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3S Interfaces of a Pebble-Bed Small Modular Advanced Reactor

Dr. Bryan van der Ende
Canadian Nuclear Laboratories, Canada

24 September 2025

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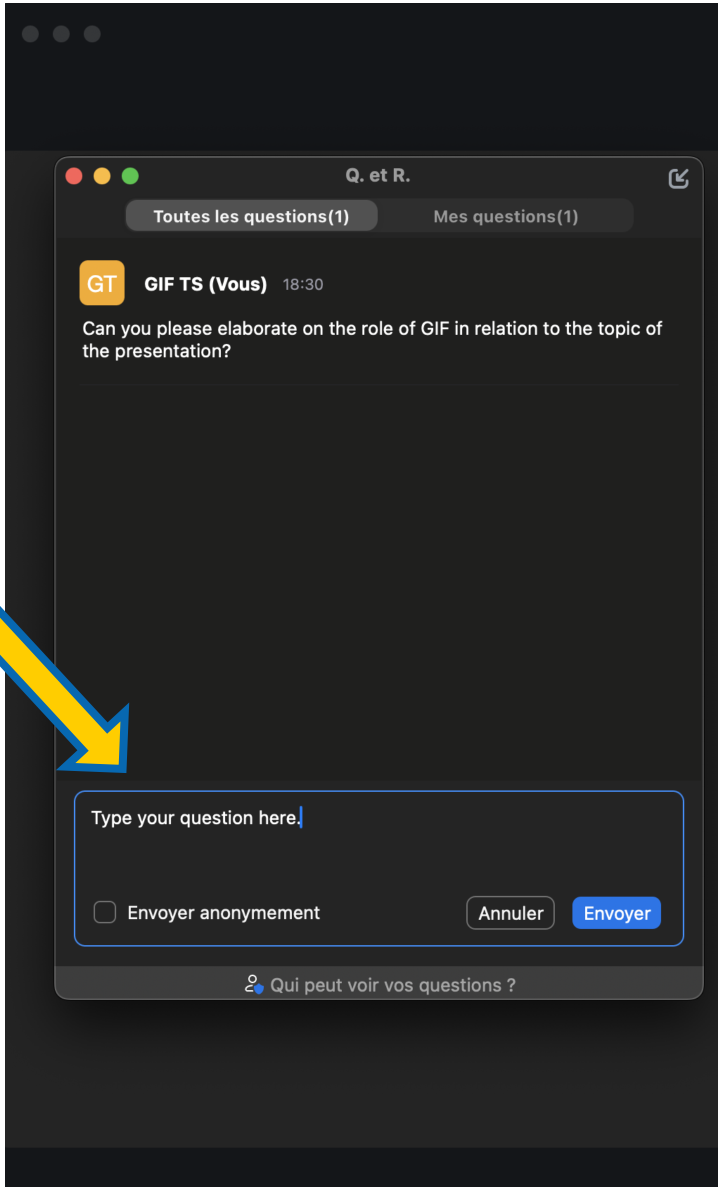

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Meet the Presenter

Dr. Bryan van der Ende is a senior research and development scientist in the Applied Physics Branch of Canadian Nuclear Laboratories (CNL) since 2013, where he is currently section head of the Experimental Safeguards group, as well as directorate lead for the area of Safeguards Systems and Analysis.

His work is focused on various detection modalities for nuclear security and safeguards applications, as well as other techniques for potential use in safeguards approaches. He is also interested in broader issues of nuclear safeguards and non-proliferation, such as the interfaces of nuclear facilities between safety, security and safeguards.

Concurrent with this work, Bryan is an active member of the Generation IV International Forum Proliferation Resistance and Physical Protection Working Group (GIF PRPPWG), since 2019.

Prior to joining CNL, Bryan served as an Assistant Professor in the Department of Physics at Acadia University from 2010 to 2013. He gained postdoctoral experience at the University of Utrecht in Utrecht, The Netherlands, from 2006 to 2009, and at Trent University in Peterborough, Ontario, Canada, from 2009 to 2010. Bryan earned his PhD in Physics at the University of Guelph in Guelph, Ontario, Canada, in 2006.

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

- Facilitate introduction of PR&PP features into the design process at the earliest possible stage of concept development.
  - **PR&PP by design**
- Assure that PR&PP results are an aid to informing decisions by policy makers in areas involving safety, economics, sustainability, and related institutional and legal issues.
- The PR&PP Working Group includes members from Canada, China, Euratom, France, IAEA, Japan, NEA, Republic of Korea, South Africa, UK, USA.

"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."

PR&PP WG Resources for Industry

- PR&PP white papers on the six Gen-IV reactor systems have been updated and are publicly available.
- A companion cross-cutting document discusses PR&PP considerations that cross-cut all reactor designs.
- A PR&PP evaluation methodology has been developed through a succession of revisions, currently in revision 6.
- A case study approach used to develop and demonstrate the PR&PP evaluation methodology resulted in a major report.
- A PR&PP bibliography is maintained by the working group.

Risk and Safety Working Group (RSWG) Objectives

- Facilitate collaboration among member countries to share expertise, methodologies, and best practices in risk and safety assessments for Gen-IV nuclear reactors.
- Work towards development of international safety criteria, guidance and methodologies for Gen-IV nuclear reactors.
- Provide designers of Gen-IV systems with concepts and methods to promote a strong safety basis and efficient licensing of advanced nuclear technologies.
- The RSWG has active members from 9 countries and Euratom.

"Generation IV nuclear energy systems operations will: excel in safety and reliability, have a very low likelihood and degree of reactor core damage, eliminate the need for offsite emergency response."

RSWG Resources for Industry

A list of recent publicly available publications from the RSWG:

- A Risk-informed Framework for Safety Design of Generation IV Systems (June 2023)
- Safety Design Criteria (SDC) for Generation IV Very High Temperature Reactor (VHTR) System (June 2023)
- Safety Design Criteria (SDC) for Generation IV Gas-Cooled Fast Reactor System (September 2022)
- Gas-Cooled Fast Reactor System Safety Assessment (September 2022)
- Basis for the Safety Approach for Design & Assessment of Generation IV Nuclear Systems (revision, 2 July 2021)
- Safety Design Criteria for Generation IV Lead-Cooled Fast Reactor System (2021)
- Lead-cooled Fast Reactor (LFR) System Safety Assessment (2020)

Very High Temperature Reactor System Steering Committee (VHTR-SSC) Objectives

- Established after the VHTR System Arrangement in the Generation IV International Forum (GIF) was signed in 2006.
- Nine members of GIF from nine countries participate in the VHTR SSC's activities.
- Oversees four projects that cover a broad range of topics related to VHTRs.
- The VHTR (and Sodium Fast Reactors): Generation IV systems that have been implemented currently and, in the past, as commercial-scale power reactors.

VHTR-SSC Project Arrangements

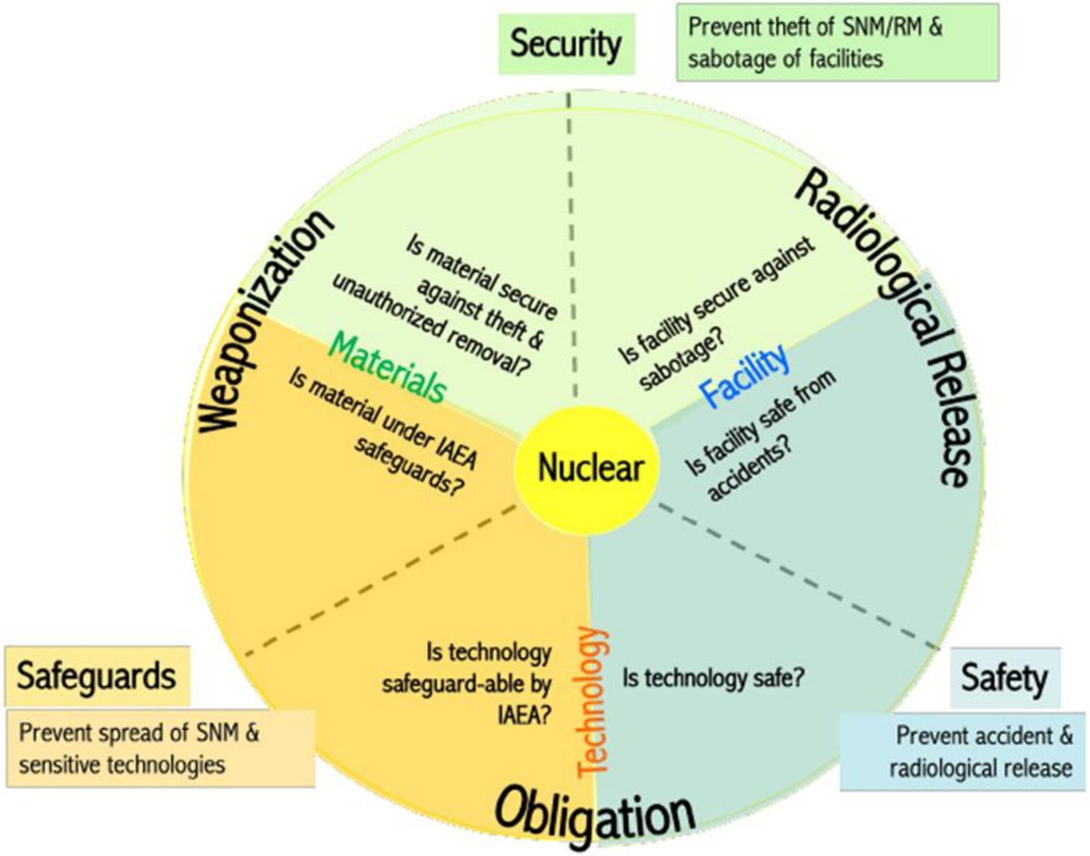
- **Fuel and Fuel Cycle (FFC):** focuses on developing solutions for VHTR fuel, specifically TRISO-coated particles.
- **Computational Methods, Validation & Benchmarks (CMVB):** Validation of new computational methods and codes in the areas of HTR thermal-hydraulics, thermal mechanics, core physics and chemical transport, which are needed for the design and licensing assessment of reactor performance in accident conditions.
- **Hydrogen Production (HP):** R&D efforts here address material development, feasibility, optimization, efficiency and economic evaluation for industrial-scale hydrogen production.
- **Material (MAT):** Focuses on advanced materials development, additional materials' testing standard and code development, and develops and maintains the "GenIV materials handbook."

3S Interfaces for the VHTR: A Case Study Outline

- Overview of case study proposal: motivation, methodology.
- Brief review of safety, security, safeguards regimes.
- Overview of reference VHTR system.
- Summary of safety, security, and safeguards descriptions of the system.
- Critical aspects of identified interfaces, and potential consequences for not considering them.
- Some general characteristics of the interfaces.

Safety, Security and Safeguards (3S) – Case Study Motivation

- There has been growing interest in 3S interfaces of nuclear facilities for over a decade now.
  - ➢ Exploiting synergies and mitigating conflicts in 3S interfaces has potential cost-savings and prevention of retrofits.
  - ➢ Most studies so far take a top-down approach, looking at the interfaces from a high level.
- Generation IV International Forum (GIF) groups (PRPPWG, RSWG, VHTR SSC) are collaborating on a case study approach to 3S interfaces on a particular type of Nuclear Energy System (NES) design.



Jor-Shan Choi, presented at PRPPWG annual meeting, 2023 January updated 6 November 2024.

PRPPWG: GIF Proliferation Resistance and Physical Protection Working Group
RSWG: GIF Risk & Safety Working Group
VHTR-SSC: GIF Very High Temperature Reactor System Steering Committee

Proposal for the Case Study

Design: Generic Pebble Bed Very High Temperature Advanced Modular Reactor (VHTR AMR).

Output: Bottom-up pilot application → limited scope exercise, concentrating on 2/3S interfaces

- The bottom-up approach will treat each “S” regime (safety, security, safeguards) distinctly and identify attributes of each “S” regime that have linkage to the other “S” regimes, in the context of a chosen NES reference design.
- The scope of the practical exercise will depend on the availability of data.

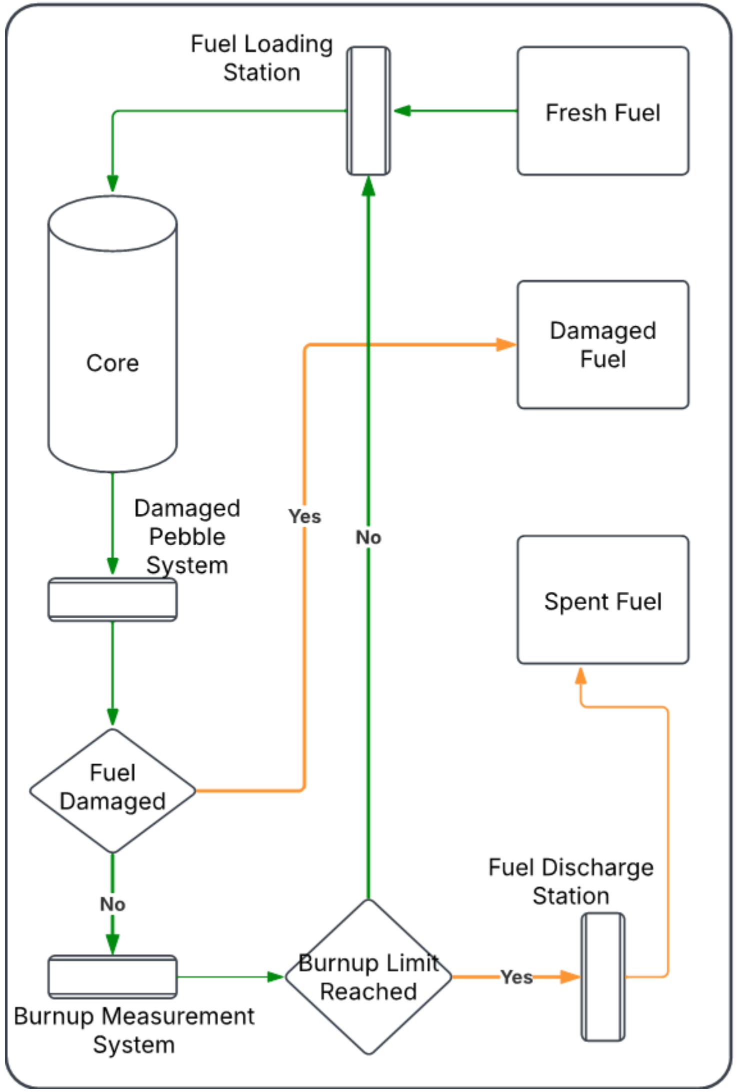
Outcome: Joint VHTR-SSC/RSWG/PRPPWG white paper on VHTR 2/3S interface assessment.

Why a Pebble Bed Very High Temperature Small Modular Reactor?

- Online-fuelled. Very large number of small items. Non-static inventory.
  - Safeguards perspective: quasi-bulk-handling facility instead of an item facility.
  - Quasi-bulk-handling could influence design and operation of nuclear material accounting and control (NMAC) system – a security-safeguards interface.
- No pebble bed reactors in commercial operation today in Non-Nuclear Weapon States.
  - Limited operational experience in safeguards and security compared to traditional designs,

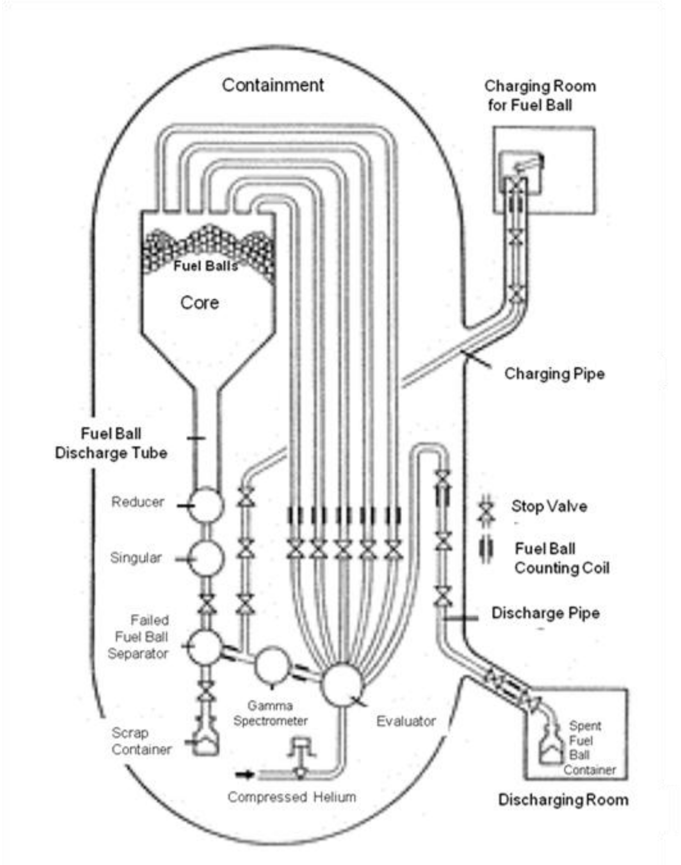
  BUT:
  - Operating experience exists on technological demonstrators in many years of studies.
  - HTR-PM (PM: Pebble-bed Module) demonstrator started operations in December 2021.
- Running on tri-structural isotropic (TRISO) fuel
  - Potential to be a walk-away safe design – safety-security interfaces could be influenced and reduced,

  BUT:
  - Walk-away safety ≠ walk-away security!



3S Interface Study – Scope and Methodology

- Objective of the study is to assess 3S interfaces in the chosen NES design.
- At the conclusion of the work, address the question:
  - ➢ What would a generic 3S approach to advanced reactors look like?
- Approach:
  - ➢ Use a reference design and available documentation.
  - ➢ Make assumptions where needed.
  - ➢ Utilize information in a bottom-up approach.
  - ➢ VHTR PBR as reference design.



Movement of the fuel pebbles for P-VHTR
U. Cleve et al., "The Technology of High-Temperature-Reactors," Proceedings of ICAPP 2011, Paper 11076, Nice, France, May 2-5, 2011.

Nuclear Safety, Security and Safeguards: Some Definitions

- **Nuclear Safety:** The achievement of proper operating conditions, prevention of accidents and mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation risks. (IAEA Nuclear Safety and Security Glossary, 2022 (Interim) edition)

- **Nuclear Security:** The prevention and detection of, and response to, criminal or intentional unauthorized acts involving or directed at nuclear material, other radioactive material, associated facilities or associated activities. (IAEA Nuclear Safety and Security Glossary, 2022 (Interim) Edition)

- **Nuclear Safeguards:** A set of legal instruments, technical measures and administrative procedures implemented by the IAEA … to verify that nuclear material, nuclear facilities and/or other items subject to safeguards are not acquired or used for proscribed purposes. (IAEA Safeguards Glossary, 2022 edition)

Regimes of Safety, Security, and Safeguards

	Safety	Security	International Safeguards
Implemented by	Operator	Operator	Regional Authority IAEA
Postulated adversary or challenge	Human error, natural disaster, equipment failure	Sub-national group	State
Verified by	State	State	IAEA

➡ Need to ensure cooperation and synergies between regimes where the same actors have different and potentially contrasting roles.

- For the assessment, must agree on definitions, actors, objectives, requirements, and acceptance criteria of each regime.
  - ➢ Distinguish between domestic material accounting and control vs. international safeguards.

Pebble Bed VHTR Reference Design

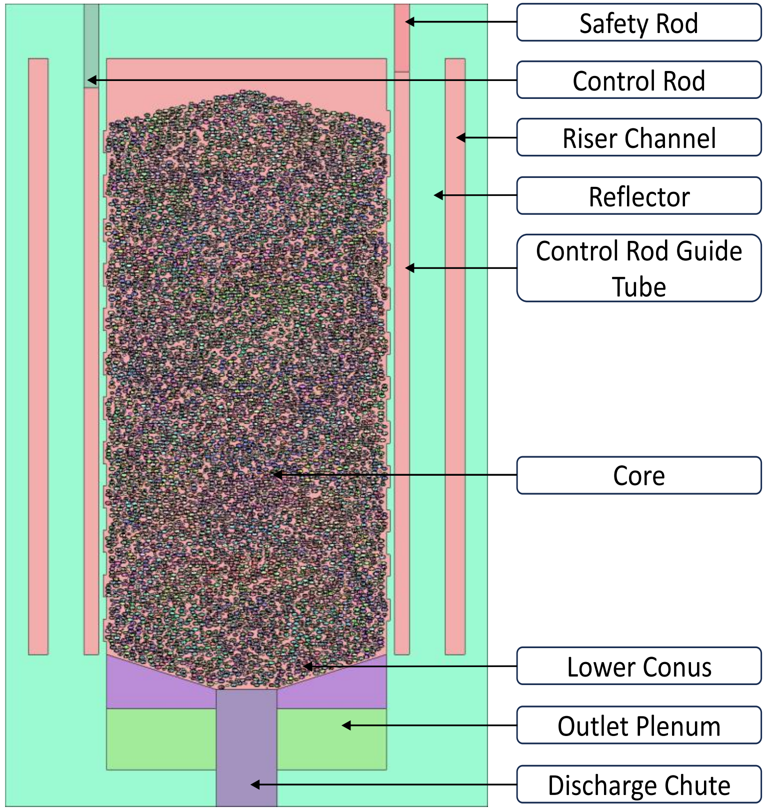
- A model of a generic pebble bed VHTR called GPBR-200 has been supplied by Idaho National Laboratory.
  - Draws upon geometry and material properties from past designs found in literature, including HTR-PM, Xe-100, and PBMR-400.
  - From the model, glean design characteristics, operations, layout and geometry that are important to each of safety, security, and safeguards.

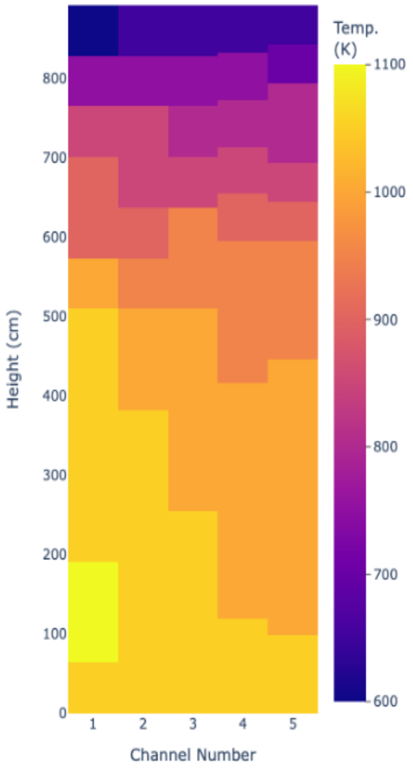
Special Nuclear Material data for the GPBR-200 and Contemporary PBRs.

	GBPR-200 Value	Contemporary Ranges
Mass of Uranium per Pebble (g)	7	6 – 8
Enrichment (wt%)	15.5	8.0 – 19.9
TRISO particles per pebble	18,687	15,000 – 20,000
Pebbles per core	220,000	200,000 – 500,000
Mass of U-235 in Core (kg)	231	150 – 275
Discharge Burnup (MWd/kg)	160	90 – 160

The System: GPBR-200

- Designed by Idaho National Lab
- Pebble bed reactor (PBR)
- Power: 200 MWth
- Primary System Pressure: 6MPa
- Helium-cooled
- TRISO fuel pebbles, ca. 200k per core
- Enrichment (equilibrium): 15.5-wt%
- Core radius: 1.2m
- Core active height: 8.93m





Components of Facility Layout

In a single building:

- Single reactor core unit
- Fresh, spent, broken fuel storage
- Fuel handling
- Single Steam generator
- Heat removal system
- Burnup measurement system included in fuel handling
- Post-irradiation facility for examining select irradiated pebbles.

System Elements	Potential Associated S
Reactor	Safety, Security, Safeguards
Heat Removal System	Safety, Security
Burnup Measurement System	Safety, Safeguards
Secondary Circuit	Safety, Security
Post-Irradiation Facility	Safety, Security, Safeguards
Fresh Fuel Storage	Safety, Safeguards, Security
Spent Fuel Storage	Safety, Safeguards, Security
Broken Fuel Storage	Safety, Safeguards, Security
Control Room	Safety, Security
Shipping/Receiving	Safety, Safeguards, Security

Safety Description

Highlighting safety systems of the GPBR-200 for the key safety functions:

- Confinement of radionuclides
- Control of reactivity
- Control of heat removal
- Control of chemical attack
- Maintain core and reactor vessel geometry

Consideration of an event sequence model from an example initiating event.

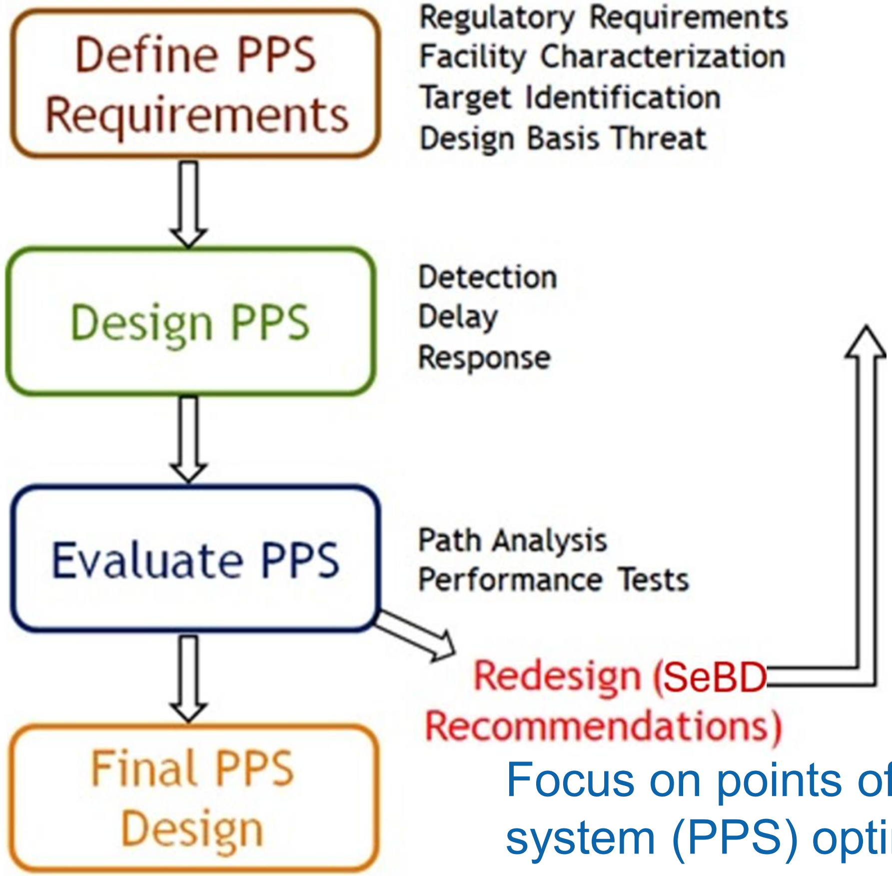
Sources of Radioactive Material:

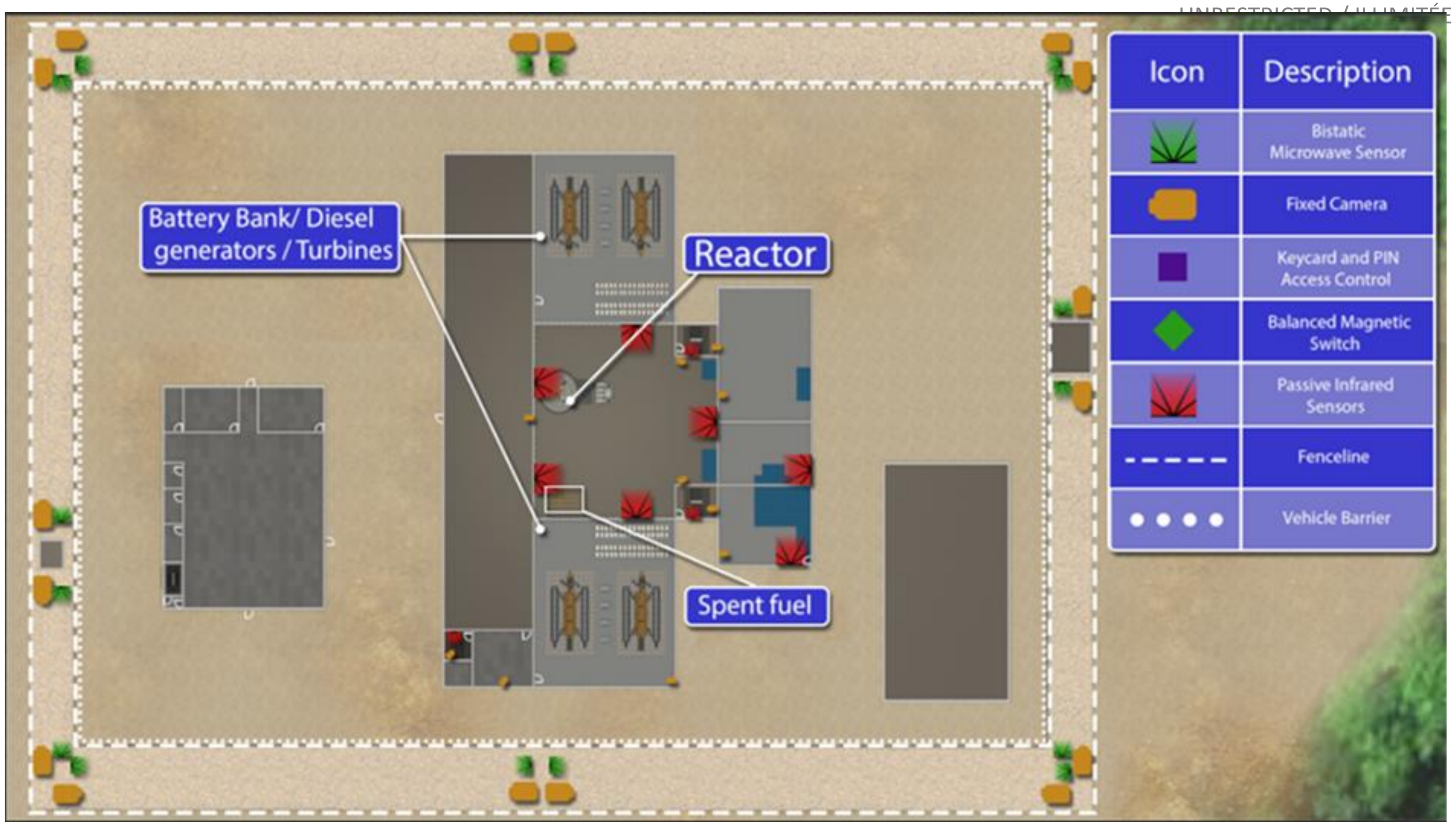
Sources within the main power system high pressure boundary (MPS HPB)	Fuel Spheres in core/fuel handling and storage system (FHSS)	- Intact coated particles - Failed or defective coated particles - Uranium contamination outside coated particles - Embedded/attached to graphite components
	Plateout on HPB surfaces and dust	
	Circulating coolant activity	
Sources outside the MPS HPB	Fuel spheres in storage systems	
	Solid and liquid radwaste systems	

Principal Barriers to Release of Radioactive Material:

Radioactive Material Source	Barriers to Radionuclide Transport
Fuel spheres in the core	Coated particles, graphite matrix, helium pressure boundary, reactor building
Fuel spheres outside the core	Coated particles, graphite matrix, FHSS piping, spent fuel tanks (SFTs), used fuel tanks (UFTs), or new fuel tanks, reactor building
Non-core sources within the MPS	HPB, reactor building
Other sources	Various tanks, piping systems and containers, reactor building or ancillary buildings housing waste management equipment

Security Description





Focus on points of interface with safety and safeguards affecting physical protection system (PPS) optimization.

- Informed by Design and Evaluation Process Outline (DEPO) from US NNSA, a security by design process.
- “Define PPS Requirements” overlaps with two other “S”s.
- “Design PPS” (more specific to security): define detection, delay, and response technologies.

Safeguards Description

Following IAEA Design Information Questionnaire (DIQ) contents:

- Facility Information
  - ➢ *Core Description*
  - ➢ *Fuel Handling System*
  - ➢ *Example Calculation: Mass Flow of Fresh Fuel*
- Plant Layout, MBAs, KMPs
- Source Data, Reporting, Loss and Production of NM
- Shipping/Receiving
- Physical Inventory, C/S, Monitoring Features
- Measurement Methods, Level of Accuracy
- Access to NM, NM Testing Areas

SUB-MBA	System Element	Inventory Key Measurement Point	Flow Key Measurement Point
1	Receiving area		FKMP-1: Fresh Fuel receipt (items)
	Fresh Fuel Storage	IKMP-A: Fresh fuel storage (items)	FKMP-2: Recategorization of FF through transfer to pebble feed system
2	Reactor System	IKMP-B: Reactor system	*FKMP-3: Fresh fuel insertion into reactor core *FKMP-4: Irradiated fuel removal from reactor core
	Burnup Measurement System		*FKMP-6: Irradiated fuel transfer to burnup measurement system *FKMP-7: Irradiated fuel reinsertion into reactor core from burnup measurement system FKMP 8: Irradiated fuel removed from burnup measurement system to spent fuel
3	Broken Fuel Storage	IKMP-C: Broken fuel storage (items)	FKMP-5: Recategorization of broken fuel and waste transferred to broken fuel storage
	Spent Fuel Storage	IKMP-D: Spent fuel storage (items)	FKMP 9: Recategorization of spent fuel transferred to spent fuel storage
	Post-Irradiation Facility	IKMP-E: Post-irradiation facility (items)	*FKMP-10: Transfer of spent fuel between storage and post-irradiation facility (items) *FKMP-11: Transfer of broken fuel between storage and post-irradiation facility (items)
	Shipping Area		FKMP-12*: Shipment of spent fuel, broken fuel, and waste (items)

*For recording internal flows, not required for material accountancy reporting

Exploring the 3S Interfaces

- Reactor designers have a strong safety culture, developed over several decades of experience, lessons learned, and regulatory requirements.
- Security culture is much less considered at early design stages, and safeguards are even less taken into account.
- A systems engineering, holistic approach to 3SbD (bD: by Design) not a realistic paradigm shift for systems currently under design.
- Leverage on the existing safety by design culture and complement it with safeguards and security cultures that could be introduced via bilateral interfaces with the better-known safety domain:
  - Introduce the security and safeguards needs in terms of relationship with the safety ones, through a 3x2S exercise.
  - An additional analysis would allow the identification of the ones that are proper 3S interfaces.

Identified Interfaces:

Safety-Security (5)
Safeguards-Security (4)
Safeguards-Safety (4)
Safety-Security-Safeguards (6)

Safety-Security Interfaces: Safety Systems and Physical Security (1/5)

- Need to protect safety systems from sabotage.
- Critical aspects of the interface in the GPBR-200:
  - ➢ Safety and control systems should be in vital areas (within the reactor building).
  - ➢ Non-core radioactivity items (spent fuel, coolant purification) must be protected.
  - ➢ Adversary paths within the building should avoid vulnerable targets.
- Consequences of not considering the interface:
  - ➢ Unforeseen vulnerabilities may arise that may need to be resolved through costly retrofits.

Safety-Security Interfaces: Safety Systems and Cybersecurity (2/5)

- Cyber-physical interface.
- Critical aspects of the interface in the GPBR-200:
  - ➢ Safety and control systems should be adequately protected (Defensive Cyber Security Architecture).
  - ➢ Independent passive safety systems are resilient to cyber-attack.
- Consequences of not considering the interface:
  - ➢ There may be inadequate protection against cybersecurity threats to safety systems.

Safety-Security Interfaces: Timeline Analysis and Response Force Strategy (3/5)

- How does enhanced safety affect the security approach?
- Critical aspects of the interface in the GPBR-200:
  - ➢ Longer timelines (up to days) before core damage occurs in the event of loss of cooling systems can allow longer than usual response times in case of attack.
  - ➢ Need to protect from intentional sabotage (including possible insider threat) not mitigated by intrinsic and/or engineered safety features.
- Consequences of not considering the interface:
  - ➢ There can be an imbalance between on-site and off-site response: too many on-site responders if off-site response can be utilized, or too few on-site responders if off-site response is not adequate.

Safety-Security Interfaces: Effect of Radiation Dose on Responders (4/5)

- Minimize radiation does to responders during normal and emergency response operations.
- Critical aspects of the interface in the GPBR-200:
  - ➢ Automation/remote handling minimizes human presence in vital areas.
  - ➢ Facility design should reduce dose to responders defending targets in the building.
- Consequences of not considering the interface:
  - ➢ Plant protection may not be optimized or additional costs for shielding may be incurred.

Safety-Security Interfaces: Emergency Exits (5/5)

- Entrance to/exit from vital areas needs to be adequately protected even during emergencies (tension between the two S’s).
- Critical aspects of the interface in the GPBR-200:
  - ➢ Automation/remote handling minimizes human presence in vital areas also reduces need for routes of egress.
  - ➢ Shark cages or mantraps can be used on all entries and exits to slow down attackers entering a facility, while still allowing egress in an emergency.
- Consequences of not considering the interface:
  - ➢ Security costs may escalate due to too many exits needing protection.

Safeguards-Security Interfaces: Fuel Handling System and Containment/Surveillance (C/S) (1/4)

- C/S is used by the state for physical protection, as well as in international safeguards for verification.
- Critical aspects of the interface in the GPBR-200:
  - Accountancy is done on the canister level, but dependent on containment/surveillance to prevent pebble diversion or misuse.
  - Diversion pathway analysis can mitigate potential for undetected diversion.
- Consequences of not considering the interface:
  - Not making use of an integrated approach will reduce efficiency in complying with the security and safeguards regimes, potentially leading to more downtime and higher costs.

Safeguards-Security Interfaces: International Safeguards and Physical Protection (2/4)

- Reduced access for security versus access for inspections.
- Critical aspects of the interface in the GPBR-200:
  - ➢ Nuclear material is almost always in “difficult to access” areas: adversary access is more difficult, but also more difficult for safeguards inspections.
  - ➢ Shared aspects of nuclear material accounting and control (NMAC): potential synergy in shared NMAC technology.
- Consequences of not considering the interface:
  - ➢ Cost of NMAC and international verification may increase if shared use and synergies are not utilized.

Safeguards-Security Interfaces: Remote Data Transmission (3/4)

- This is common to any reactor and a source of tension for any reactor.
- Critical aspects of the interface in the GPBR-200:
  - Data that may be useful to safeguards may also be deemed sensitive from a security standpoint.
  - Data should be collected and transmitted in a way that is beneficial to safeguards while mitigating security concerns.
- Consequences of not considering the interface:
  - Incompliance with security requirements in the implementation of remote data transmission for safeguards may induce severe consequences from security events.

Safeguards-Security Interfaces: Surveillance Systems (4/4)

- Shared surveillance equipment for security and safeguards is generally not allowed.
- Critical aspects of the interface in the GPBR-200:
  - ➢ Surveillance is cornerstone for domestic security and international safeguards, but the systems cannot be shared.
  - ➢ Both systems may compete for the same viewing angles (3S by design is important to the building layout).
- Consequences of not considering the interface:
  - ➢ Not considering the surveillance needs of security and safeguards early in design stages could lead to costly retrofits.

Safeguards-Safety Interfaces: Fuel Movement During Accidents or Inspections (1/4)

- Implications for both S’s should be considered.
- Critical aspects of the interface in the GPBR-200:
  - In an accident scenario, preventing movement of fuel (for safety) is also of benefit to safeguards.
  - Inspections may require movement of the fuel, which can have safety implications.
- Consequences of not considering the interface:
  - Increased inspection time or safety issues for inspectors may ultimately induce operational inefficiency.

Safeguards-Safety Interfaces: Access Restrictions (2/4)

- Consider safety to safeguards inspectors.
- Critical aspects of the interface in the GPBR-200:
  - ➢ The GPBR-200 utilizes automated refuelling, which could make access for inspections difficult.
  - ➢ Safe methods for safeguards inspections should be considered early in the design process.
- Consequences of not considering the interface:
  - ➢ Difficulty of access will increase inspection complexity and reduce its efficiency.

Safeguards-Safety Interfaces: Equipment Failure (3/4)

- Failure of safeguards equipment and the effect on the reactor operation and safety.
- Critical aspects of the interface in the GPBR-200:
  - ➢ Failure of safeguards related equipment attached to operator equipment could impact the safety of the facility: this must be prevented at the design stages.
- Consequences of not considering the interface:
  - ➢ The impact of failed equipment under shared use can result in severe incompliances in safety and safeguards.

Safeguards-Safety Interfaces: Damaged Fuel Elements (4/4)

- Synergy between safety and safeguards to ensure that fuel pebbles remain intact.
- Critical aspects of the interface in the GPBR-200:
  - Damaged fuel pebbles will need to be identified and stored separately after leaving the reactor.
  - Measurements of these losses will be needed both to assess safety (if there is radioactive release) and for accountancy for safeguards.
- Consequences of not considering the interface:
  - Failing to identify damaged fuel as early as possible can result in incompliances in safety and (if the element breaks apart) in nuclear material accountancy for safeguards.

3S Interfaces: Digital Connectivity (1/6)

- Common potential entry point for disruptions of all three S's.
- Critical aspects of the interface in the GPBR-200:
  - ➢ Design of the Defensive Cybersecurity Architecture must examine all three S's.
  - ➢ Ensure no weak point in one domain that could cascade to other domains.
  - ➢ Remote data transmission should avoid weak points in facility's digital connectivity.
- Consequences of not considering the interface:
  - ➢ Unidentified vulnerabilities may increase the likelihood of attack, loss of revenue, failure of plant, and loss of trust in capabilities.

3S Interfaces: Nuclear Material Containment and Access (2/6)

- Conflicts and synergies among containment and access needs of all three S's.
- Critical aspects of the interface in the GPBR-200:
  - ➢ The location and access of material should take into account all three S's.
  - ➢ Potential conflicts can arise in terms of accessibility to safety systems, vital areas and nuclear material locations.
  - ➢ Effective dual-use C/S systems and shared signals supports this 3S interface.
- Consequences of not considering the interface:
  - ➢ Cost of international verification may increase if access is too difficult, or security vulnerabilities may increase if access is not adequately protected.

3S Interfaces: Plant Operations (3/6)

- Operational procedures should not adversely affect those of other S's.
- Critical aspects of the interface in the GPBR-200:
  - ➢ Planned operational programs should consider security and safeguards in the design of the procedures.
  - ➢ A high level of integrated automation offers opportunities to develop synergistic operational programs for all 3 S's.
- Consequences of not considering the interface:
  - ➢ Can lead to inefficiencies in the overall system design or wasted resources when operational changes (design/procedure) to address events are not properly communicated among the 3S regimes.

3S Interfaces: Reactivity Control and NMAC (4/6)

- Sharing of information and technology for reactivity control and NMAC should be implemented synergistically.
- Critical aspects of the interface in the GPBR-200:
  - ➢ Reactivity control utilizes burnup measurement, reactor physics codes, and pebble counting systems.
  - ➢ The said systems are also utilized in maintaining accountancy and control for security and safeguards purposes.
- Consequences of not considering the interface:
  - ➢ Inefficiency in design and not taking advantage of other systems will increase the cost of operations and inaccuracies in reporting.

3S Interfaces: Fuel Characteristics (5/6)

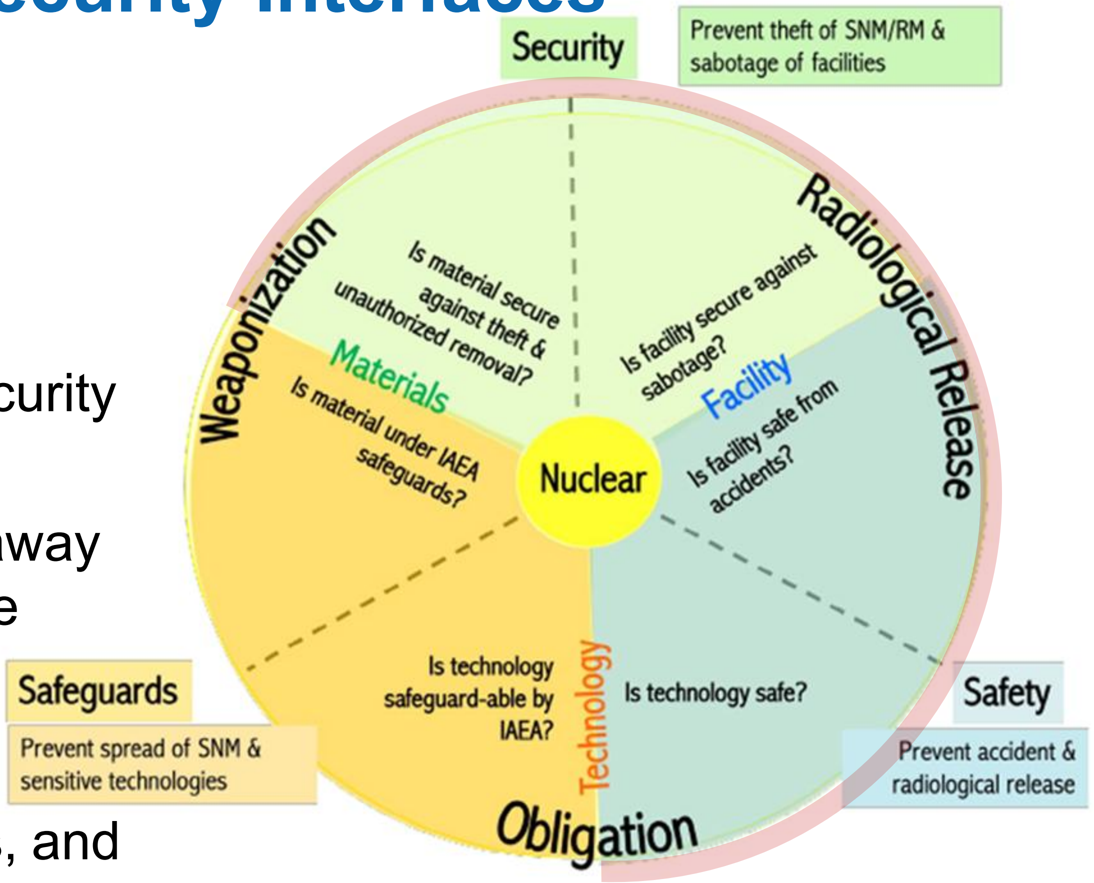
- TRISO fuel has benefits for all three S domains.
- Critical aspects of the interface in the GPBR-200:
  - Low core power density ensures passive evacuation of decay heat under severe accident conditions.
  - Large number of pebbles needed for 1 SQ (Significant Quantity of nuclear material), reducing proliferation pathways and reducing attractiveness of pebbles.
  - High degree of burnup at discharge reduces attractiveness of spent fuel for diversion to nuclear weapons, or theft.
- Consequences of not considering the interface:
  - Not recognizing early the potential opportunity for synergistically enhancing the effectiveness of security and safeguards approaches may incur future implementation costs.

3S Interfaces: Facility Layout Constraints for Equipment/Design Feature Installation (6/6)

- Careful consideration of how and where equipment and/or design features should be laid out as to not interfere with other two regimes.
- Critical aspects of the interface in the GPBR-200:
  - ➢ Fuel handling system is a complex, dynamic system moving fuel within a physically constrained geometry, which must:
    - i. ensure criticality safety during operation,
    - ii. provide security against theft or sabotage, and
    - iii. facilitate accountancy of fuel pebbles.
  - ➢ Design features must be decided upon early in design stage to avoid retrofitting.
- Consequences of not considering the interface:
  - ➢ Not considering this interface in the early design stages may incur costly retrofitting later in the operating life of the facility.

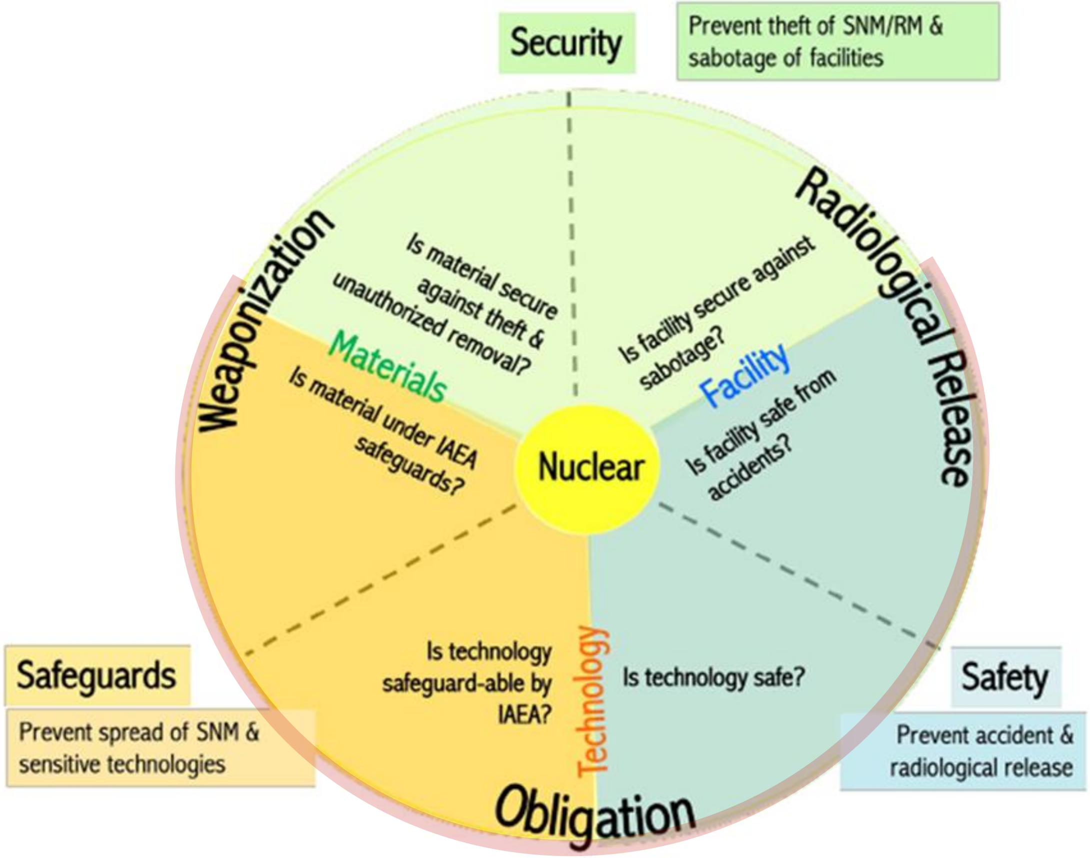
General Characteristics of Safety-Security Interfaces

- Focus on facility as a whole.
- Safety: "Is the facility safe from accidents?"
- Security: "Is the facility secured against sabotage?"
- Interfaces of safety systems with physical/cyber security protect the facility.
- Inherent safety features for the facility do not take away from the need to protect against intentional sabotage leading to radioactive release.
- Facility design plays a role:
  - ➢ in how radiation dose is minimized to responders, and
  - ➢ in how entrances and exits to and from vital areas are protected during emergencies.



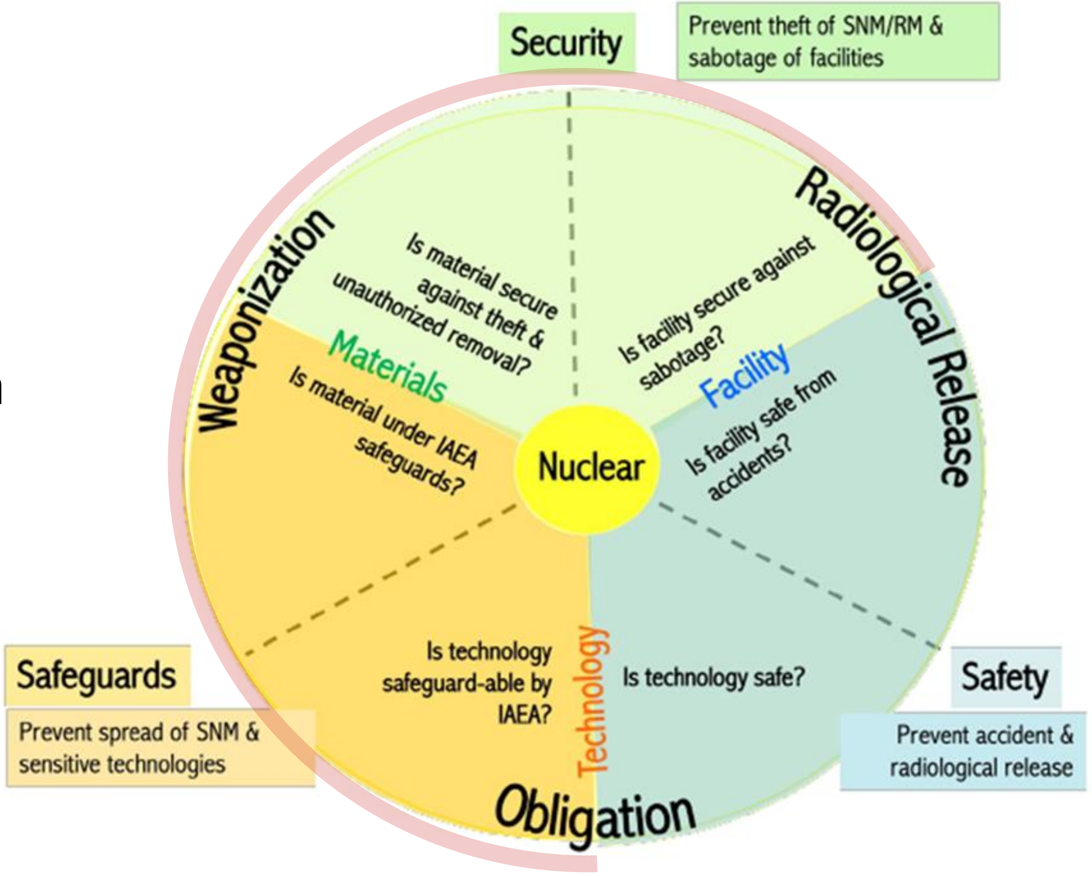
General Characteristics of Safety-Safeguards Interfaces

- Focus on technology employed in the facility.
- Safety: “Is the technology safe?”
- Safeguards: “Does the technology surrounding the nuclear material make the facility safeguardable?”
- Technology in fuel handling minimizes manual movement of fuel during safeguards inspections
- Technology of fuel cycle within the facility results in access restrictions, with implications for safeguards.
- Technical equipment failure has implications for both safety and safeguards.
- Technical features enhancing safety can also reduce the possibility of nuclear material diversion.



General Characteristics of Security-Safeguards Interfaces

- Focus on nuclear material in the facility.
- Security: "Is the nuclear material secure against theft?"
- Safeguards: "Is the nuclear material properly safeguarded?"
- Both regimes need C/S to prevent theft or diversion of fuel pebbles.
- Remote transmission of surveillance data should follow secure methods.
- Choice of TRISO pebbles enhances unattractiveness of nuclear material for proliferators and thieves.
- NMAC is used by security and safeguards; safeguards needs further verification.



Take-aways

- The GIF 3S sub-group set up a bottom-up case study of safety-security-safeguards interfaces in Gen IV reactors.
  - ➢ Many of the observations made in this study would apply generically to other advanced reactor types.
- The final aim: provide guidance to designers and vendors to apply a 3SbD approach to the development of a Gen IV AMR.
- A process highlight: 3SbD and PR&PP by Design are not new concepts.
- Need to foster security and safeguards by design; integrate the existing safety by design.
- Efficient path to ultimate goal of 3SbD: interim 3x2S analysis of the existing interfaces.
- Tighter 3S integration beneficial for all new reactor systems; especially for SMRs.

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Thank You!

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05 November 2025	Severe accidents in Sodium Fast Reactors: Safety Study Approach, Prevention and Mitigation by Design	Dr. Frederic Bertrand, Commissariat a l'Energie Atomique et aux Energies Alternatives (CEA), France
10 December 2025	Overview of Nuclear Energy Advanced Modeling and Simulation (NEAMS) tools to Accelerate the Development of Advanced Reactor Systems	Dr. Mauricio Tano-Retamales, Idaho National Laboratory, USA