U.S. Approach for Inherent Prevention and Mitigation of SFR Severe Accidents

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Safety Approach

- Defense-in-depth is the key concept on which all of nuclear safety is based.
- The traditional approach to demonstrating adequacy of defense-in-depth in a design is deterministic, but a combination of deterministic and probabilistic approaches is increasingly recommended.
  - Deterministic approach classifies initiating events by likelihood, while the risk-informed approach introduces a quantified probability estimate.
- Risk-informed and performance-based safety approach considers both probability and consequences of events.
  - Accidents with large consequences are reduced in risk significance by requiring that their likelihoods are acceptably small.

Safety Approach (cont.)

- The safety of a nuclear reactor depends both on:
  - intrinsic built-in stability and reliability of the machine,
  - administered control of its safe operation.
- In order to rely more on the intrinsic features, safety has to be "*built-in*" rather than "*added on*" by influencing the direction of the design development.
  - Design work should also focus on evaluating the various possibilities for making optimum use of the passive features and inherent safety response of the design.

SFR Safety

- Like LWRs, SFR safety is first based on utilization of multiple redundant engineered protection systems to lower the probability of accident occurrence and to limit its consequences:
  - independent scram systems,
  - multiple coolant pumps and heat transport loops,
  - auxiliary decay heat removal systems, and
  - multiple barriers to release of radioactive materials.
- The safety design features that enhance inherent negative reactivity feedback and passive decay heat removal capabilities provide additional measures to protect the reactor even during very low probability accidents.

Safety Framework

- The licensing basis for a reactor is constructed around the definition of events to be considered:
  - within the safety framework of the reactor,
  - beyond the safety framework of the reactor.

Plant states considered in design			
Operational States		Accident Conditions	
Normal Operation	Anticipated Operational Occurrences (AOOs)	Design Basis Accidents (DBAs)	Design Extension Conditions (DECs)

- Severe accidents fall "beyond the safety framework of the reactor", under the Design Extension Conditions (DECs).

SFR Safety Fundamentals

- SFR safety analyses traditionally focus on double-fault events during which the reactor scram system is assumed to fail.
  - First fault can be any event that introduces significant unbalance between the heat production and removal.
  - Even though probability of double-fault events is very low, reactor must be designed to withstand such accidents without core damage.
- This approach differs significantly from LWR safety analyses where the emphasis is usually on single-fault events.
  - Difference is generally due to the fact that SFR core is not in its most reactive configuration, and core damage could theoretically lead to energetic events.
  - However, inherent safety characteristics of SFRs can provide much larger safety margins for even the more severe double-fault events.

SFR Safety Fundamentals (cont.)

- The focus of inherent safety is to avoid
  - large uncontrolled increases in core power,
  - insufficient cooling of the reactor core, and
  - rearrangement of fuel that would lead to energetic recriticalities.
- Therefore, inherent safety uses three basic principles:
  - favorable reactivity feedback,
  - natural circulation cooling and passive decay heat removal systems, and
  - appropriate selection of fuel and cladding materials.
- In more challenging (and much less likely) hypothetical accidents that could lead to fuel failures, the energetic events can be avoided by taking advantage of
  - compatibility of metallic fuel with liquid sodium coolant,
  - favorable dispersal characteristics of the molten fuel elements, and
  - by maintaining core coolability after fuel failures.

Severe Accidents

- Hypothetical Core Disruption Accidents (HCDAs) will likely receive worldwide regulatory attention after Fukushima.
- Best approach to address this concern is to drive the likelihood of HCDAs to a very low number with enough certainty.
  - Design features can be provided to reduce the impact of initiators with high uncertainty (i.e., seismic isolation against large earthquakes).
- Inherent and passive safety measures can be used to reduce the likelihood of severe accidents to a level that they belong in residual risk category
  - They can be handled with defense-in-depth considerations with adequate emergency planning.

U.S. SFR Experience

- SFRs have long been both studied and operated by the DOE and its predecessor, AEC.
  - In addition to EBR-I, EBR-II, Fermi and FFTF, DOE-complex designed, built and operated a wide range of fast reactor related experimental facilities.
  - Past and present SFR R&D programs have focused on development and demonstration by testing of the concepts with passive safety features that lead to no serious consequence.
- The current U.S. SFR licensing experience comes from the Clinch River Breeder Reactor (CRBR) and the Advanced Liquid Metal Reactor (ALMR) program interactions with the U.S. Nuclear Regulatory Commission (NRC).

U.S. SFR Experience (cont.)

- In 1970s and early 1980s, DOE attempted to license CRBR, but Congress cut funding before the project was completed.
  - While hypothetical core disruptive accidents (HCDAs) were not considered as part of the design basis for CRBR, accidents that could lead to HCDAs (including unprotected accidents and large-break LOCA) received regulatory scrutiny prolonging the licensing process.
  - The U.S. NRC Atomic Safety and Licensing Board (ASLB) eventually excluded HCDAs from the licensing basis, stating that "*probability of core melt and disruptive accidents can and must be reduced to a sufficiently low level to justify their exclusion from the design basis accident spectrum*".
  - CRBR licensing process resulted in a U.S. NRC Safety Evaluation Report in 1983, NUREG-0968.

U.S. SFR Experience (cont.)

- After CRBR was canceled, DOE embarked on the Advanced Liquid Metal Reactor (ALMR) and Integral Fast Reactor (IFR) programs.
  – Emphasis on a pool-type reactor concept and metal fuel to avoid severe accident related regulatory issues that impeded CRBR licensing.
- Both PRISM (GE) and Sodium Advanced Fast Reactor (SAFR) (Rockwell/Westinghouse) reactor concepts submitted Preliminary Safety Information Document (PSID) to the U.S. NRC in 1986.
  – GE-led PRISM reactor became the focus of the ALMR program in 1988.
- Eventually, GE's PRISM reactor concept was integrated into the IFR program as the leading reactor design candidate.

U.S. SFR Experience (cont.)

- NRC's Pre-application Safety Evaluation Report (PSER) for PRISM PSID highlighted key regulatory issues at that time:
  - limited performance and reliability data for passive safety feature,
  - unverified analytical tools used to predict plant response,
  - limited supporting technology and research,
  - limited construction and operating experience, and
  - incomplete information on the proposed metallic fuel.
- IFR program continued to address these identified issues until its termination in 1994.
- Ongoing work under DOE-NE's Advanced Reactor Concepts (ARC) program continues to address these concerns.

U.S. SFR Fuels Experience

- The decision on fuel type can be based on many criteria (performance, fabrication, safety and fuel cycle implications).
- Early US SFR experience focused on metal-alloy fuel.
  - Testing in EBR-II in the late 1960's identified difficulties with achieving significant burnup with metal fuel, so the oxide fuel type that had been successfully used in commercial LWRs and naval propulsion was selected for further development in the FFTF and CRBR projects.
- Subsequent metal fuel testing, both in parallel with oxide fuel development during the 1970s and as part of the IFR program in the 1980s demonstrated that the burnup limitation could be overcome by changing the fuel pin design.
- Today, both oxide and metal fuel types have had significant development, testing, and operational experience, with either fuel type being available for use in a future fast reactor.

U.S. SFR Fuels Experience (cont.)

- Substantially different thermophysical properties of oxide and metal fuel play a significant role in the safety performance of the reactor system.
  - The difference in the thermal conductivity results in a much higher steady-state operating temperature for oxide fuel.
  - Along with the higher heat capacity, this leads to a much larger stored thermal energy in the reactor core for oxide fuel than for metal fuel.
  - Despite significant difference in melting point, both oxide and metal fuel have approximately the same relative margin to melting during transients.
  - For metal fuel, primary pin failure mechanism is the chemical interaction between the fuel constituents and the cladding at ~1000 K.
  - For oxide fuel, primary pin failure mechanism is the mechanical interaction as the fuel swells and stresses the cladding.

U.S. SFR Fuels Experience (cont.)

- For AOOs and DBAs, the main difference is the higher operating temperature and stored heat with oxide fuel, but it doesn’t lead to major difference in safety response of the reactor.
  - Oxide fuel chemically reacts with sodium and local faults can lead to formation of reaction products with potential for local blockage.
  - Since metal fuel is not chemically reactive with sodium, local faults can be tolerated for extended periods of time with proper monitoring of fission gas release (RBCB tests at EBR-II).
- For more severe double-fault events, the difference between the two fuel types can be more safety significant.
  - However, analysis and testing has shown that it is possible to use the inherent reactivity feedback to limit the severity of such events for both oxide and metal fuels.
  - More design accommodation may be needed with oxide fuel due to the high steady-state operating temperature for the fuel (i.e., GEMs).

Oxide Fuel Performance in Severe Accidents

- In severe accident scenarios where fuel melting (core damage) may occur, important considerations for oxide fuel are the melting point and the compatibility with the sodium coolant.
  - Conditions at the time of fuel melting, including coolant boiling, can dictate the severity of the accident progression.
  - Failures are usually around the core mid-plane.
- When the molten material is entrained into the cooler regions of the assembly above or below the core, it rapidly solidifies and can creates flow blockages.
  - Accident progression could include core damage propagation and energetic events.
  - Such an event was assessed to possibly threaten CRBR containment.
- Recent efforts (by JAEA) explore design options to facilitate unimpeded flow of molten fuel out of the core to avoid recriticalities.
  - By providing a large channel within the assembly to avoid blockage by solidifying fuel/cladding mixture.

Metal Fuel Performance in Severe Accidents

- For metal fuel, the scenarios that lead to temperatures sufficient to melt the fuel and/or cladding do not result in blockages.
  - Metal fuel has relatively low melting point and it forms lower-melting-point eutectic alloys through chemical interaction with the cladding.
  - Failures are consistently near the top of the fuel column.
  - Temperature of the above core region is at or above the melting point of the relocating fuel and steel eutectic mixture.
- Experiments demonstrate that the fuel and steel eutectic mixture is carried well above core structure without blockages resulting in early termination of the severe accident for transient overpower and loss-of-heat-sink events.
  - Experiments have not yet been performed for severe loss-of-flow conditions, but simulations using phenomenological models predict similarly early termination.

Summary

- SFR safety principles are based on Defense-in-Depth (DiD).
  - Multiple redundant systems and barriers.
- Inherent safety phenomena are added to prevent consequences of unprotected accidents
  - Favorable reactivity feedback and natural circulation cooling
- In more severe (but much less likely) events, favorable fuel dispersal characteristics of the metallic fuel prevents energetic recriticalities, maintains core coolability and primary coolant system integrity.
- Accident-related large radioactive releases from an SFR may be virtually eliminated if only mechanistic, physically-realizable accident conditions are considered to be relevant for safety.
  - Likely guided by the risk-informed and performance-based safety approach.

Summary (cont.)

- There is a substantial fundamental difference between oxide fuel and metal fuel safety performance in severe accidents due to:
  - high melting point of oxide fuel,
  - low melting point of metal fuel and its ability to alloy with cladding to form materials with lower eutectic points.
- Both oxide and metal fuel can be successfully used in a fast reactor, and the regulatory goals can be met with both fuel types for significantly reduced core damage frequencies.
- Metal fuel has significantly less capability to threaten the reactor vessel and containment boundaries with energetic events resulting from accident conditions.