hot cell)
  - Inert hot cell
- Fuel services building staging/washing area
- Reactors

Physical Protection Lessons Learned

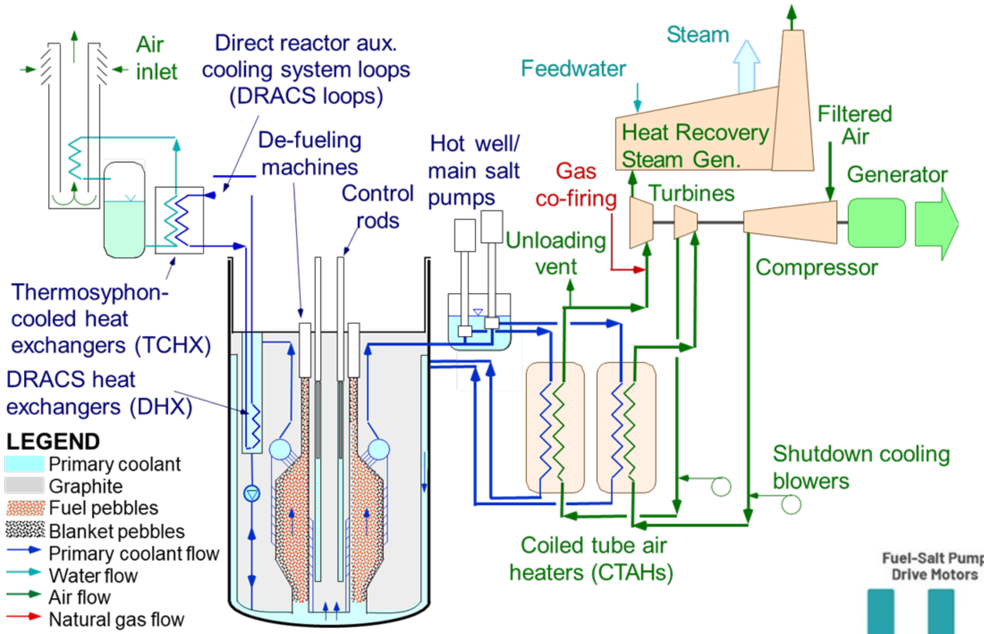
- For theft scenarios, multiple target and pathways exist; however, the most attractive target materials appeared to be located in a few target areas
- For radiological sabotage scenarios, five primary attack strategies should be considered:
  - loss of cooling,
  - reactivity,
  - direct attack,
  - fire/chemical, and
  - other forms of attack.
- For theft and sabotage scenarios where early detection probability was low, the response force time had the greatest impact on adversary success.
- For theft and sabotage scenarios where early detection probability was high, probability of adversary success decreased rapidly as response times decreased.

Evaluation of GEN IV Systems
- White Paper Update

GIF Systems Under Evaluation

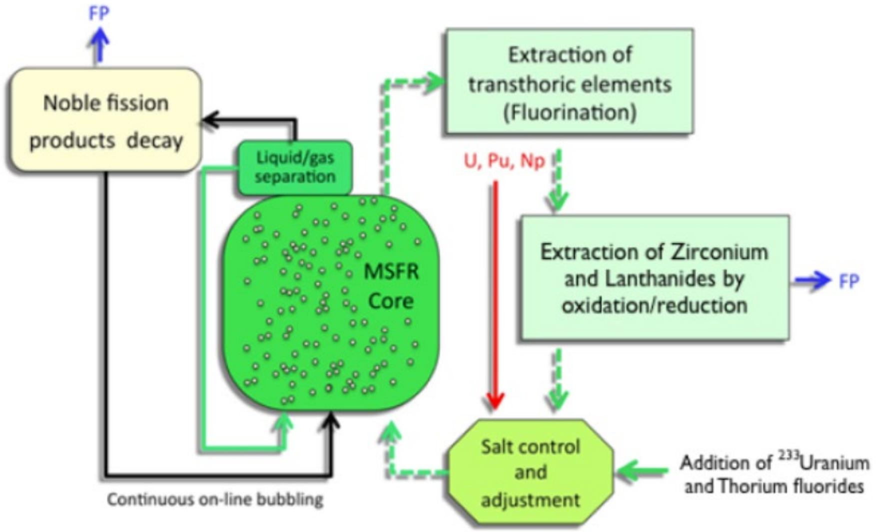
GIF System	System Options considered in update	Design Tracks considered in update	Comment
GFR	Reference Concept	2400MWt GFR ALLEGRO as a GFR demonstrator (EU)	Other GEN IV designs include: EM2 (GA) ALLEGRO (V4G4) HEN MHR (High Energy Neutron Modular Helium Reactor) (CEA-ANL and GA-AREVA)
LFR	Large System	ELFR, (EU))	These are the three reference design configurations discussed in the GIF LFR System Research Plan
	Intermediate System	BREST-OD-300, (RF)	
	Small Transportable	SSTAR, (US)	
MSR	Liquid-fueled with Integrated Salt Processing	MSFR (EU), MOSART (RF)	There is a wide variety of MSR technologies, encompassing thermal/fast spectrum reactors, solid/fluid fuel, burner/breeder modes, Th/Pu fuel cycles, and onsite/offsite fissile separation.
	Solid-fueled with Salt Coolant	Mk1 PB-FHR (US)	
	Liquid-fueled without Integrated Salt Processing	IMSR (Canada)	
SCWR	Pressure Vessel	HPLWR (EU) (Thermal)	Most concepts are based on “familiar’ technology, such as light-water coolant, solid fuel assemblies, and batch refuelling. Implementation of Th and Pu fuel cycles creates additional special nuclear materials of concern.
		Super FR (Japan)	
		Super LWR (Japan) (Thermal)	
		CSR 1000 (China) (Thermal)	
		Mixed spectrum (China)	
		Fast core (RF)	
	Pressure Tube	Canadian SCWR (Canada) (Thermal)	
SFR	Loop Configuration	JSFR (Japan)	Expect key PR&PP issues to be tied to fuel handling, TRU inventory and fuel cycle options.
	Pool Configuration	ESFR (EU), BN-1200 (RF), KALIMER-600 (RoK)	
	Small Modular	AFR-100 (US)	
VHTR	Prismatic Fuel Block	Modular HTR, Framatome (ANTARES)	SC-HTGR is a follow on of the ANTARES and the GA GT-MHR development. Expect some PR&PP differences between the prismatic block and pebble bed design.
		SC-HTGR, Framatome (US)	
		GT-MHR General Atomics (US)	
		GT-MHR OKBM (RF)	
		GTHTR300C, JAEA (Japan)	
		NHDD,KAERI (RoK)	
	Pebble Bed	Xe-100, X-Energy (US)	
		HTR-PM (China)	

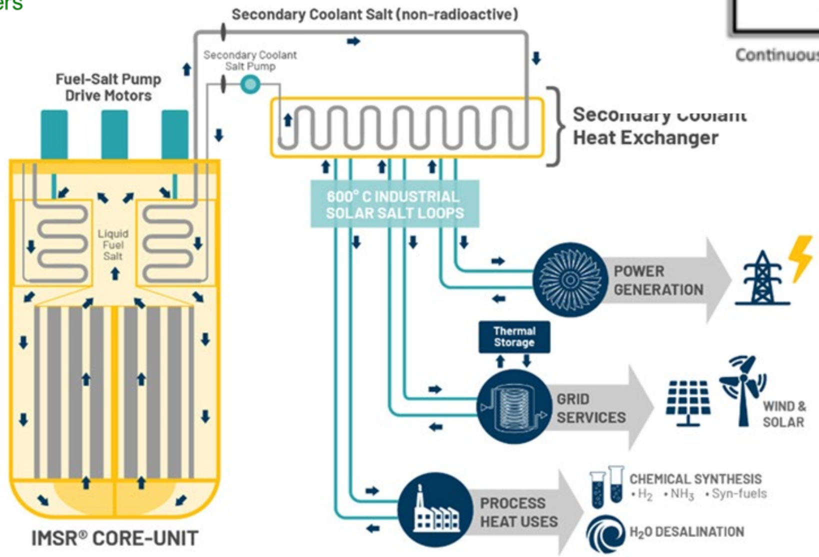
Three Classes of Molten Salt Reactors



Solid-fueled with molten salt coolant:
MK1 PB-FHR

Liquid-fueled with integrated salt processing: MSFR





Liquid-fueled without integrated salt processing: IMSR

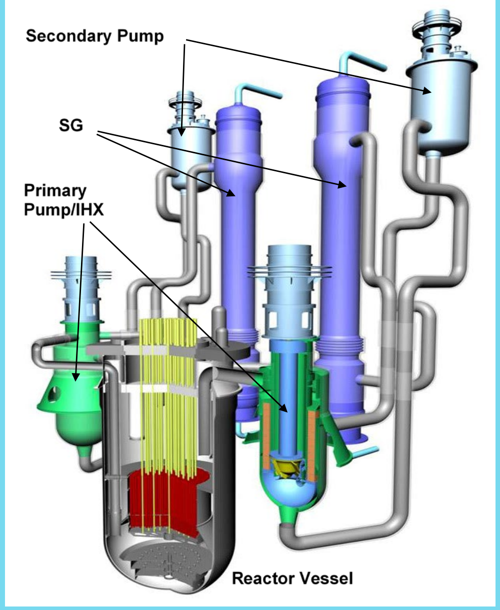
Some Observation of MSR PR&PP Issues

- All three classes of MSR have intrinsic and design features that are favorable to PR&PP.
- Differences are most evident in their adopted fuel cycles.
- Low fissile inventory in the fuel salt and fuel pebbles.
- Fueling and defueling lines are potential points for diversion, theft and sabotage.
- Potential of UF_6 removal by fluorination during fuel salt treatment.
- Remote operation behind shielded vaults and the use of low-pressure and chemically insert coolant contribute to the physical protection robustness of MSRs.
- Radioactive fuel materials presents an intrinsic barrier to theft.
- Remote handling of fuel salt in a hot cell environment makes physical access for theft or sabotage difficult or impossible.
- Low pressure and chemically inert salt minimize driving force for radiological releases during a sabotage event.
- Draining of fuel salt from the core shuts down the reactor.
- TRISO fuel particles are robust and difficult to reprocess.
- Offsite central fuel handling facility still requires safeguards.

Sodium Fast Reactor (SFR) Design Tracks

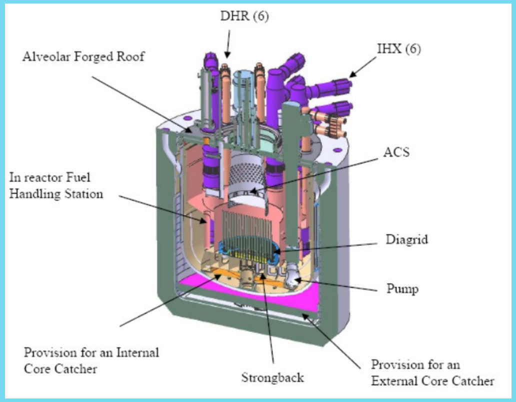
LOOP

JSFR - JAEA

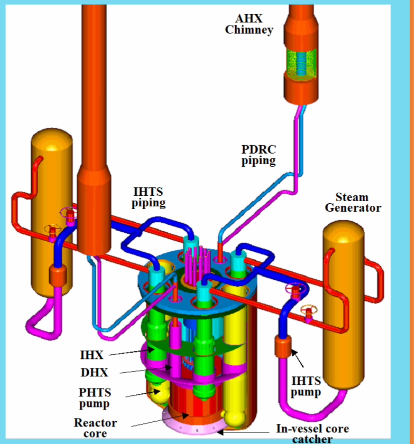


POOL

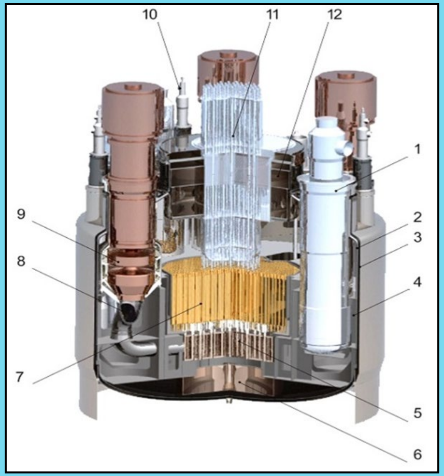
ESFR - Euratom



KALIMER - KAERI

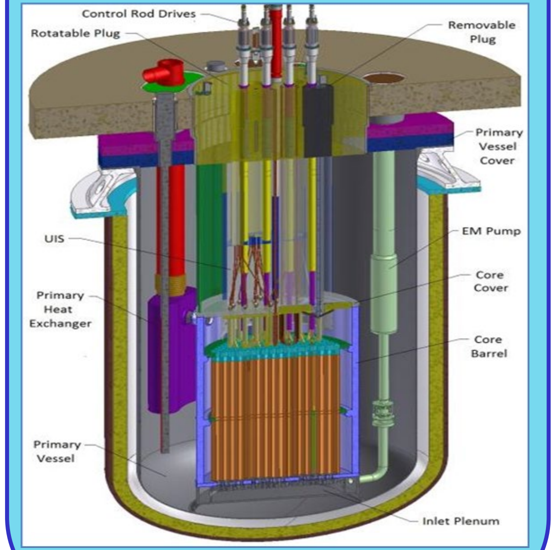


BN-1200 - ROSATOM



Small Modular

AFR-100 - USDOE



Some SFR PR&PP Observations

- High burnup fuel may provide PR advantage but need to apply safeguards on fresh and spent fuel.
- Long-lived cores as well as sealed cores reduce the frequency of fuel transfers but a larger amount of fuel per transfer.
- Blanket assemblies, if present, require similar safeguards to fuel.
- Special fuel handling operations (e.g. under sodium) make diversion and misuse difficult to conceal.
- Use of remote fuel handling restricts access, a PP benefit.
- Theft targets are more likely to be fresh fuel or spent fuel after cleaning and cooling.
- Sabotage scenarios include attacks on reactor, sodium loop, core cooling and heat rejection systems

Summary

- Many lessons learned from the GIF PR&PP Working Group are applicable to the advanced reactor community.
- All six PRPP white papers updates will be done before end of the year (LFR and SFR are in preparation for publication).
- A companion study to examine PRPP-relevant crosscut issues arising from all six GIF systems is underway.
- The group is collaborating with the GIF Risk and Safety Working Group and the IAEA INPRO program to explore the interfaces and integration of safety, security and safeguards.

Questions/Comments?