Molten Salt Reactor Fundamental Safety Function PIRT

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2021 Virtual Molten Salt Reactor Workshop

Safety & Licensing Session

October 13th, 2021

What is a PIRT?

- Phenomenon Identification and Ranking Technique (PIRT) is a systematic way of gathering information from experts on a specific subject, and ranking the importance of the information, in order to meet some decision-making objective
- PIRTs are used to by the nuclear power industry to identify areas to focus on to improve performance and ensure adequate safety
  - DOE – identify topics for future research
  - Developers – identify issues to address as part of design
  - Regulators – identify topics to focus on for safety adequacy evaluation

What is distinctive about this PIRT?

- Focused on achievement of fundamental safety functions (FSFs) as a way of understanding common safety elements
  - Broad identification and ranking of key aspects of MSR safety
  - No precedents exist for MSR safety adequacy evaluation for commercial power production
  - Prior nuclear power PIRTs have had narrower focus and included substantial amounts of engineering depth
- FSFs are a performance based safety adequacy representation
  1. Contain radionuclides
  2. Remove residual heat
  3. Control reactivity
- Multiple diverse MSR designs exist
  - Nearly all developed over the past decade
  - Cannot reasonably predict which will be successful

PIRT applied to liquid-fueled MSRs to identify and rank key safety phenomena

- Evaluation metrics are achievement of each of the FSFs
- Results intended to be applicable to any liquid salt fueled reactor independent of spectra, fuel cycle, core configuration, moderator, or heat transfer configuration
- ~20 molten salt reactor experts from several national laboratories, reactor developers, universities, and the nuclear regulatory commission form the PIRT panel
- Virtual meetings (2 hour duration) have been conducted every ~2 weeks since January
  - Prior PIRTs employed a few extended, in-person meetings

PIRT process

Phase 1: Preparation
- Construct the project
- Select Experts
- Develop the project plan

Phase 2: Pre-elicitation
- Develop data sets
- Understand the technical issues
- Training

Phase 3: Elicitation
- Conduct evaluation via workshop
- Integrate results of elicitation

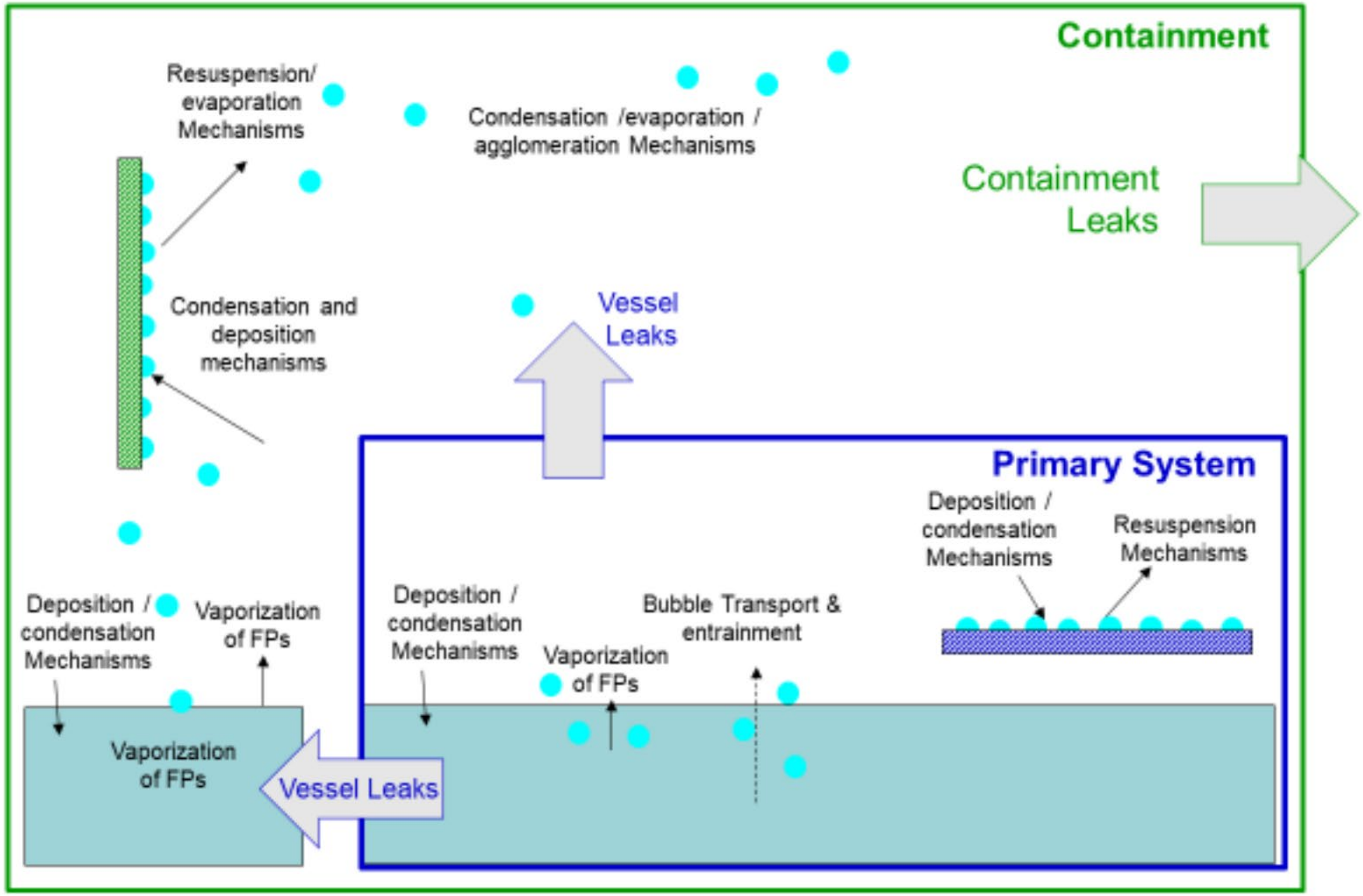
Phase 4: Final Documentation
- Prepare, revise, review document

- Pre-elicitation was performed with overview presentations from MSR reactor designers, MELCOR code developers, and experimentalists from national laboratories
- The elicitation phase of the PIRT process was completed in mid July
- Final documentation completed in September:

  Holcomb, D. E., A. J. Huning, M. D. Muhlheim, R. S. Denning, G. F. Flanagan, "*Molten Salt Reactor Fundamental Safety Function PIRT,*" ORNL/TM-2021/2176, (September 2021).

Name	Affiliation	PIRT Presentation
Guy Anderson	Moltex	Overview of SSR-W Reactor Design
Kurt Harris	Flibe Energy, Inc. (FBE)	Overview of Lithium Fluoride Thorium Reactor (LFTR)
Dane Wilson	ThorCon	ThorCon's Implementation Of Control, Cool and Contain
Tony Hill	Natura Energy	Introductions, Licensing Pathway and Technical Summary
Aslak Stubsgaard	Copenhagen Atomics	Copenhagen Atomics reactor design overview
Jake McMurray	ONRL now Kairos	Molten salt thermophysical properties database
Tommy Cisneros	TerraPower	MCFR System Description
David LeBlanc	Terrestrial Energy Inc.	Overview of the IMSR®
Wendy Reed	NRC	Phenomena Identification and Ranking Tables: US NRC Perspective
Ed Pheil	Elysium	Molten Chloride Salt Fast Reactor PIRT Presentation
Sara Thomas	ANL	Salt Spill Experiments
Joanna McFarlane	ORNL	Molten Salt Chemistry and Off-Gas Monitoring
David Holcomb	ORNL	Current Status of Fuel Salt Qualification Guidance Development
Dave Luxat	SNL	MELCOR for non-LWR Analysis
Melissa Rose	ANL	Quality Aspects Of Molten Salt Property Measurements
Rui Hu	ANL	SAM Overview for MSR Analyses
Scott Greenwood	ORNL	TRANSFORM: Description and Application to MSRs
Will Wieselquist	ORNL	Overview of MSR Capabilities in SCALE
	Affiliation	**Role**
David E. Holcomb	ORNL	Lead Technical Integrator
Alex Huning	ORNL	Facilitator and Co-LTI
Mike Muhlheim	ORNL	Co-LTI
Rich Denning	Consultant	Co-LTI
George F. Flanagan	ORNL	Peer Reviewer

Example Liquid-fueled MSR FP Transport Phenomena [1]



[1] NRC, *NRC Non-Light Water Reactor (Non-LWR) Vision and Strategy, Volume 3: Computer Code Development Plans for Severe Accident Progression, Source Term, and Consequence Analysis,* ML19093B404, April 2019.

PIRT Figures of Merit (FOMs) are the FSFs

- During the elicitation phase, a comprehensive list, discussion, and ranking of phenomena and their impact on FOMs is performed

FSF 1: Limiting the release of radioactive materials

→ **FOM 1:** What is the potential of a release of radioactive material?

FSF 2: Removing heat from the reactor and waste stores

→ **FOM 2:** What is the potential unbalanced heat removal?

FSF 3: Controlling reactivity

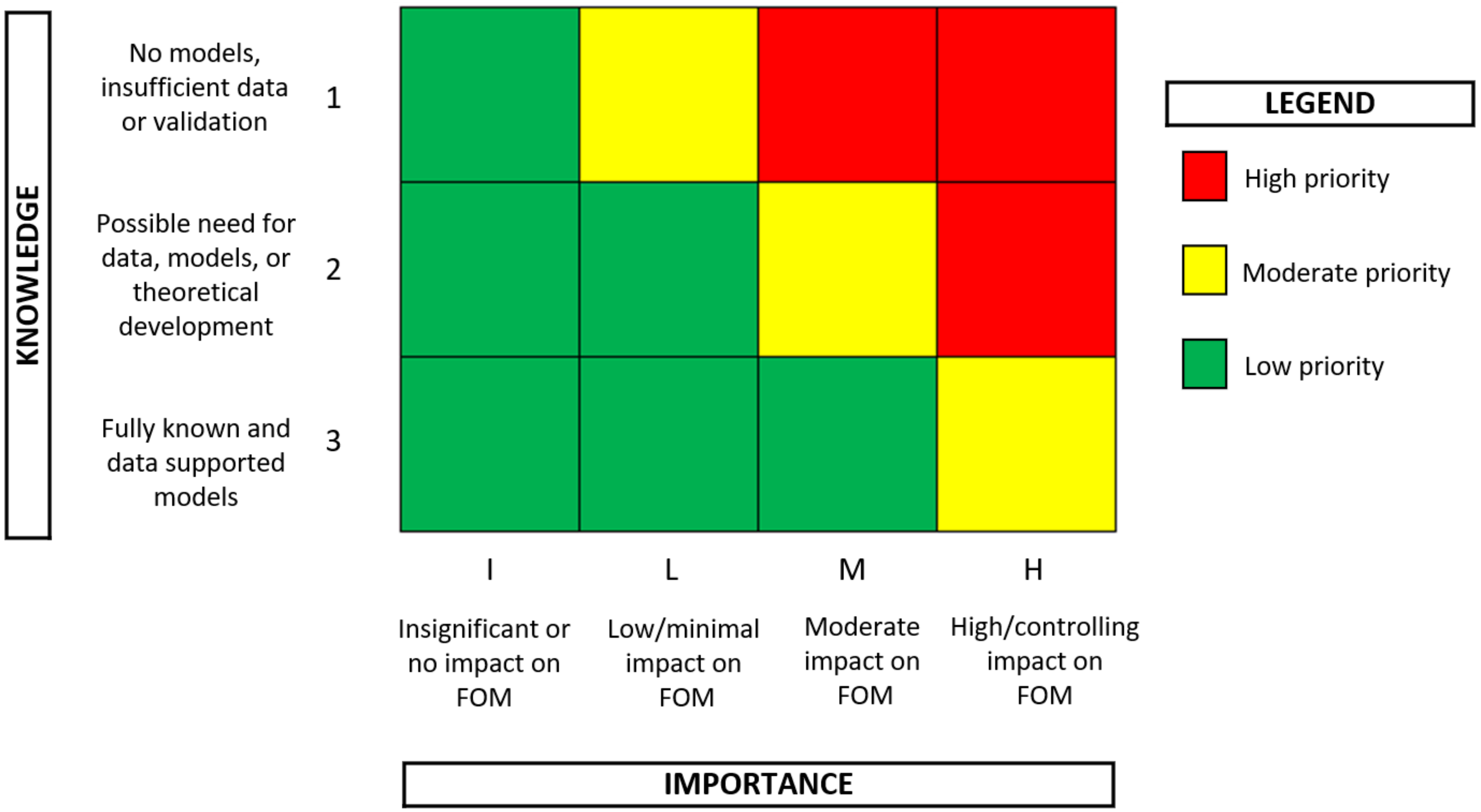
→ **FOM 3:** What is the potential for an uncontrolled nuclear reaction?

FOM ranking guidelines

Importance		State of Knowledge	
H	High – The phenomenon has a controlling impact on the FOM.	**3**	Models exist supported by validation experiments. Data exist for the underlying properties over the range of applications (e.g., thermophysical properties).
M	Medium – The phenomenon has a moderate impact on the FOM.	**2**	Models exist that can be extended to the required application but with the need for additional data, theoretical development, or validation.
L	Low – The phenomenon has a minimal impact on the FOM.	**1**	Models either do not exist, are simplistic, or have insufficient data.
I	Insignificant – The phenomenon has insignificant or no impact on the FOM.		

- Rank for each FOM
- Importance values for different design or design categories will be noted in rationale and description fields

Phenomena are Ranked by ***Importance*** and ***Knowledge*** on Their Impact to Each FOM



How are phenomena identified, how to know what to rank?

- **Scenario categories** facilitate the identification of phenomena potentially impacting FSFs
- In contrast to **Licensing Basis Events (LBEs)**, scenario categories:
  - Organize phenomena that could be present across many LBEs
  - Are more generic and don't require a specific or reference design
  - Allow for a more holistic identification of potential phenomena without prejudging low frequency or beyond design basis events
- LTI-team identified scenario categories:

1. Salt spill accident	4. Accidental criticality
2. Dynamic system thermal hydraulic and/or power response	5. Emergency response system failures
3. Water-salt interactions	6. Radwaste management system failures

How are phenomena identified, how to know what to rank?

PIRT panel decided to eliminate from discussion as the design and function of particular systems is too specific to adequately rank in a generic setting

- **Scenario categories** facilitate the identific… impacting ESFs

PIRT panel decided to make a single phenomenon rather than an entire category

…vents (LBEs)**, scenario categories:
  - …d be present across many LBEs
  - Are more generic and don't require …
  - Allow for a more holistic identification … udging low frequency or beyond design basi…

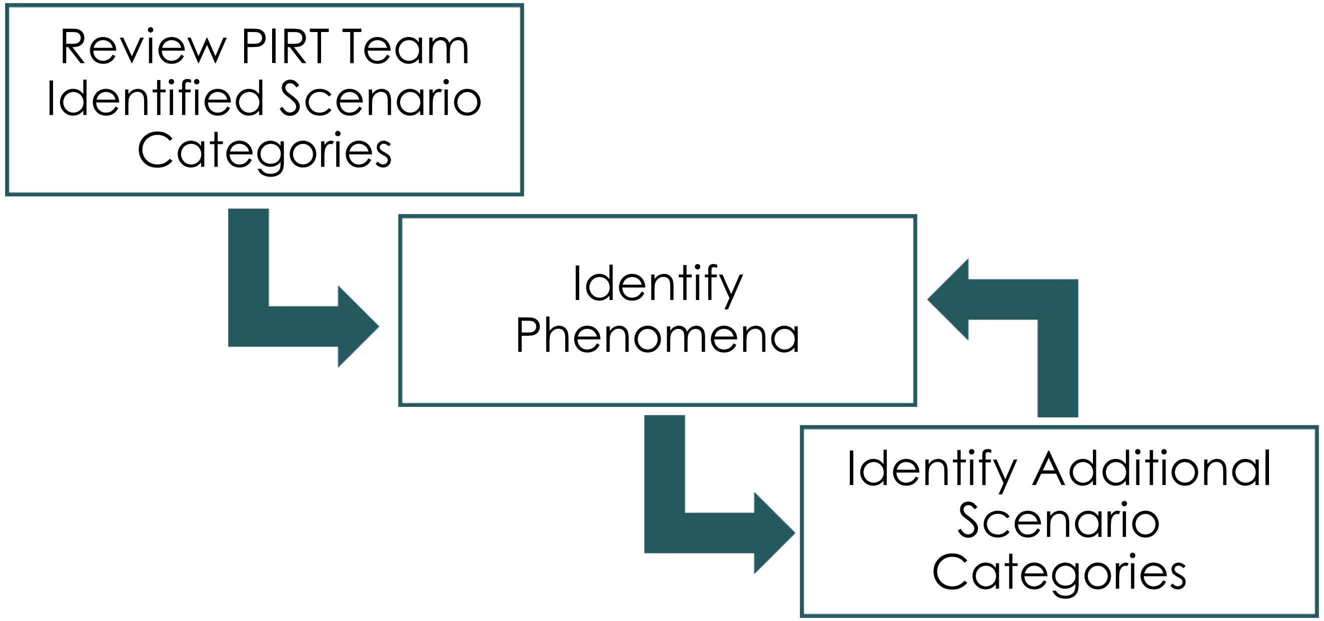
Left as a category with a single phenomena. Highlighting the need for an additional PIRT just on these technologies

- LTI-team identified scenario categories:

1. Salt spill accident	4. Accidental criticality
2. Dynamic system thermal hydraulic and/or power response	5. Emergency response system failures
3. Water salt interactions	6. Radwaste management system failures

Elicitation Process – Part 1

- Meeting 1+: Identify MSR phenomena which may impact FSFs

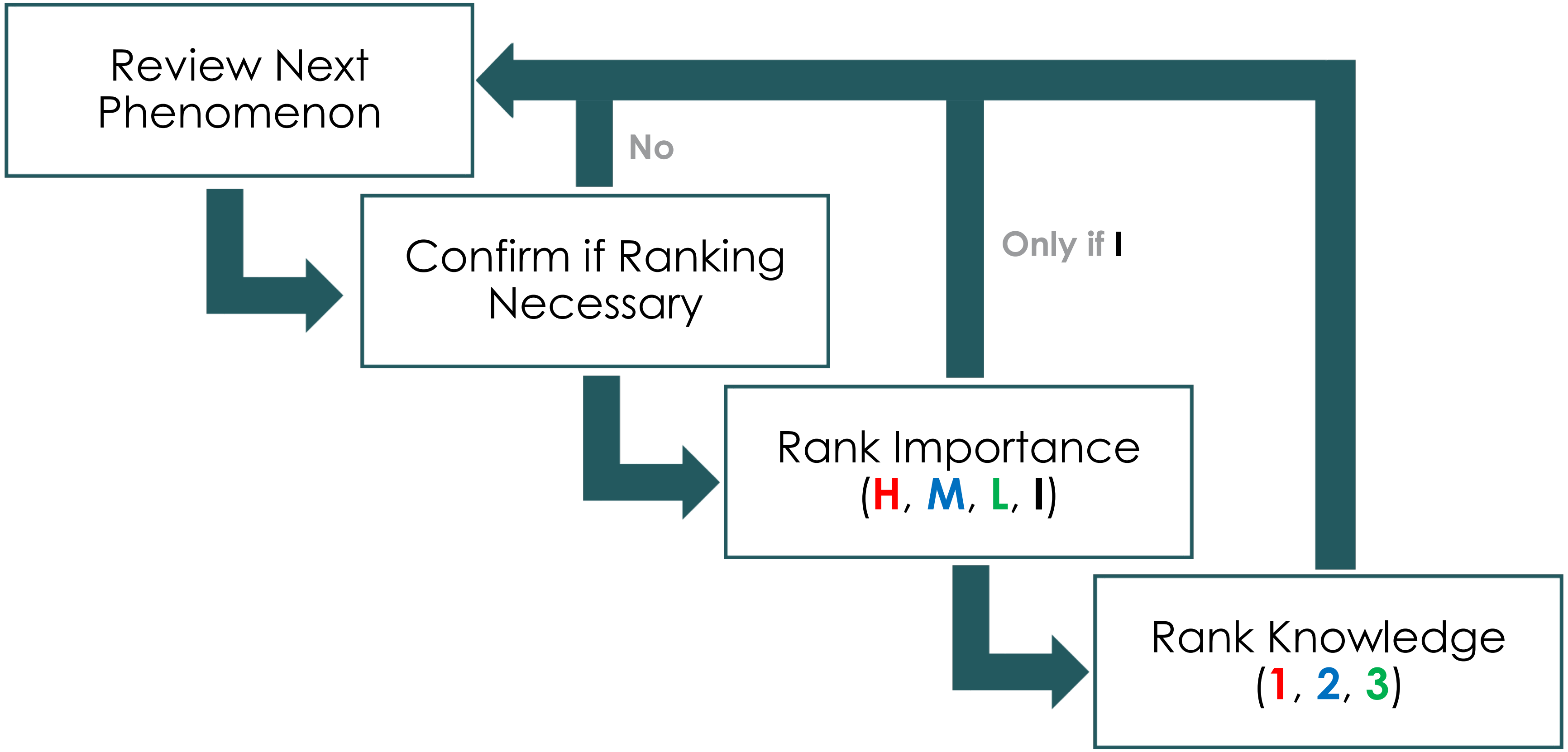


What we need to know about the phenomena:
- **Scenario category**
- **ID** *(to be added later)*
- **Title**
- **Description**

- **No ranking the first+ meeting**

Elicitation Process – Part 2

- Meeting 2+ : Discuss and rank phenomena



Perform documentation throughout the process

Results, Identified Phenomena

- After condensing, 25 phenomena elicited
- Most for salt spill accident (SC I)
- None for SC III or SC V
- SC VI, only one phenomenon

ID#	Phenomenon name	Page
I01	Base/floor material thermochemical interactions with molten salt (e.g., concrete, steel, etc.)	B-3
I02	Radionuclide inventory (mass) or activity, speciation, and distribution	B-5
I03	Mass/volume and energy of molten salt (fueled salt) pool	B-7
I04	Initial temperature of molten salt pool and structures within the volume	B-8
I05	Molten salt spreading	B-10
I06	Salt fragmentation	B-11
I07	Generation of dross/crust layer on surface of salt pool	B-12
I08	Vaporization and release of salt components and radioactive material from the surface of a molten salt pool	B-13
I09	Solubility of constituents within the salt pool	B-15
I10	Reactions with fuel salt and atmosphere	B-16
I11	Bubble rupture and splash at the surface of a molten salt pool	B-17
I12	Beta-recoil droplet release	B-18
I13	Mixing and fluid dynamics within the molten salt pool	B-19
I14	Mass transport and diffusion of radionuclides within the molten salt pool and to the surface of the pool	B-20
I15	Heat transfer within the molten salt pool	B-21
I16	Heat transport from pool to cell atmosphere and structures	B-22
I17	Mixing and convection of air/gas flow with the atmosphere	B-23
I18	Radionuclide transport and interactions within the cell atmosphere	B-24
I19	Radiolysis of salt, moisture in cell atmosphere, and concrete decomposition or water incursion into cell	B-25
I20	Water salt interactions including hydrolysis in salt	B-26
II01	Over-temperature, over-pressure conditions	B-27
II02	Leak/rupture of primary heat exchanger tube and radionuclide release to secondary systems	B-29
IV01	Unrecognized accumulation of fissile material	B-30
IV02	Overcooling leading to precipitation and accumulation	B-31
VI01	Radwaste and other non-fuel radioactive gas/fluid system failures	B-32

Phenomena overview

- Several potentially important phenomena have been identified that require additional understanding to develop adequate accident progression models.
  - Crust formation on salt spill inhibiting heat transfer from the spilled salt,
  - Thermally insulative snow like deposits formation on surfaces within containment inhibiting heat transfer,
  - Frozen layer formation when liquid salt contacts a catch pan inhibiting conductive heat transfer,
  - Mists and fogs formation in the containment atmosphere inhibiting radiative heat transfer,
  - Fuel salt interactions with component or structural coolants potentially causing pressure generation or inhibiting heat transfer,
  - Ignition and resulting smoke formation resulting from hot salt interacting with materials in containment inhibiting radiative heat transfer, and
  - Chemical interactions between the salt and the containment materials resulting in solid material formation (e.g., oxide chunks) that decreases convective heat transfer

Discussion of results

- **The salt spill accident is the most critical scenario** from the viewpoint of the potential for a large environmental release of radioactive material irrespective of MSR design.
- Many of the identified phenomena for the salt spill accident are **also applicable to accidents involving a release from a breach in the cover gas region**.
- The thermophysical and thermochemical behavior of the molten salt affects nearly all the identified phenomena. **It was decided to focus the PIRT on phenomena rather than properties.** Nevertheless, the assessed state of knowledge of phenomena was impacted by recognized deficiencies in the state of knowledge of the underlying salt properties

Additional discussion of results

- **Phenomena that are common to other reactor types**, such as aerosol growth and deposition processes, independent of salt thermochemistry **were generally assessed to have a higher knowledge ranking**
- Although many important observations were made for liquid fueled MSRs with common design features, **design dependence played a significant role** in the discussion and ranking of phenomena
- Design dependence and constraints on the time commitment of members of the PIRT Panel each played a role in determining the **level of refinement of phenomena**.

MSR safety implications

- The achievement of FSFs is design dependent. Each of the different reactor configurations results in a substantially different fuel salt spill accident progression sequence requiring different simulation capabilities to effectively model.
- Acquiring the experimental data necessary to adequately model decay heat removal following a major fuel salt spill will be the central focus recommended future research activities.
- MSRs have distinctive radionuclide movement characteristics due to the fluid nature of their fuel. A much higher fraction (than would be in the plenum of solid fuel pins) of the short-lived radionuclides would be in the vapor space above the liquid fuel. All gaseous, vapor phase, and aerosol fission products could be released from an unmitigated, early breach or bypass of containment. The consequences of such an accident would be so high that the accident probability must be sufficiently low as to be outside of credible accident space.
- A key accident progression issue is establishing its initial conditions – where are the radionuclides at the start of an accident. No available reactor modeling toolset includes significant MSR phenomena such as cover gas content and location, plated out radionuclides, or insoluble particle filtering.

Conclusions

- The presented PIRT is broader in scope with less technical detail for any particular design and more performance-based than prior efforts for other PIRTs
- The PIRT was desired to have the outcome be as broadly applicable as possible to the multiple, widely varied, MSR designs currently under development
- The results of the PIRT are intended to be of value to three distinct groups:
  - The information provides guidance to DOE to focus its limited MSR research, development, and demonstration resources on the highest value activities.
  - Designers can use the PIRT results to focus on mitigating the most potentially significant events
  - The NRC can use the information to ensure that potential accident consequences or the probability of occurrence has been adequately reduced.
- Overall, the virtual format drew active participation from the panel and support from a larger, more diverse set of participants

Questions

Thank you!

Selected results from the elicitations – I01

Phenomena		Importance	Knowledge	Priority	Rationale
I01. Base/floor material thermochemical interaction with molten salt (e.g., concrete, steel, etc.)	FOM-1	M - H (concrete)	1 - 2	Red - Yellow	The base/floor of the cell into which salt spills is likely to be steel or steel-lined concrete. For those conditions, there is likely to be little thermochemical interaction. If the salt spills onto concrete, there is likely to be spallation, the mixture of concrete decomposition products with the salt, including a release of bound water and the production of hydrogen. Contamination by products of the decomposition of concrete could affect the chemical form and release of radioactive material. The effects on heat balance and criticality potential are not likely to be substantial. There has been no research identified that directly relates to radioactive material release or thermal conditions of the salt. Neutronic modeling with available tools (SCALE) is feasible. The assessment indicated potential high priority for research associated with molten salt thermochemical interaction with concrete, but only if designs are identified involving this potential.
	FOM-1	L - M (steel)	1 - 2	Yellow - Green	
	FOM-2	M	1 - 2	Red - Yellow	
	FOM-3	L - M	2 - 3	Yellow - Green	

- Many phenomena have split rankings
  - Different for different designs
- For any FOM, little to no importance if barrier is not impacted

Selected results from the elicitations – I02, I03

- Initial conditions are very important (high priority)
- Key knowledge required:
  - Thermochemistry,
  - Operational history,
  - Salt properties

Phenomena		Importance	Knowledge	Priority	Rationale
I02. Radionuclide inventory (mass) or radioactivity level, speciation, and distribution (at the start of the accident)	FOM-1	H	2	■ (red)	These processes relate to conditions while the salt is still in-vessel at the time of the breach. They have a substantial impact on the characteristics of the molten pool that forms in the cell. There has been relevant research that impacts all three FOMs but additional research is required achieve a level consistent with the importance the three FOMs. Thus, this phenomenon has high priority for research.
	FOM-2	H	2	■ (red)	
	FOM-3	H	2	■ (red)	
I03. Mass/volume and energy of molten salt (fueled salt) pool	FOM-1	H	2	■ (red)	These characteristics of the molten salt pool formed in the cell external to the primary system directly impact all three FOMs. Relevant research has been performed that relates to all three FOMs but because of the high importance of the phenomenon, high priority is assigned for additional research.
	FOM-2	H	2	■ (red)	
	FOM-3	H	2	■ (red)	

Selected results from the elicitations – I07, I09

Phenomena		Importance	Knowledge	Priority	Rationale
I07. Generation of dross/crust layer on surface of salt pool	FOM-1	M - H	1	■ - ■	This is an area of very high uncertainty with substantial potential impact on FOM-1 and FOM-2.
	FOM-2	M	1	■	
	FOM-3	L	1	■	
I09. Solubility of constituents within the salt pool	FOM-1	H	2	■	There are three diverse reasons this set of phenomena has high research priority: for radionuclide release, noble gases could be a significant source of offsite radiation exposure either due to the gas or its daughter products, noble gases could be a significant source of decay heat in the cell, and fissile isotope species precipitating from the melt could potentially result in increased reactivity.
	FOM-2	M	1	■	
	FOM-3	M	1	■	

- These are other high priority phenomena
- Constituents and phase change (liquid to solid) can play a huge role in the quantity of radionuclides released

Selected results from the elicitations – IV01, IV02 (Accidental Criticality)

- Reactivity initiated events generally a high concern for MSRs, however, the PIRT and experts view as more moderate than high

Phenomena		Importance	Knowledge	Priority	Rationale
IV01. Unrecognized accumulation of fissile material	FOM-1	M	2	Yellow	Any plant system that will contain fissile material will be designed with high confidence to avoid accidental criticality. However, the potential for an uncontrolled nuclear reaction could result from an unrecognized buildup of material. Given a configuration, mass, degree of reflection and degree of moderation, the ability to predict criticality is good.[67],[68] Nevertheless, by its nature this issue addresses uncertainty regarding mechanisms that could result in an unexpected accumulation. As a result, the panel identified the state of knowledge as low or moderate.
	FOM-2	M	2	Yellow	
	FOM-3	H	1 - 2	Red	
IV02. Overcooling leading to precipitation and accumulation	FOM-1	M	2	Yellow	This scenario is highly dependent on event scenario characteristics and the design features for limiting overcooling events. The equations of state, conditions leading to precipitation of actinide species, and the characteristics of the precipitates are not well known.[69] The priority of these events is moderate because they can likely be addressed through conservative analysis (i.e., sufficient margin).
	FOM-2	M	2	Yellow	
	FOM-3	M	2	Yellow	

Salt spill phenomena priority ranking distribution

Table 8. Scenario Category I. Salt Spill Accident Ranked Research Priorities

	High Priority	Moderate Priority	Low Priority
FOM 1	I01, I02, I03, I05*, I06, I07*, I08, I09, I10*, I11, I12*, I14, I16,	I04, I05*, I07*, I10*, I12*, I13, I15, I17, I18, I20	I19
FOM 2	I01*,I02, I03, I04, I05*, I07, I08*, I09, I10*, I15, I16,	I01*, I05*, I06, I08*, I10*, I12*, I13, I14, I17, I18,	I11, I12*, I19, I20
FOM 3	I02, I03, I09, I10*	I01*, I07, I10*, I19, I20	I01*, I04, I05, I06, I08, I11, I12, I13, I14, I15, I16, I17, I18
Any FOM†	I01, I02, I03, I04, I05, I06, I07, I08, I09, I10, I11, I12, I14, I15, I16	I13, I17, I18, I19, I20	

*Phenomenon has a split ranking (*e.g.*, knowledge is a 1 – 2, instead of either just a 1 or a 2 value)
†Phenomena with the highest priority of any FOM

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