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Sodium Integral Effect Test Loop for Safety Simulation and Assessment (STELLA)

Jewhan Lee
Korea Atomic Energy Research Institute
Republic of Korea

26 October 2022

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KAERI Korea Atomic Energy Research Institute

Meet the Presenter

Dr. Jewhan Lee is currently the project manager of STELLA program and the team leader of the sodium experiment team in the Korea Atomic Energy Research Institute. He earned his Ph.D. in nuclear engineering and established his career as a sodium experiment professional.

He served as a supporter of the Technical Director of EG and now he is a member of GIF SFR-SSC SO-PMB.

His expertise is in the sodium heat transfer of both analytical and experimental works. He has experience on handling and managing the alkali metal and evaluating the performance of various heat transfer systems using various analysis tools. He has a deep understanding of the liquid metal system from component level to system level.

His recent interest expands to the innovative instrumentation for high temperature liquid metal as well as various liquid metal applications, such as a thermal energy storage system.

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KAERI

- I Introduction
- II Separate Effect Test (STELLA-1 & SELFA)
- III Integral Effect Test (STELLA-2)
- IV Current Status and Future Plan
- V Summary

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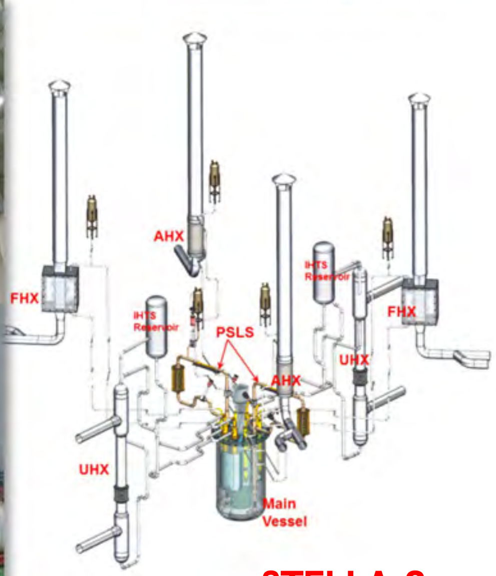
Introduction

- Program Overview -

Introduction
- Program Overview -

- STELLA Program (2009~)
  - A large-scale sodium thermal-hydraulic test program
- Phase 1: STELLA-1 (2012) & SELFA (2016)
  - Sodium component test loop for Separate Effect Test(SET)
  - Thermal-hydraulic performance test for key heat exchangers
    - Validation of thermal-sizing and design codes
- Phase 2: STELLA-2 (2014~)
  - Integral Effect Test(IET) for verification of plant dynamic response
    - Comprehensive review of key safety issues
    - Safety analysis code validation

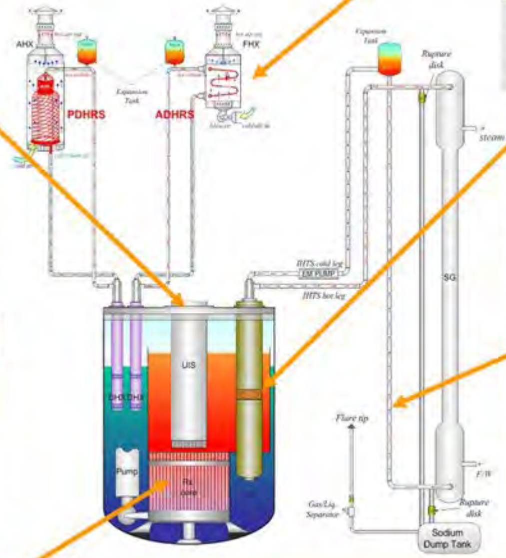


STELLA-2
(In operation)

Introduction

- Reference Reactor -

- Prototype Gen-IV SFR(PGSFR)
  - Technology demonstration for TRU transmutation (2012~2020)
- Main Design Features
  - Sodium-cooled/pool-type reactor
  - Superheated steam cycle
  - 2-loop IHTS/SGS
  - Safety-grade DHRS
  - Independent Passive & Active DHRS



Fuel Handling System

Dual Rotating Plug, Fixed Arm IVTM, Fuel Transfer Port, EVTM

Reactor Enclosure System

RV (H: 15.5m, OD: 10.5m), CV (OD: 11 m), 20cm gap, Forged Solid Head

CRDM

6 Primary CRs, 3 Secondary CRs

Passive shutdown feature was implemented for secondary CRs

Reactor Core and Fuel Design

U-Zr Fuel, 112 FAs, ~90cm Height, ~290EFPD (Eq. core)
IVS Locations inside Core Shroud

Decay Heat Removal System

2 PDHRS + 2 ADHRS, Capacity of ~ 2.5%, Cold Pool DHX

ADHRS has more than 50% of passive decay heat removal capability

Primary Heat Transport System

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

Intermediate Heat Transport System

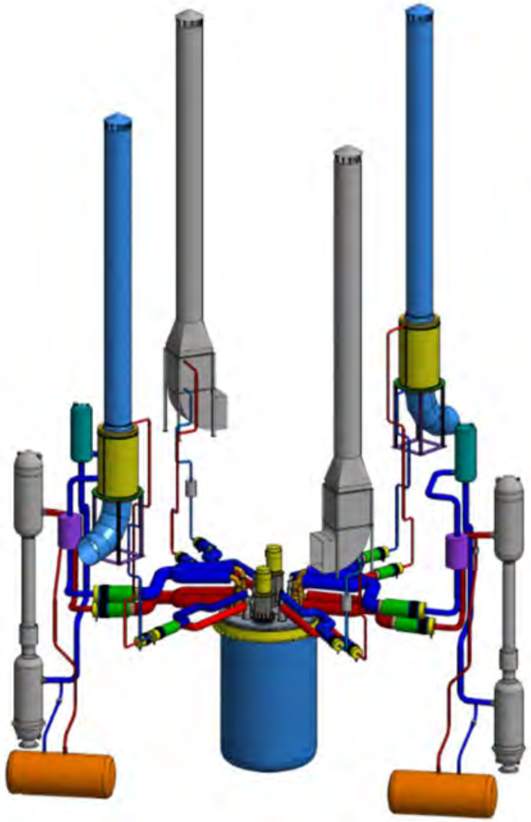
2 Loops, 2 SGs(single wall tube), 2 EM Pumps, SWRPRS

Other systems

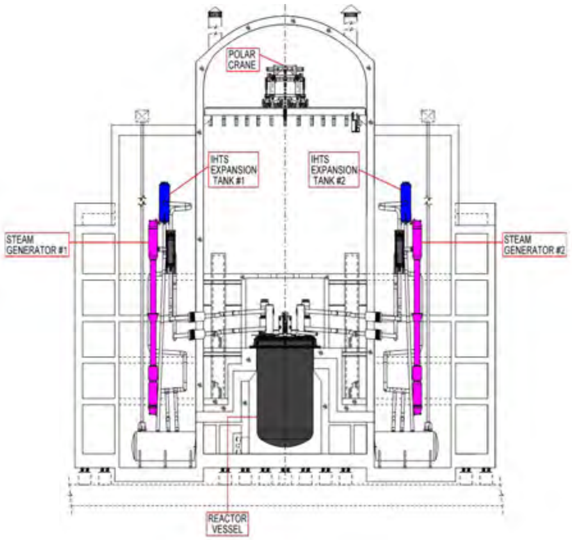
Sodium Purification Systems for PHTS/IHTS/DHRS, Primary Cover Gas Processing System, Superheated Steam Rankine Cycle for PCS, Instrumentations for Failed Fuel & SG Leak Detections

Introduction

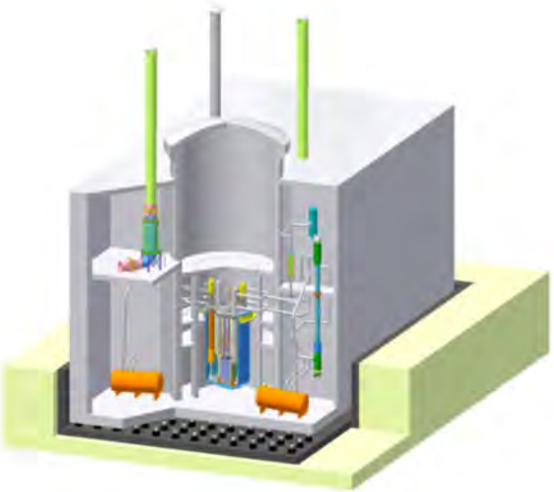
- Reference Reactor -

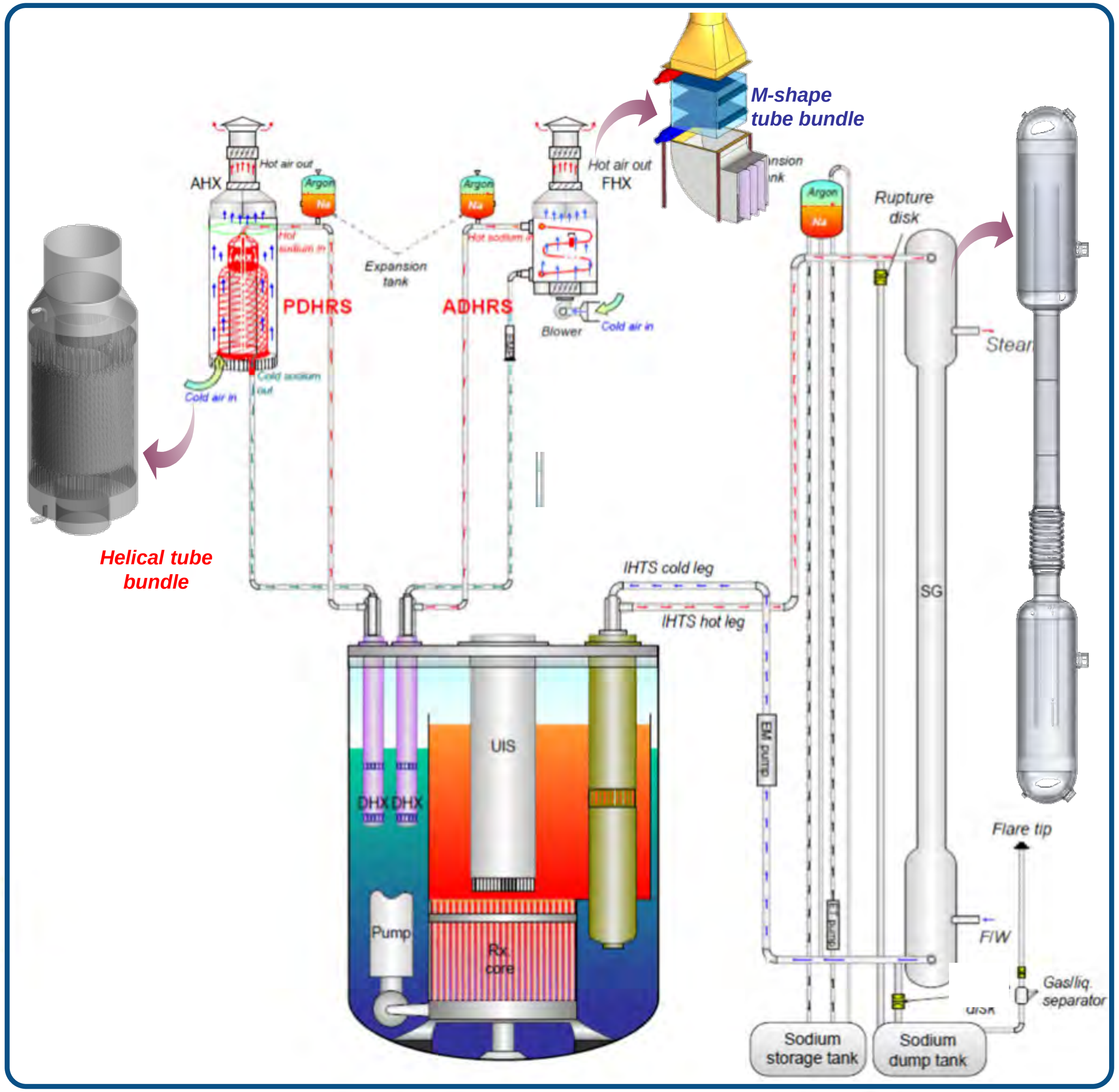


< PGSFR Solid Modeling >



< PGSFR GA >





< Schematic of PGSFR Heat Transport System >

Separate Effect Test

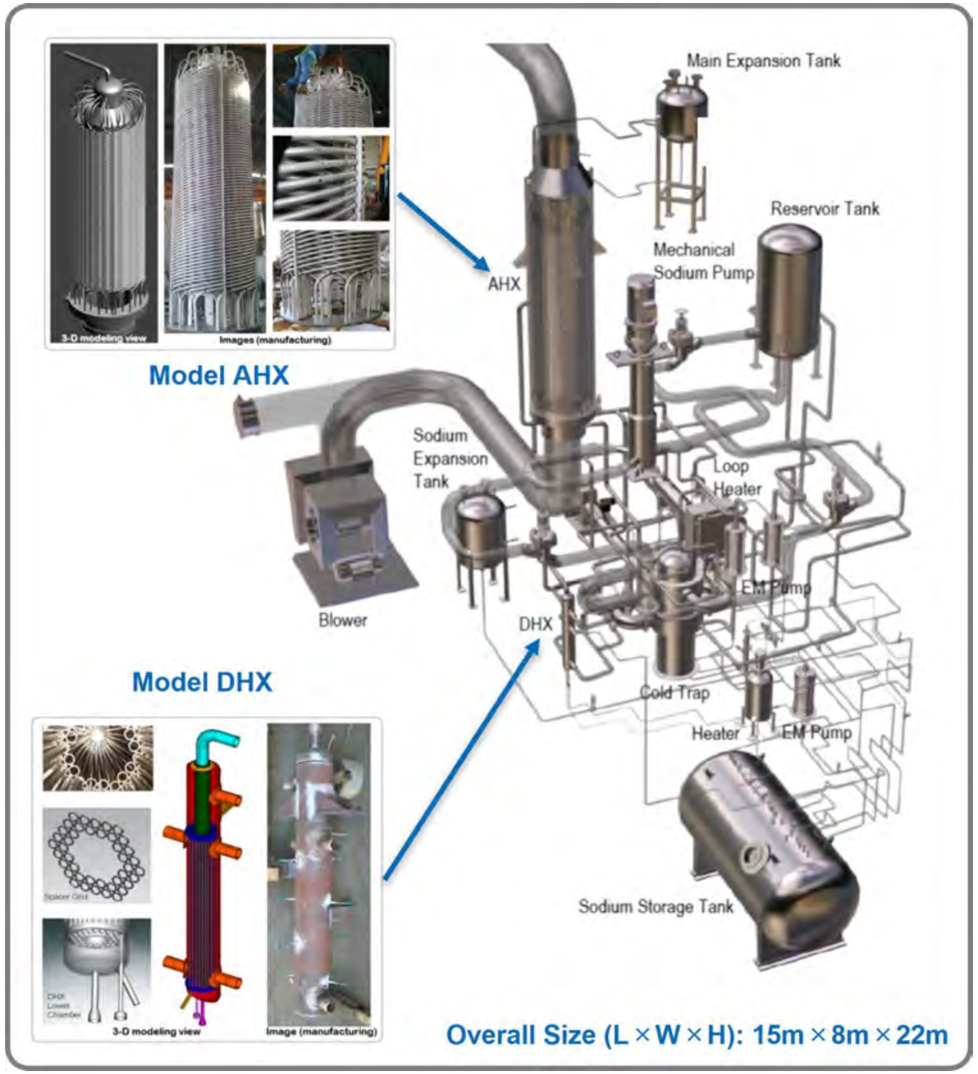
- STELLA-1 & SELFA -

Phase I: Separate Effect Test

- Component Test -

- STELLA-1
  - Purpose: performance test of HXs (DHX & AHX)
- Main Features
  - Two key heat exchangers
    - Straight-tube type sodium-to-sodium HX (DHX)
    - Helical-tube type sodium-to-air HX (AHX)
  - Mechanical sodium pump
- Specification

Total Na Inventory	~18 tons	Total Elec. Power	~ 2.5 MW
Design Temp.	600 °C	Heat Capacity of HX	1.0 MW
Design Press.	10 bars	Max. Flowrate	25 kg/s



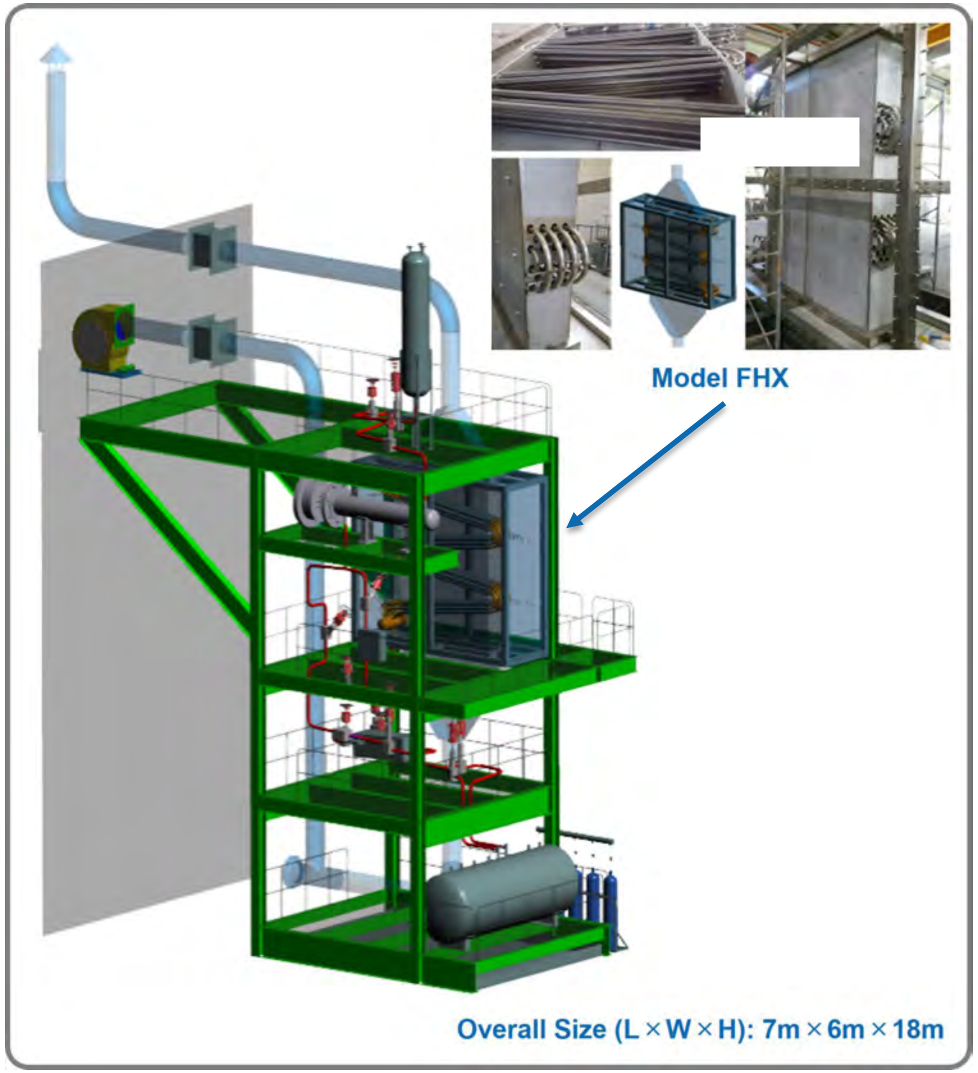
Overall Size (L × W × H): 15m × 8m × 22m

Phase I: Separate Effect Test

- Component Test -

- SELFA
  - Purpose: performance test of HXs (FHX)
  - Extension of STELLA-1
- Main Features
  - One key heat exchanger
    - Finned-tube type sodium-to-air HX (FHX)
- Specification

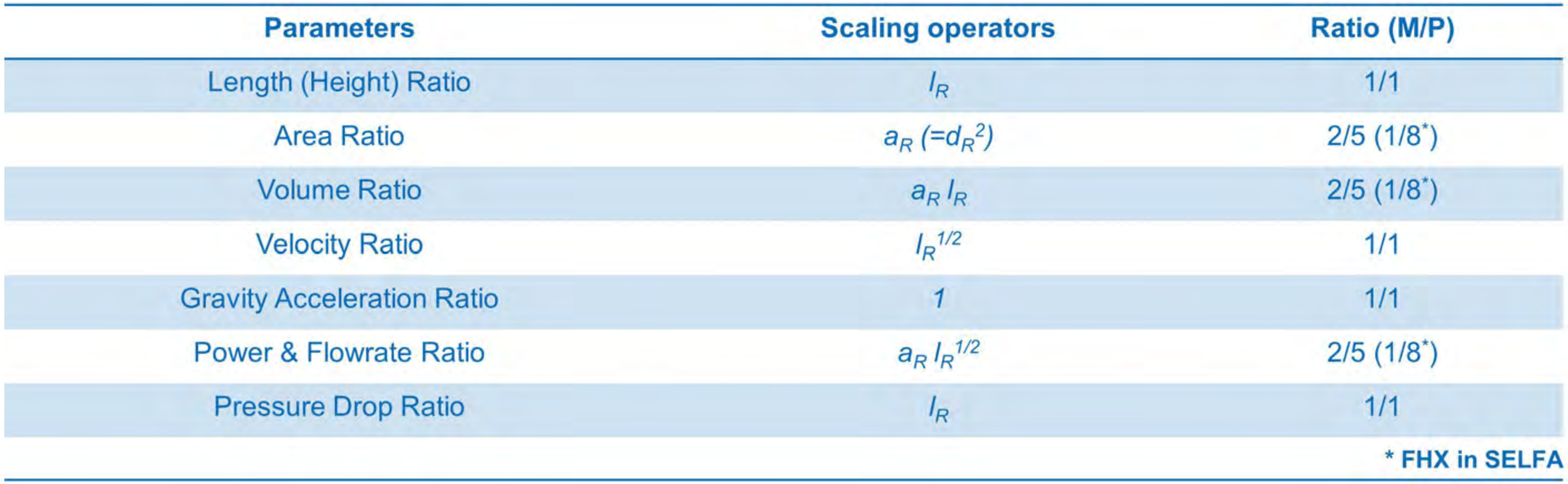
Total Na Inventory	~1.5 tons	Total Elec. Power	~ 1.0 MW
Design Temp.	550 ºC	Heat Capacity of HX	315 kW
Design Press.	3 bars	Max. Flowrate	6 kg/s



Model Heat Exchangers Design

- Design Requirements -

- Volume Scaling Method
  - Length scale ratio: 1/1
  - Preservation of tube size, pitch, U and LMTD



Parameters	Scaling operators	Ratio (M/P)
Length (Height) Ratio	l_R	1/1
Area Ratio	a_R (=d_R^2)	2/5 (1/8*)
Volume Ratio	$a_R\, l_R$	2/5 (1/8*)
Velocity Ratio	$l_R^{1/2}$	1/1
Gravity Acceleration Ratio	1	1/1
Power & Flowrate Ratio	$a_R\, l_R^{1/2}$	2/5 (1/8*)
Pressure Drop Ratio	l_R	1/1

*** FHX in SELFA**

Model Heat Exchangers Design

- Design Code & Mathematical Model -

- In-house Codes for Thermal-sizing
  - SHXSA
    - Straight-tube sodium-to-sodium HX (DHX, IHX)
  - AHXSA
    - Helical-tube sodium-to-air HX (AHX)
  - FHXSA
    - Finned-tube sodium-to-air HX (FHX)

STELLA Phase I is for V&V of design codes

Mathematical models for HX design

☐ Control volume approach

- Mass conservation

$$w_s = const \qquad w_t = const$$

- Momentum equation

$$\Delta P = \Delta P_{acc,i} + \Delta P_{fric,i} + \Delta P_{grav,i}$$

$$\begin{cases} \Delta P_{acc,i} = \left(\dfrac{G^2}{\rho}\right)_i - \left(\dfrac{G^2}{\rho}\right)_{i+1} \\ \Delta P_{fric,i} = f\dfrac{L_i}{d_i}\cdot\dfrac{G^2}{2\cdot\bar{\rho}_i} \\ \Delta P_{grav,i} = \bar{\rho}_i\cdot g\cdot L_i\cdot\sin\theta \end{cases}$$

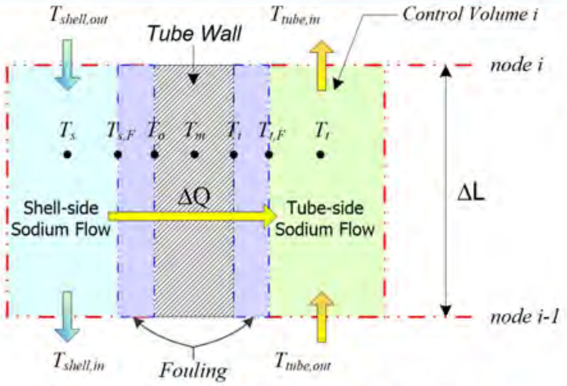
- Energy balance:

$$\Delta Q = U\cdot\Delta A_o\cdot\Delta T_o$$

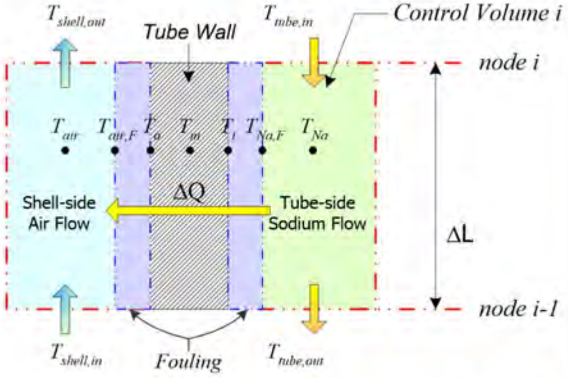
$$\begin{cases} \Delta Q = w_t\cdot(i_{t,in} - i_{t,out}) \\ \Delta Q = w_s\cdot(i_{s,out} - i_{s,in}) \end{cases}$$

$$\Delta Q = \; h_t\cdot\Delta A_i\cdot(T_t - T_{t,F}) = h_{t,F}\cdot\Delta A_i\cdot(T_{t,F} - T_i)$$

$$= \; \Delta A_o\frac{2\cdot k}{d_o}\cdot\frac{T_i - T_o}{\ln(d_o/d_i)} = h_s\cdot\Delta A_o\cdot(T_{s,F} - T_s)$$



Control volume for Sodium-to-sodium HXs (IHX & DHX)



Control volume for Sodium-to-air HXs (AHX & FHX)

$$U = \left[\frac{d_o}{d_i}\frac{1}{h_t} + \frac{d_o}{d_i}\frac{1}{h_{t,F}} + \frac{d_o}{2k}\ln\left(\frac{d_o}{d_i}\right) + \frac{1}{\eta_s\cdot h_{s,F}} + \frac{1}{\eta_s\cdot h_s}\right]^{-1}$$

$$\text{where, } \begin{cases} \eta_s = 1 \text{ for the bare tubes} \\ \eta_s \neq 1 \text{ for the tube including fins} \end{cases}$$

< Overall heat transfer coefficient >

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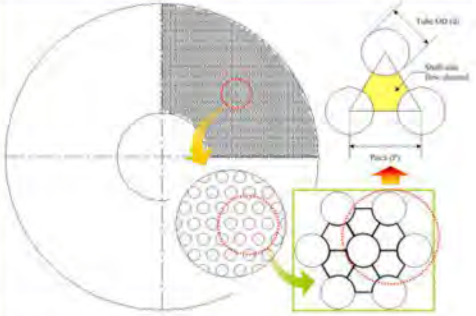
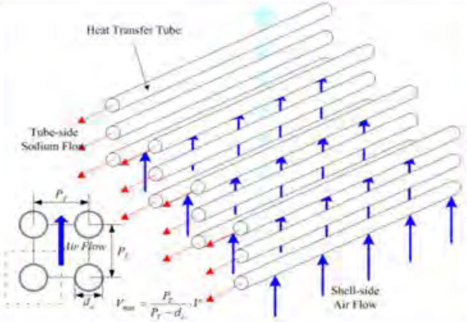
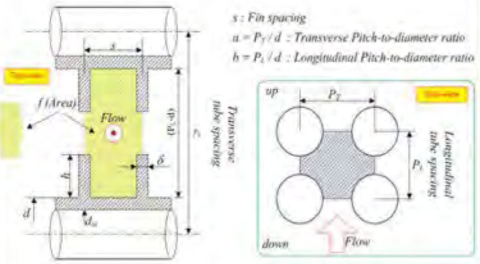
Model Heat Exchangers Design

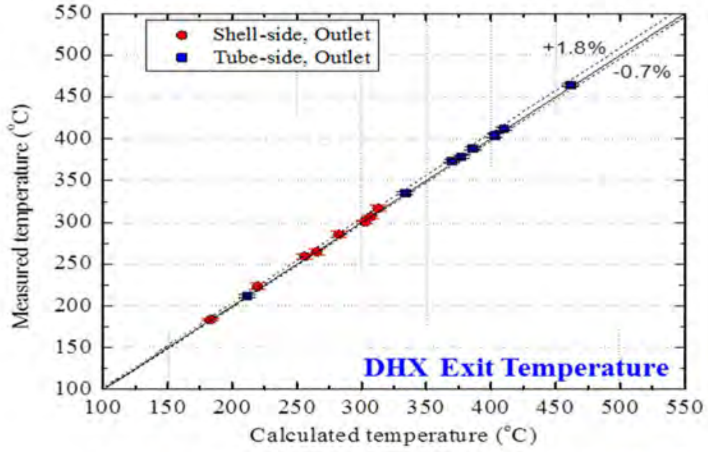
- Physical Model -

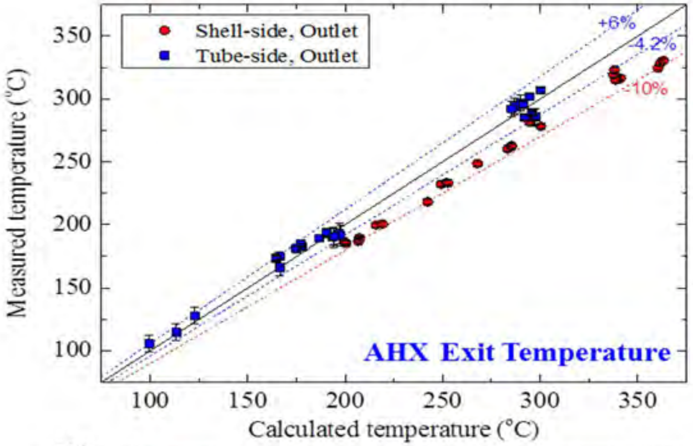
Code	SHXSA	AHXSA	FHXSA
Target Heat Exchanger(s)	**Straight tube-type** **sodium-to-sodium HXs** **(IHX & DHX)**	**Helical-tube type** **sodium-to-air HXs** **(AHX)**	**Finned-tube type** **sodium-to-air HXs** **(FHX)**
Schematics of Flow paths or channels			
Pressure drop Models and Heat Transfer Correlations	❖ Tube-side (Sodium) – Frictional ΔP for straight tube inside • Darcy's friction factor $f = \begin{cases} \frac{64}{\mathrm{Re}} & \text{for Re} < 2000 \\ \frac{1}{[1.8 \cdot \log(\mathrm{Re}) - 1.64]^2} & \text{for Re} > 4000 \end{cases}$ – Heat Transfer • Lyon-Martinelli (1948) : $Nu = 4.0 + 0.025 \cdot Pe^{0.8}$ • Seban & Shimazaki (1951) : $Nu = 5.0 + 0.025 \cdot Pe^{0.8}$ ❖ Shell-side (Sodium) – Total ΔP (From loss + friction loss) $\Delta P_{tot} = \Delta P_{form} + \Delta P_{fric} = \left(K_i + f_i \frac{l}{d_h} \right) \cdot \frac{1}{2} \rho v^2$ – Heat Transfer • Graber and Rieger correlation (1973) $Nu = 0.25 + 6.2(P/D) + [0.032(P/D) - 0.007] \cdot Pe^{0.8-0.024(P/D)}$ $\text{for } 1.25 \le P/D \le 1.95 \text{ and } 150 \le Pe \le 3000$	❖ Tube-side (Sodium) – Frictional ΔP for a Helical tube inside • Mori-Nakayama (1967) $f = \left(\frac{d_i}{D_c} \right)^{0.5} \cdot \frac{0.192}{\left[\mathrm{Re} \cdot (d_i/D_c)^{2.5} \right]^{1/6}} \cdot \left(1 + \frac{0.068}{\left[\mathrm{Re} \cdot (d_i/D_c)^{2.5} \right]^{1/6}} \right)$ – Heat Transfer • Lyon-Martinelli (1948) : $Nu = 4.0 + 0.025 \cdot Pe^{0.8}$ • Lubarski-Kaufman (1955): $Nu = 0.625 \cdot Pe^{0.4}$ ❖ Shell-side (Air) – Frictional ΔP : Zhukauskas *et al*. (1968) • Flow across tube bank $\Delta P = N_L \cdot \chi \cdot \left(\frac{\rho \cdot V_{max}^2}{2} \right) \cdot K_D, \ K_D = f(Re_{max}, Configuration)$ – Heat Transfer • Zhukauskas formula (1968) $Nu_{air} = C \cdot \mathrm{Re}_{D,max}^m \cdot \mathrm{Pr}^{0.36} \cdot \left(\frac{\mathrm{Pr}}{\mathrm{Pr}_s} \right)^{0.25}$ $for \ N_L \ge 20, \ 0.7 < \mathrm{Pr} < 500, 10^3 < \mathrm{Re}_{D,max} < 2 \times 10^6$	❖ Tube-side (Sodium) – Frictional ΔP for a Finned-tube inside • Darcy friction factor $f = \begin{cases} \frac{64}{\mathrm{Re}} & \text{for Re} < 2000 \\ \frac{1}{[1.8 \cdot \log(\mathrm{Re}) - 1.64]^2} & \text{for Re} > 4000 \end{cases}$ – Heat Transfer • Lyon-Martinelli (1948) : $Nu = 4.0 + 0.025 \cdot Pe^{0.8}$ • Lubarski-Kaufman (1955): $Nu = 0.625 \cdot Pe^{0.4}$ ❖ Shell-side (Air) – Frictional ΔP : Yudin, Lokshin & Fomina • Flow across tube bank $K_{Drag} = f(Re, h/d, s/d, s_1/d, s_2/d, etc.)$ – Heat Transfer • Zhukauskas formula (1968) $Nu_f = 0.192 (a/b)^{0.2} (s/d)^{0.18} (h/b)^{-0.14} Re_f^{0.65} Pr_f^{0.36} (Pr_f / Pr_w)^{0.25}$

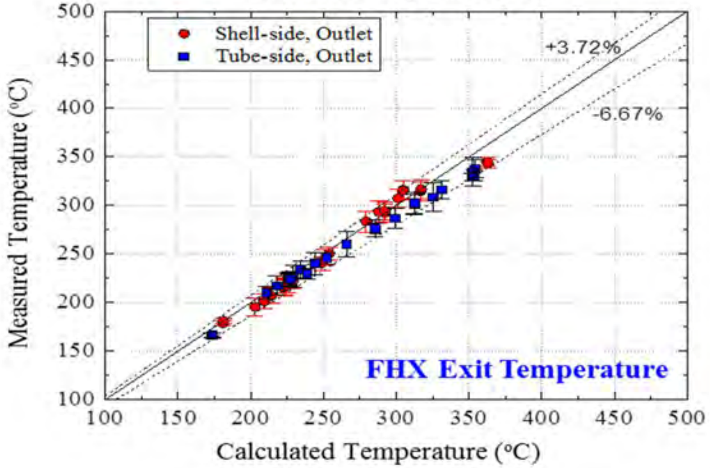
Results of Separate Effect Test

- Heat Exchanger Performance -

- Validation of HX codes
- SHXSA
  - Excellence in DHX outlet temperature (~1.8% & ~0.7% deviation)
  - Good agreement in heat transfer rate (~4.4% deviation, Max.)
- AHXSA
  - Good agreement in sodium outlet temperature (~6% deviation)
  - Larger discrepancy in air outlet temperature (~10% deviation)
- FHXSA
  - Good agreement in sodium outlet temperature (~7% deviation)
  - Larger discrepancy in air outlet temperature (~14% deviation)







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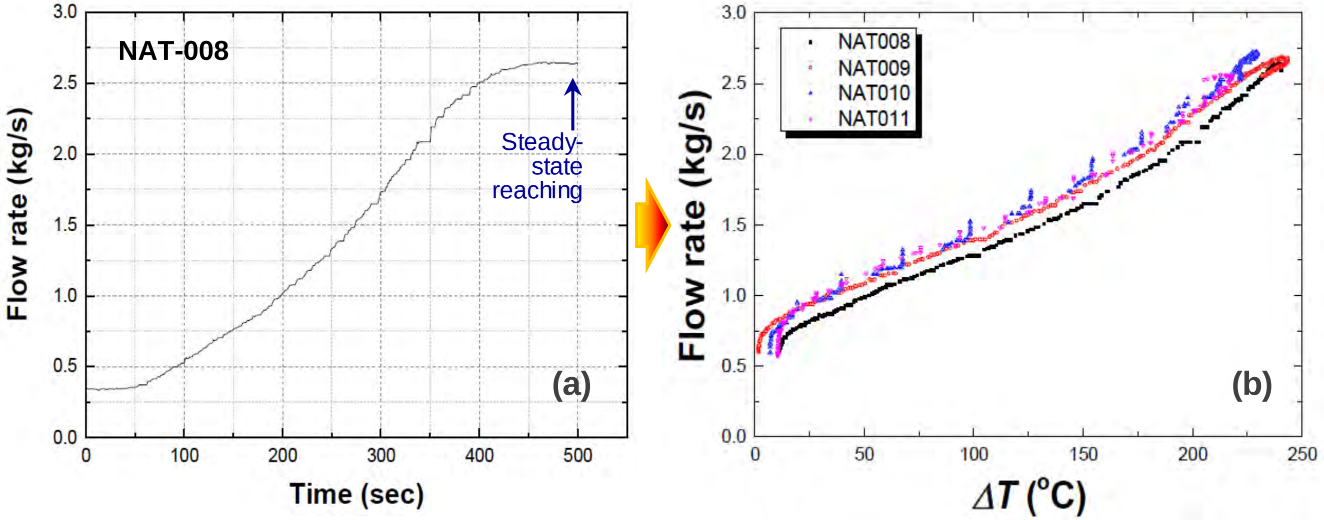
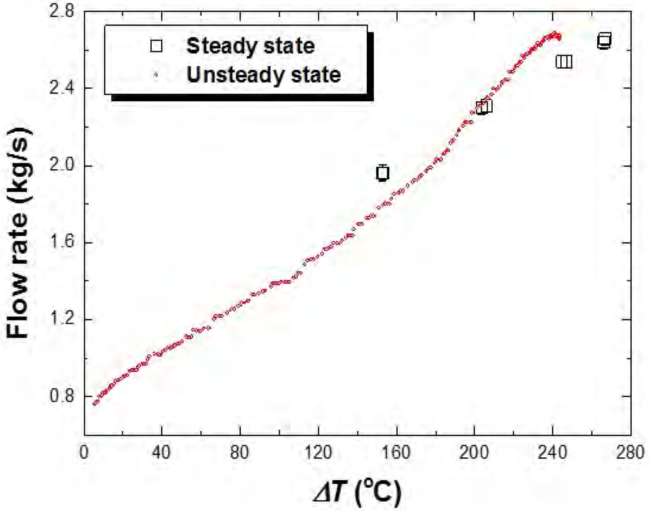
Results of Separate Effect Test

- Natural Circulation Flow -

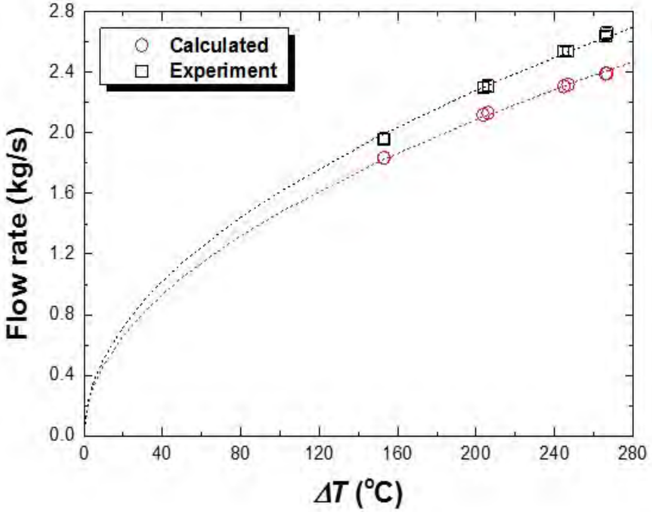
- Investigation of natural circulation flow build-up and flow transient in closed loop system
- Validation of ‘FLOWTRAN’ code
  - Good agreement in trend
  - But relatively low prediction at ~10%



Natural Circulation Flow build-up in terms of (a) Time and (b) $\Delta T_{\text{Hot-\&Cold-leg}}$



Steady-state Flow rate in terms of $\Delta T_{\text{Hot-\&Cold-leg}}$



Comparison of Measured Flow rate with FLOWTRAN code prediction

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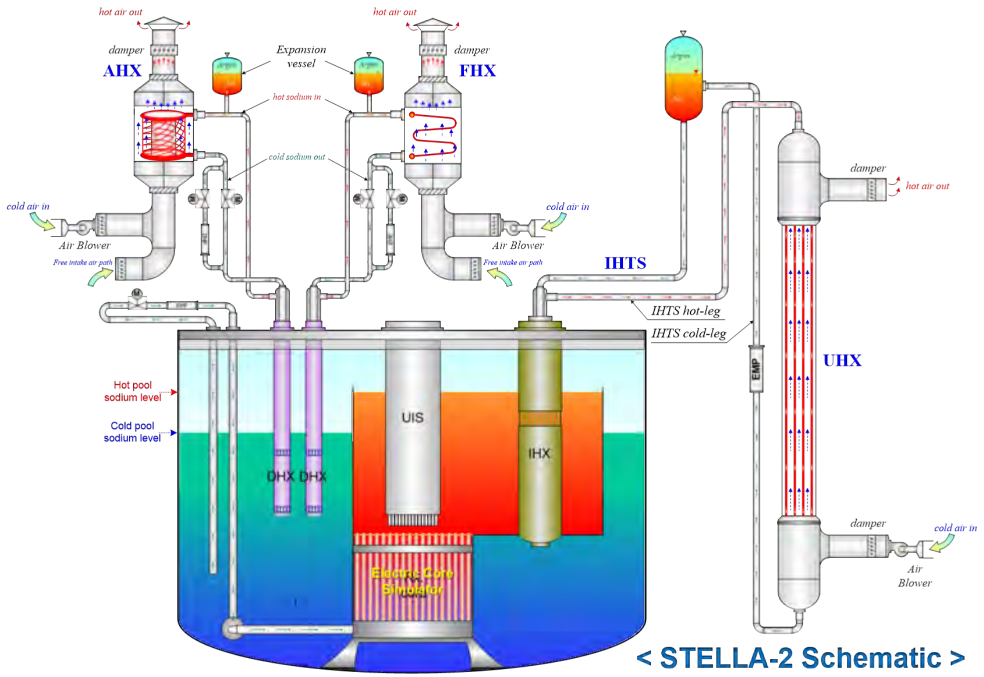
Integral Effect Test

- STELLA-2 -

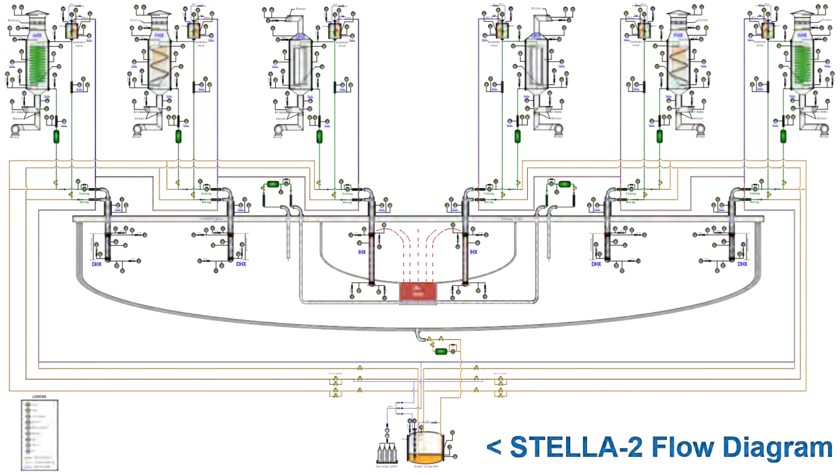
Phase II: Integral Effect Test

- System Test -

- STELLA-2
  - Purpose
    - Comprehensive review of safety issue
    - Safety analysis code validation
- Capability
  - Simulation of transient response for both forced and natural circulation modes
  - Observation of plant dynamic behaviors for off-normal conditions
  - Decay heat removal performance
  - Identification of multi-dimensional effect during transient



< STELLA-2 Schematic >

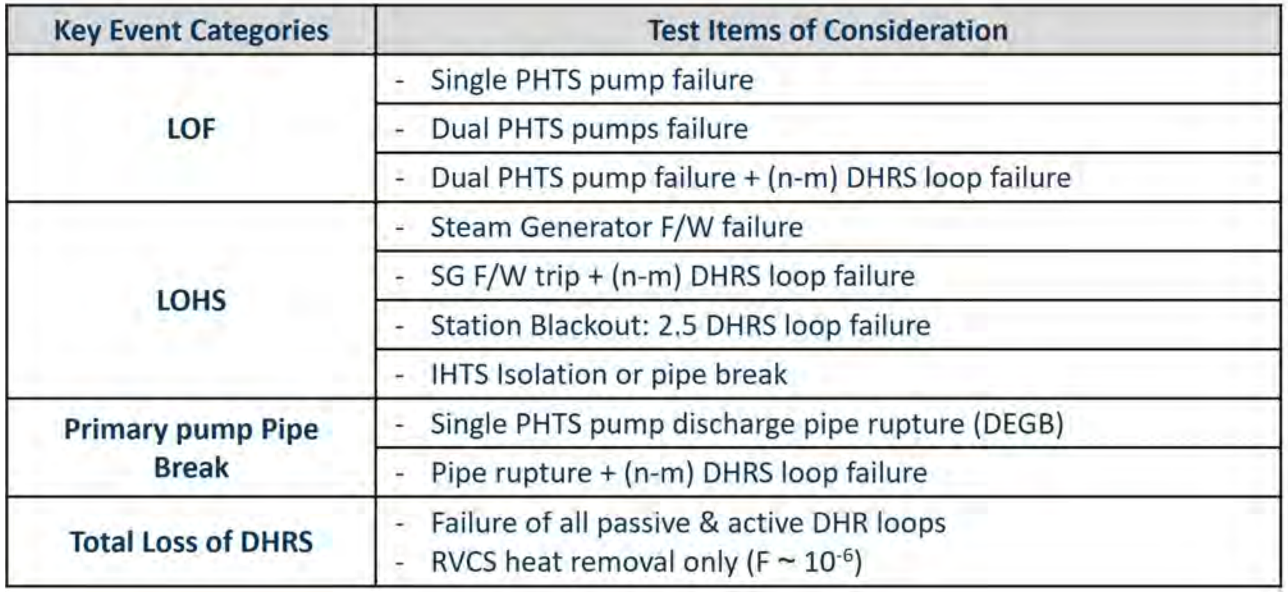


< STELLA-2 Flow Diagram >

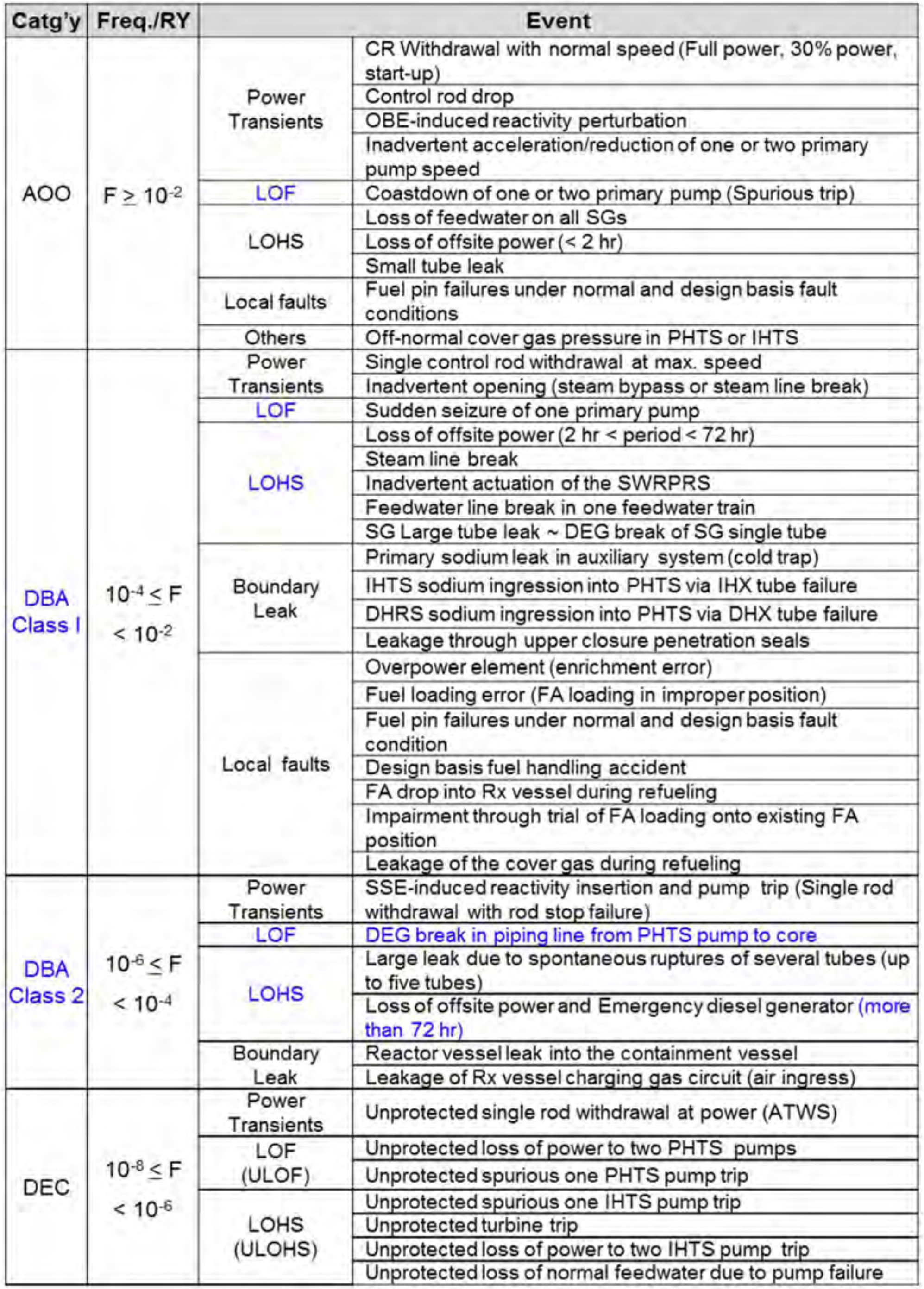
Test Scope & Conditions

- Test Matrix -

- Classification of Key Safety Event
  - Based on the event categorization of PGSFR
- Potential Transients for Simulation
  - DBAs (LOF, LOHS, PHTS pump discharge pipe break)
  - Total loss of safety-grade DHRS



Key Event Categories	Test Items of Consideration
LOF	- Single PHTS pump failure
	- Dual PHTS pumps failure
	- Dual PHTS pump failure + (n-m) DHRS loop failure
LOHS	- Steam Generator F/W failure
	- SG F/W trip + (n-m) DHRS loop failure
	- Station Blackout: 2.5 DHRS loop failure
	- IHTS Isolation or pipe break
Primary pump Pipe Break	- Single PHTS pump discharge pipe rupture (DEGB)
	- Pipe rupture + (n-m) DHRS loop failure
Total Loss of DHRS	- Failure of all passive & active DHR loops - RVCS heat removal only ($F \sim 10^{-6}$)



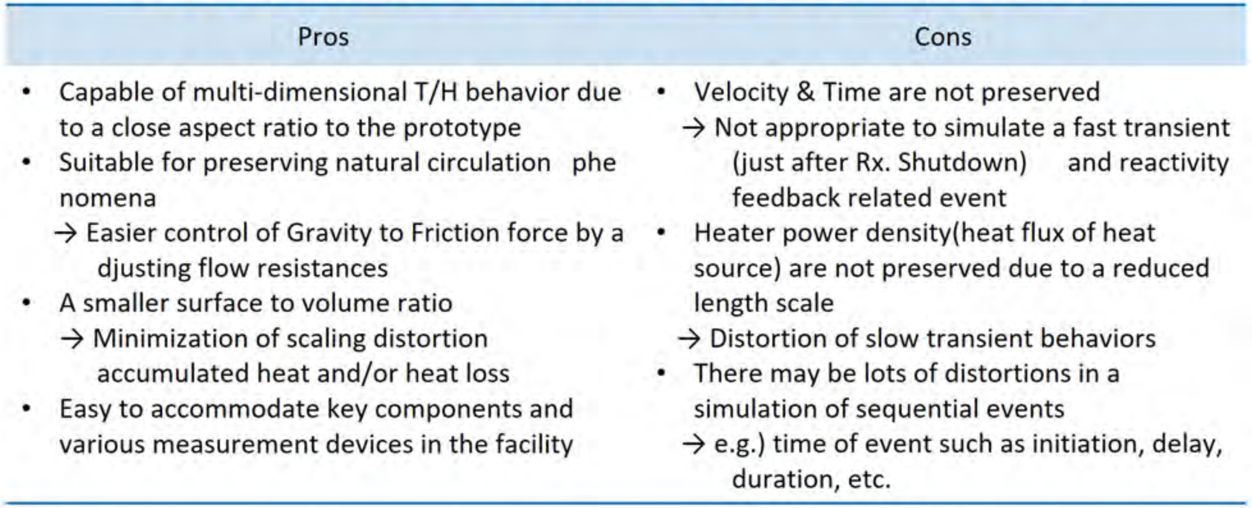
Catg'y	Freq./RY	Event	
AOO	$F \geq 10^{-2}$	Power Transients	CR Withdrawal with normal speed (Full power, 30% power, start-up)
			Control rod drop
			OBE-induced reactivity perturbation
			Inadvertent acceleration/reduction of one or two primary pump speed
		LOF	Coastdown of one or two primary pump (Spurious trip)
		LOHS	Loss of feedwater on all SGs
			Loss of offsite power (< 2 hr)
			Small tube leak
		Local faults	Fuel pin failures under normal and design basis fault conditions
		Others	Off-normal cover gas pressure in PHTS or IHTS
DBA Class I	$10^{-4} \leq F$ $< 10^{-2}$	Power Transients	Single control rod withdrawal at max. speed
			Inadvertent opening (steam bypass or steam line break)
		LOF	Sudden seizure of one primary pump
		LOHS	Loss of offsite power (2 hr < period < 72 hr)
			Steam line break
			Inadvertent actuation of the SWRPRS
			Feedwater line break in one feedwater train
			SG Large tube leak ~ DEG break of SG single tube
		Boundary Leak	Primary sodium leak in auxiliary system (cold trap)
			IHTS sodium ingression into PHTS via IHX tube failure
			DHRS sodium ingression into PHTS via DHX tube failure
			Leakage through upper closure penetration seals
		Local faults	Overpower element (enrichment error)
			Fuel loading error (FA loading in improper position)
			Fuel pin failures under normal and design basis fault condition
			Design basis fuel handling accident
			FA drop into Rx vessel during refueling
			Impairment through trial of FA loading onto existing FA position
			Leakage of the cover gas during refueling
DBA Class 2	$10^{-6} \leq F$ $< 10^{-4}$	Power Transients	SSE-induced reactivity insertion and pump trip (Single rod withdrawal with rod stop failure)
		LOF	DEG break in piping line from PHTS pump to core
		LOHS	Large leak due to spontaneous ruptures of several tubes (up to five tubes)
			Loss of offsite power and Emergency diesel generator (more than 72 hr)
		Boundary Leak	Reactor vessel leak into the containment vessel
			Leakage of Rx vessel charging gas circuit (air ingress)
DEC	$10^{-8} \leq F$ $< 10^{-6}$	Power Transients	Unprotected single rod withdrawal at power (ATWS)
		LOF (ULOF)	Unprotected loss of power to two PHTS pumps
			Unprotected spurious one PHTS pump trip
		LOHS (ULOHS)	Unprotected spurious one IHTS pump trip
			Unprotected turbine trip
			Unprotected loss of power to two IHTS pump trip
			Unprotected loss of normal feedwater due to pump failure

Scaling Methodology

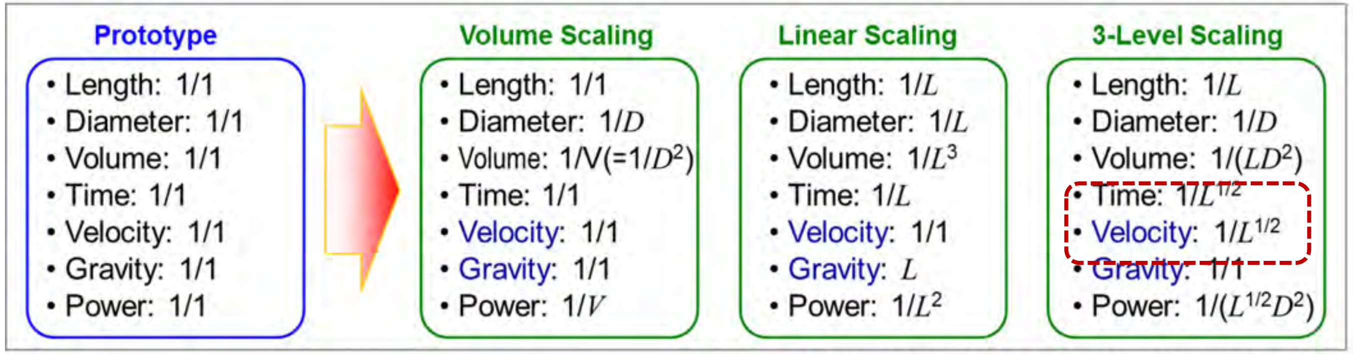
- Pre-evaluation & Fundamentals -

- Minimization of Cost Factors
  - Power, Space, and etc.
- Evaluation of Reduced- over Full-height
  - Volume scaling law (Nahavandi et al., 1979)
    - Height, Velocity, Gravity : 1/1
    - Real time scale
  - Linear scaling law (Carbiner & Cudnik, 1969)
    - Aspect ratio : 1/1
    - Reduced time scale & Increased gravity scale
  - 3 level scaling law (Ishii & Kataoka, 1984)
    - PUMA (Purdue Univ), ATLAS (KAERI)
    - Suitable for natural circulation phenomena

< Pros & Cons of Reduced-height scale over a Full-height concept >



Pros	Cons
• Capable of multi-dimensional T/H behavior due to a close aspect ratio to the prototype • Suitable for preserving natural circulation phenomena → Easier control of Gravity to Friction force by adjusting flow resistances • A smaller surface to volume ratio → Minimization of scaling distortion accumulated heat and/or heat loss • Easy to accommodate key components and various measurement devices in the facility	• Velocity & Time are not preserved → Not appropriate to simulate a fast transient (just after Rx. Shutdown) and reactivity feedback related event • Heater power density(heat flux of heat source) are not preserved due to a reduced length scale → Distortion of slow transient behaviors • There may be lots of distortions in a simulation of sequential events → e.g.) time of event such as initiation, delay, duration, etc.



Prototype
- Length: 1/1
- Diameter: 1/1
- Volume: 1/1
- Time: 1/1
- Velocity: 1/1
- Gravity: 1/1
- Power: 1/1

Volume Scaling
- Length: 1/1
- Diameter: $1/D$
- Volume: $1/V (=1/D^2)$
- Time: 1/1
- Velocity: 1/1
- Gravity: 1/1
- Power: $1/V$

Linear Scaling
- Length: $1/L$
- Diameter: $1/L$
- Volume: $1/L^3$
- Time: $1/L$
- Velocity: 1/1
- Gravity: L
- Power: $1/L^2$

3-Level Scaling
- Length: $1/L$
- Diameter: $1/D$
- Volume: $1/(LD^2)$
- Time: $1/L^{1/2}$
- Velocity: $1/L^{1/2}$
- Gravity: 1/1
- Power: $1/(L^{1/2}D^2)$

▶ Volume scaling law is a special case of Ishii's scaling law

▶ Reference:
Yoon B.J., 2007, "Introduction of Scaling Methodology for Thermal Hydraulics Test," KAERI Seminar (August 16, 2007)

Scaling Methodology

- 3 level Scaling Law -

- 1st Step : Global Scaling
  - Geometric condition, time scale, and TH parameters
- 2nd Step : Inventory Scaling
  - Mass and energy inventory
- 3rd Step : Local Phenomena Scaling
  - Heat transfer in HXs, Flow and energy mixing in pool, Heat loss, and etc.

Key Dimensionless Numbers

◆ Richardson No.

$$Ri \equiv \frac{g\beta\Delta T_0 l_0}{u_0^2} = \frac{buoyancy}{inertia\ force}$$

◆ Friction No. or Euler No.

$$F_i \equiv \left(\frac{fl}{d} + K\right)_i \equiv Eu_i = \frac{friction}{inertia\ force}$$

◆ Mod. Stanton No.

$$St_i \equiv \left(\frac{4hl_0}{\rho C_p u_0 d}\right) = \frac{wall\ convection}{axial\ convection}$$

◆ Time ratio No.

$$T_i^* \equiv \left(\frac{\alpha_s}{\delta^2}\frac{l_0}{u_0}\right) = \frac{transport\ time}{conduction\ time}$$

◆ Biot No.

$$B_i \equiv \left(\frac{h\delta}{k_s}\right) = \frac{wall\ convection}{conduction}$$

◆ Heat Source No.

$$Q_{si} \equiv \left(\frac{q_s l_0}{\rho_s C_{ps} u_0 \Delta T_0}\right)_i = \frac{heat\ source}{axial\ energy\ change}$$

Conservation Equations (1-D, Boussinesq approx.)

$$u_i a_i = a_r u_r$$

$$\rho \frac{du_r}{dt}\sum_i \frac{a_r}{a_i} l_i = \beta g \Delta T_h l_h - \frac{\rho u_r^2}{2}\sum_i \left(\frac{fl}{d} + K\right)_i \left(\frac{a_r}{a_i}\right)^2$$

$$\rho C_p \left\{\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial z}\right\} = \frac{4h}{d}(T_s - T)$$

$$\rho_s C_{ps}\frac{\partial T_s}{\partial t} + k_s \nabla^2 T_s - \dot{q}_s = 0$$

$$-k_s \frac{\partial T_s}{\partial y} = h(T_s - T)$$

Dimensionless Conservation Equations

$$U_i = U_r / A_i$$

Continuity

$$\frac{dU_r}{dt}\left(\sum_i \frac{L_i}{A_i}\right) = \boxed{\left(\frac{g\beta\Delta T_o l_o}{u_o^2}\right)}(\theta_h - \theta_c)L_h - \frac{u_r^2}{2}\sum_i \boxed{\left(\frac{fl}{d} + K\right)_i \frac{1}{A_i^2}}$$

Integral Momentum

$$\frac{\partial \theta_i}{\partial \tau} + \frac{U_r}{A_i}\frac{\partial \theta_i}{\partial Z} = \boxed{\left(\frac{4hl_o}{\rho C_p u_o d}\right)_i}(\theta_{si} - \theta_i)$$

Fluid Energy for ith section

$$\frac{\partial \theta_{si}}{\partial \tau} + \boxed{\left(\frac{\alpha_s}{\delta^2}\frac{l_o}{u_o}\right)_i}\nabla_i^{*2}\theta_{si} - \boxed{\left(\frac{\dot{q}_s l_o}{\rho_s C_{ps} u_o \Delta T_o}\right)_i} = 0$$

Solid energy for ith section

$$\frac{\partial \theta_{si}}{\partial Y} = \boxed{\left(\frac{h\delta}{k_s}\right)_i}(\theta_{si} - \theta_i)$$

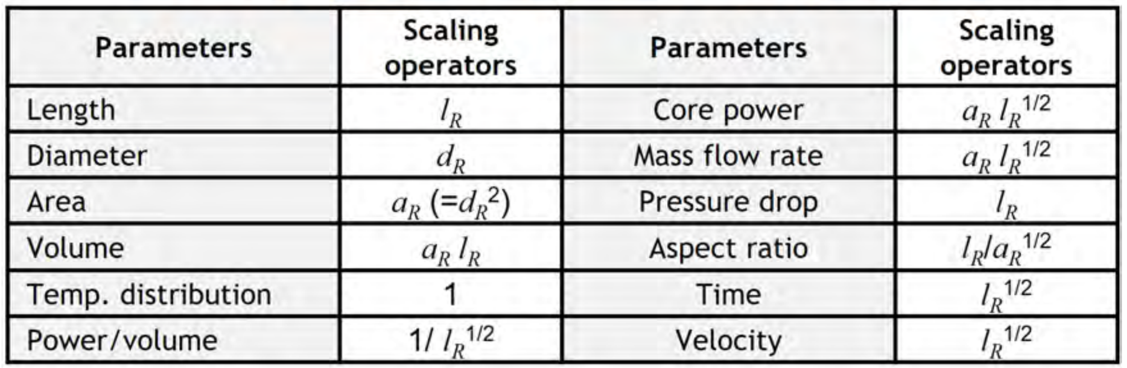
Boundary condition between fluid & energy

Scaling Results

- Requirements for STELLA-2 -

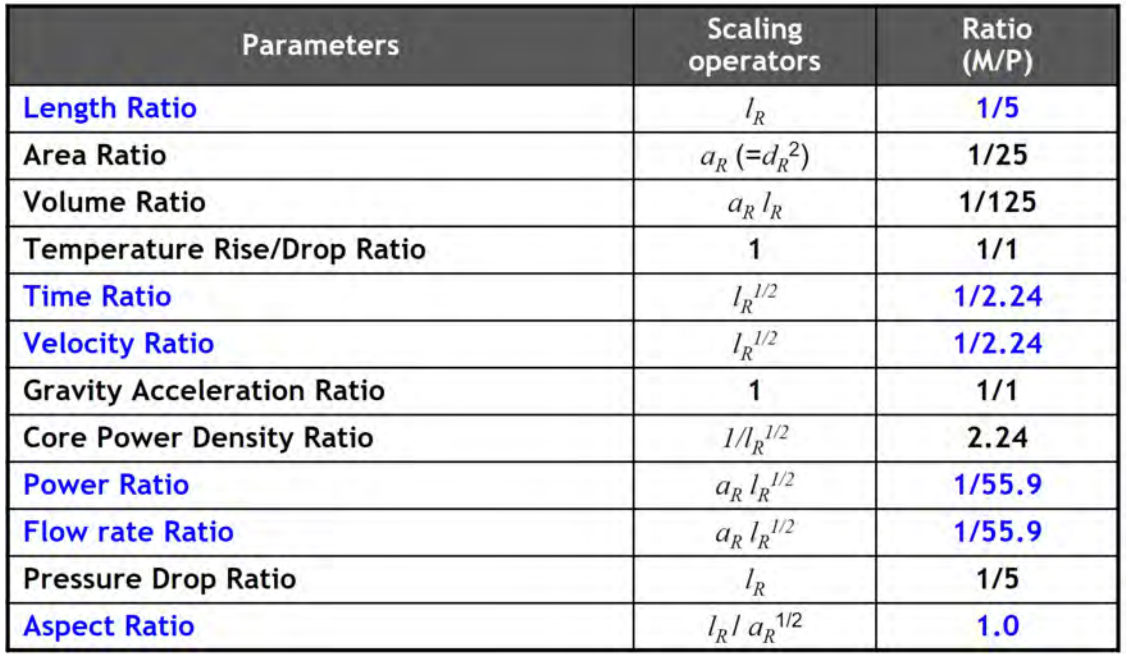
- System Scale
  - Height 1/5, Volume : 1/125
- Identical working fluid & pressure/temperature conditions
- Preservation of general arrangement of RI & components
- Simulation of decay heat generation
  - 7% of scaled full power
- Simulation of PHTS pump coast-down
- Simulation of PHTS pump pipe break
- Simulation of RVCS heat removal

< Scaling operators from Global scaling criteria >



Parameters	Scaling operators	Parameters	Scaling operators
Length	l_R	Core power	$a_R\, l_R^{1/2}$
Diameter	d_R	Mass flow rate	$a_R\, l_R^{1/2}$
Area	$a_R\ (=d_R^2)$	Pressure drop	l_R
Volume	$a_R\, l_R$	Aspect ratio	$l_R/a_R^{1/2}$
Temp. distribution	1	Time	$l_R^{1/2}$
Power/volume	$1/\,l_R^{1/2}$	Velocity	$l_R^{1/2}$

< Major scaling characteristics >



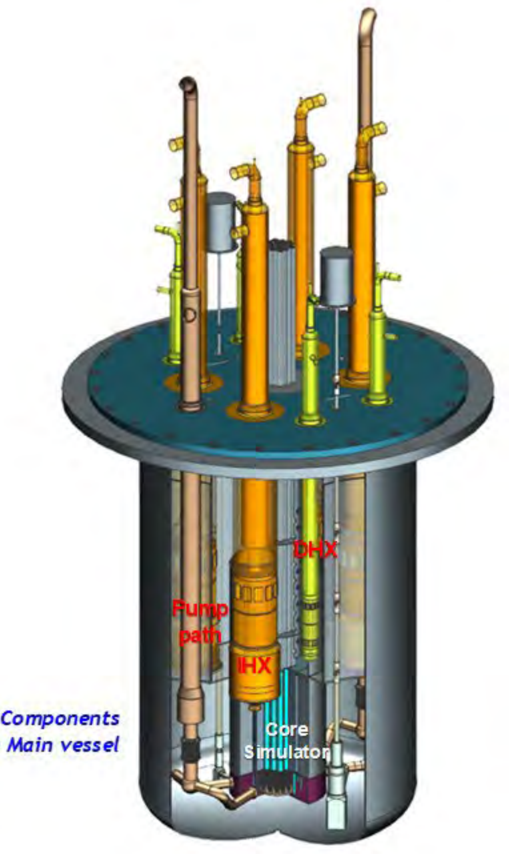
Parameters	Scaling operators	Ratio (M/P)
Length Ratio	l_R	1/5
Area Ratio	$a_R\ (=d_R^2)$	1/25
Volume Ratio	$a_R\, l_R$	1/125
Temperature Rise/Drop Ratio	1	1/1
Time Ratio	$l_R^{1/2}$	1/2.24
Velocity Ratio	$l_R^{1/2}$	1/2.24
Gravity Acceleration Ratio	1	1/1
Core Power Density Ratio	$1/l_R^{1/2}$	2.24
Power Ratio	$a_R\, l_R^{1/2}$	1/55.9
Flow rate Ratio	$a_R\, l_R^{1/2}$	1/55.9
Pressure Drop Ratio	l_R	1/5
Aspect Ratio	$l_R/\,a_R^{1/2}$	1.0

What to be seen?

- Dynamic Reactor Response after Shutdown
  - Short- and long-term cooling capability
  - Asymmetric DHR operation
    - (n-m) loop operation
  - Flow and heat transfer characteristics in the system
    - Throughout the core, various heat exchangers, components & piping, and etc.
  - Flow distribution and energy mixing in sodium pool
    - Multi-dimensional effect

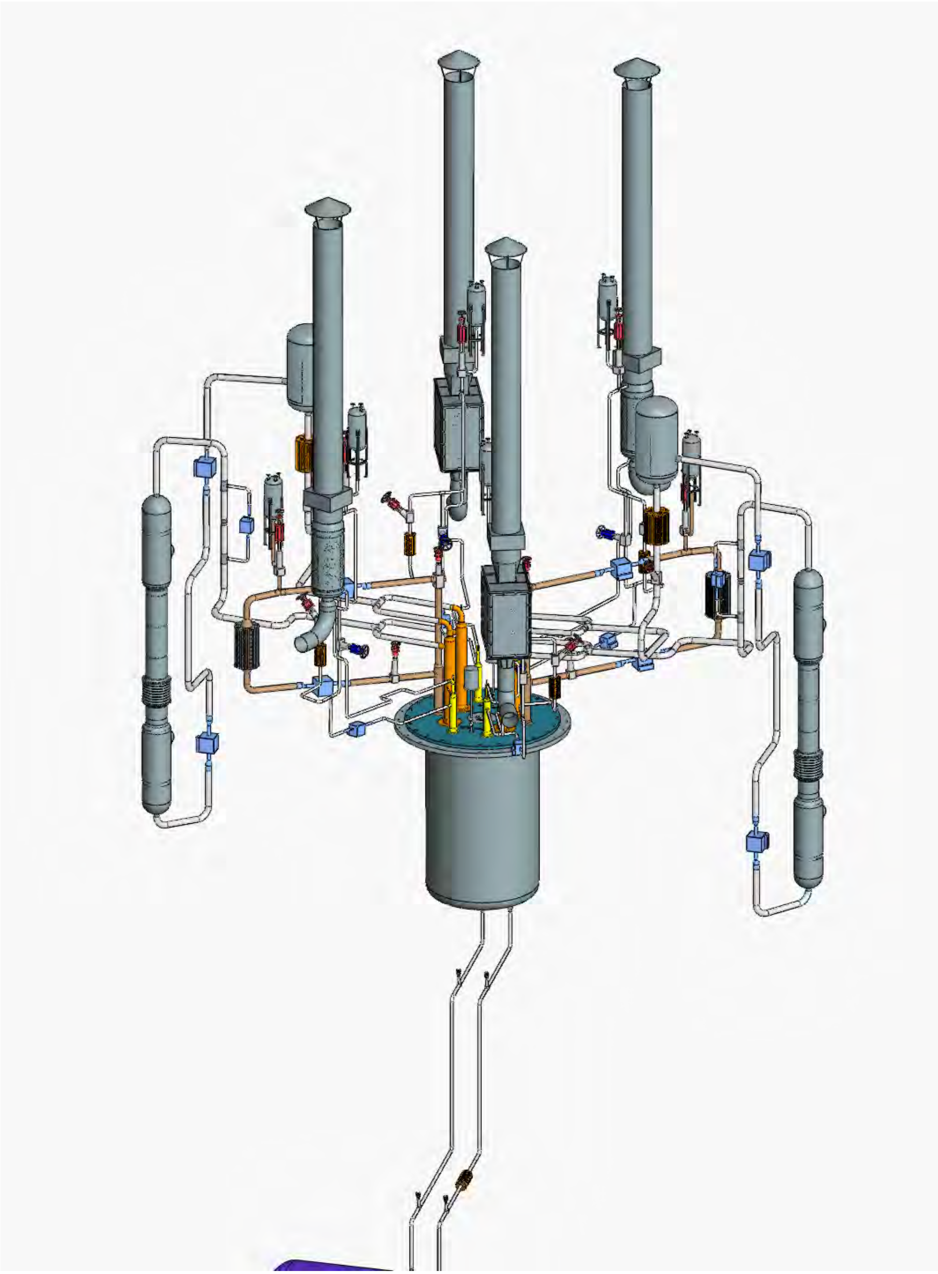
STELLA-2

- Design Feature -



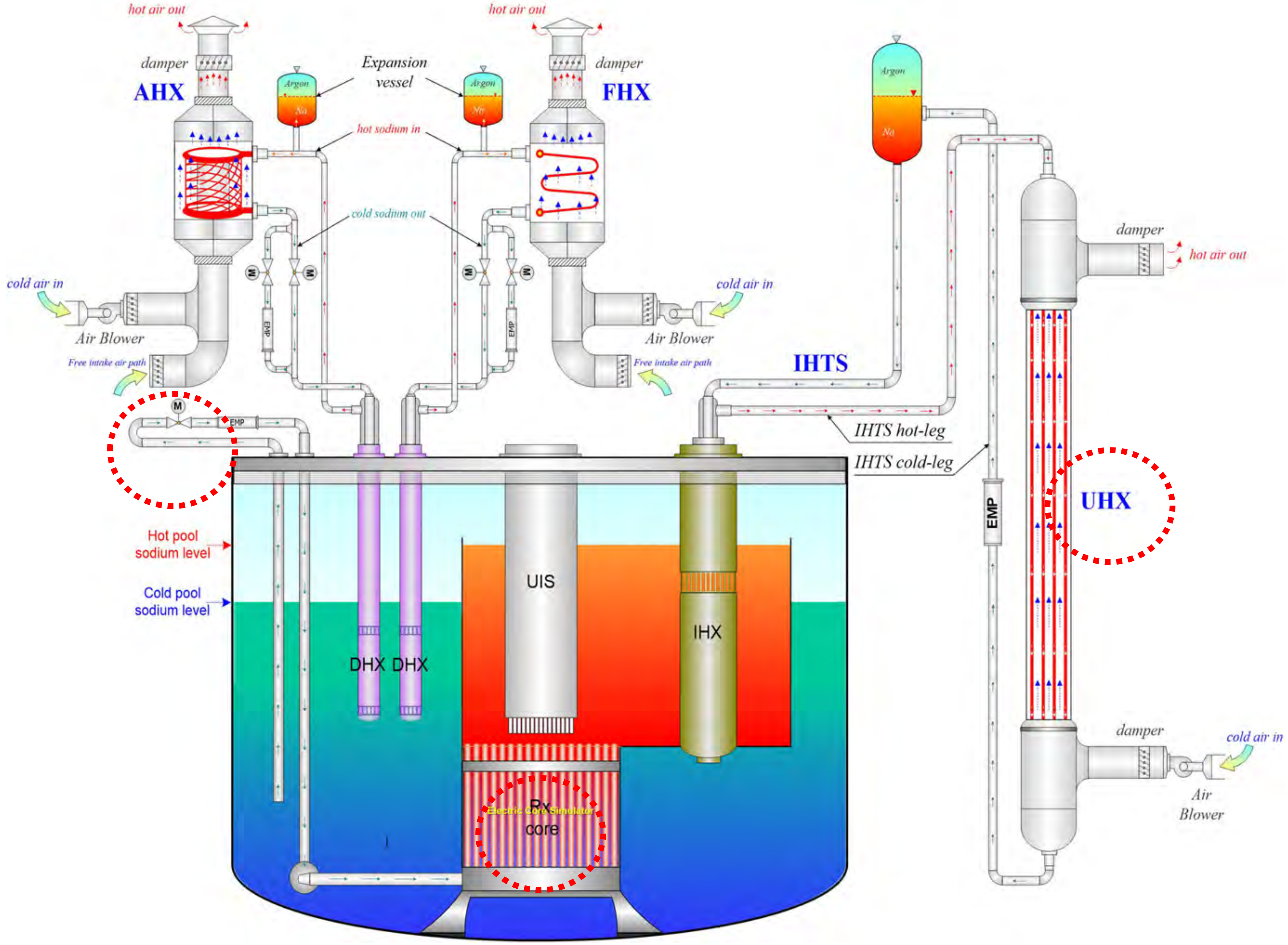
Components inside Main vessel

- **Systems**
  - Main vessel (1), sodium loops (8), 5 different types of sodium HXs, and auxiliary systems
- **Design Temperature & Pressure**
  - 600 ^{o}C & 5 bars
- **Facility Dimension** (L×W×H)
  - 18m×15m×30m
- **Main Vessel Size**
  - 2.2m in dia. & 3.7m in height
- **Sodium Inventory**
  - 15 tons
- **Max Flowrate**
  - 25 kg/s
- **Power**
  - Core power : ~500 kW
  - Total : ~3.0 MW



STELLA-2

- Design Feature -

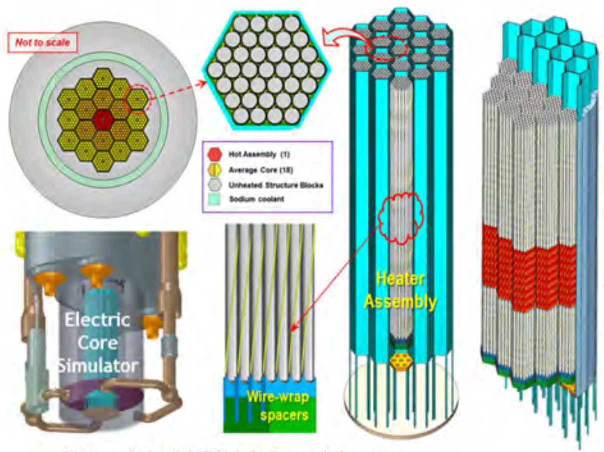


STELLA-2

- Electric Core Simulator Design -

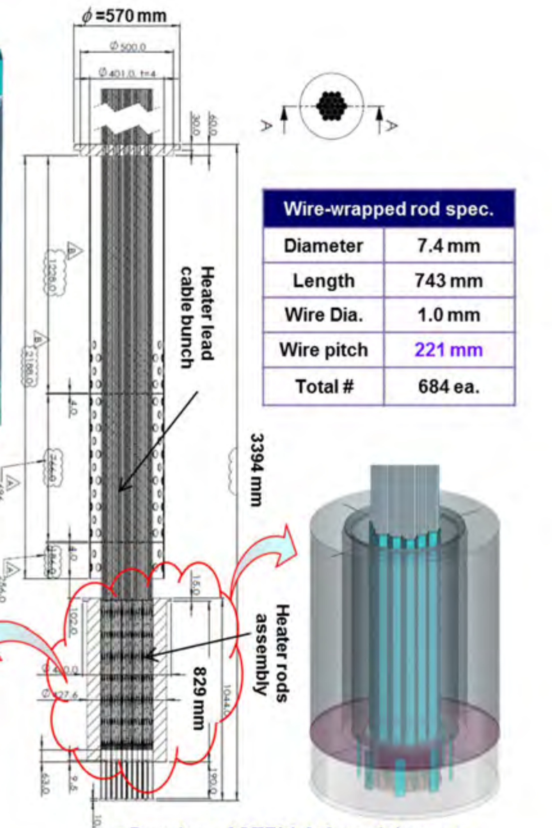
- Heater Rod
  - Optimization with high conductivity insulator (BN)
  - Identical rod dia. to reference reactor fuel pin
- Rod Assembly and Core
  - 19 assemblies + unheated structure (reflector, shield)
    - 36 pins + 1 dummy for instrumentation
    - Total 684 rods (19 dummies)

Parameters	Prototype [P]	Model Core [M]	Ratio [M/P] (Actual)	Ratio [M/P] (Ideal)
Total power [MW]	392.2	7.016	1/55.9	1/55.9
Rod diameter [mm]	7.4	7.4	1/1	-
Pitch to diameter	1.140	1.142	1/1	-
Total no. of rod	24304	684	1/35.5	1/33.1
Whole core area [m²]	5.330	0.196	1/27.2	1/25
Active core height [m]	0.900	0.18	1/5	1/5



< 3D model of STELLA-2 model core >

< Images of model core fabrication >



Wire-wrapped rod spec.	
Diameter	7.4 mm
Length	743 mm
Wire Dia.	1.0 mm
Wire pitch	221 mm
Total #	684 ea.

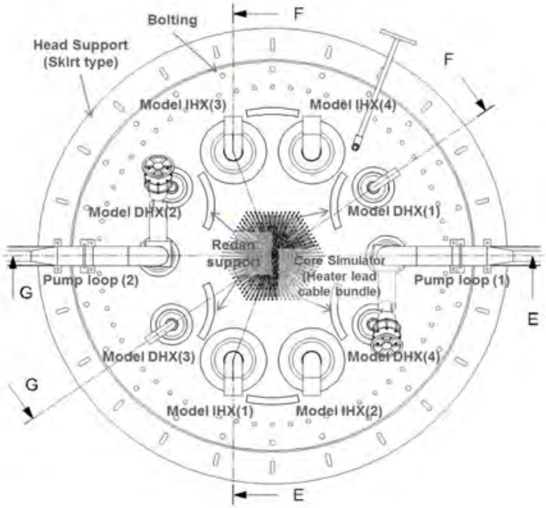
< Drawing of STELLA-2 model core >

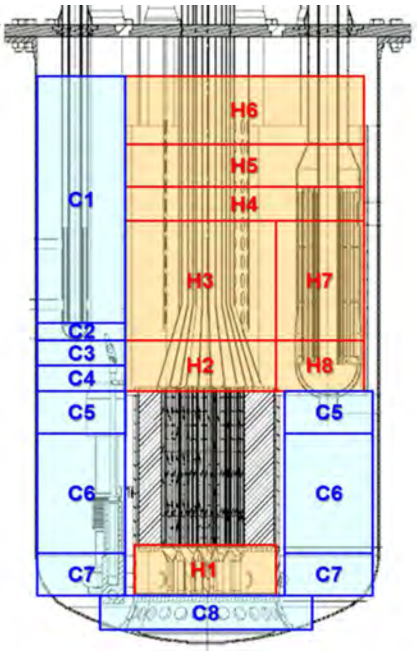

Stock of STELLA-2 Core Simulator

STELLA-2

- RV & RI Design -

- PHTS
  - Vessel, Redan, Separation plate, Reactor Head, Inlet Plenum, Pump path, UIS, and etc.
- Preservation of Similarity
  - Sodium inventory to conserve thermal inertia and mixing effect
  - Relative elevations for simulation of natural circulation flow inside vessel





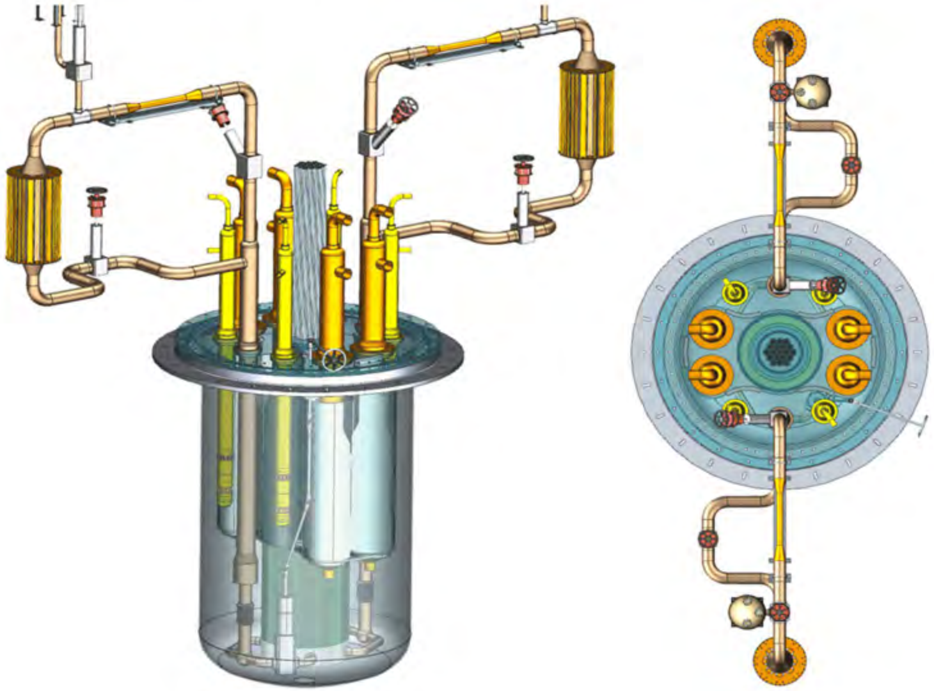
< RI vertical position comparison>

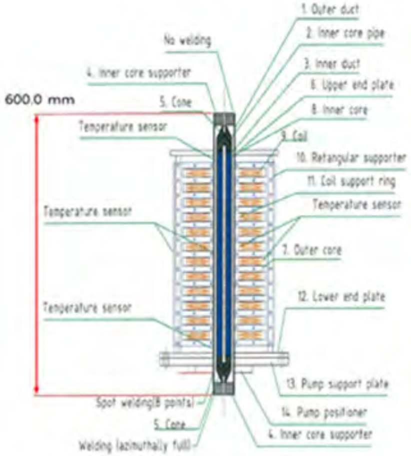
Elements	ST2 / PGSFR		Distortion	
	top	bottom	top	bottom
Redan	0.195	0.200	-2.5%	0.0%
UIS shell	0.200	0.168	0.0%	-16.0%
Pump	0.209	0.200	4.5%	0.0%
Core	0.193	0.201	-3.5%	0.5%
Inlet plenum	0.201	0.199	0.5%	-0.5%
RV	0.200	0.204	0.0%	2.0%

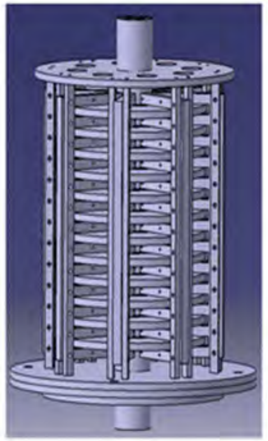
STELLA-2

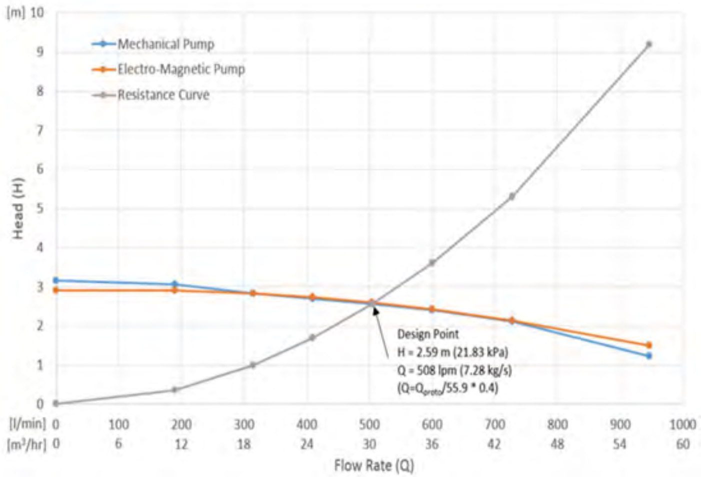
- Pump Simulation Loop Design -

- Components
  - EMP, valves, EMF, tanks, annular pipe
- Characteristics
  - Coastdown flow simulation
  - Identical performance of mechanical pump
- Preservation of Similarity
  - Pressure drop
  - Intake/Discharge position
  - Dimensionless numbers (*Ri, Fi, Eu*)





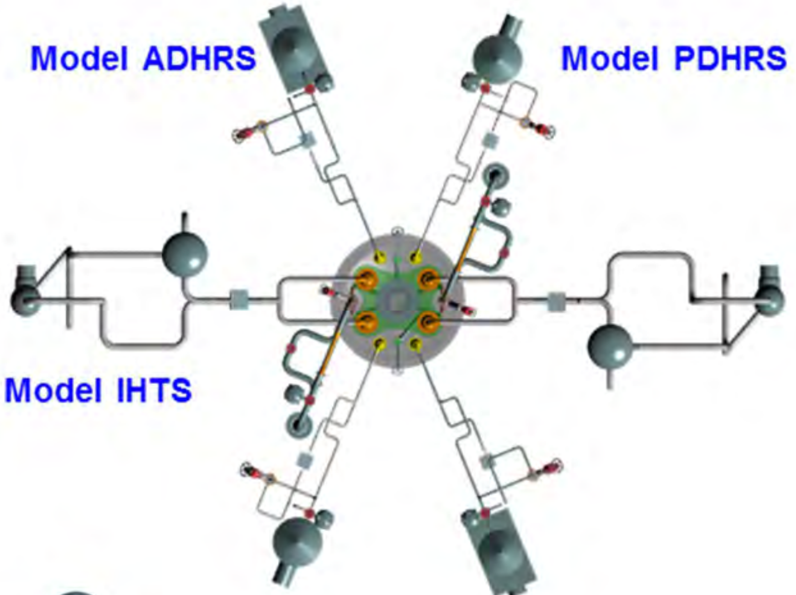


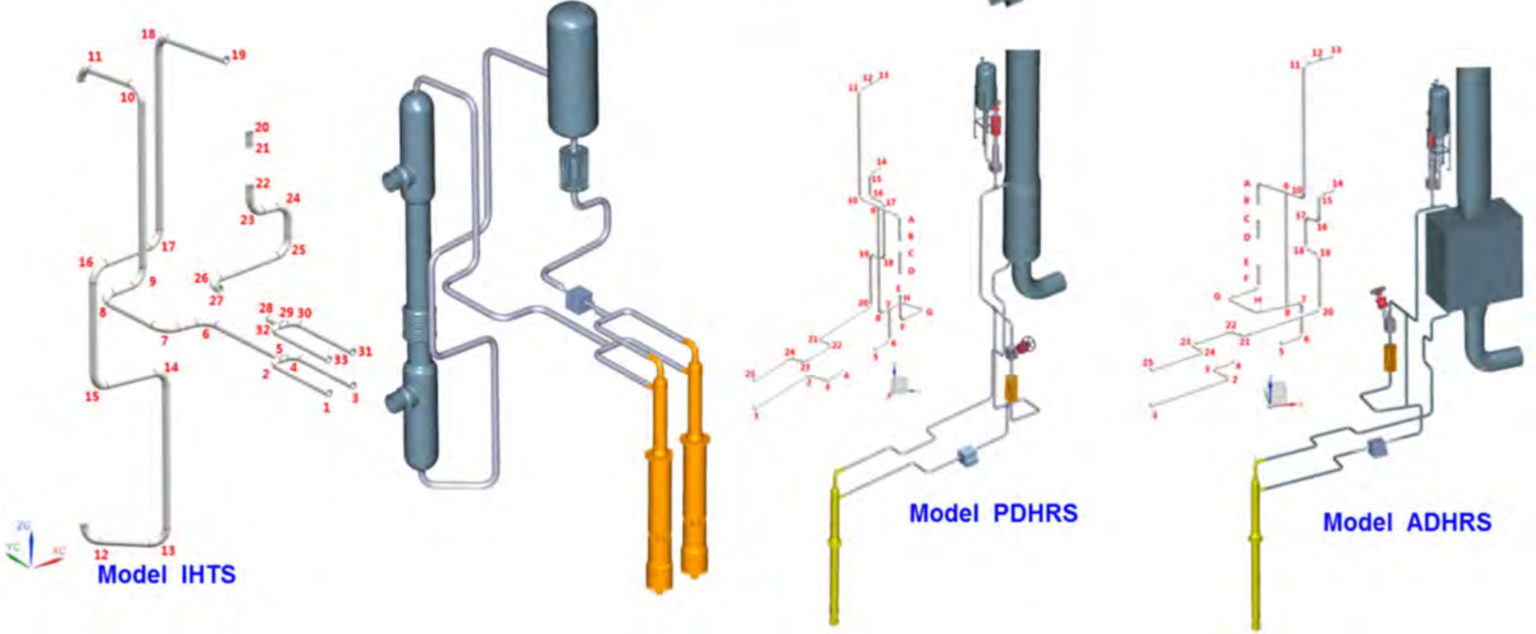


STELLA-2

- Sodium Loop Design -

- IHTS & DHRS
  - Loop design under global scaling criteria
  - IHTS, Passive DHRS, and Active DHRS
- Preservation of Similarity
  - Relative elevation
  - Sodium inventory inside pipe
  - Dimensionless numbers
    - *Eu* number
    - *Ri* number





STELLA-2

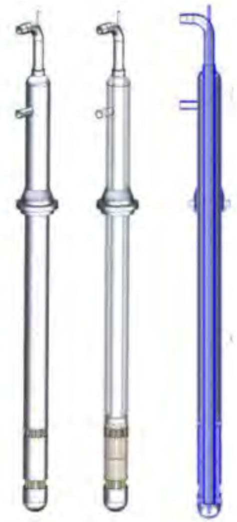
- Heat Exchangers Design -

- Sodium-Sodium Heat Exchanger
  - IHX & DHX
- Sodium-Air Heat Exchanger
  - AHX, FHX, UHX

- Preservation of Similarity
  - Total heat transfer coefficient (U)
  - Temperature difference (LMTD)
  - Dimensionless numbers (*St, Bi, Ri*)

Parameter		IHX			Ideal scale ratio
		PGSFR	STELLA-2	M/P	
Heat transfer rate, Q (kWt)		97.8x10^3	1,750	0.018	0.018
U (W/m²/K)		9082.7	9055.3	0.997	1.0
Heat transfer Area (m²)		323.87	5.916	0.0183	0.018
ΔT_{LMTD} (℃)		33.42	32.87	0.984	1.0
Tube Arrangement		Straight & Vertical			P
Pitch to Diameter ratio (P/D)		1.5	1.5	1.0	P
Effective tube length (m)		3.8	0.784	0.206	0.2
Tube bundle height (m)		↑	↑	-	N/A
Number of tubes (EA)		1,512	174	0.1151	N/A
No. of Grid plate		5	2	-	N/P
Flow hole diameter (mm)		8.5	6.0	0.5882	N/P
No. of Flow holes (EA)		3,024	348	0.1151	N/P
Heat transfer Tube	ID (m)	0.0155	0.0118	0.7613	N/A
	OD (m)	0.0179	0.0138	0.7709	N/A
	thck. (mm)	1.2	1.0	0.8333	N/A
	Material	T91	T91	Y	Y
Flow rate (kg/s)	tube-side	391.08	6.976	0.0178	0.018
	shell-side	496.05	8.856	0.0178	0.018
Velocity (m/s)	tube-side	1.571	0.420	0.267	0.447
	shell-side	1.048	0.273	0.260	0.447
Pressure drop (Pa)	tube-side	12,529	1,007	0.080	0.2
	shell-side	12,870	2,185	0.170	0.2

Parameter		DHX			Ideal scale ratio
		PGSFR	Model	M/P	
Heat transfer rate, Q (kWt)		2.5x10^3	44.73	0.0179	0.018
U (W/m²/K)		6240.25	6568.72	1.0526	1.0
Heat transfer Area (m²)		13.44	0.232	0.0173	0.018
ΔT_{LMTD} (℃)		29.67	29.26	0.986	1.0
Tube Arrangement		Straight & Vertical			P
Pitch to Diameter ratio (P/D)		1.5	1.5	1.0	P
Effective tube length (m)		1.733	0.356	0.2054	0.2
Tube bundle height (m)		1.733	0.356	0.2054	0.2
Number of tubes (EA)		114	12	0.1053	N/A
No. of Grid plate		2	1	0.5	N/P
Flow hole diameter (mm)		11.5	5.0	0.5882	N/P
No. of Flow holes (EA)		228	24	0.1182	N/P
Heat transfer Tube	ID (m)	0.0184	0.014	0.7609	N/A
	OD (m)	0.0217	0.0173	0.7972	N/A
	thck. (mm)	1.65	1.65	1.0000	N/A
	Material	T91	T91	Y	Y
Flow rate (kg/s)	tube-side	17.54	0.3140	0.0179	0.018
	shell-side	12.76	0.2280	0.0179	0.018
Velocity (m/s)	tube-side	0.645	0.189	0.2930	0.447
	shell-side	0.233	0.062	0.2661	0.447
Pressure drop (Pa)	tube-side	798	54	0.0677	0.2
	shell-side	242	16	0.0661	0.2



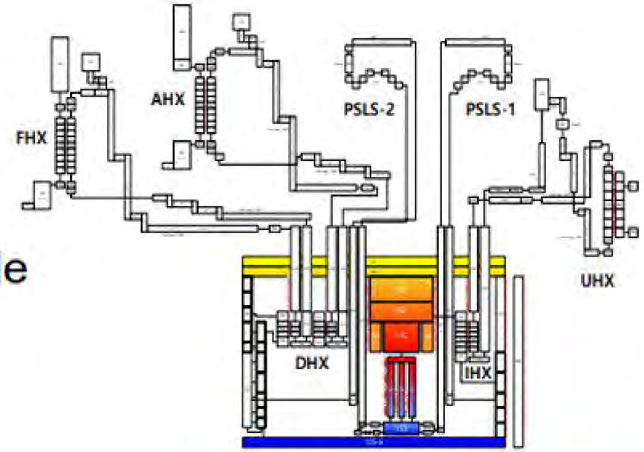
Parameter		AHX			Ideal scale ratio
		PGSFR	Model	M/P	
Heat transfer rate, Q (kWt)		2.5x10^3	43.56	0.0174	0.018
U (W/m²/K)		48.27	43.31	0.8972	1.0
Heat transfer Area (m²)		482.2	8.653	0.0179	0.018
ΔT_{LMTD} (℃)		106.17	115.34	1.086	1.0
Tube Arrangement		Helical coil type			P
$(P/D)_L$ & $(P/D)_T$		1.71 & 2.5	1.71 & 2.5	1.0	P
Effective tube length (m)		23.76	4.752	0.200	0.2
Tube bundle height (m)		4.13	0.826	0.200	0.2
Number of tubes (EA)		190	42	0.221	N/A
Average Bundle height (m)		4.19	0.826	0.197	0.2
Tube inclined angle (degree)		9.9	9.8	0.990	1.0
Tube outside fouling (W/m/K)		2841	2841	1.0	1.0
Inner Cylinder OD (m)		2.84	0.3185	0.112	0.2
Shroud ID (m)		3.86	0.595	0.154	0.2
Heat transfer Tube	ID (m)	0.0307	0.0114	0.3713	N/A
	OD (m)	0.034	0.0138	0.4059	N/A
	thck. (mm)	1.65	1.2	0.7273	N/A
	Material	T91	STS316	N	Y
Flow rate (kg/s)	tube-side	17.54	0.3138	0.0179	0.018
	shell-side	10.65	0.1950	0.0183	0.018
Velocity (m/s)	tube-side	0.139	0.082	0.5899	0.447
	shell-side	5.164	2.515	0.4870	0.447
Pressure drop (Pa)	tube-side	466	73	0.1567	0.2
	shell-side	140	28	0.2000	0.2

Parameter		FHX			Ideal scale ratio
		PGSFR	Model	M/P	
Heat transfer rate, Q (kWt)		2.5x10^3	44.06	0.0176	0.018
U (W/m²/K)		26.81	24.73	0.9224	1.0
Heat transfer Area with Fin (m²)		656.34	11.642	0.0177	0.018
ΔT_{LMTD} (℃)		141.21	152.31	1.079	1.0
Tube Arrangement		Straight- & Finned-tube, M-type			P
$(P/D)_L$ & $(P/D)_T$		2.05 & 2.5	2.05 & 2.5	1.0	P
Finned tube length, total (m)		8.0	1.6	0.200	0.2
Total height of tube banks (m)		2.118	0.827	0.390	0.2
Number of tubes (EA)		96	18	0.1875	N/A
Tube inclined angle (degree)		7.2	7.2	1.0	P
Tube outside fouling (W/m/K)		2841	2841	1.0	1.0
Fin height (mm)		15.0	8.5	0.557	N/A
Fin thickness (mm)		1.5	0.8	0.533	N/A
No. Fins per unit length (# / m)		152	220	1.447	N/A
Fin spacing (mm)		5.08	3.75	0.738	N/A
Total # Fins per each tube row		1216	352	0.289	N/A
Heat transfer Tube (Bare tube)	ID (m)	0.0307	0.0149	0.4853	N/A
	OD (m)	0.034	0.0191	0.5618	N/A
	thck. (mm)	1.65	2.1	1.2727	N/A
	Material	T91	STS316	N	Y
Flow rate (kg/s)	tube-side	17.54	0.3138	0.0179	0.018
	shell-side	13.63	0.2657	0.0195	0.018
Velocity (m/s)	tube-side	0.275	0.111	0.4036	0.447
	shell-side	6.788	5.496	0.8097	0.447
Pressure drop (Pa)	tube-side	742	112	0.1509	0.2
	shell-side	452	62	0.1372	0.2

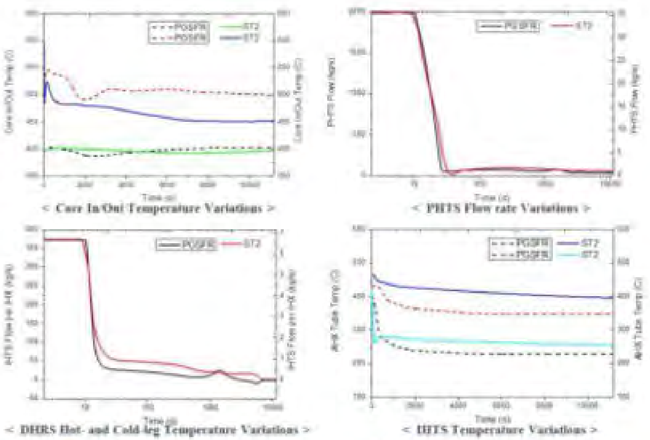
STELLA-2

- Design Evaluation -

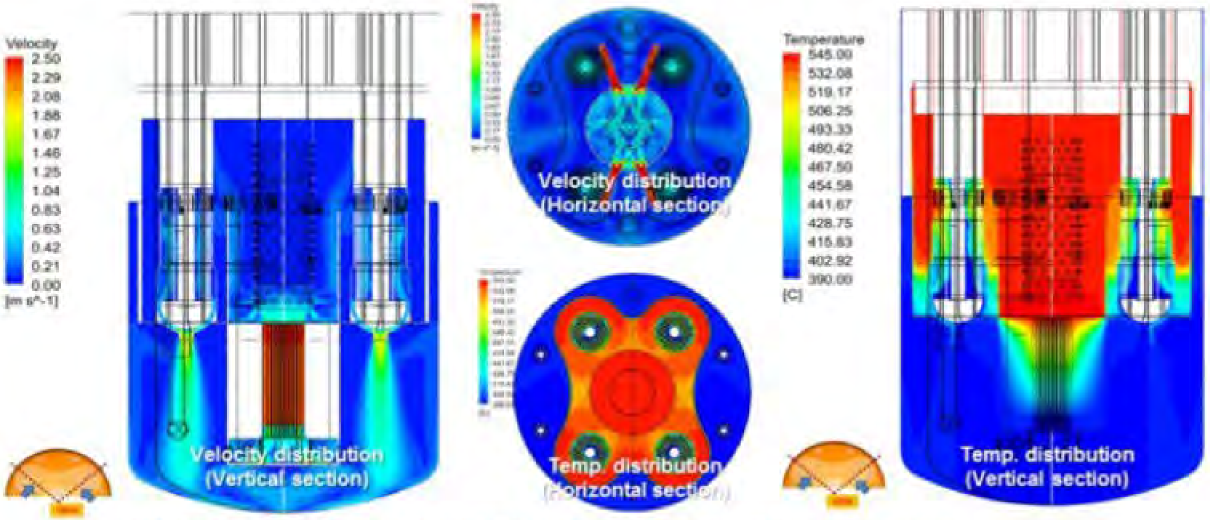
- Scoping Analysis
  - Transient comparison using system code
- CFD Analysis
  - Various numerical simulations
- Water Mock-up Tests



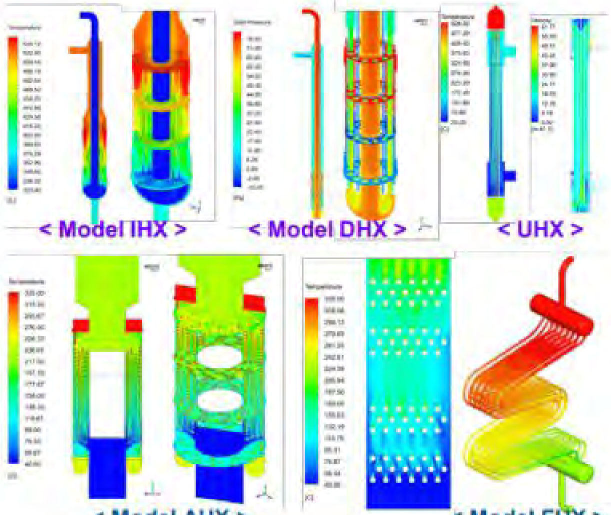
< Node Diagram for MARS-LMR Calculation >



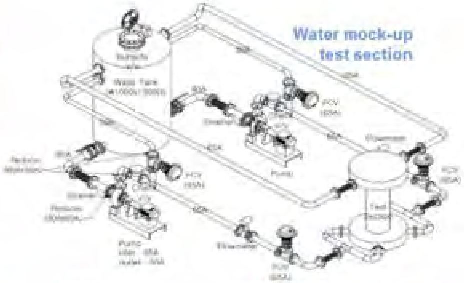
< Results of Scoping Analysis for STELLA-2 design >

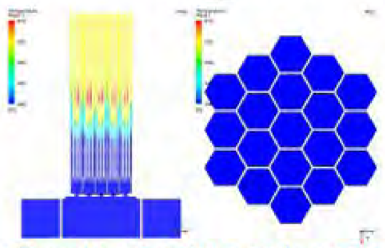


< Velocity and Temperature distributions in sodium pool regions >



< CFD Analysis Results for Model HXs >





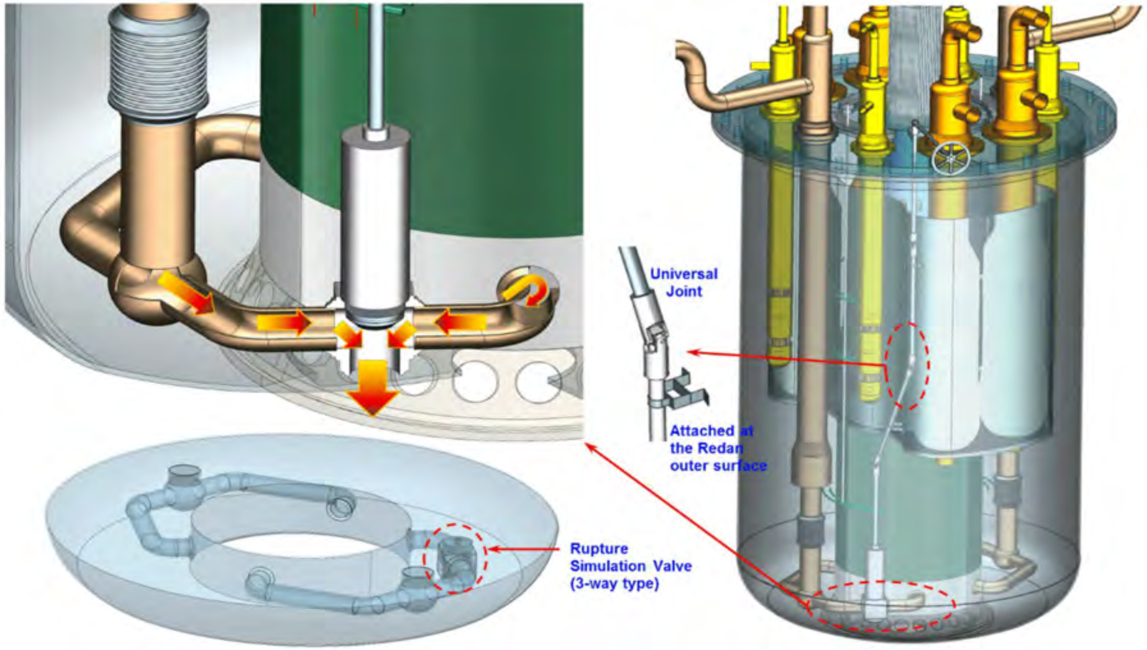
< Results of water mock-up test for the model core assembly >

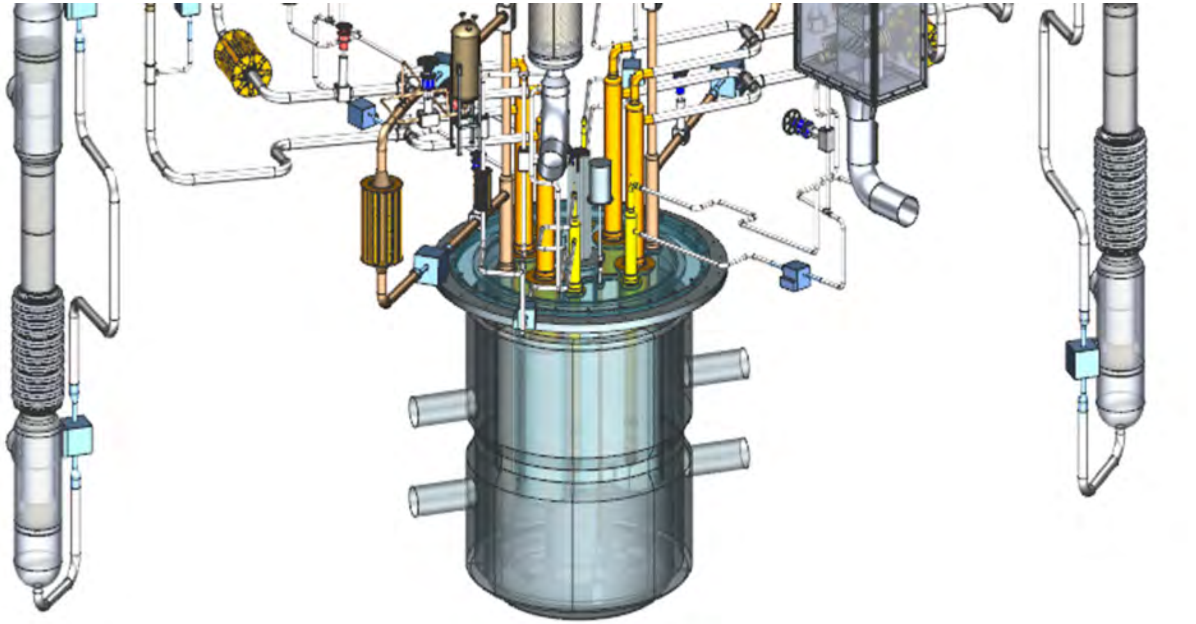
STELLA-2

- Specialty & Uniqueness -

- Pipe Break Simulation
  - Specially designed 3-way valve
    - Universal joint long-reach arm
    - Short actuation time

- Ex-vessel Cooling Simulation
  - Reactor Vessel Cooling System(RVCS)
    - Air flow jacket
    - Flowrate is controlled by blowers





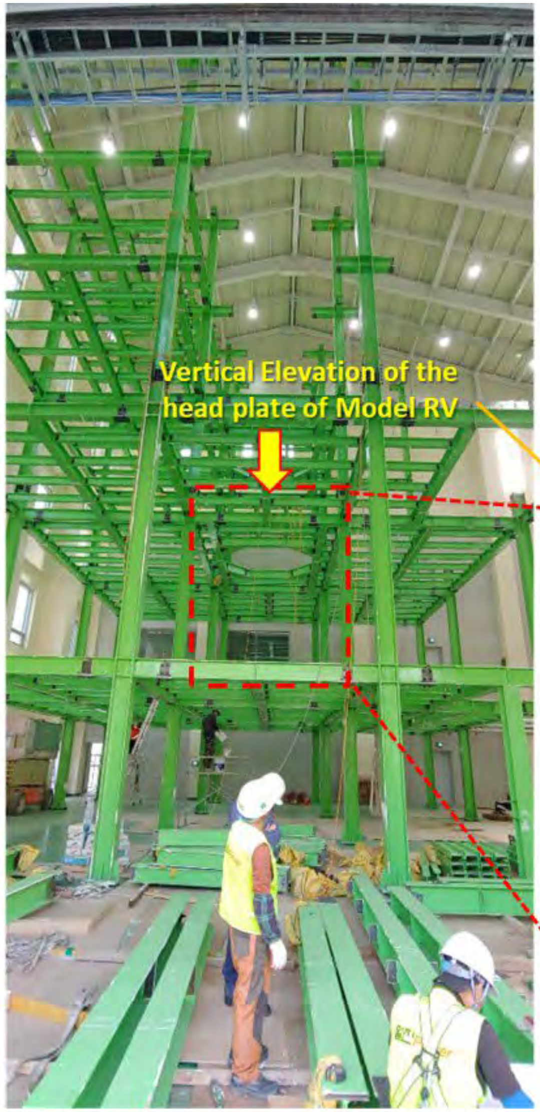
Status & Future Plan

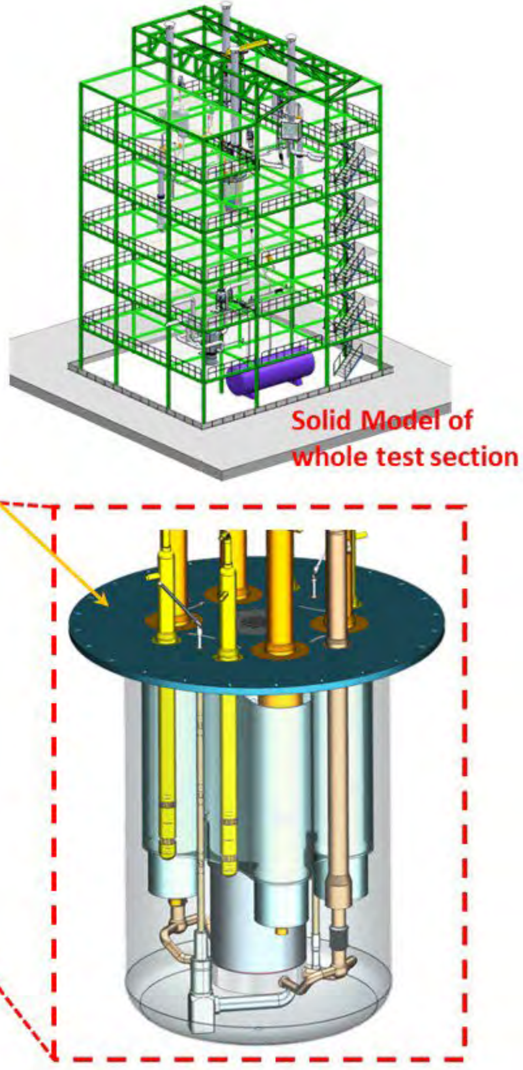
Past

- Construction & Installation -


New Sodium Test Building for STELLA-2


Installation of Frame Structure


Vertical Elevation of the head plate of Model RV


Solid Model of whole test section

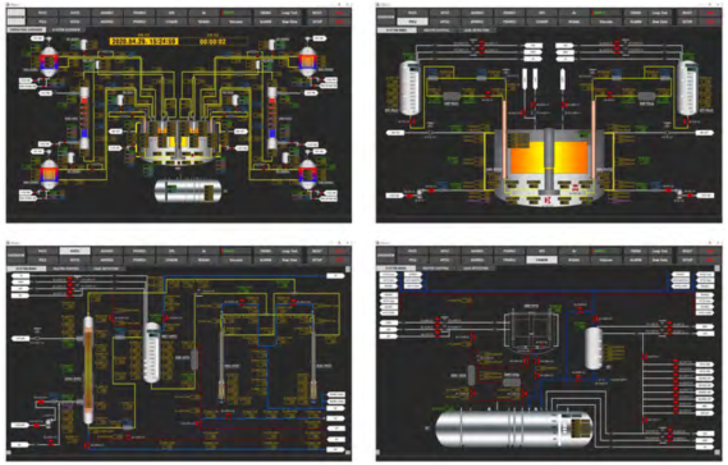
Model RV and its Internals

Past

- Construction & Installation -

Now

- In operation -

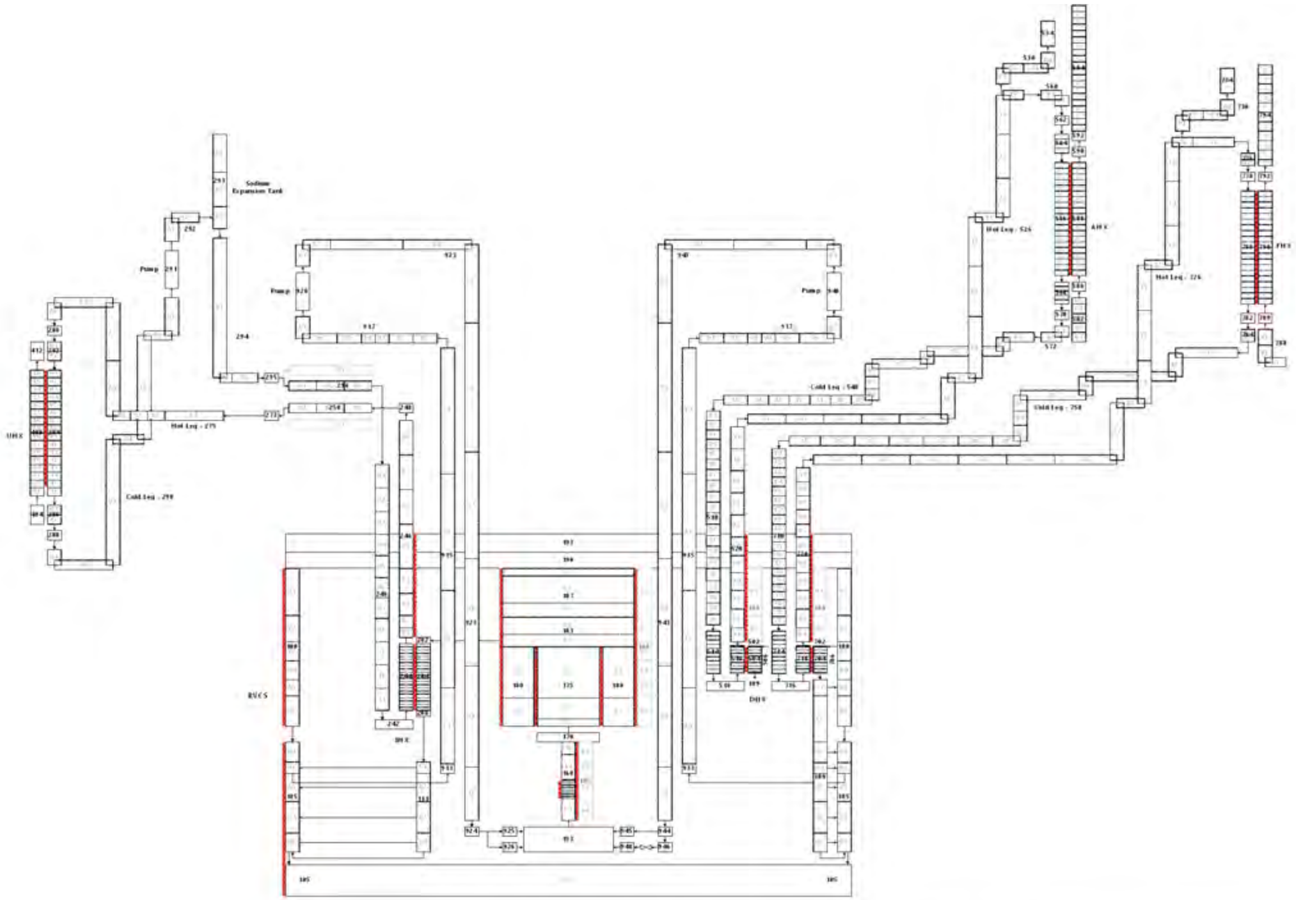


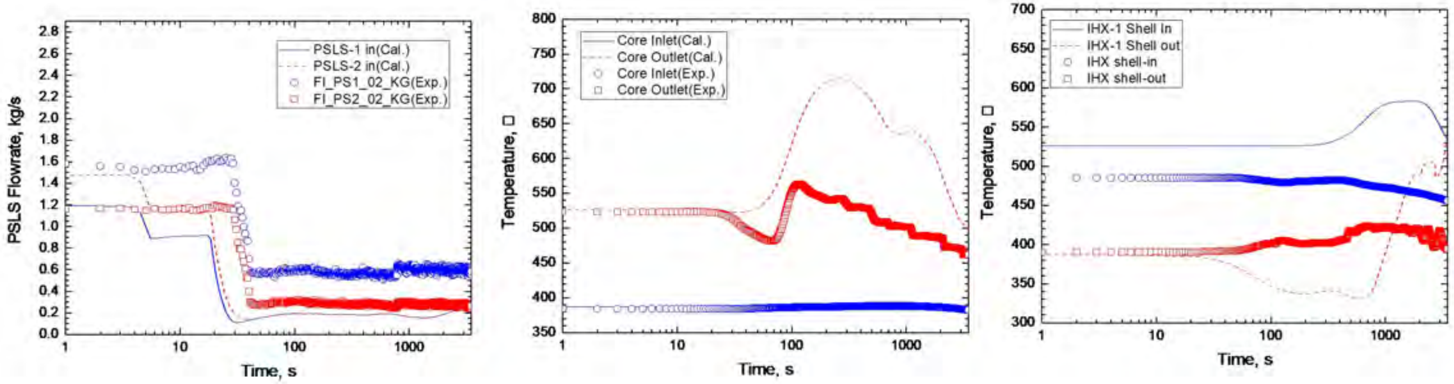
Example of STELLA-2 Result

- Preliminary Analysis -

- System Code Analysis
  - Codes of concern : MARS-LMR, GAMMA+
  - Representative DBE : LOF
  - Event sequence
    - PHTS Pump stop
    - IHTS Pump stop
    - UHX stop
    - Reactor trip & decay
    - DHRS starts to operate

      with various combination





Future

- International Collaboration -

- GIF SFR System
  - Benchmark calculation activity proposal (SO PMB)
- IAEA TWG-FR
  - Co-ordinated Research Project (CRP) proposal next year
- Mutual Collaboration with Research Groups
  - INL, ANL, CEA, JAEA
- Collaboration with Industry
  - ARC, Terra Power, etc.

GEN IV International Forum

Expertise | Collaboration | Excellence

Summary

Summary

- STELLA Program was launched to support the development of first SFR in Korea
  - It will serve as a strong supporter of PGSFR licensing in future
  - It is a basic infrastructure for sodium system
- STELLA-1 accomplished its mission successfully
  - Key components for safety of SFR was tested
  - Code V&V completed to assure the calculation results
- STELLA-2 is ready to achieve valuable data
  - Potentially be used for licensing
  - Various activities and works planned under international collaboration framework

Thank you!

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Upcoming Webinars

Date	Title	Presenter
28 November 2022	Geospatial Analytics for Energy and Resilience Analysis	Dr. Mark Deinert, Colorado School of Mines, USA
14 December 2022	The Mechanisms Engineering Test Loop (METL) facility at Argonne National Lab	Dr. Derek Kultgen, Argonne National Laboratory, USA
25 January 2022	Molten Salt Reactors Taxonomy and Fuel Cycle Performance	Dr. Jiri Krepel, Paul Scherrer Institute, Switzerland