Fundamental Approach to Safety Design of Prototype Gen-IV SFR

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PGSFR: Prototype of Gen-IV Sodium-cooled Fast Reactor

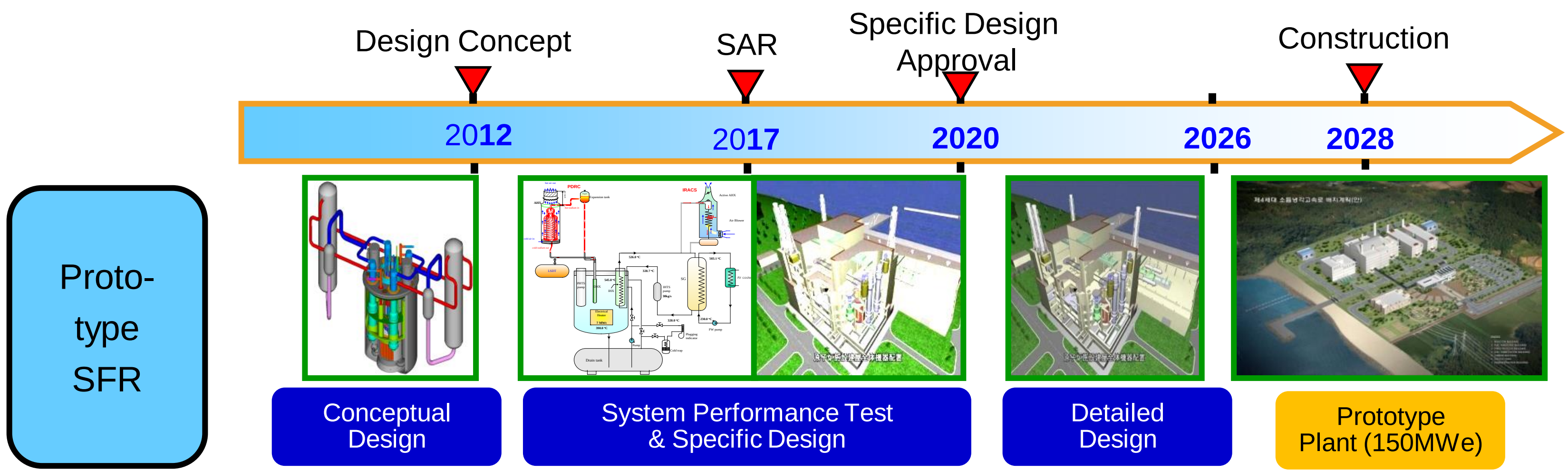
I Development Plan & Overall Design Features

Development plan of PGSFR

❖ Objectives of a Prototype SFR Program

- Acquisition and demonstration of design, construction, and operation technologies
- Irradiation test of TRU fuels from spent LWR fuel

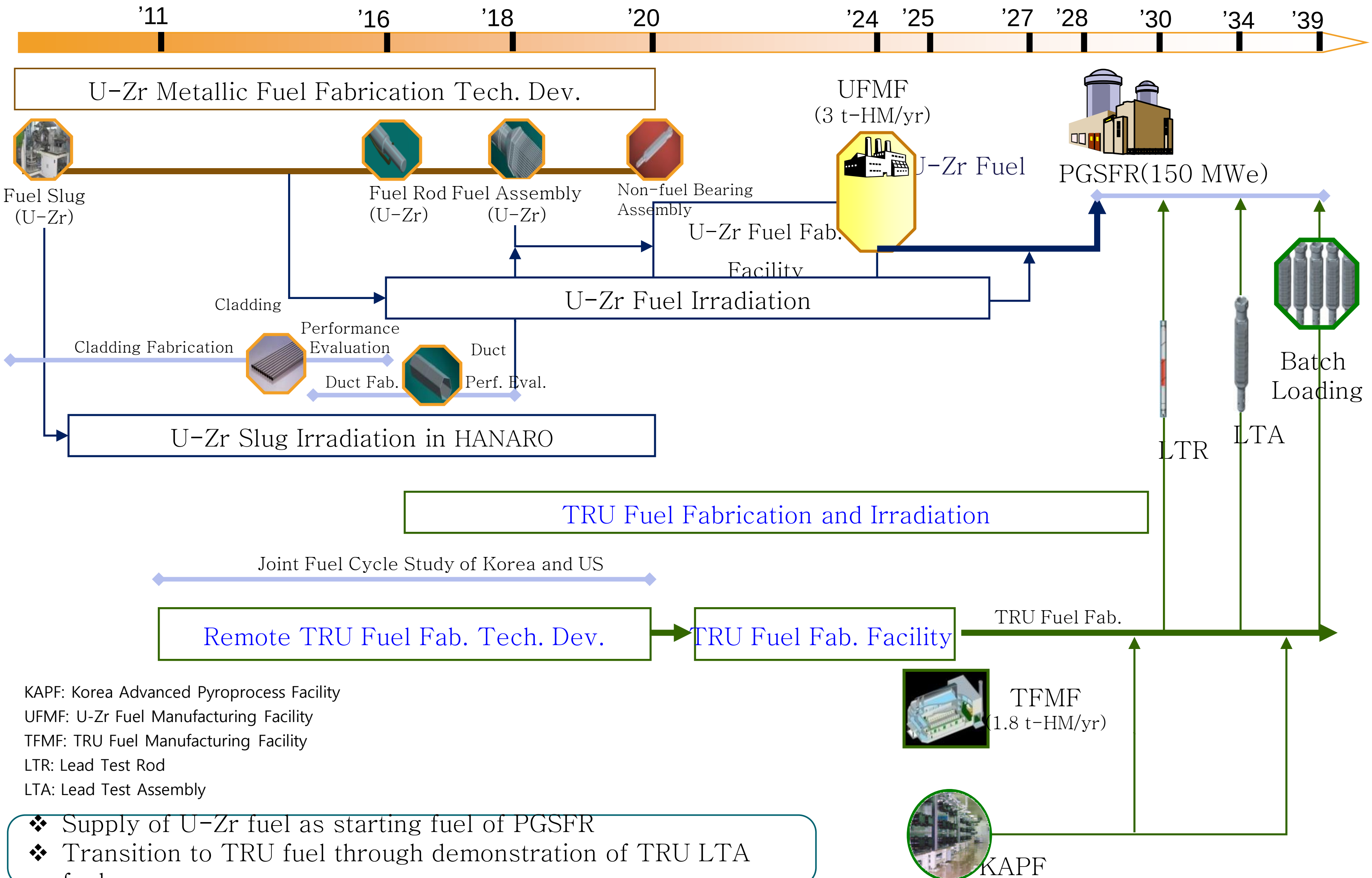
❖ Milestones for a Prototype SFR Development



❖ Prototype SFR System Design

- NSSS design by KAERI (joint program with ANL)
- Fuel Development by KAERI
- BOP design by Korean nuclear industries

Metallic fuel Development Plan

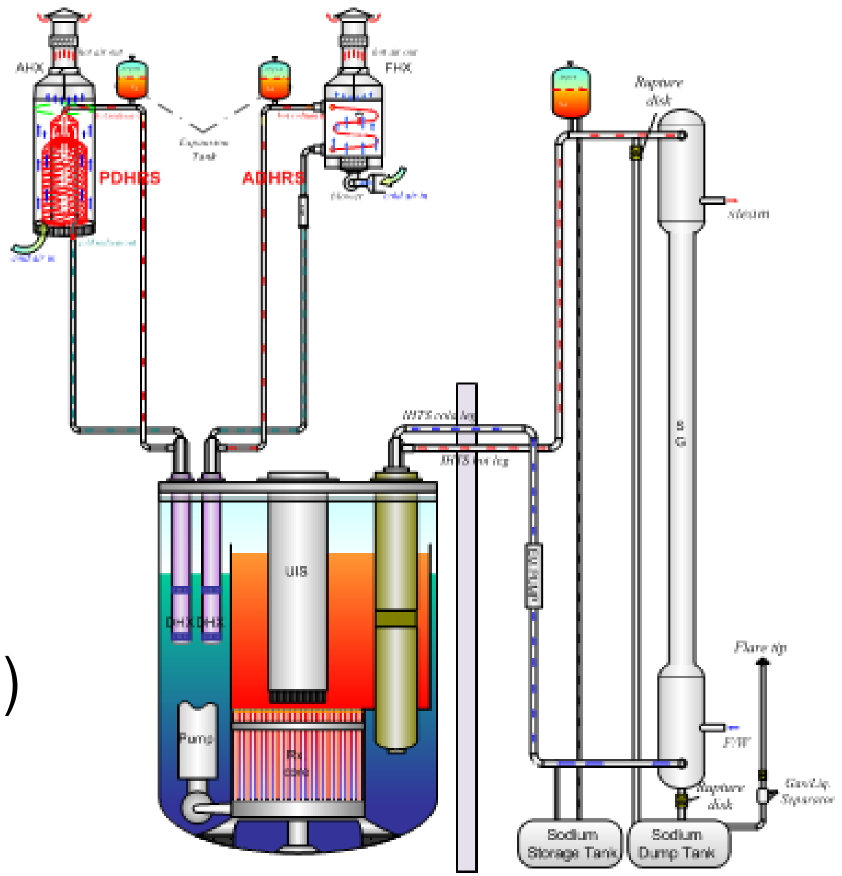


KAPF: Korea Advanced Pyroprocess Facility
UFMF: U-Zr Fuel Manufacturing Facility
TFMF: TRU Fuel Manufacturing Facility
LTR: Lead Test Rod
LTA: Lead Test Assembly

- Supply of U-Zr fuel as starting fuel of PGSFR
- Transition to TRU fuel through demonstration of TRU LTA fuel

Key Design Features

- ❖ Pool-type
- ❖ 150 MWe
- ❖ Metallic fueled core:
  - – U-Zr (initial core) → U-TRU-Zr (Reload core)
- ❖ Core I/O Temp.: 390/545 ^{o}C
- ❖ DHRS System: PDHRS/ADHRS
- ❖ 2-loop IHTS (with Single-wall tube SG)
- ❖ Superheated Steam Rankine Cycle (SCO$_2$ cycle option)



Design Features of PGSFR

Fuel Handling System

Single Rotating Plug, Pantograph IVTM, Fuel Transfer Port, 3 Bundle EVTM

Reactor Enclosure System

RV & GV (25cm gap), RV (H: 15.4m, D: 8.7 m), Forged Solid Head

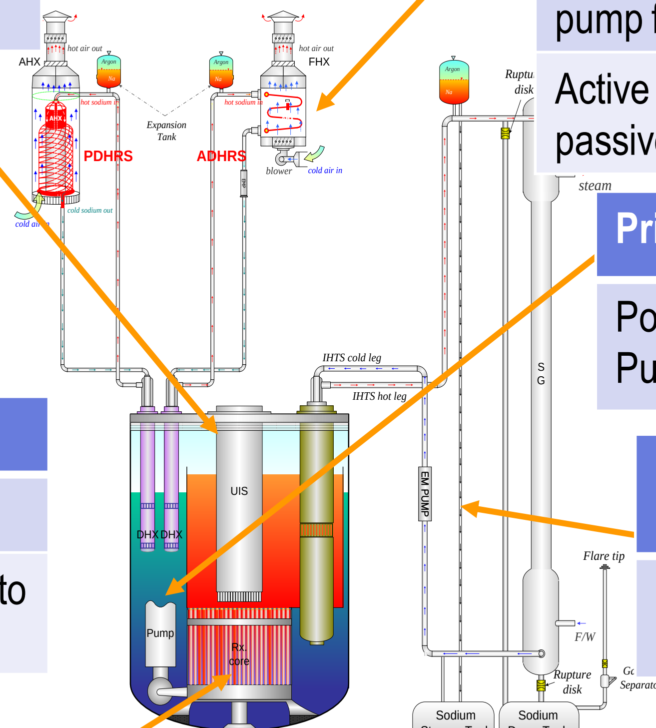
CRDM

6 Primary System, 3 Secondary System

Passive shutdown system is implemented to Secondary system

Reactor Core and Fuel Design

U-Zr Fuel, 112 FAs, ~90cm Height, ~290EFPD (Eq. core),



Decay Heat Removal System

2 PDHRS + 2 ADHRS, Capacity of ~ 2.5%, Cold Pool DHX, DC conduction pump for ADHRS

Active DHRS have more than 50% of passive decay heat removal capability

Primary Heat Transport System

Pool type, 4 IHX, 2 Mechanical Pump, Redan (Peanut type)

Intermediate Heat Transport System

2 Loops, 2 SGs(single wall tube), 2 EM Pumps, SWRPRS

Other systems

Failed fuel detection and location system, SG leak detection system, Sodium purification system for PHTS/IHTS, Primary cover gas purification system

II Fundamental Approach for Safety Design

Fundamental Safety Design Approach (1/4)

- Fundamental Safety Objective is to protect the public and the environment from harmful effects of ionizing radiation.
- Fundamental approach to safety design of nuclear reactor is defense-in-depth.
- Overall objective is to develop a design based on the unique features of pool-type metal-fueled SFR.
  - To provide an inherently safe response to all credible events;
  - To minimize the potential that any event will not lead to a severe accident; and
  - To eliminate the need for extensive off-site evacuation planning by demonstrating low risk to the public health and safety

Fundamental Safety Design Approach (2/4)

- Guiding principles to help translate the overall safety objective into specific safety criteria are applied in conjunction with a defense-in-depth.
  - To capitalize on the inherent safety attributes of the pool concept and metal fuel;
  - To design safety systems to be independent of power generation systems;
  - To emphasize accident prevention rather than mitigation; and
  - To keep the design simple
- Safety design shall provide suitable features to prevent accidents, limit accident progression, maintain containment integrity and mitigate radiological consequences of a release.
- 1st level of safety provides reliable plant operation and prevention of accidents during normal operating conditions through features of the design, construction, operation, and maintenance.
  - QA, redundancy, in-service inspectability, substantial tolerances for normal operating transients, ease of maintenance, fail-safe characteristics etc.

Fundamental Safety Design Approach (3/4)

- 2nd level of safety provides protection against AOOs and DBAs, such as loss of forced coolant flow and reactivity insertions.
  - Second-level protection is provided through redundancy of critical safety systems and protective features and systems that prevent the propagation of faults into serious accidents by maintaining reliable reactivity control and decay heat removal capability.
  - Redundant & diverse Plant Protection System (PPS) and Decay Heat Removal System (DHRS) are key protection systems at this level.
- 3rd level of safety assures acceptable plant responses to certain DBAs, including postulated sodium fires.
  - Radiological containment is provided by a combination of the conservative design of the primary coolant system and containment system barriers.
  - Inherent plant features limit any possible energy release within the containment and, thereby, prevent unacceptable radiological releases to the external environment.

Fundamental Safety Design Approach (4/4)

- The above three levels of safety is supplemented by providing additional margin and measures beyond the design basis.
  - Through safe accommodation by inherent response to the three unprotected plant events [unprotected loss-of-flow (ULOF), unprotected transient overpower (UTOP), and unprotected loss-of-heat sink (ULOHS) to ensure low-risk reactor plant.
  - Through providing measure against the loss of safety-grade DHRS
- Passive means is incorporated in the design for performing the fundamental safety functions of reactivity control, heat removal, and containment of radioactive materials to the extent possible.
  - Passive means include inherent negative reactivity feedbacks, low fuel temperatures and large margin to sodium coolant boiling, low individual control rod worth and mechanical stops to limit the magnitude of potential positive reactivity insertion from control rod withdrawal, natural circulation heat removal systems, a guard vessel to limit sodium leakage, and a low leakage containment building.

Acceptance Criteria for Safety Analysis

	AOO	DBA Class I	DBA Class II	DEC
Frequency/RY	$10^{-1} > F \geq 10^{-2}$	$10^{-2} > F \geq 10^{-4}$	$10^{-4} > F \geq 10^{-6}$	$10^{-6} > F \geq 10^{-8}$
Fuel/Cladding	No reduction of plant life time - No fuel melting - Clad integrity - Core coolability $CDF_{\sum AOO} < 0.05$	A small fraction of fuel pin failures $CDF_{each} < 0.05$	Pin coolable geometry - Temp. of cladding inner surface < 1075 °C - Bulk temperature of primary coolant < Sodium boiling temperature	Core coolable geometry (Under discussion)
RCB/PHTS	ASME Level B No corrective action required	ASME Level C Inspected	ASME Level D Repair	ASME Level D Vessel cannot be reused
Containment	Maintain design leakage rate			

CDF: Cumulative Damage Fraction

III Design Consideration for Implementation of SDC

SDC for Development of Safety Approach SDG

- Reactivity and decay heat removal issues for DBA and DEC are considered for development of safety approach SDG report.
  - SDCs related to reactivity issue: Criteria 44, 45, 46, 47, 51
  - SDCs related to decay heat removal issue: Criteria 49, 51
- DEC is emphasized, and the followings are addressed as typical DEC.
  - ATWS (UTOP, ULOF, ULOHS)
  - Loss of decay heat removal system including reduction of coolant inventory in the reactor
- DEC considered in PGSFR design

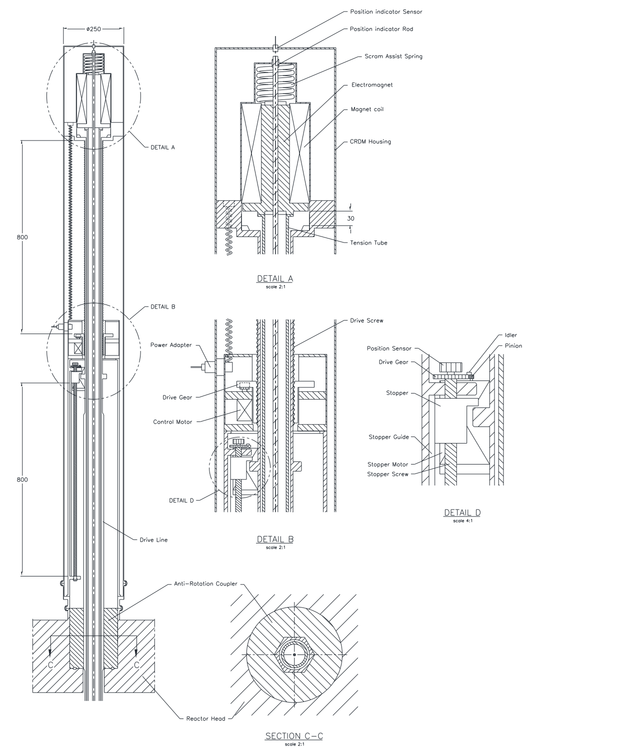
Category	Frequency/RY	Event	
DEC	$10^{-8} \leq F < 10^{-6}$	UTOP	Unprotected single rod withdrawal at power
		ULOF	Unprotected loss of power to all PHTS pumps
			Unprotected spurious one PHTS pump trip
			Simultaneous seizure of all PHTS pumps
		LOHS	Unprotected spurious one IHTS pump trip
			Unprotected turbine trip
			Unprotected loss of power to all IHTS pump trip
			Unprotected loss of normal FW due to pump failure
	$F < 10^{-8}$	SA	Total loss of decay heat removal

Design Consideration for Reactivity Issue (1/3)

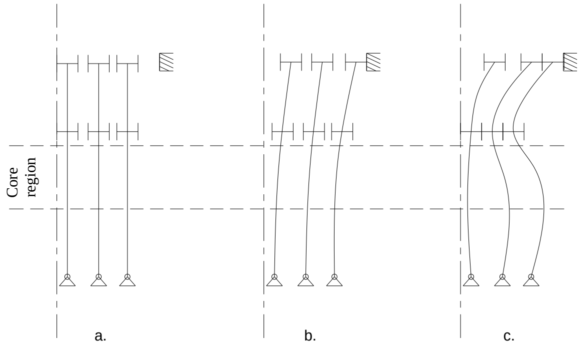
- Reactor shutdown for DBA
  - Two diverse and independent active shutdown systems (Primary & Secondary) are provided to shutdown the reactor. During the reactor trip, all control rods drop by gravity into the core to make it shutdown (subcritical).
    - Any one of two shutdown system is able to shutdown and retain subcritical.
    - Neutron flux, core inlet/outlet temperatures, PHTS flow are measured to generate the automatic trip signals considering diversification of detection parameters.
    - One of the two shutdown system is designed considering single failure criteria and 2/4 logic is applied for reactor trip.
    - Electrical independence, physical separation and fail safe features are considered in the design

Design Consideration for Reactivity Issue (2/3)

- Reactor shutdown for DEC
  - Negative reactivity feedbacks of metal fuel are utilized for Inherent reactor power reduction in balance with heat rejection
    - Low stored Doppler reactivity
    - Significant axial expansion of metal fuel
    - Control rod driveline expansion
  - Passive shutdown system using thermal expansion mechanism is considered to drop of CR at core outlet temperature rise.
    - Implemented into the secondary shutdown systems



- Passive core constraint system
  - Limited free flowering core concept
  - Avoid compaction of active core region during transient
  - Ensure neg. reactivity insertion by core geom. change

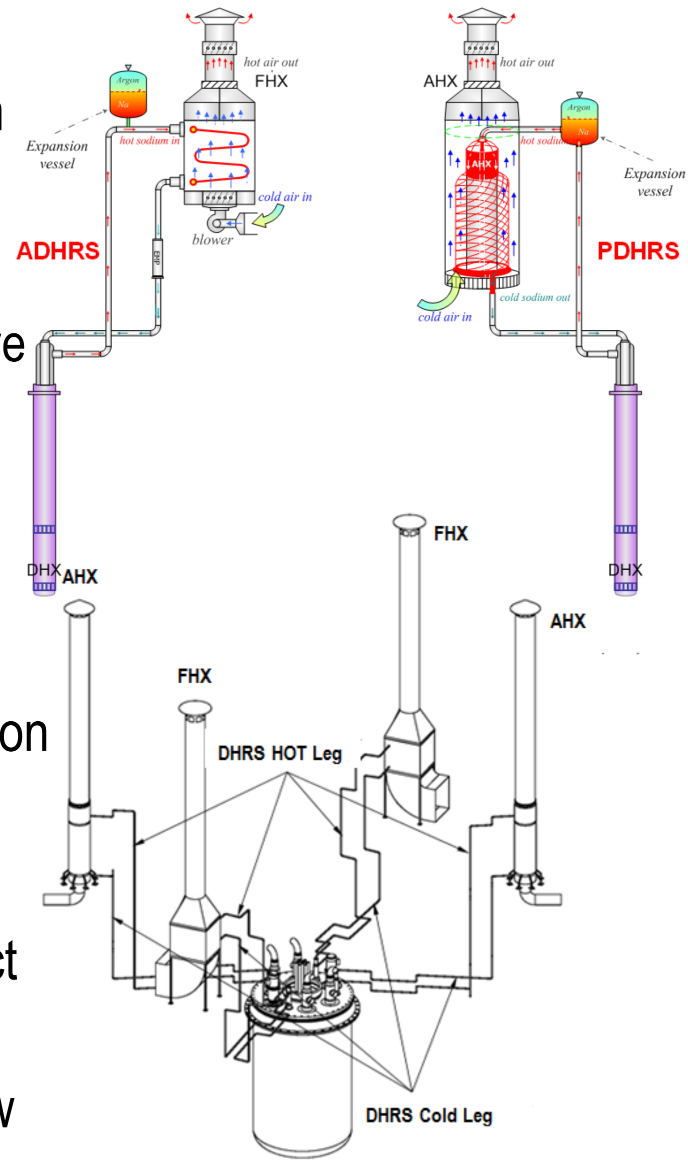


Design Consideration for Reactivity Issue (3/3)

- Core reactivity characteristics
  - Total reactivity feedback during hypothetical event should be (-) negative or less than 1 dollar to prevent from significant release of mechanical energy which might precede to core damage
    - Isothermal temp. + expansion and dispersion (fuel, structure) + sodium void reactivity
  - Early stage with U core loading shows all negative reactivity feedback and also negative sodium void reactivity
  - Later stage with TRU loading have positive sodium density coeff. but total sum of reactivity coeff. is negative
  - The dispersive behavior of metal fuel in overpower transients
    - Even in accident that lead to fuel failure, metal-fuel-cladding eutectic mix disperses in the sodium coolant and gets entrained out of the core instead of freezing and creating coolant channel blockages that propagates the damage.
    - No in-core blockage. Core pin geometry is maintained and dispersed fuel flows out through core regions → Negative reactivity

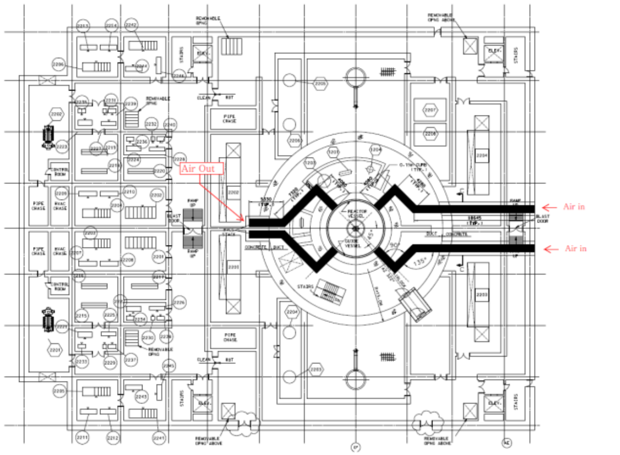
Design Consideration for DHR Issue (1/2)

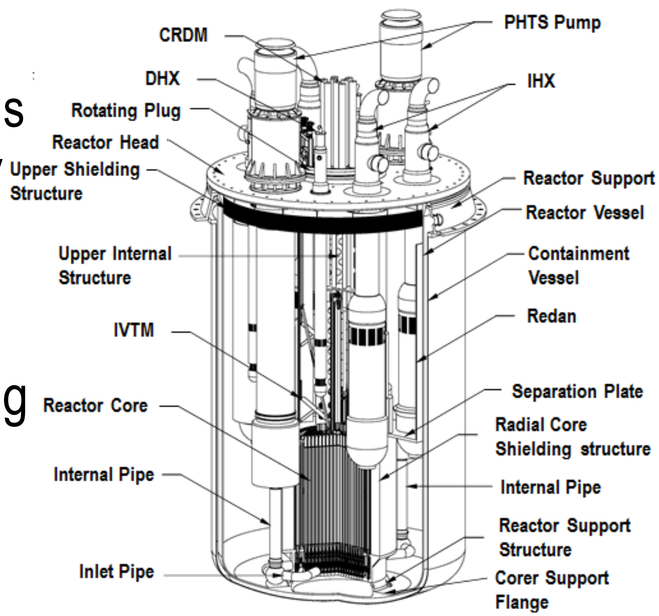
- Decay heat removal for DBA
  - Combination of safety-grade passive and active system
    - Total heat removal capacity ~ 2.5% of rated power
    - 2 trains of passive system + 2 trains of active system
    - Active system operated by EM pump & HX blower have also passive heat removal capability
  - Cold pool DRACS concepts:
    - DHXs are located in cold pool
  - Independent 4 train design considering redundancy
  - Diversity to prevent from common mode failure (operation principle/heat exchanger/damper type)
  - Guard piping within containment boundary
  - Emergency power and sodium leak detection by contact type detector
  - Prevention of sodium freezing by keeping minimum flow and electrical heater



Design Consideration for DHR Issue (2/2)

- Decay heat removal for DEC
  - Ex-vessel cooling by nat. convection of air to ensure IVR
  - Under conceptual design based on preliminary layout
    - 1.2x1.2 m duct size, 30 m of outlet duct height
- Prevention of loss of reactor coolant inventory
  - RV and GV are to be designed with the highest level of reliability to prevent the dependent and common cause failures to ensure the containment function,
    - Prevention of GV due to thermal and mechanical loads by leaked sodium form RV, Separate supports for RV and GV, Sufficient margin against earthquake
  - Gap between RV & GV is sized (25 cm) to maintain primary sodium circulation through IHX & DHX following RV sodium leak and to enable inservice inspection.
  - Contact type and aerosol detectors are installed to monitor primary sodium leak from RV.



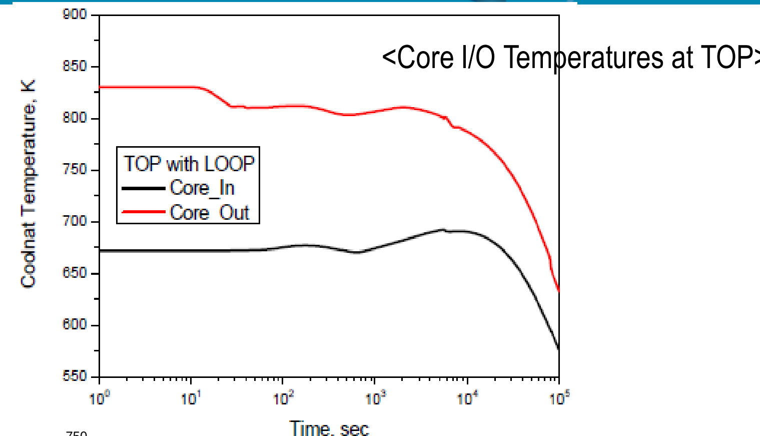


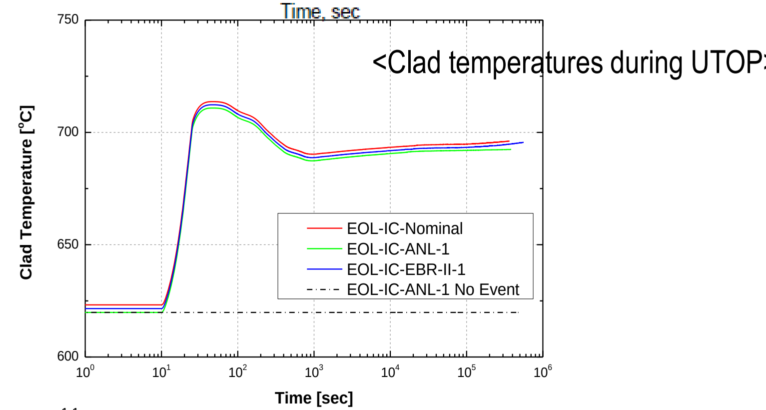
Design Measures for DEC

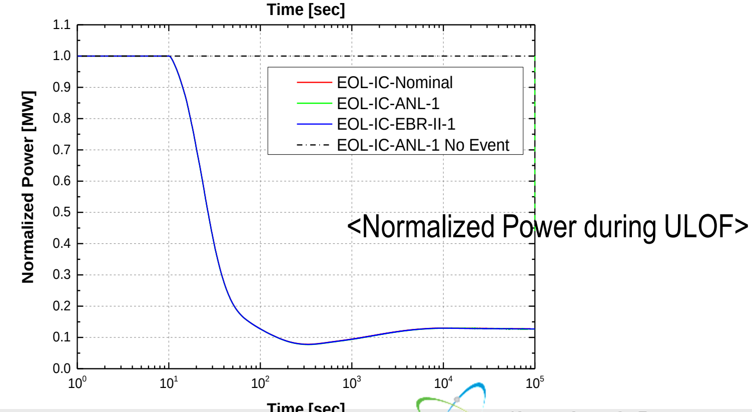
- ATWS
  - Prevention of core damage
    - Inherent reactivity feedback of metal fuel and structural responses
    - Self-actuated shutdown system
  - Mitigation to ensure containment function
    - Safety-grade decay heat removal system
    - In-vessel retention
    - Early termination by using metal fuel with low melting temperature
  - Significant mechanical energy release in CDA is to be practically eliminated by design measures for prevention and mitigation against ATWS.
    - Containment design basis accident is a spill or leak of sodium coolant from the IHTS piping, DHRS piping, or the primary sodium coolant purification system inside the containment, leading to a fire in the containment.
- Loss of decay heat removal system including reduction of primary coolant inventory
  - Core damage is prevented by ensuring core un-coverage and using decay heat removal system with high reliability designed for DBA
  - To ensure the containment function, RV and GV are to be designed with the highest level of reliability to prevent the dependent and common cause failures
  - Additional ex-vessel cooling system is utilized for cooling in case of total loss of DHRS

Safety Evaluation for Conceptual Design

- The following transients have been evaluated with the MARS-LMR.
  - Protected events: TOP, LOF, LOHS, Primary pipe break, RV leak, SBO
  - Unprotected events: UTOP, ULOF, ULOHS
- The safety analysis results showed the safety characteristics of PGSFR design with an appropriate margin.
- Clad temperatures for all ATWS events were well stabilized below of eutectic temperature.
- The performance of the DHRS has been checked by showing that the DHRS design has ability to prevent the fuel rod heat-up





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