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SFR Safety Approach in the United States

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US Experience with Fast Reactors

Facility	Location	Mission	Dates	Power (MWt)
EBR-I	Idaho	R&D	1951-1963	1.4
EBR-II	Idaho	R&D	1963-1994	62.5
Fermi-1	Michigan	Power	1963-1972	200
SEFOR	Arkansas	Safety Test	1969-1972	20
FFTF	Washington	Fuel & Material Test	1980-1992	400

- **Experimental Breeder Reactor-I (EBR-I) was built to demonstrate fuel breeding**
- **Experimental Breeder Reactor-II (EBR-II) was built to demonstrate closure of the metallic fuel cycle and recycling of reactor fuel**
- **Fermi-1 was built as a metallic uranium-fueled reactor on a utility grid**
- **Southwest Experimental Fast Oxide Reactor (SEFOR) was built to demonstrate the safety properties of the Doppler feedback for oxide fuel**
- **Fast Flux Test Facility (FFTF) was built to test fuel and cladding materials for the Liquid Metal Fast Breeder Reactor (LMFBR) program**

U.S. SFR Safety Experience

- **The US reactor development program has demonstrated that liquid sodium metal cooling in an SFR contributes to excellent safety performance**
  - **Excellent heat removal and heat transport characteristics**
  - **Natural circulation decay heat removal**
  - **Passive reactor power reduction in beyond-design-basis accidents**
- **Core melting accidents have shown that safe shutdown of an SFR is possible without severe consequences**
  - **Metallic fuel is compatible with liquid sodium**
  - **Accident progression can be safely terminated**
  - **Reactors were refueled and operated after the accidents**

Note: American Nuclear Society has started development of an update and revision to ANS Standard 54.1, “Nuclear Safety Criteria and Design Process for Sodium-Cooled Reactor Nuclear Power Plants”

Overall SFR Safety Approach

- **The approach to safety for the SFR consists of three concepts that lower accident (and consequence) probability**
  - **Active safety systems**
    - **Safety systems that require both an activation signal and a system response that have failure probabilities, such as inserting control rods**
  - **Passive safety systems**
    - **Safety systems that do not rely on an activation signal, but still require a system response that has a failure probability, such as magnetic latches on control rod drives**
  - **Inherent safety response features**
    - **Response that does not rely on an activation signal and does not require a system response that has a failure probability, such as fuel Doppler reactivity feedback**
- **All of these concepts can be used for SFR design**

SFR Defense-in-Depth

- **Multiple redundant safety systems (active and passive) to lower the probability of accident occurrence**
  - **Two independent scram systems**
  - **Multiple coolant pumps**
  - **Auxiliary decay heat removal systems**
- **Multiple barriers to the release of radioactive materials**
  - **Cladding on fuel pins**
  - **Primary coolant system boundary**
  - **Containment building**
- **Inherent safety response to lower the probability of severe accident consequences**
  - **Negative power and temperature total reactivity feedback**
- **Only mechanistic (i.e., physical realizable) accident conditions are considered to be relevant for safety**

SFR Inherent Safety Response

- **Inherent safety response was developed as an additional safety concept to protect the reactor during accidents when other protection systems have failed**
  - **Does not require the functioning of a system with failure probability**
  - **Relevant for accident conditions such as the unprotected (unscrammed) loss-of-flow (ULOF), unprotected loss of main heat sink (ULOHS), and unprotected uncontrolled withdrawal of reactor control rod(s) resulting in a transient overpower accident (UTOP)**
  - **Fundamental phenomena are used for inherent safety response, such as thermal expansion, buoyancy-driven flow, and Doppler**
- **The focus of inherent safety response is to address the three main conditions for safe operation of the reactor**
  - **Avoid large uncontrolled increases in core power**
  - **Avoid insufficient cooling of the reactor core**
  - **Avoid rearrangement of fuel that would lead to energetic events**

SFR Inherent Safety Features

- **Inherent safety response uses three basic features**
  1. **Favorable reactivity feedback**
  2. **Sufficient natural circulation cooling**
  3. **Fuel pin failures that do not lead to severe consequences**
- **Research was conducted in each area leading to developments that could substantially improve safety**
  - **Concepts were developed and demonstrated by testing**
- **With proper design for the first two features, the ULOF, ULOHS, and UTOP accidents have no serious consequences**
  - **US favors metallic fuel to prevent energetic recriticalities, maintain core coolability and primary coolant system integrity**
  - **Fuel pin failure does not occur**
  - **There is no release of radioactive materials**
  - **Even less probable, more challenging accident initiators are required to cause fuel pin failure**

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Inherent Safety Features Demonstrated by EBR-II

- **From 1964 through 1994, EBR-II operated as a prototype breeder power station demonstrating fuel cycle closure**
  - **Sodium cooled, 371°C inlet, 473°C outlet, 47 psig**
  - **Fuel pins 0.17 in. OD, 13.5 in. core height; metal fuel in SS cladding**
- **First fuel processed in Fuel Cycle Facility in September 1964; recycled fuel irradiation in April 1965**
- **Mission changed to irradiation testing in 1969 to support FFTF and CRBRP oxide fuel development**
- **Integral Fast Reactor (IFR) program began in mid 1980's**
  - **Testing and demonstration of high burnup metallic fuels**
  - **Shutdown Heat Removal Test series 1984-86; natural circulation decay heat removal and passive shutdown in ATWS events (unprotected loss-of-flow and loss-of-heat-sink)**
- **Operated through 1994**

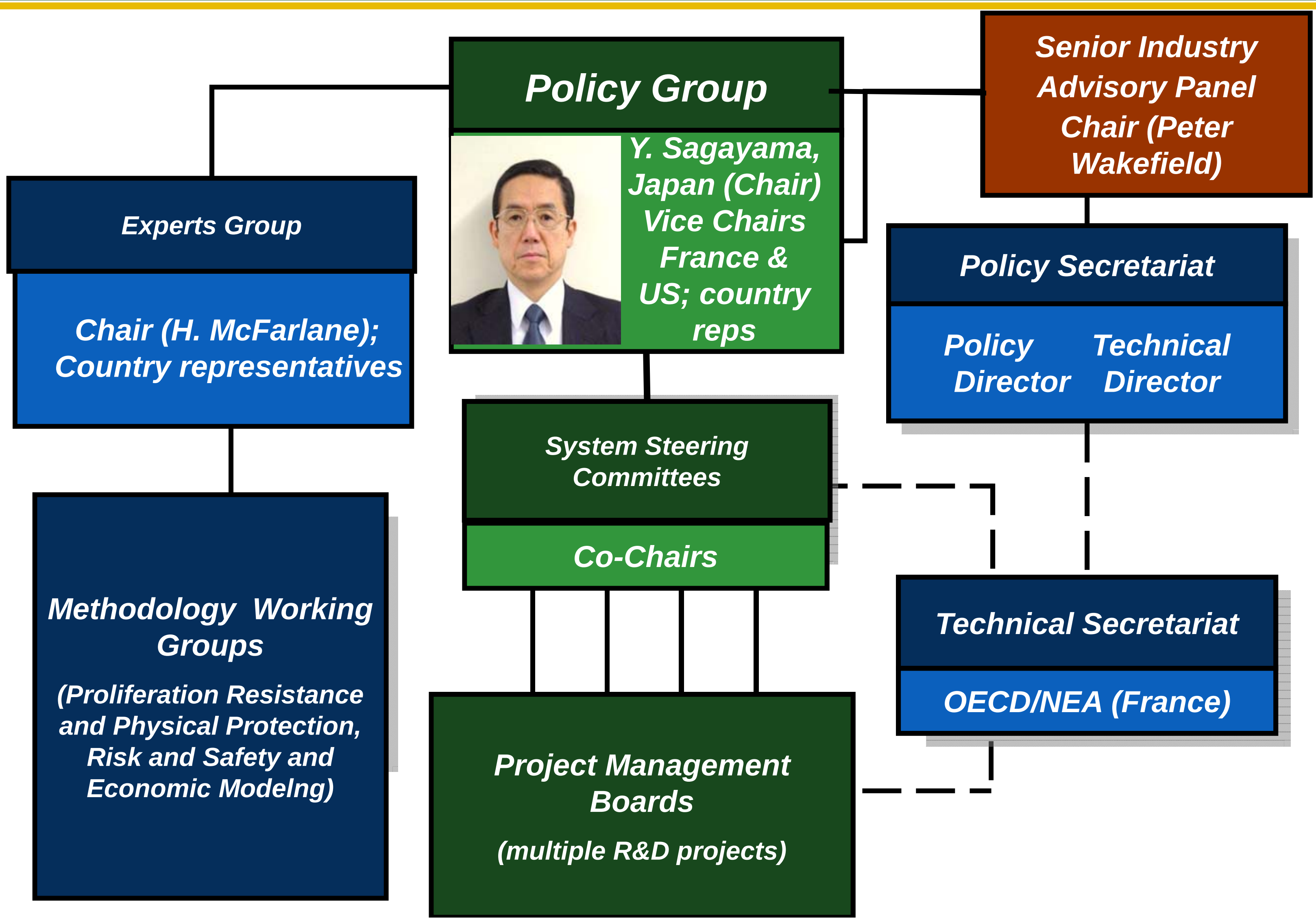
Lessons Learned from Fukushima for an SFR

- **SFRs have different characteristics compared to LWRs**
  - **Backup decay heat removal systems are typically passive or inherent, not requiring electrical power**
  - **How robust are they against extreme events?**
  - **Failure to remove decay heat has severe consequences**
- **Emergency planning should always be expected**
  - **Evacuation capability will likely always be part of licensing regardless of the prevention features**

International Cooperation on Sodium Fast Reactor Development

- **13 leading nuclear nations are cooperating on development of advanced nuclear energy systems through the Generation IV International Forum (GIF)**
  - Formed in 2000 and chartered in 2001 by 9 countries; China, Russia, Switzerland, and the EU have since joined GIF
- **Agree to cooperate on development of 6 advanced systems that represent improvements in safety, proliferation-resistance, sustainability, and economics – deployable after 2030**
- **Sodium fast reactors are among the 6 systems**
  - **Fast reactor cooperation in areas of advanced fuels, transmutation of minor actinides, component design and balance of plant and operation and safety**
  - **In addition, the GIF recently drafted safety design criteria for SFRs in informed by input from other standards bodies (e.g., IAEA)**

Japan Currently Leads the GIF



Final Thoughts

- **Use defense-in-depth to lower accident (and consequence) probability**
  - **Multiple redundant systems and barriers**
- **Use inherent safety features to lower the probability of severe consequences from unprotected accidents**
  - **Favorable reactivity feedback and natural circulation cooling**
- **It may be possible to virtually eliminate accident-related large radioactive releases from an SFR**
  - **Only mechanistic, physically-realizable accident conditions are considered to be relevant for safety, likely guided by PRA**
- **World is moving forward with development of fast reactors (e.g., India, ROK, China, etc.) and experience of Japan, France, US, and Russia which have many decades of experience with SFRs will be needed**