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International Atomic Energy Agency
*Atoms for Peace and Development*

# Towards a Technology Neutral Nuclear Safety and Regulatory Framework: Applicability of IAEA Safety Standards to SMRs

## Questionnaire to SMR Vendors

Division of Nuclear Installation Safety
Department of Nuclear Safety and Security
International Atomic Energy Agency

# Presenters

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- Giacomo Grasso (Italian National Agency for New Technologies, Energy and Sustainable Economic Development)
- Gerd Brinkmann (BriVaTech Consulting)
- Shigenobu Kubo (Japan Atomic Energy Agency)
- David Holcomb (Oak Ridge National Laboratory)
- Carrie Fosaaen (NUSCALE)
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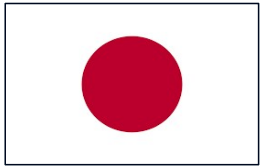
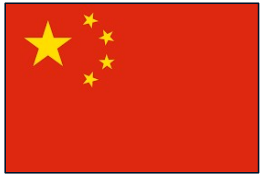




# Participants

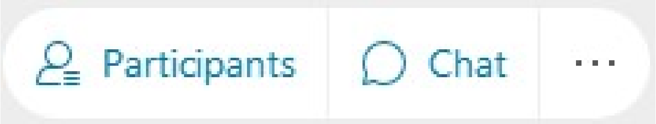
Approximately…

- 350 participants
- 115 Technology Developers and Research Organisations working on Water-cooled SMRs, Hight Temperature Gas-cooled reactors, Liquid Metal-cooled reactors, Molten Salt reactors, etc.
- 45 Regulatory Authorities, Technical Support Organisations and International Organisations
- 50 countries

# Agenda

| Topics | Presenter |
|---|---|
| Opening Remarks | Vesselina Ranguelova |
| The ongoing work to map applicability of IAEA Safety Standards to SMRs | Paula Calle Vives |
| An overview of the SMR questionnaire and relevant Safety Standards | Paula Calle Vives |
| Preliminary compilation exercise<br>Application to Lead Fast SMRs | Giacomo Grasso |
| Application to Sodium Fast SMRs | Kubo Shigenobu |
| Application to High Temperature Gas-cooled SMRs | Gerd Brinkmann |
| Application to Molten Salt SMRs | David Holcomb |
| Experiences from vendors that have already filled the questionnaire | Carrie Fosaaen<br>Fubing Chen |

- Duration of approximatively 1h30
- **Questions and Answers** session at the end
- Please **write your questions** in the chat (if we do not have time to address the question during the webinar we will reply by email)



# Opening Remarks

- Rapid development of SMR technologies, including innovative systems
- Regulators looking at some of these designs for the first time
- Need for more harmonization
- Engaging first with designers, then with regulators
- IAEA focus on nuclear safety activities for SMRs

# The ongoing work to map applicability of IAEA Safety Standards to SMRs

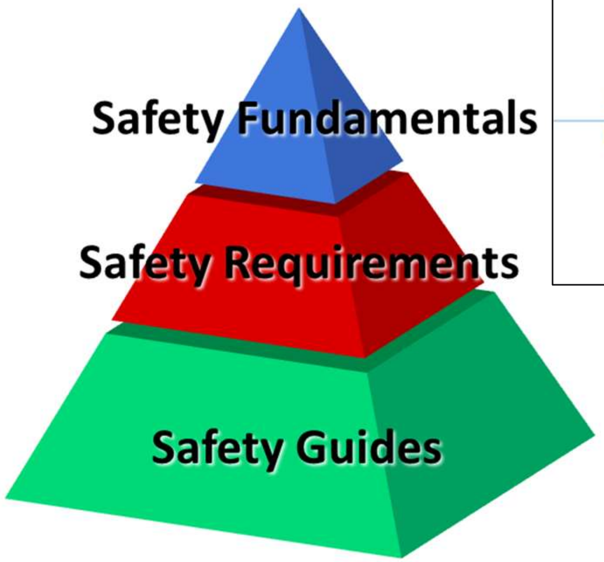
# The IAEA Safety Standards

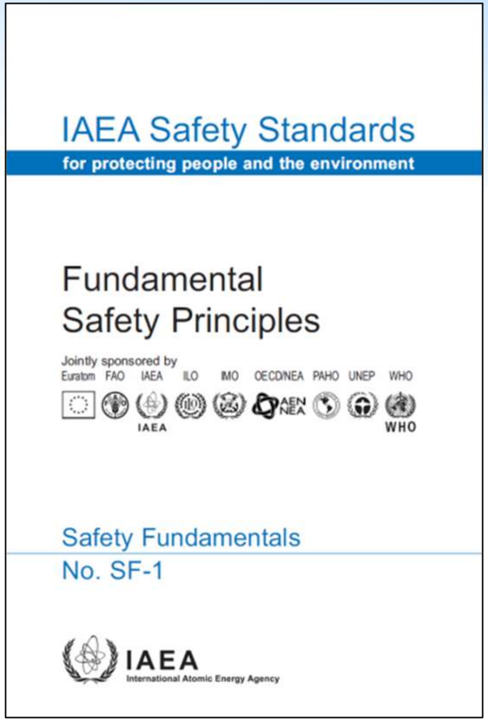
- Reflect an international consensus among Member States on what constitutes a high level of safety

- Include safety principles, requirements and associated recommendations and guidance

- Intended to be technology neutral (unintentionally influenced by technology specific issues of water cooled large reactors?)

- Growing interest among Member States in the design, development and deployment of SMRs with different types of coolant and neutron spectrum



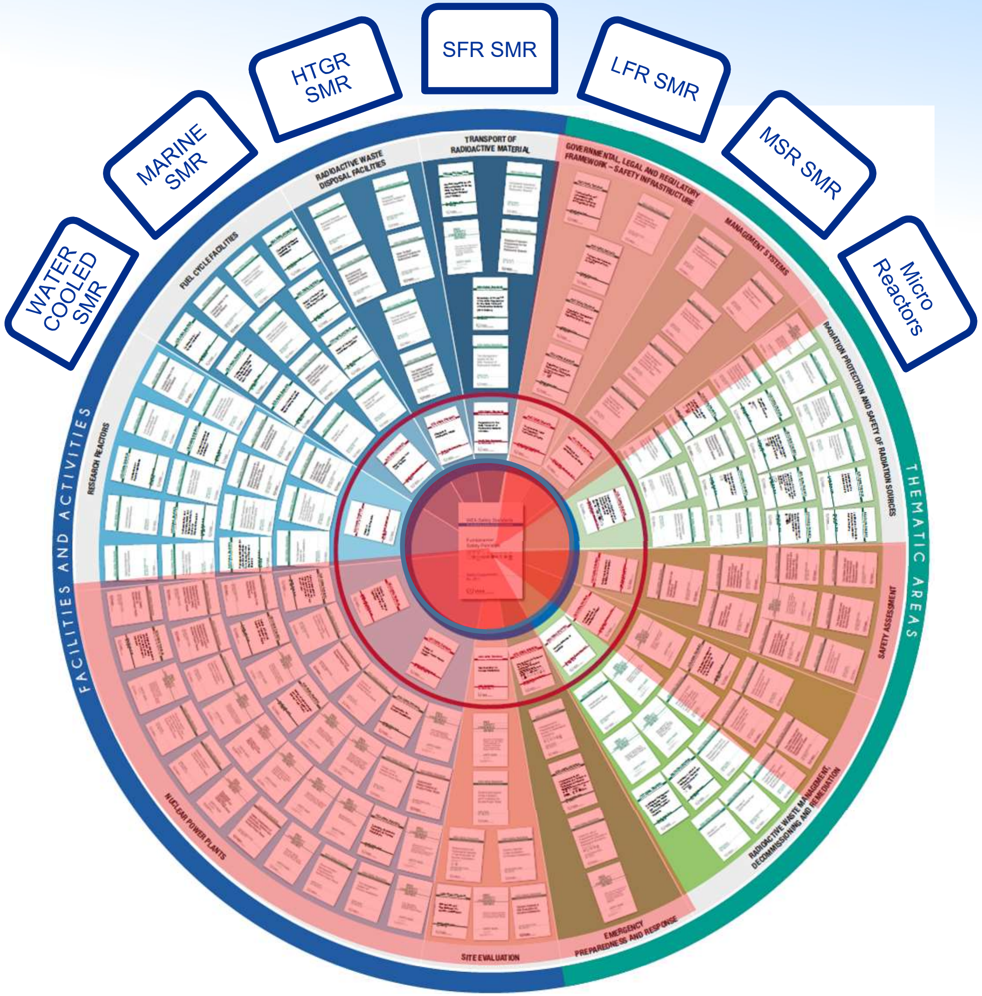



# Scope

- Developing a framework of application of IAEA safety standards to all types of SMR

- A high-level mapping of areas of the safety standards applicability to  SMRs

- Interface between safety security and safeguards will also be addressed



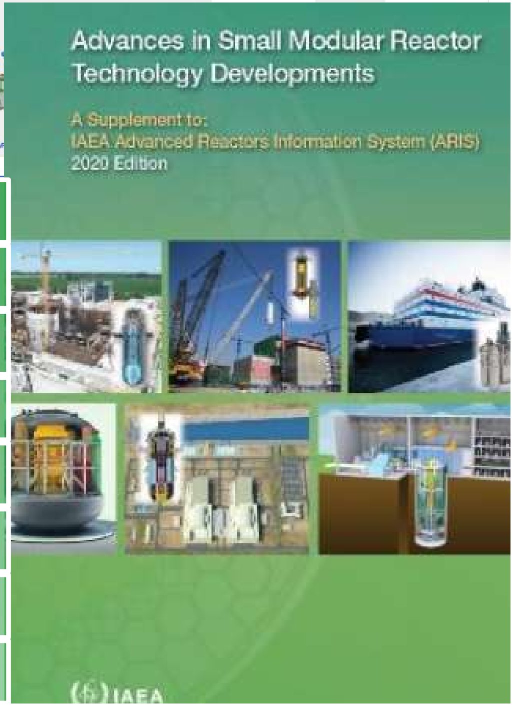
# Identification of Themes of Novelty

- Questionnaire for SMR vendors developed by the IAEA to identify areas of novelty in a comprehensive and systematic manner (differences with Gen III)

- The information collected will be used to identify **themes of novelty**

- Themes of novelty will be high level generic themes, some will be related to the specifies of SMRs, some will be related to the technology types (and can also be relevant to non-SMR technologies). A clear distinction will be made.

- Feedback from Regulators and from the Generation IV International Forum will be sought


- 25 Water Cooled
- 6 marine base
- 11 HTGR
- 2 SFR
- 7 LFR
- 1 GFR
- 10 MSR
- 6 micro

# Applicability of Safety Standards

- Review applicability of the safety standards to SMRs
  - ✓ Technology neutral and applicable to all types
  - ✓ Technology neutral in principle but their implementation may be different for some or all types
  - ✓ Technology specific and therefore may not be directly applicable to some or all types

- Addressing gaps through consideration of:
  - ✓ The need for new safety standard(s)
  - ✓ The need to develop technical document(s) to support implementation of current standards
  - ✓ Other options to support member states

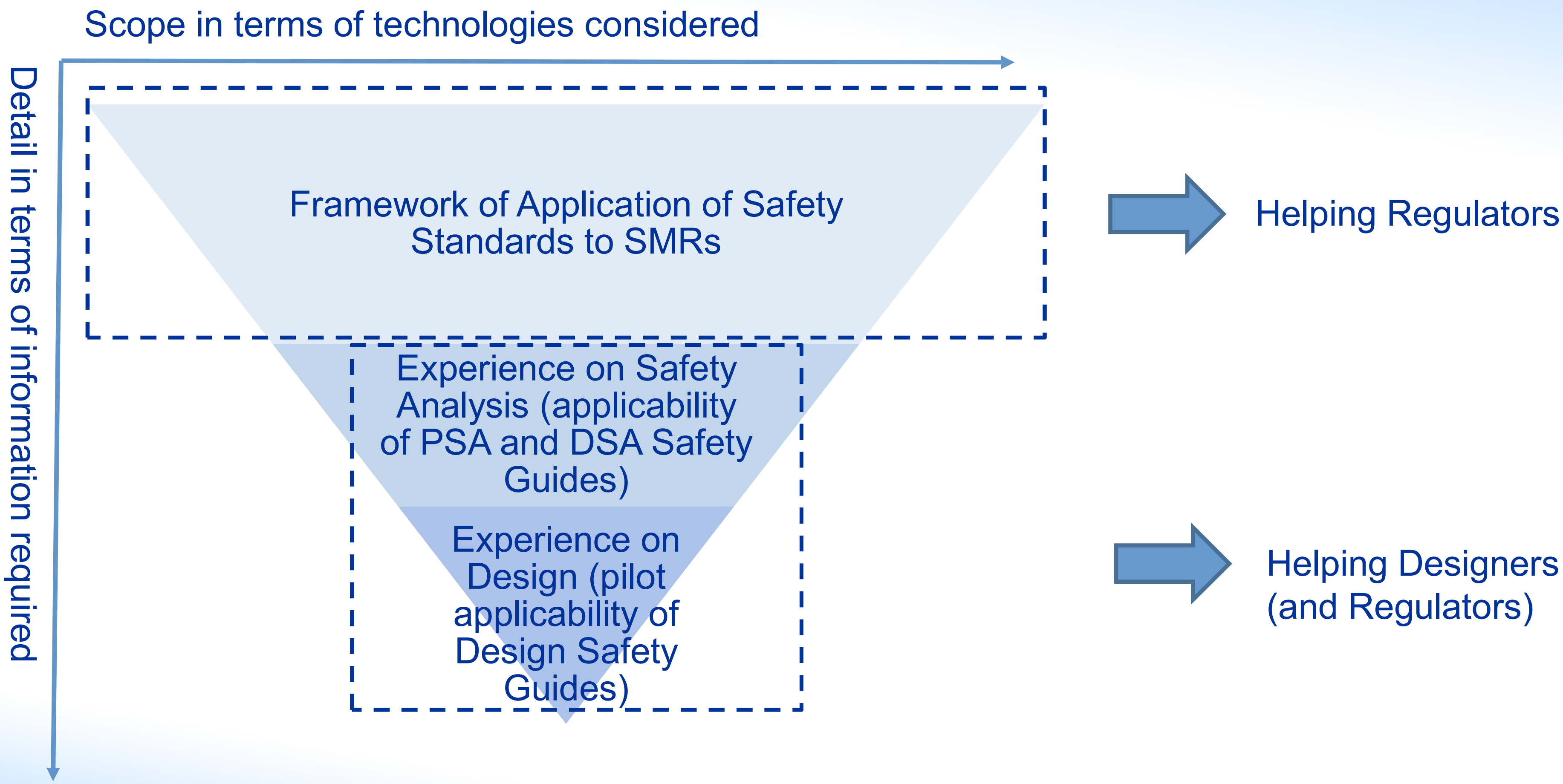
  Path for resolution will consider member states needs and nature of the issue

- Provide recommendations

**Intermediate Level (EXAMPLE)**

| INTENT | | IAEA Safety Standards (Requierments) | | Technology Neutral | Technology neutral approach but application may be different for SMRs | Technology Specific |
|---|---|---|---|---|---|---|
| Protect the public and the environment | Regulating safety | GSR Part 1 (Rev 1) | Legal and Regulation | | | |
| | Safety in the design, siting, construction and operation | SSR1 | Site Evaluation for Nuclear Installations | | | |
| | | SSR2/1 | Safety in Design for NPPs | | | |
| | | SSR2/2 | Comissioning and Operations | | | |
| | Managing safety | GSR Part 2 | LMfS | | | |
| | | GSR Part 4 (Rev 1) | Safety Assessment for Activities and Facilities | | | |

# Complementary IAEA Activities



# An Overview of the Questionnaire and Relevant Safety Standards

# The Development

**Concept**

- IAEA multidisciplinary team

**Test**

- Database on Advanced Nuclear Power Reactors (ARIS)
- SMR technology developers

**Review**

- Technology experts and development of generic responses

**Available at**

- https://www.iaea.org/nuclear-safety-and-security/department-of-nuclear-safety-and-security-webinars/towards-a-technology-neutral-safety-and-regulatory-framework-applicability-of-iaea-safety-standards-to-smrs-questionnaire-to-smr-vendors


A key input to this publication is the identification of relevant **areas of novelty of SMRs**. This will be based on the information obtained through a questionnaire that will be distributed to SMR vendors that are mentioned in the

# The Contents

- How the SMR is sited
- The design
  - Fission products retention barriers
  - Design safety approach
  - Design of SSCs
  - Radiation protection in the design
  - Decommissioning in the design
- The level of standardisation in the design needed within the deployment of SMR series
- The construction
- The commissioning
- The differences between the design, construction and commissioning of the First of a Kind (FOAK) SMR and the N of a Kind (NOAK)
- The operating philosophy
- The safety assessment including:
  - Typical boundary sequences leading to core damage (or equivalent) and releases;
  - Overview of the source terms
- The emergency preparedness and response
- The fuel cycle and waste management
- The interface between safety, safeguards and physical security
- The regulatory practices and hold points

Areas of Novelty

# Examples of Relevant Safety Standards

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## Siting (Q1)

IAEA Safety Standards
for protecting people and the environment
Site Evaluation for Nuclear Installations
Specific Safety Requirements
No. SSR-1
IAEA International Atomic Energy Agency

NS-G-1.5 (under revision), NS-G-1.6, NS-G-3.1, NS-G-3.2, NS-G-3.6, SSG-9, SSG-18, SSG-21, SSG-35

## Design-Construction (Q2-5, 7, 13)

IAEA Safety Standards
for protecting people and the environment
Safety of Nuclear Power Plants: Design
Specific Safety Requirements
No. SSR-2/1 (Rev. 1)
IAEA International Atomic Energy Agency

NS-G-1.7, NS-G-1.11, NS-G-1.13, SSG-30, SSG-34, SSG-38, SSG-39, SSG-51, SSG-52, SSG-53, SSG-56

## Com. - Operation (Q6, 7, 8)

IAEA Safety Standards
for protecting people and the environment
Safety of Nuclear Power Plants: Commissioning and Operation
Specific Safety Requirements
No. SSR-2/2 (Rev. 1)
IAEA International Atomic Energy Agency

NS-G-2.1 to NS-G-2.6, NS-G-2.8, NS-G-2.14 (all under revision), SSG-13, SSG-27 (under revision), SSG-28, SSG-48, SSG-50

## Emergency (Q 11)

IAEA Safety Standards
for protecting people and the environment
Preparedness and Response for a Nuclear or Radiological Emergency
Jointly sponsored by the FAO, IAEA, ICAO, ILO, IMO, INTERPOL, OECD/NEA, PAHO, CTBTO, UNEP, OCHA, WHO, WMO
General Safety Requirements
No. GSR Part 7
IAEA International Atomic Energy Agency

GSG-2, GS-G-2.1

## Waste (Q12)

IAEA Safety Standards
for protecting people and the environment
Predisposal Management of Radioactive Waste
General Safety Requirements Part 5
No. GSR Part 5
IAEA International Atomic Energy Agency

SSG-15 (under revision)

## Assessment (Q2, 9, 10)

IAEA Safety Standards
for protecting people and the environment
Safety Assessment for Facilities and Activities
General Safety Requirements
No. GSR Part 4 (Rev. 1)
IAEA International Atomic Energy Agency

GS-G-4.1 (under revision) SSG-2 (Rev. 1), SSG-3 and 4 (under revision), SSG-25

## Regulation (All, Q14)

IAEA Safety Standards
for protecting people and the environment
Leadership and Management for Safety
General Safety Requirements
No. GSR Part 2
IAEA International Atomic Energy Agency

GS-G-3.1 (under revision) GS-G-3.5

IAEA Safety Standards
for protecting people and the environment
Governmental, Legal and Regulatory Framework for Safety
General Safety Requirements
No. GSR Part 1 (Rev. 1)
IAEA International Atomic Energy Agency

GSG-12 GSG-13, SSG-12, SSG-16 (Rev.1)

# Commercial Issues

- It not our intention to publish your questionnaire responses
- There are options for confidentiality agreements
- Your feedback on how to facilitate filling the questionnaire is important for us – eg. more directed (Y/N) questions?
- The questionnaire will still be improved in the days after the webinar

**Q3A: Please identify areas of novelty in the design safety approach. Examples of areas of novelty are provided below.**

- Areas of novelty in the definition of safe state for this design (eg. indicate status of fuel, coolant, plant systems). Differences in the classification of safety systems, for example, for equivalent systems in LWR vs your design is there any difference in classification? If possible, provide a list of systems that are needed for DBA (no need to indicate classification).
- Areas of novelty in the implementation of defence in depth (DiD) in terms of
  - safety functions
  - objectives of each level of DiD (e.g. avoid core damage, avoid large release, etc.)
  - the plant states considered in the design, particularly the definition of severe accident
  - systems shared between levels of DiD
  - any issue that you believe make the implementation of concept of DiD as described in the safety standards (SSR2/1) not fully applicable to your design
- Faults/PIE/event sequence typically considered in Gen III NPPs that are physically impossible for this design and key faults/PIE/event sequence not relevant to Gen III NPPs that you have considered in your design
- Areas of novelty in the scope of the internal hazards and external hazards considered in the design of the SMR
- Any other areas related to design safety approach that you consider novel?

**Vendor Response to Q3A**

*Do you define a safe stable state for DBA? Is this definition different from cold shutdown?*

*Do you implement safety functions in layers of defense? Is this in line with the five levels of DiD?*

*For non-water-cooled reactor, how do you define severe accident? Are there specific design provisions to deal with these accidents?*

*Do you consider all Gen III NPP faults/PIE/event sequences?*

*Do you consider new faults/PIE/event sequences in your design?*

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# Preliminary Compilation Exercise
(Database on Advanced Nuclear Power Reactors, ARIS)

# Application to Lead Fast Reactors

# Preliminary compilation exercise

- Before involvement of the LFR Vendors to provide relevant information to feed the development of the technology neutral framework, a preliminary compilation exercise has been performed based on information available in ARIS
- The surveyed LFR systems are
  - the Hydromine's LFR-AS-200
  - the LeadCold's SEALER-UK
  - the Westinghouse's Lead Fast Reactor
- An additional questionnaire has been compiled for a «generic LFR SMR» to point out elements not covered in the above designs but considered in other concepts

# General considerations

- The information in ARIS is not always sufficient for an exhaustive reply, so integration by the Vendors would be very beneficial
- Although it is understood that all the reviewed systems have not yet initiated a licensing process, it is believed that a study of (and possibly a comparison with) the existing regulatory framework has been performed, whose outcomes would be very useful in this process

# Example 1
# Novel systems

The ARIS entries for all designs extensively discuss the main reactor components, whose role in protecting the fission products retention barriers can be understood.

Less information is provided instead on additional novel systems that are required, e.g. in normal operation to protect from Lead corrosion, whose description could be beneficial to complement the picture for a technology neutral framework.

**Vendor Response to Q2**

[…]

***Fundamental safety functions and associated "front line" safety systems needed to protect the barriers***

Associated front line safety systems (and inherent safety characteristics) to protect the barriers.

| Barrier | In normal operation | In accident conditions |
|---|---|---|
| Fuel matrix | | Inherent negative Doppler coefficient |
| Fuel rod | Corrosion protection means (coating)<br>Flow channels plugging prevention (coolant purification) | Inherent negative reactivity coefficients;<br>Shutdown systems;<br>Decay heat removal system |
| Lead coolant | | High coolant boiling point;<br>Guard vessel |
| Reactor coolant boundary | Corrosion protection means (Oxygen control) | Inherent negative reactivity coefficients<br>Shutdown systems;<br>Decay heat removal system;<br>Pressure relief system;<br>Coolant chemical inertness |
| Confinement building | | High coolant boiling point;<br>Coolant chemical inertness |

***Novel systems needed to protect the fission product retention barriers***

- buoyancy-driven shutdown rods
- buoyancy-driven shutdown devices and their passive actuation mechanism based on overtemperature
- guard vessel
- DHR system
- alumina coating
- coolant chemistry control system
- coolant purification system

# Example 2
# Faults/PIE/Event sequences

In the ARIS entries, only limited information is provided on the possible faults, postulated initiating events and event sequences specific to an LFR and the proposed design.

It is believed however that all the designs were set on the basis of a thorough analysis of such faults, PIE and event sequences, so that their more extensive discussion would be beneficial to provide an exhaustive overview of the threats to be considered by a technology neutral framework.

**Vendor Response to Q3A**

[…]

***Faults/PIE/event sequences differing from those of a Gen-III NPP***

The use of molten Lead makes its freezing in cold parts of the plant – upon loss of control – a potential threat (although the safety relevance is still to be verified, possibly depending on the primary system layout).

The corrosion of structures introduces the possibility of plugging of coolant channels, with flow blockage of a fuel assembly (due to the use of wrapper tubes which prevent cross-flow, although facilitating detection) a potentially safety related event.

The reactor coolant system being not pressurized, ejection of a CRA is impossible. Additionally, and in combination with the high Lead boiling point and the use of a guard vessel, the loss of coolant accident (LOCA) is also made impossible.

The inclusion of the steam generators within the reactor vessel makes the rupture of one of its tubes a significant event.

Void ingress in the core (e.g., fission gases by clad rupture or steam/water by steam generator tube rupture, but not coolant boiling due to the very high boiling point) could introduce positive reactivity insertions. Core compaction (e.g., due to transmitted seismic forces) would also introduce positive reactivity.

In advancing accident sequences, no coolant-structure chemical interaction occurs that generates a potential chemical hazard.

The higher enrichment necessary for criticality makes fuel reaggregations (in case of core degradation) more prone to criticalities.

[…]

# Example 3
# Accident management

Some designs call for the elimination of off-site emergency responses, others for simple/ reduced emergency preparedness requirements (i.e., protective measures for the public limited in area and time).

Besides this information, it would be beneficial to indicate also which are the severe plant conditions considered for accident management, and the associated accident management measures, in order to provide an exhaustive overview of the peculiarities in this area.

**Vendor Response to Q3A**

[…]

***Novelty in the implementation of defence in depth***

The objective of DiD Level 4 is strengthened by targeting avoidance of core damage (i.e., significant core degradation) to a degree that might imply early or large releases such to require off-site emergency response. This pairs with the definition of severe accident as core degradation without significant extent.

At Level 5, thus, design provisions are sought to confine a degraded core for indefinite time, so that only on-site responses are considered for accident management in the long term.

[…]

**Vendor Response to Q8**

[…]

***Novelties in emergency and severe accident management strategies***

On-site severe accident management strategies rely on the forgiving behaviour of the plant and the provisions for passive reactor shutdown and decay heat removal, minimising operators' actions. The grace time of the plant delays any requested action by 72 hours, which are limited to refilling cooling water to the DHR system 1 through dedicated engineered provisions with access from outside the reactor building, and to replacing the DC power sources for monitoring by dedicated banks stored on site. Support from off-site for the provision of portable equipment is required only after several days.

Off-site accident management strategies involving the population living in the surrounding areas is excluded coherently with the safety objective of exclusion of large releases.

# Comments and remarks

- Some information available in the public domain suggested that some information not present in ARIS could be available to the Vendors
  - comments have been introduced in the precompiled questionnaires to point out such parts
- In some key questions, the ARIS provided elements that could have provided only a partial view
  - these were not reported in the reply to stimulate the Vendors to providing more comprehensive information

# Application to Sodium Fast Reactors

# Typical SFR Characteristics

| | |
|---|---|
| Core and Fuel | • Fast neutron system<br>• High fissile density<br>• High fuel burn up |
| Coolant | Sodium<br>✓ High thermal conductivity<br>✓ High boiling point<br>883 degree C at atmospheric pressure<br>✓ High chemical reactivity |
| System pressure | • Nearly atmospheric pressure |
| Environment | • High temperature (300 to 600 degree C)<br>• Fast neutron<br>• Sodium |

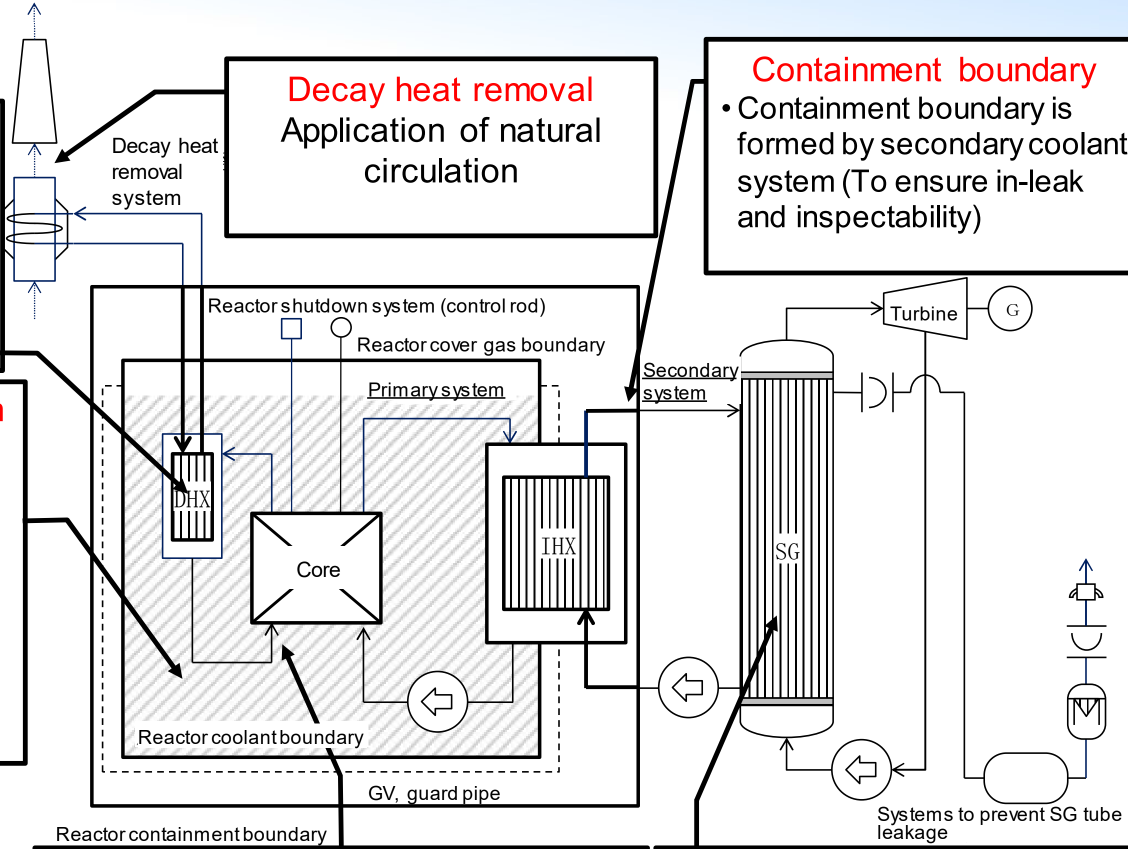
# Typical SFR Reactor Coolant System

**Operational condition**
High temperature, low pressure (Stress due to thermal expansion, creep, temperature change)

**Primary coolant system**
- Cover gas boundary
- Coolant level maintenance under normal operation
- Coolant level maintenance by GV (& guard pipes)

**Decay heat removal**
Application of natural circulation

**Containment boundary**
- Containment boundary is formed by secondary coolant system (To ensure in-leak and inspectability)




**Coolant**
- Characteristics of Na (High boiling point, risk of freezing, etc.)
- Na leakage prevention and detection

**Chemical reaction**
Na-water reaction countermeasure (Detection, blow, pressure release, reaction products treatment, etc.)

# Enhancement of Core Safety

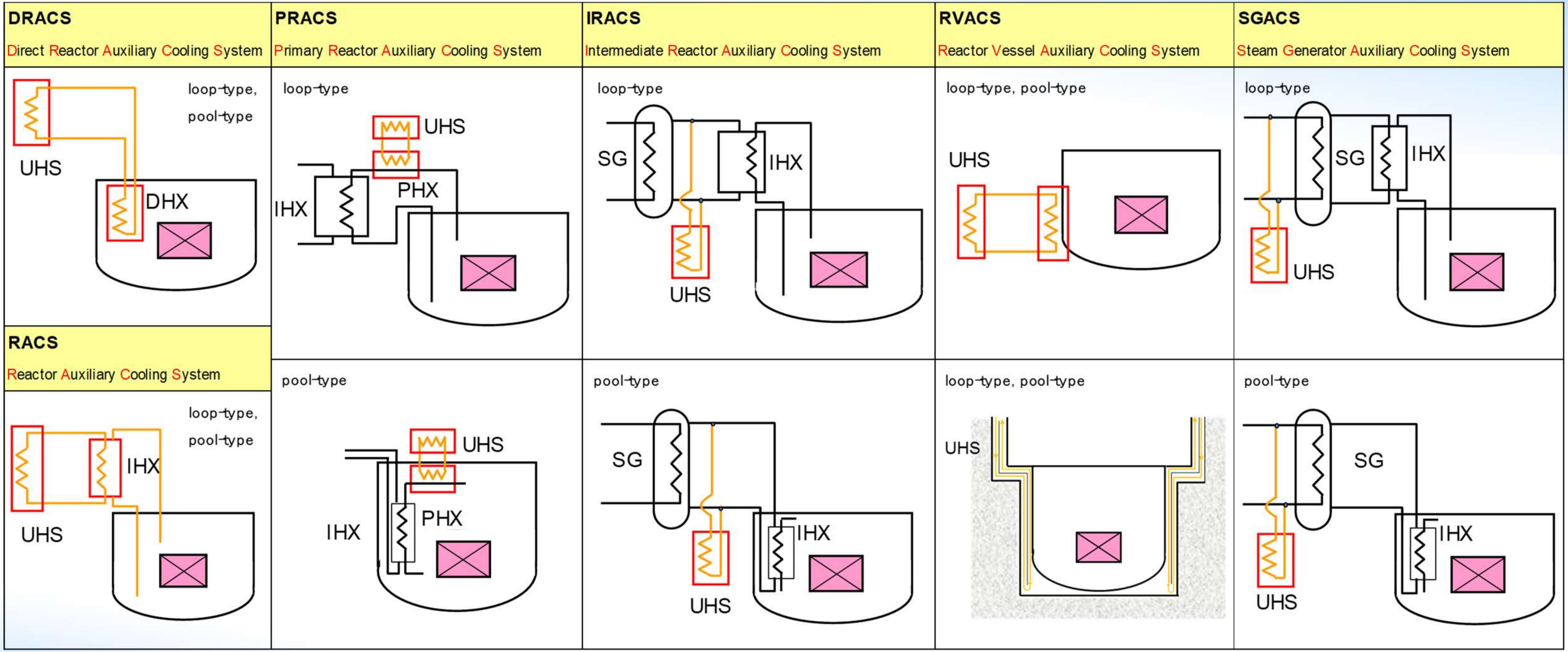
**Inherent Reactivity Feedback**

- Doppler Effect
- Fuel Axial Expansion
- Core Radial Expansion
- Control Rod Driveline Expansion
- ……

**Passive Reactivity Reduction Mechanisms**

- Passive control rod insertion by gravity achieved by their release due to magnetic property change of temperature sensing alloy when the reactor coolant temperature reaches the Curie-Point
- Passive control rod insertion by gravity achieved by thermal expansion-based release of control rods
- Hydraulically levitated absorbers that lower a neutron absorber into the core region when primary sodium flow is reduced due to pump trip.
- Gas Expansion Module (GEM) that increases neutron leakage from the core when primary sodium flow is reduced due to pump trip
- ……

# Decay Heat Removal System




DHX：heat exchanger of DRACS IHX：intermediate heat exchanger PHX：heat exchanger of PRACS SG：steam generator UHS：ultimate heat sink
Orange and red lines show decay heat removal systems.

# SFR example; response to the questionnaire

## Q2: Key fission products retention barriers, safety functions needed to protect the barriers (1/4)

- **Typical key fission products retention barriers for a SFR consist of:**
  - fuel cladding tubes
  - a reactor vessel with a roof slab, reactor coolant boundary and cover gas boundary
  - a containment system that houses the reactor coolant boundary.
- **Typical fundamental safety functions and associated "front line" safety systems**
  - Reactivity control:
    - Active control rod operation system
    - Inherent reactivity feedback such as doppler effect, fuel axial thermal expansion reactivity, core support plate thermal expansion reactivity
  - Reactor shutdown:
    - Active reactor shutdown systems such as rapid control insertion
    - Passive negative reactivity insertion mechanisms such as Curie point electromagnet

# SFR example; response to the questionnaire

## Q2: Key fission products retention barriers, safety functions needed to protect the barriers (2/4)

- **Typical fundamental safety functions and associated "front line" safety systems (Continued)**
  - ◆ Heat removal from core
    - ☐ Active systems such as dedicated sodium loops connected to air coolers with pumps and blowers, i.e., DRACS; Direct Reactor Auxiliary Cooling System, PRACS; Primary Reactor Auxiliary Cooling System, IRACS; Intermediate Reactor Auxiliary Cooling System.
    - ☐ These systems use the atmosphere as ultimate heat sink and can be designed as passive systems.
    - ☐ RVACS; Reactor Vessel Auxiliary Cooling System, can be designed to remove the decay heat from the outer surface of the safety vessel. This system also uses the atmosphere as ultimate heat sink and can be designed as passive system.
  - ◆ Confinement of radioactive material
    - ☐ Various configuration to ensure acceptable leak rate such as steel lined concrete building, safety vessel, and top dome or protective cover which surround the penetrations on the reactor roof

# SFR example; response to the questionnaire

## Q2: Key fission products retention barriers, safety functions needed to protect the barriers (3/4)

- **Typical SFR 'novel' features**
  - ◆ Measures to control and shut down the reactor core
    - ☐ Inherent reactivity of a core, such as fuel thermal expansion and radial expansion of a core
    - ☐ Utilization of passive reactor shutdown or reactivity feedback such as Curie point electromagnet, hydraulic suspension rods, gas expansion module
  - ◆ Measures to remove decay heat
    - ☐ Utilization of passive decay heat removal such as dedicated sodium loops connected to air coolers, remove the decay heat from the outer surface of the safety vessel to the atmosphere
  - ◆ Preventive measures against coolant leakage from a reactor coolant boundary
    - ☐ Coolant level maintenance by using static components such as a guard vessel, no need for depressurization and coolant injections

# SFR example; response to the questionnaire

## Q2: Key fission products retention barriers, safety functions needed to protect the barriers (4/4)

- **Typical SFR 'novel' features (Continued)**
  - Measures to limit radioactive materials release
    - in-vessel retention of degraded core material
    - radioactive material retention in a liquid sodium pool, and plate out by sodium aerosol
  - Measures against sodium chemical reactions
    - Early detection of sodium leak, and mitigation of leaked sodium combustion
    - Early detection of sodium-water reaction around steam generators, pressure relief, isolation of a water-steam system, and treatment of sodium-water reaction products
  - SFR novel auxiliary/support systems important for safety
    - Sodium heating system to prevent loss of fundamental safety functions by sodium freezing

# SFR example; response to the questionnaire

## Q3A: Novelty in the design safety approach (1/3)

- **Definition of safe state**
  - To prevent sodium from freezing, reactor coolant systems should keep reactor shutdown state at around 200 degree C.
- **Implementation of defence in depth**
  - Abnormal events related to the reactor core integrity can be generally grouped into the following: abnormality in the reactor coolant flow (LOF: Loss Of Flow), in the reactor power (TOP: Transient Over Power), and in the heat sink (in the heat transport in the secondary or tertiary coolant systems)(LOHS: Loss Of Heat Sink).
  - Event sequences that can lead to core damage can be generally grouped into two: reactor shutdown failure type (ATWS type) and loss of decay heat removal type (LOHRS type).
  - Safety features that combine active and passive mechanisms with redundancy and diversity are provided as DiD levels 2 to 4 to address these postulated events and event sequences so that core damage can be prevented. Key safety functions consist of reactor shutdown and decay heat removal.
  - Typical reactor shutdown systems are equipped with independent two systems that shut down the core rapidly as well as passive core shutdown mechanisms. SFR-SMRs will much rely on inherent reactivity features to demonstrate core damage prevention capability.

# SFR example; response to the questionnaire

## Q3A: Novelty in the design safety approach (2/3)

- **Implementation of defence in depth (Contined)**
  - Core damage events resulting from ATWS type evet sequences have been historically considered for large-scale SFRs. Based on this, SFR-SMRs can be designed to retain molten core materials inside the reactor vessel (IVR: In-Vessel Retention), as a mitigation measure for DiD level 4. Another approach is to empathize inherent reactivity feature, which has been demonstrated by EBR-II, to shut down the core so that core degradation can be prevented.
  - To address LOHRS type event sequences, SFRs can use a various configurations of decay heat removal measures, as well as natural circulation of coolant sodium and air, to prevent significant core degradation.
  - SFRs are designed to have containment functions that limit radioactive material releases including FP gas into the atmosphere.

# SFR example; response to the questionnaire

## Q3A: Novelty in the design safety approach (3/3)

- **Faults/PIE/event sequence**
  - ◆ Even reactor coolant boundary fail, depressurization and coolant boiling cannot happen, thus no loss of coolant accident (LOCA) occurs because of the high-temperature, low-pressure systems of SFRs.
  - ◆ If reactor shutdown fails, local positive sodium void reactivity insertion may occur, depending on the design. Generally, the SFR designs will have features that would help the prevention of sodium boiling (as described in Q2). Even if core damage happen due to sodium boiling and local positive sodium void reactivity, in-vessel retention (IVR) of degraded core materials is achievable by limiting total sodium void reactivity (SVR). In general, SVR of SFR-SMR is negative or sufficiently small to prevent core damage or to achieve IVR.
  - ◆ Combustion of leaked sodium, and sodium-water reaction caused by sodium leak from heat transfer tube of a steam generator can adversely affect the containment barrier of the core.
- **Internal hazards and external hazards**
  - ◆ To ensure the integrity of components containing sodium, measures against internal and external hazards are typically taken in SFR designs.
    - ☐ Typical internal hazards: combustion of leaked sodium, internal flooding in water-steam systems
    - ☐ Typical external hazards: earthquake, tsunami, flooding, and aircraft crash

# SFR example; response to the questionnaire

## Q3B: Novelty in the design of structures, systems and components (SSCs) (1/2)

- **Safety classification of SSCs**
  - ◆ Major safety functions for SFR are reactor shutdown, decay heat removal, safety vessel to maintain sodium level in the reactor vessel and containment as explained in the previous questions. Importance of measures against sodium chemical reactions, auxiliary or support systems such as electric power supply, sodium heating depends on the design.
- **Fuel design**
  - ◆ To ensure design appropriate for high temperatures and the sodium environment, fuels are made from proven materials such as austenitic or ferritic steel for the cladding materials, U-Zr alloy or $(U\text{-}Pu)O_2$ for fuel, and proven material specifications are used. (Some SFR-SMRs may use new materials or new techniques.)

# SFR example; response to the questionnaire

## Q3B: Novelty in the design of structures, systems and components (SSCs) (2/2)

- **Component design**
  - ◆ To ensure design appropriate for high-temperature low-pressure systems as well as sodium environment, high temperature structure design has referred to established codes and standards such as ASME. (Some SFR-SMRs may use new materials or new techniques.)
  - ◆ There is a possibility that SFR components (e.g., a reactor vessel, heat exchangers, pumps, and coolant purification systems) have been developed and are ready for use but used differently—for example, a pump is combined with a heat exchanger—or that some components have been newly developed.
- **SSCs for multi-module**
  - ◆ If an SFR-SMR is a multi-module, facilities such as control rooms, fuel treatment facilities, and maintenance facilities, can be designed as shared facilities between the modules.
- **Passive systems**
  - ◆ There are many passive systems that have been developed for SFRs: decay heat removal using natural circulation, and reactor shutdown or reactivity control by using passive devices. Examples include direct reactor auxiliary cooling system called DRACS, RVACS; Reactor Vessel Auxiliary Cooling System, and self-actuated shutdown system called SASS.

# SFR example; response to the questionnaire

## Q3C: Novelty in the radiation protection

- Based on design and operation experiences, SFRs are provided with measures for reducing radiation dose for site workers and mitigating radioactive material releases during normal operation.
    - ◆ During normal operation, random fuel pin failure will be detected early to identify the failed fuel and remove it from the core while collecting released FP gas in a dedicated gaseous wastage treatment system.
    - ◆ Radioactive corrosion product in the primary coolant will be collected during the normal operation in a dedicated impurity treatment system.
    - ◆ During an in-service period, components containing sodium will be remotely inspected and maintained to reduce radiation dose to site workers.

## Q3D: Novelty in decommissioning

- Decommissioning work would typically be conducted on the basis of experiences from SFR decommissioning in the past, such as remote removal of fuels immersed in sodium, treatment of radioactive and non-radioactive sodium, and decontamination and treatment of irradiated components.

# Application to High Temperature Gas-cooled Reactors

# High Temperature Gas Reactors ( Modular HTGRs)

The major safety goal for modular HTGRs is that significant fuel failure should neither result from postulated design basis accidents (DBAs) and as far as possible nor from other events (e.g. design extended conditions (DECs))

This safety goal drives the design features that define modular HTGRs

# Typical Design Features for Modular HTGRS

High quality ceramic coated- particle fuel of proven design, which adequately retains its ability to contain radioactive fission products over the full range of operating and accidental conditions

Single- phase inert helium coolant, with no heat transfer limits that would be associated with phase change

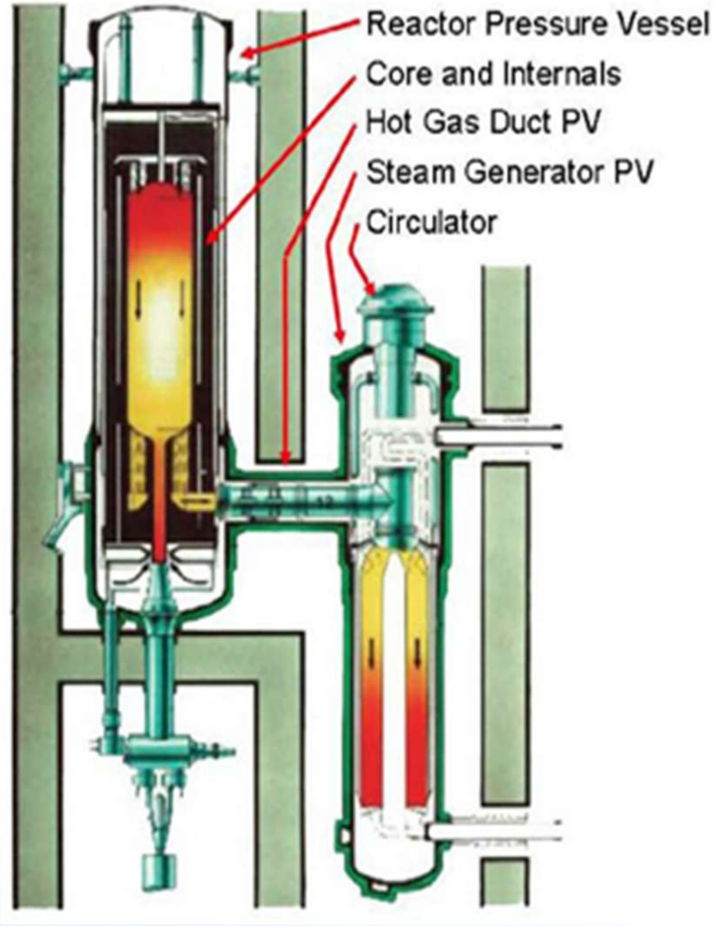
Fuel temperature margins and negative temperature-reactivity coefficients sufficient to accommodate any foreseeable reactivity insertions without damage to the fuel

Post shutdown decay heat removal achievable through conduction, natural convection and radiation heat transfer, limiting maximum temperatures to values consistent with fuel and structural design limits. In typical HTGRs designs a reactor cavity cooling system (RCCS) is used to remove the decay heat under accident conditions with or without the presence of coolant in the core, and in design extension conditions

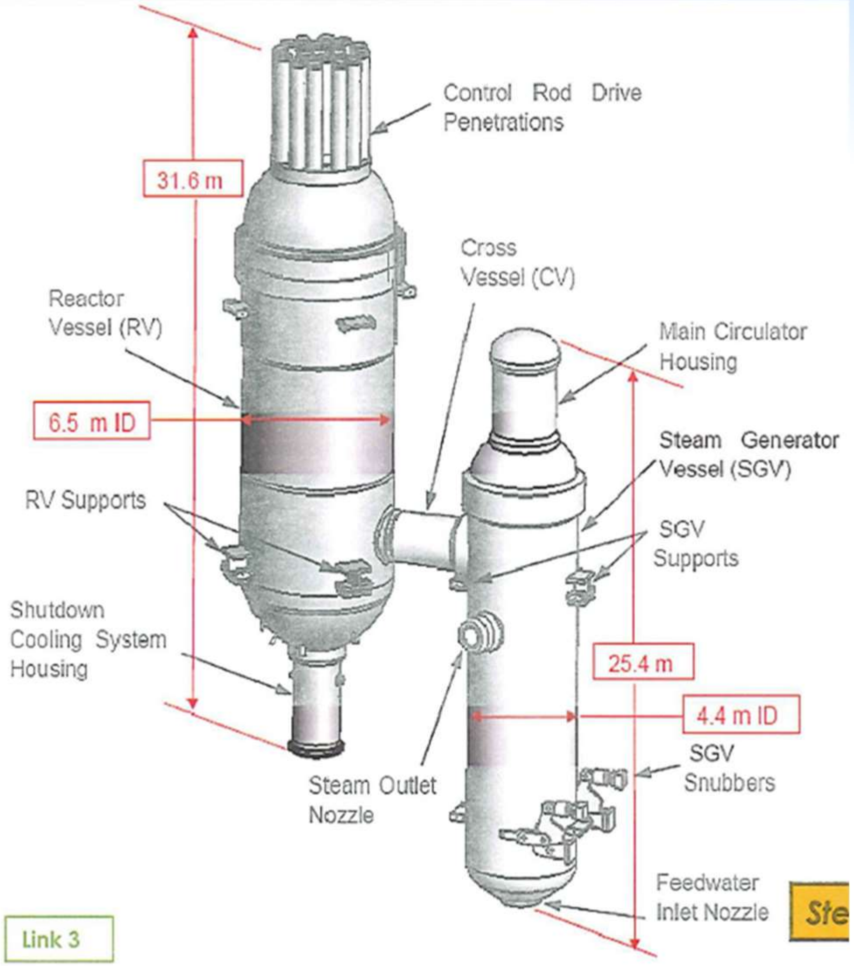
Ceramic core – combination of low core power density, large reactor core and internals heat capacity, high core thermal conductivity and large fuel thermal margins, resulting in a very long time (days) for evolution of response to loss of normal shutdown functions without protective actions

# Typical Layout of a Modular HTGR

## Pebble Bed Reactor




## Block Reactor

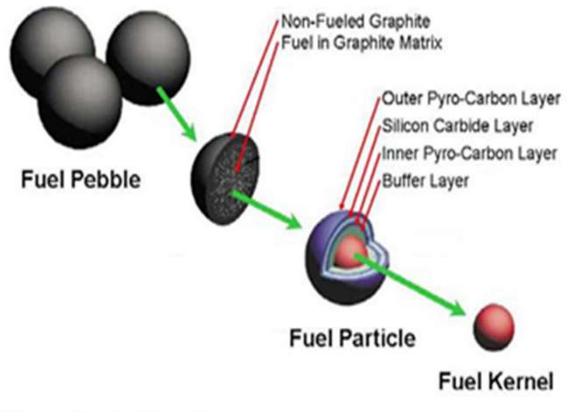


## HTGR example; response to the questionnaire
## Q2: key fission products retention barriers (1/3)

**Key fission products retention barriers for the reactor:**

**- Coated fuel particles**

The fuel elements with coated particles serve as the first barrier. The fuel elements used have been extensively tested as part of the demonstration to be capable of retaining fission products within the coated particles under temperatures around 1600 °C which is not expected for any conceivable accident scenarios



## HTGR example; response to the questionnaire
## Q2: key fission products retention barriers (2/3)

**- Primary pressure boundary**

The second barrier is the primary pressure boundary which consists of the pressure vessels of the primary components, e.g. reactor pressure vessel, steam generator pressure vessel, hot gas duct pressure vessel

The primary pressure boundary is a good confinement of radioactivity.
For HTGRs with temperatures up to 750°C the state of the art of LWRs can be used for safety and licensing, that means the HTGRs can assume the same break postulations

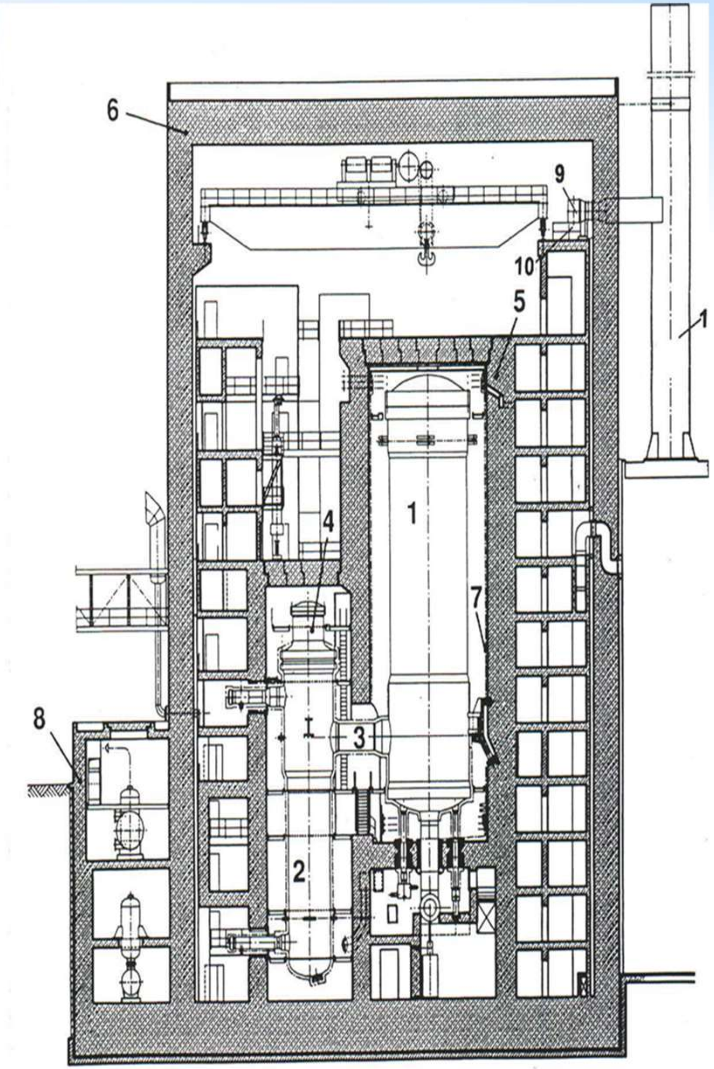
- no through wall cracks in vessels
- 2A breaks in connected piping with known probability

## HTGR example; response to the questionnaire
## <u>Q2: key fission products retention barriers (3/3)</u>

**- Vented low-pressure containment (confinement)**

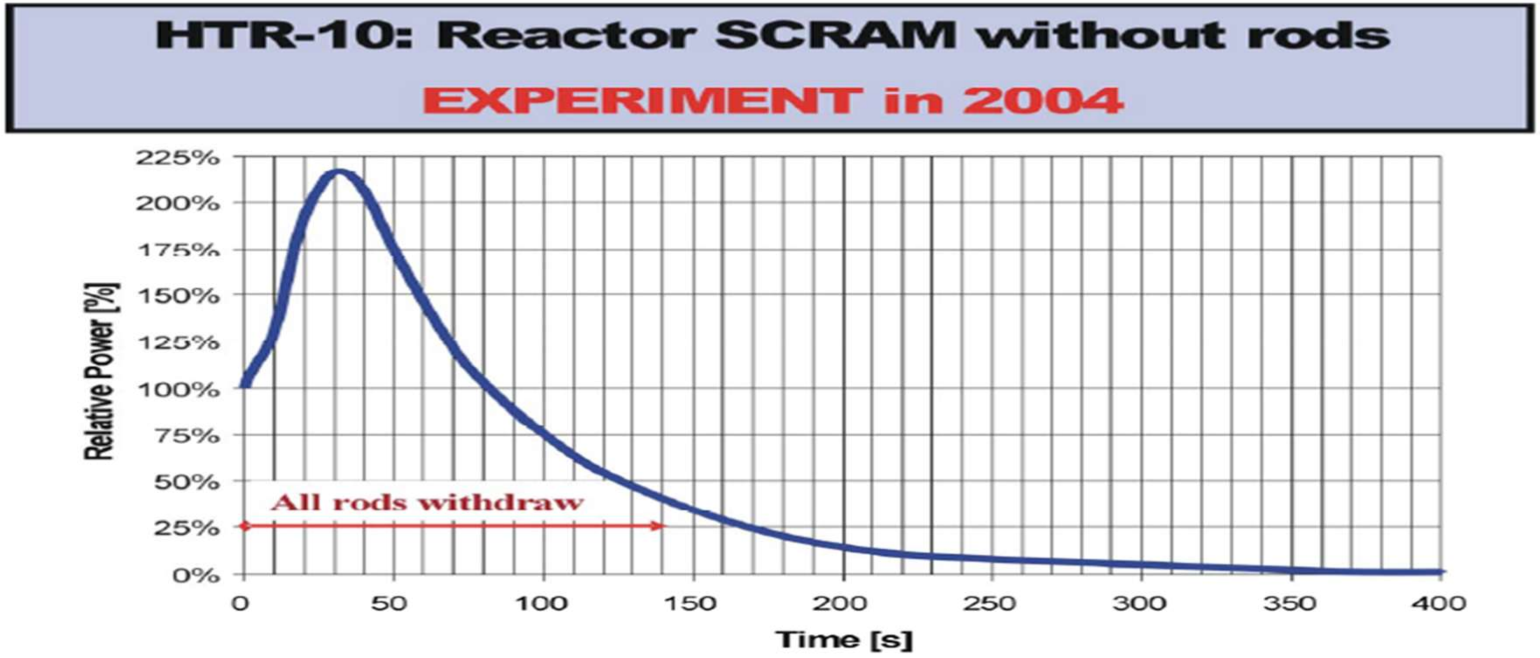
The low-pressure vented containment (confinement) consists of the reactor building or parts of it and some auxiliary systems such as sub-atmosphere ventilation, and filters

It is designed according to ALARA principle to mitigate the influence of DBAs and DECs, e.g. the release of radioactive effluents to the environment



## HTGR example; response to the questionnaire
## Q2: fundamental safety functions and associated "front line" safety systems (1/3)

**Reactor shutdown:**
- Control rod system
- Reserve shutdown system (small absorber sphere system)
- Self-shutdown by negative temperature feedback under ATWS condition



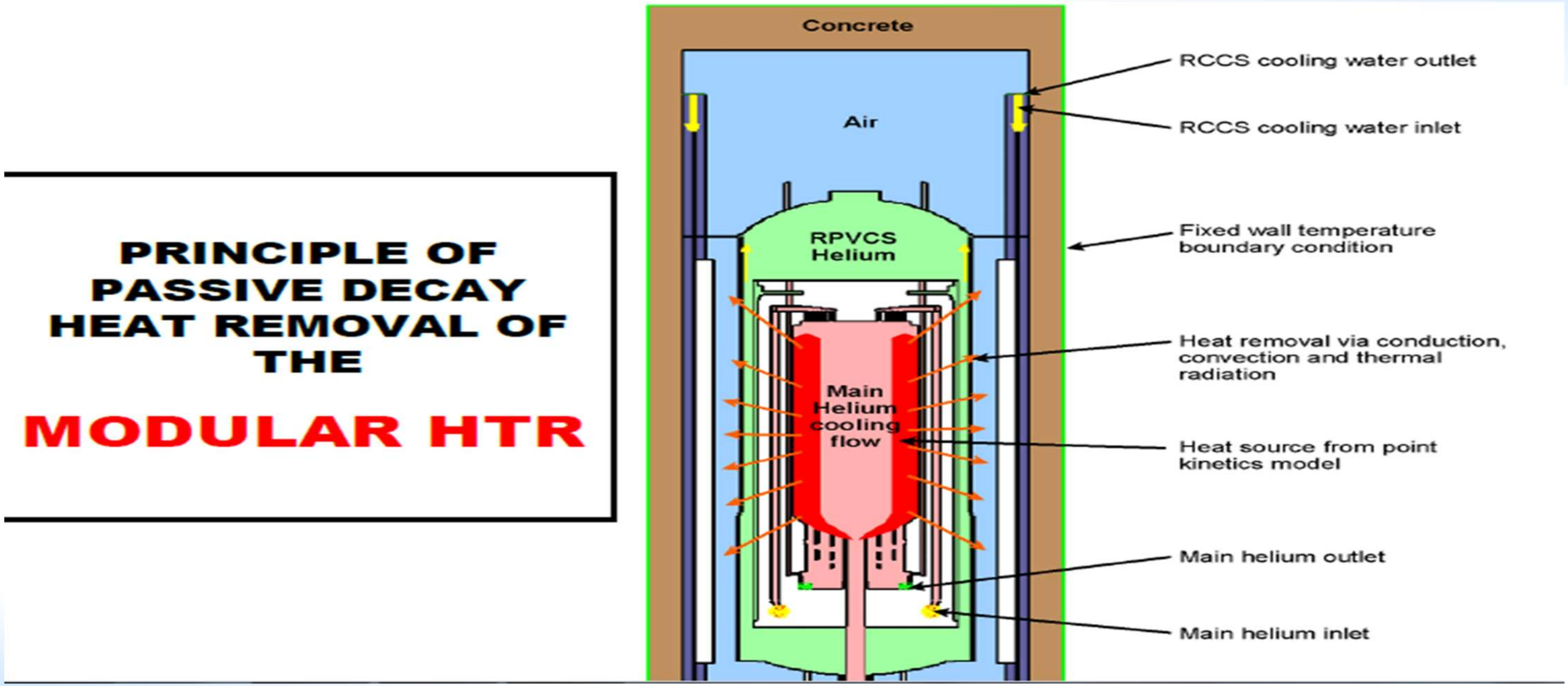
## HTGR example; response to the questionnaire
## Q2: fundamental safety functions and associated “front line” safety systems (2/3)

**Heat removal from core:**

-In normal operation the reactor core is cooled by helium (main helium blower and steam generating system)

- Under accident conditions, the main helium blower is stopped automatically. Because of the low power density of the core and the large heat capacity of the graphite structures, the decay heat in the fuel elements can be dissipated to the outside of the reactor pressure vessel by means of heat conduction and radiation (no need for coolant during accident conditions) within the core internal structures, without leading to unacceptable fuel temperature. And the fuel temperature increase in this phase will compensate accident reactivity and shutdown the reactor automatically via negative temperature feedback. The decay heat shall be removed to heat sink passively by reactor cavity cooling system (RCCS). Even if the RCCS fails, the decay heat can be removed by transferring it through the concrete structure of reactor cavity while the temperatures of fuel elements are under design limit

# HTGR example; response to the questionnaire
## Q2: fundamental safety functions and associated “front line” safety systems (3/3)



**HTGR example; response to the questionnaire**
**<u>Q3A: novelty in the safety approach (1/4)</u>**

An HTGR plant is designed with the following safety features:

- radioactive inventory in the primary helium coolant is very small during normal operation conditions, and even if released technically there is no need to take any emergency measures

- for any reactivity accident or loss of coolant accident, the rise of the fuel elements' temperature will not cause a significant additional release of radioactive substances

- the consequences of water or air ingress accidents depend on the quantity of such ingresses. The ingress processes and the associated chemical reactions are slow, and can readily be terminated within a day/ several days by taking very simple actions

## HTGR example; response to the questionnaire
## Q3A: novelty in the safety approach (2/4)

The HTGR plant incorporates the inherent safety principles of the modular HTGR:

- The lower power density, good coated particle fuel performance and a balanced system design ensures that the fundamental safety functions are maintained. A large negative temperature coefficient, large temperature margin, low excess reactivity and control rods ensure safe operation and limit accident temperatures

- The decay heat is passively removed from the core under any designed accident conditions by natural mechanisms, such as heat conduction or heat radiation, and keeps the maximum fuel temperature around 1600°C, so as to contain nearly all of the fission products inside the SiC layer of the TRISO coated fuel particles. This aims to practically eliminate the possibility of core melt and large releases of radioactivity into the environment

- Another feature of the design is the long-time period of accident progression due to the large heat capacity of fuel elements and graphite internal structures. It requires days for the fuel elements to reach the maximum temperature when the coolant is completely lost

# HTGR example; response to the questionnaire
## Q3A: novelty in the safety approach (3/4)

**Implementation of Defence in Depth (DID)**

The DID objectives are in line with the IAEA publication IAEA-TECDOC-1366
(Consideration in the development of safety requirements, Application to modular HTGRs)

**Faults/PIE/Event sequences**

Plant states considered in the design are: normal operation, AOO, DBA and DECs

- The lower power density, good coated particle fuel performance and a balanced system design ensures that the fundamental safety functions are maintained. A large negative temperature coefficient, large temperature margin, low excess reactivity and control rods ensure safe operation and limit accident temperatures

- The decay heat is passively removed from the core under any accident conditions considered in the design (DBA, DEC) by heat conduction and heat radiation, and keeps the maximum fuel temperature around 1600°C, so as to contain nearly all of the fission products inside the SiC layer of the TRISO coated fuel particles. <u>This practically eliminates the possibility of core melt and large releases of radioactivity into the environment, even under postulated events like air or water ingress</u>

**HTGR example; response to the questionnaire**
**Q3A: novelty in the safety approach (4/4)**

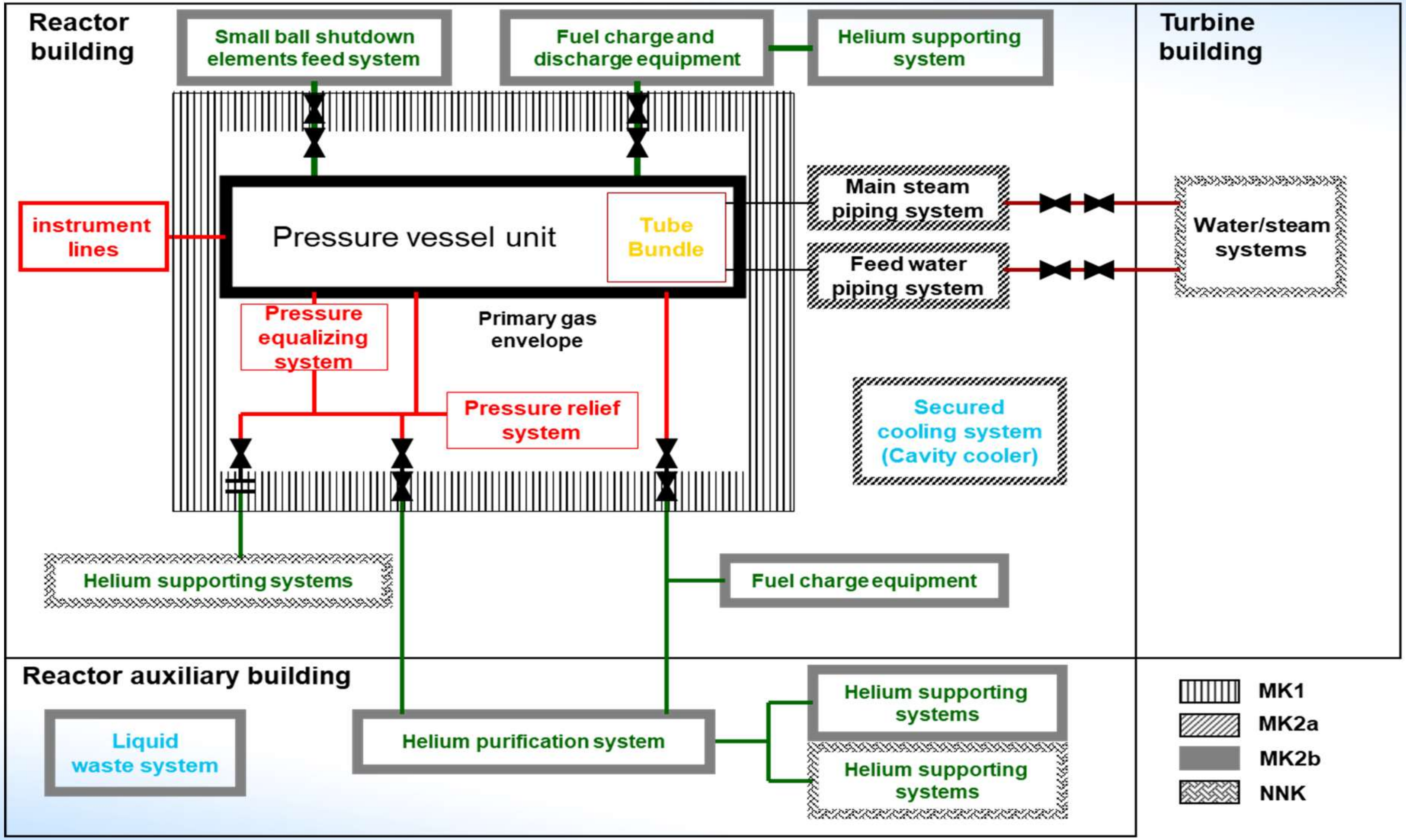
 Another feature of the design is the long-time period of accident progression due to the large heat capacity of fuel elements and graphite internal structures. It requires days for the fuel elements to reach the maximum temperature when the coolant is completely lost

When accidents (DBA,DEC) occur, reactor protection actions are called upon by the reactor protection system. No or very limited systems actuation or human interventions are foreseen after the reactor protection actions are activated. The reactor protection actions are to trip the reactor and the helium circulator, to isolate the primary and secondary systems. When there is large leak or rupture of steam generator heat transfer tubes, a drainage system is designed to minimize the amount of water ingress into the primary circuit

In general, a good overview of events considered is given in the IAEA publication – Accident analysis for NPP with modular HTGRs (Safety Reports Series No. 54)

# HTGR example; response to the questionnaire

## Q3B: novelty in the design of SSCs (example for pebble bed reactor)




Systems without radioactivity

Primary coolant, leak can't be isolated

Primary coolant, leak can be isolated

Systems radioactivity containing but not primary coolant

# Application to Molten Salt Reactors

# Fundamental Safety Functions are Common to Any Nuclear Power Plant

- Potential adverse consequence of NPP operation is release or radioactive materials to the environment
  - Retain radioactive materials
  - Control reactivity
  - Remove decay heat
    - IAEA SSR-2/1 provides FSFs
- How the safety functions are achieved vary with the reactor design and the choices of the applicant

# MSR Characteristics Support Performing Fundamental Safety Functions

- Strong inherent radionuclide retention
  - Low pressure
    - Large margin to boiling
    - Minimal amounts of water or other pressure generating materials within containment
    - Power cycle separated from fuel salt with rupture disks along piping
  - Fuel salt retains some radionuclides
    - Up to 40 % can be released into cover gas
      - Only recent production available for release remainder trapped outside of fuel or incorporated into fuel
    - Fuel salt chemically binds some fission products
    - Other radionuclides plate onto salt wetted surfaces
  - Fuel salt is in low chemical energy state (low Gibbs free energy)
    - No energetic chemical reactions with environmental materials

# MSR Characteristics Support Performing Fundamental Safety Functions (contd.)

- Effective negative reactivity feedback
  - Fuel in maximum reactivity configuration
  - Strong Doppler and density feedback mechanisms
  - Substantial margin to structural damage
    - MSRs considered as prompt burst reactors
- Effective passive decay heat rejection
  - Fuel salt has advantageous combination of heat capacity, thermal expansion, and viscosity for natural circulation cooling
  - High temperature facilitates radiative cooling
- No operational cliff-edge effects

# MSR Safety Design Criteria Need to be Performance Based

MSRs have so many design variants that employing a single set of prescriptive requirements results in excessive conservatism

| Property | Variants |
|---|---|
| Fuel Phase | Liquid, Solid (TRISO) |
| Spectrum | Thermal, Fast, Time Variant, Spatially Variant |
| Start-up Fissile Material | LEU-235 (2% or 5%), HA-LEU-235, TRU, U-233 |
| Fissile/Fertile Feed | Th, LEU, Natural Uranium, TRU, HA-LEU-235 |
| Coolant | Fluoride Salt, Chloride Salt, NaOH, Pb, Na |
| Moderator | None, Graphite, NaOH, $D_20$ |
| On-site fuel salt processing | Physical (bubbling, plate-out, and filtering), Intense (10 days / core), Mild (year/core) |
| Core configuration | Channels in graphite, Tubed (connected or partially closed), Open |
| Fissile Material Utilization | Burner, Converter, Breeder |
| Passive decay heat removal | DRACS, RVACS, PRACS with or without drain tank, Drain Tank with DRACS or RVACS |

# Risk Provides a Common Evaluation Framework Across Diverse Set of MSR Design Options

Risk – The Possibility that Something Undesirable Will Happen

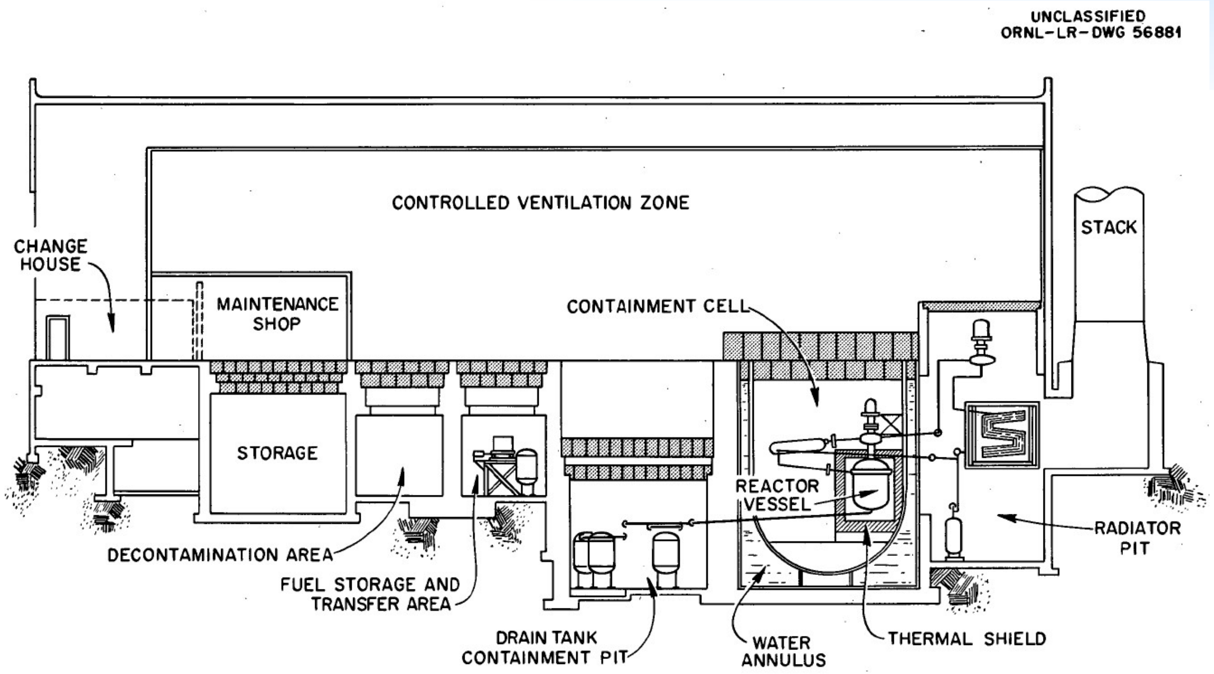
- Defense-in-depth is a primary mechanism to accommodate uncertainty
  - What if we are wrong?

# MSR Designs Can Employ Different Radionuclide Retention Strategies

- MSRs will have multiple barriers
  - Adequate defense-in-depth needs to be maintained
- Which barriers to credit for safety will be a design choice
  - Fuel salt boundary could provide a leak tight barrier during normal operations, but not be credited to contain radionuclides under accident conditions
- Most labile radionuclides will be in the cover gas
- Functional containment provides design flexibility
  - Evaluate combined effects of all of the radioactive material release barriers

# Functional Containment Enables Performance-Based Evaluation of Radionuclide Retention

- Multiple barriers - some of which are not normally stressed
  - Barrier performance requirements depend on their safety function
- Segmented containment
  - Limits accident scope
- Independent barriers
  - Failure of single barrier does not substantially stress other barriers
  - Minimizes potential for cascading or escalating failures




Multi-Layer, Segmented Containment at Molten Salt Reactor Experiment (MSRE)

# Low Releasable Stored Energy is a Key Safety Concept for MSRs

- Identifying potential accident sequences is a key issue in reactor safety assessment
  - Complex sequences involving multiple component failures can have high risk significance in systems with substantial releasable energy
- Lack of releasable energy minimizes potential for cascading or escalating accidents
  - Low pressure
  - Lack of phase change materials
  - Fuel salt in low chemical energy state
  - Adequate separation from power cycle

# MSRs Present Different Challenges Than Other Reactor Classes

- Radionuclides distributed across plant
  - Solid fuel concentrates radionuclides in core and used fuel pool
  - Gaseous fission products inherently separate from fuel salt
- Integrated fuel salt processing possible
- Salt wetted components have limited lifetimes resulting in unconventional high-activity waste stream
- Fuel salt does not have a mechanically determined lifetime
  - Only becomes waste when no longer able to perform safety or operational functions
    - Rise in melting point or increase in viscosity
    - Too many neutron absorbers
- Containment has much larger dose challenging inspection and maintenance
- Less (and dated) operating experience
  - Only one prior reactor operating for significant period
    - MSRE ~7.34 MWth operated from 1965-69
  - No large-scale reactor or component demonstrations
  - No fast spectrum systems demonstrated
  - Minimal prior accident performance demonstrations

# MSRs Present Different Material Diversion Issues Than Solid Fuel Reactors

- MSRs can be highly proliferation resistant or vulnerable depending on the plant design
  - MSR designs until the mid-1970s did not consider proliferation issues
  - Several current MSR design variants do not include separation of actinide materials
- Liquid fuel changes the barriers to materials diversion
  - Lack of discrete fuel elements combined with continuous transmutation prevents simple accounting
  - Solid LEU fresh fuel salt in transport and storage accountancy resembles LWR fuel
  - Homogenized fuel results in an undesirable isotopic ratio a few months following initial startup (no short cycling)
  - Extreme radiation environment near fuel makes changes to plant configuration necessary for fuel diversion very difficult
  - High salt melting temperature makes ad hoc salt removal technically difficult
  - Low excess reactivity prevents covert fuel diversion

# Experiences from vendors that have already filled the questionnaire

# NuScale (NuScale Power, LLC, USA) - Examples

- Novelty in the construction
  - Factory built, modular components
  - Manufacturing of novel SSCs such as real time display and monitoring system
  - Parallel construction and operation

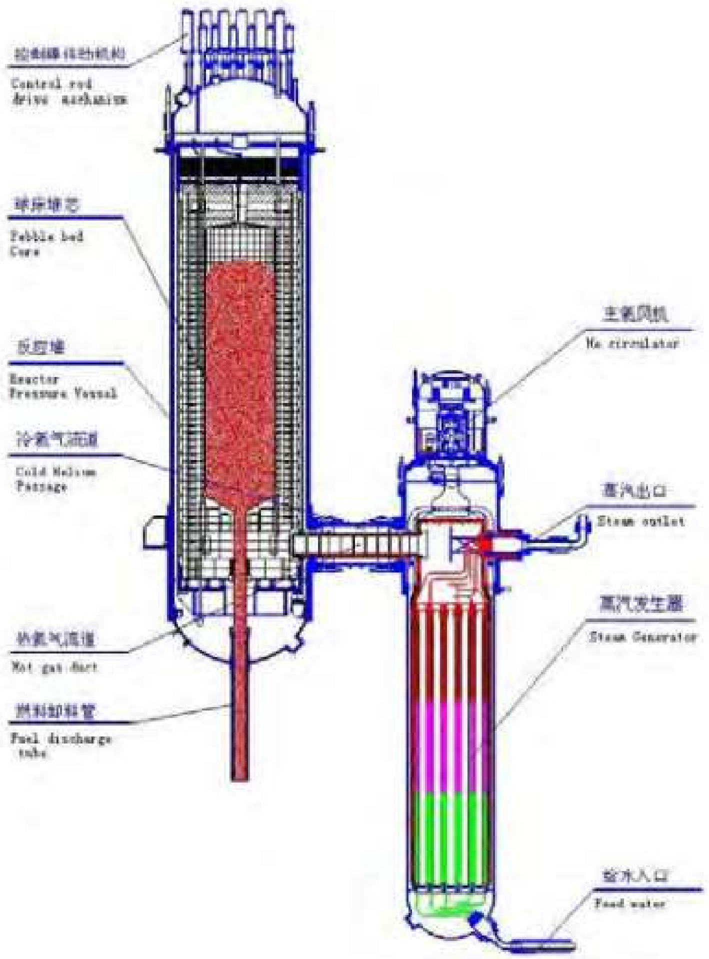
- Novelty in the commissioning
  - Tests performed in factory and on site

- High level of standardization of the modules (but site structures can be adapted)

- Novelty in the operating philosophy
  - reduced staff and a new approach to refuelling

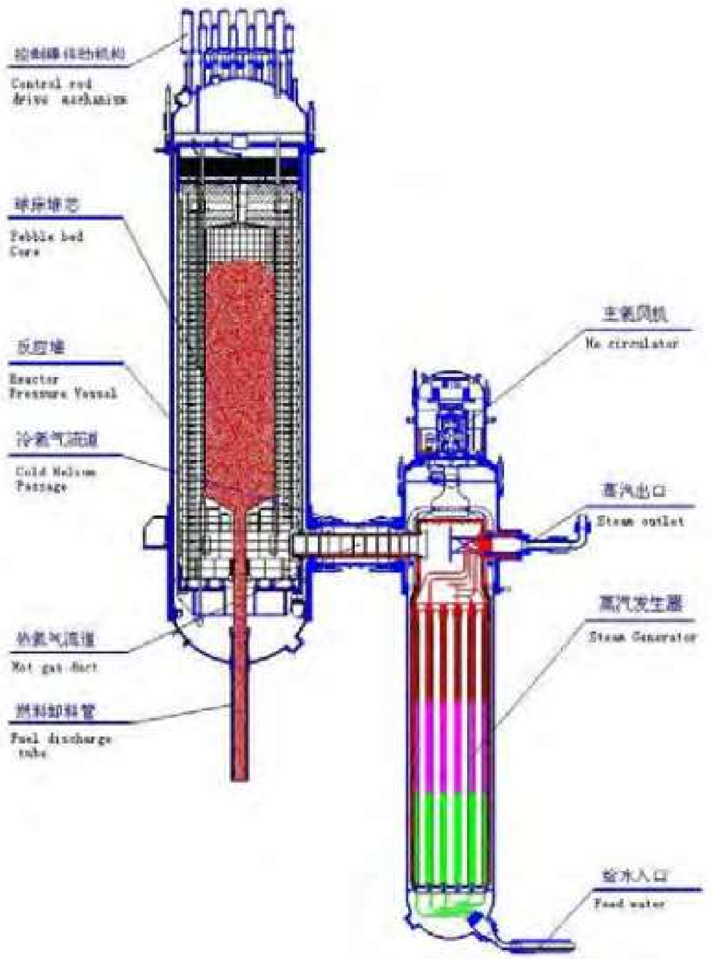
# HTR-PM (Tsinghua University, China) - Examples

- INET filled the questionnaire in advance
- The HTR-PM project is under the stage of hot test and will obtain the first criticality in 2021
- Novel design features needed to protect the fission product retention barriers
  - **Coated fuel particles:** high quality in the fabrication process, samples irradiated in the HFR in the Netherlands and examined after the post-irradiation heatup test in Germany show very good performance
  - Reactor coolant pressure boundary: primary relief system, cavity cooling system to limit the RPV temperature under accident conditions, specific cooling system for the RPV supporting structure, helium purification system to adjust the primary pressure under accident conditions
  - Vented low pressure containment: burst disk on the wall of the cavity allows the primary coolant to be discharged directly into the environment under LOCA accident under the premise that the radiological consequence is below the dose limit set by the regulatory authority, operation of the filtration system after the pressure balance achieved between the cavity and the environment



# HTR-PM (Tsinghua University, China) - Examples

- Novelty in the design safety approach
  - The implementation of the DID principle
    - relies more on the inherent safety features, e.g., reactor shutdown by negative temperature feedback, residual heat removal merely by natural mechanisms (heat conduction, thermal radiation, natural circulation), radioactivity confinement mainly by high-quality coated fuel particles
    - In DID level 4, only DEC-A, NO SEVERE ACCIDENT, practically eliminate the large release of radioactivity, no need of offsite protective actions in technical terms
  - The progression and consequences of faults such as LOCA, SGTR and therefore in the related design features to prevent and mitigate these sequences
    - The accident transient is very slow due to the large heat capacity of the fuels and internals
    - Enough time for the operator to take countermeasures
    - AOOs and DBAs: Emergency Operation Procedure
    - DECs: Beyond design basis accident Additional Mitigation Guideline



# Next Steps

- You will receive an invitation to participate in this work and fill the questionnaire for your design(s)
- Answers by **7th of December 2020** would be appreciated
- Contact:
  - P.Calle-Vives@iaea.org
  - R.Minibaev@iaea.org
  - S.Hadzic@iaea.org

# Questions and Answers

Please **write your questions** in the chat

Chat ...

We will address remaining questions by email

Questions can be also emailed to:

P.Calle-Vives@iaea.org

R.Minibaev@iaea.org

S.Hadzic@iaea.org

# Thank you!