Oregon State University OSU College of Engineering

Department of Nuclear Engineering &
Radiation Health Physics

INTEGRAL SYSTEM EXPERIMENT SCALING METHODOLOGY (Lecture T14)

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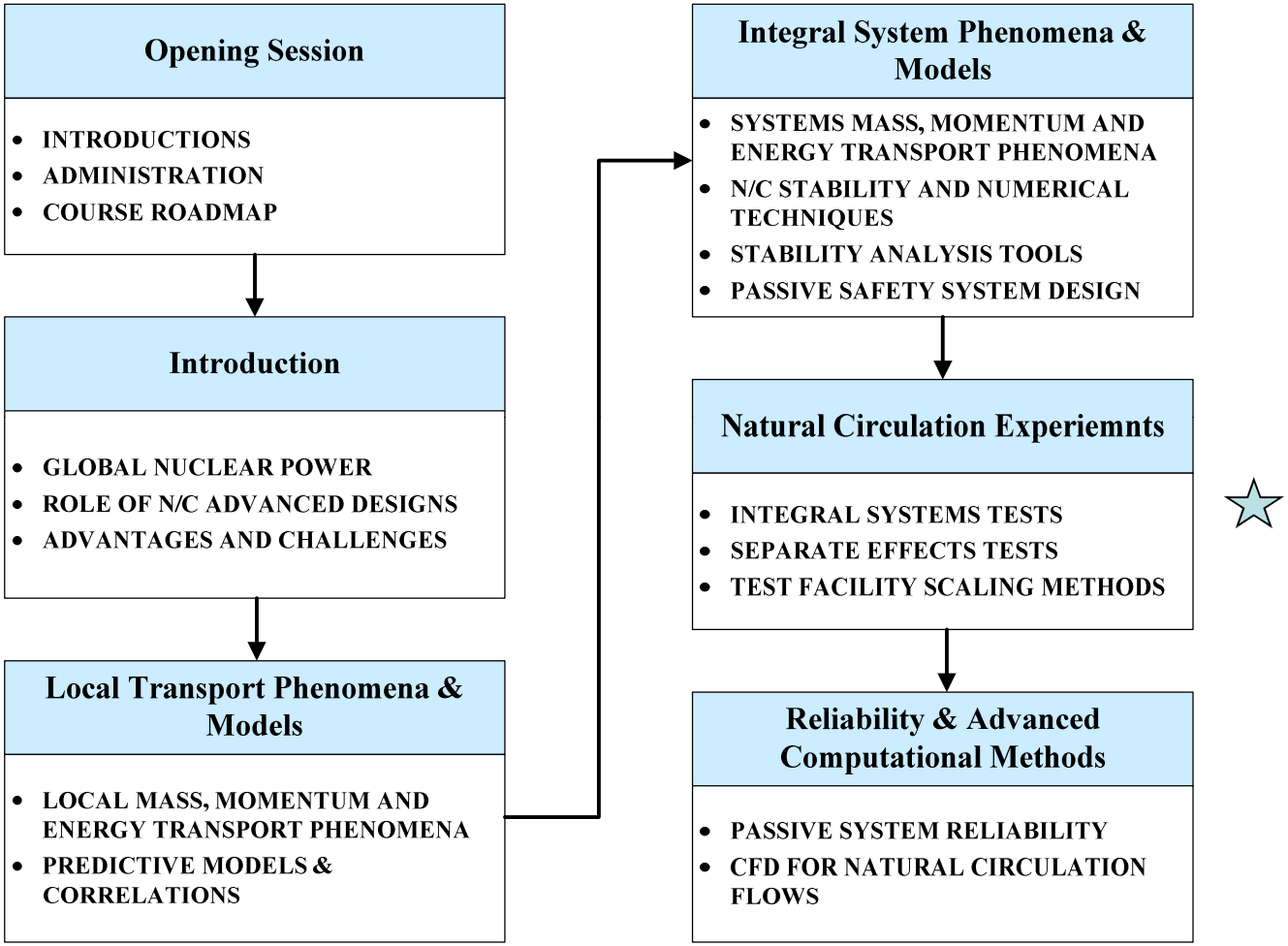
Course Roadmap



Lecture Objectives

- Describe the methodology needed to design a single-phase or two-phase natural circulation Integral System Test Facility.
  - Understand the structure of a Phenomena Identification Ranking Table (PIRT) for a Natural Circulation Based System
  - Understand the method used to conduct a detailed scaling analysis to obtain the geometric dimensions and operating conditions for an integral system test facility.

Outline

- Introduction
  - Scaling Analysis Objectives
- General Scaling Methodology
  - Description of the MASLWR Design
  - PIRT
  - H2TS Methodology
- Single-Phase Natural Circulation Scaling Analysis
  - Dimensionless Governing Equations
  - Steady-State Analytical Solution
- Two-Phase Natural Circulation Scaling Analysis
  - Dimensionless Governing Equations
- Conclusions

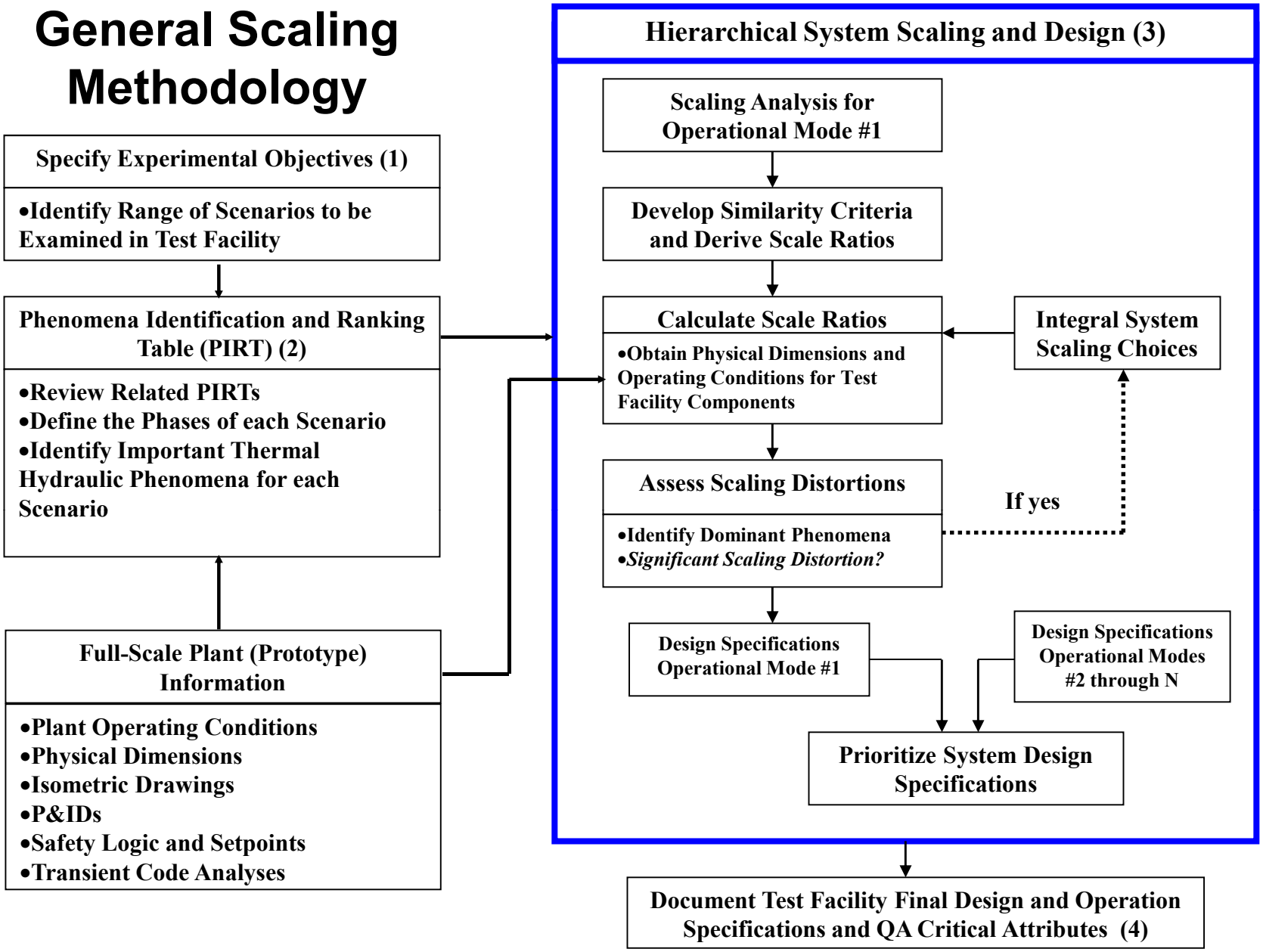
Introduction

- Integral system test (IST) facilities play a key role in the design, assessment and certification of innovative reactor designs.
  - Data used to benchmark the best-estimate safety analysis computer codes used to evaluate nuclear plant safety.
  - Tests to assess the effectiveness of safety system functions under simulated accident conditions.
- Requires detailed scaling analysis.
  - Scaling analyses have been successfully used to design APEX and MASLWR at OSU.
  - AP600 and AP1000 design certification involved 3 scaled test facilities.

Scaling Analysis Objectives

- To develop a properly scaled test facility, the following specific objectives must be met for each operational mode of interest.
  - Identify the thermal hydraulic processes that should be modeled.
  - Obtain the similarity criteria that should be preserved between the test facility and the full-scale prototype.
  - Establish priorities for preserving the similarity criteria.
  - Provide specifications for the test facility design
  - Quantify biases due to scaling distortions.
  - Identify the critical attributes of the test facility that must be preserved to meet Quality Assurance requirements.

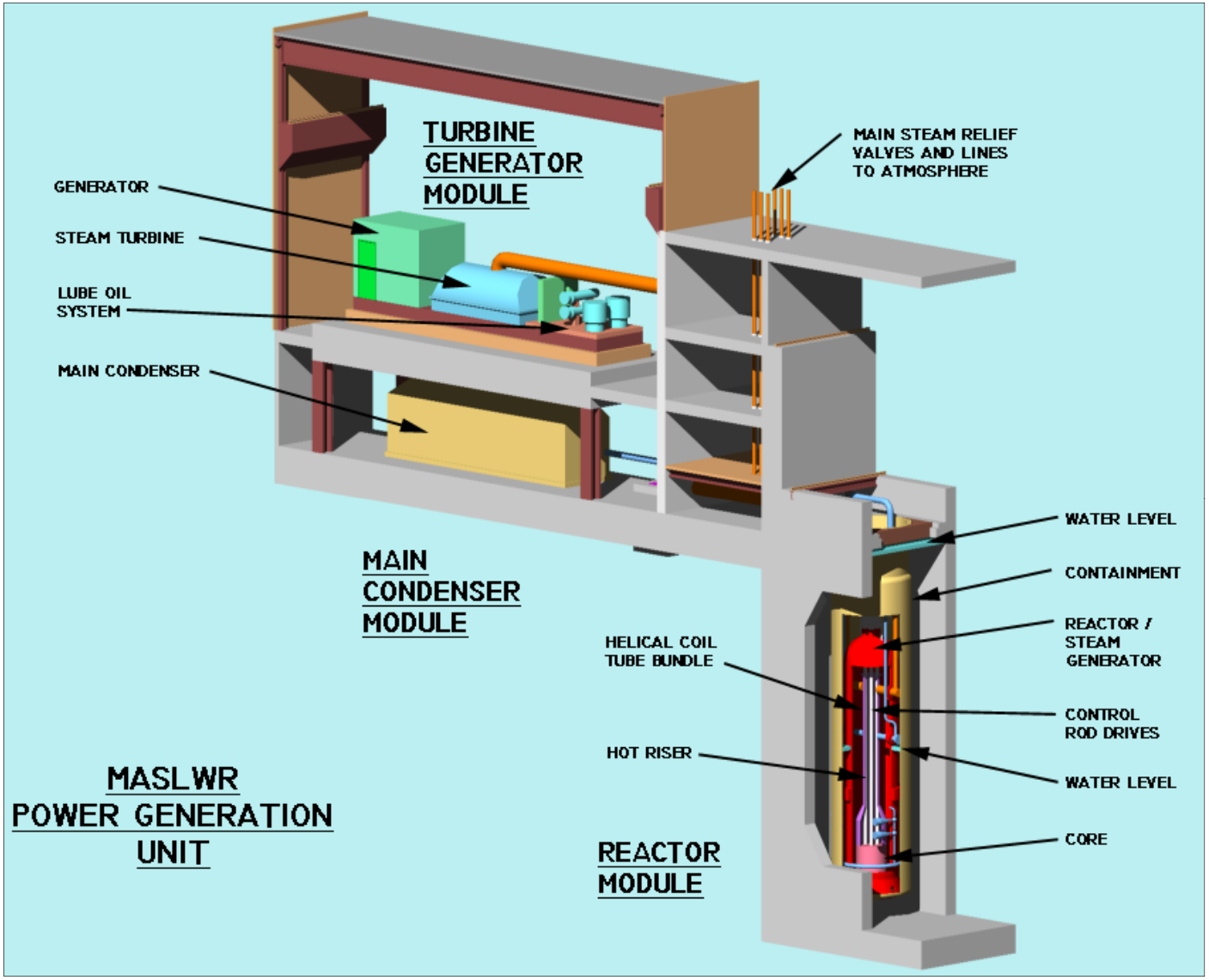
General Scaling Methodology



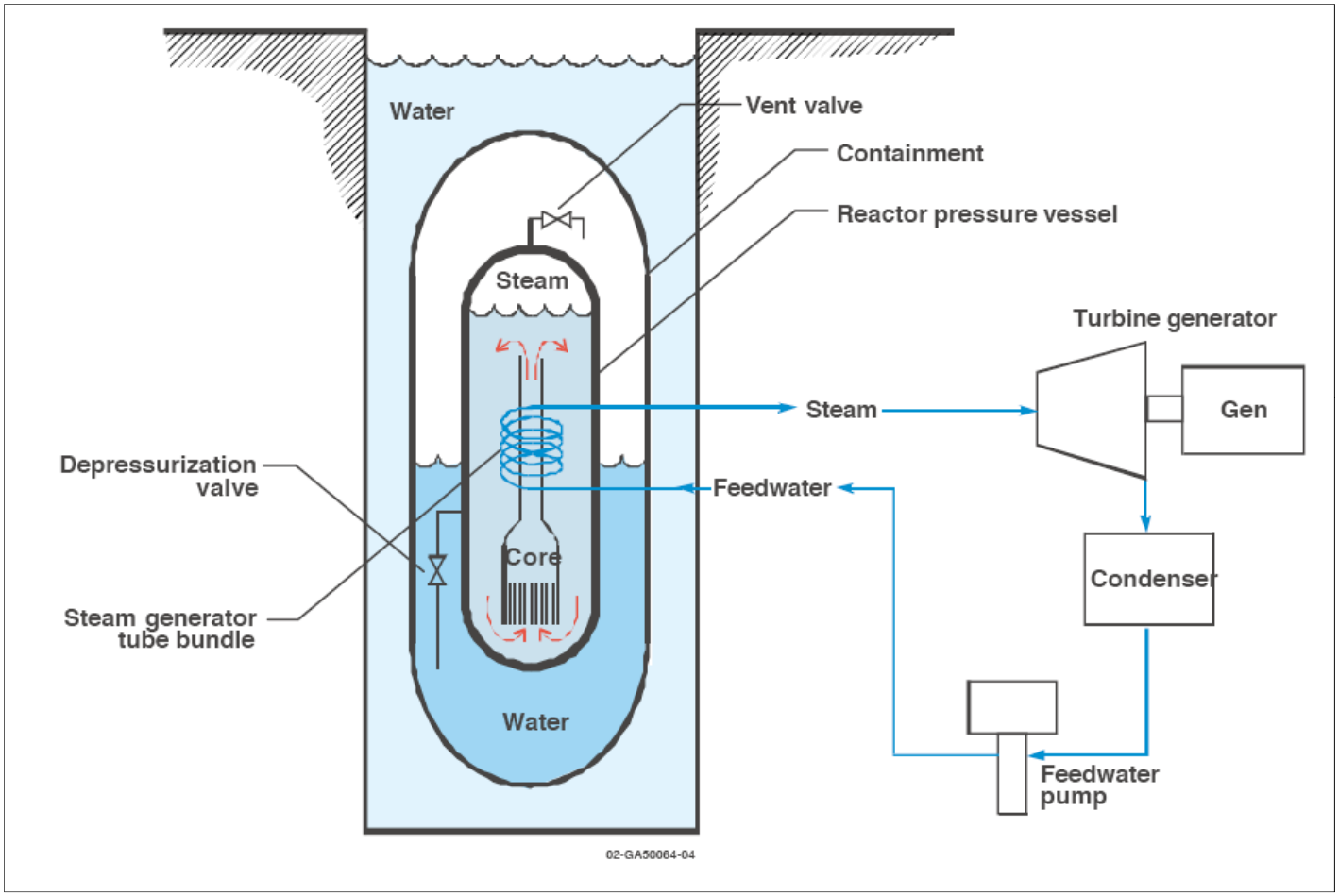
Description of the MASLWR Design

- The Multi-Application Small Light Water Reactor (MASLWR)
  - 150 MW(t) modular nuclear reactor that uses natural circulation for primary loop cooling.
  - MASLWR implements an integrated reactor vessel with an internal helical coil steam generator.
  - Enclosed in a high-pressure steel containment vessel that is partially filled with water to serve as a suppression pool.
  - Containment vessel in turn resides in a large exterior cooling pool that acts as the ultimate heat sink.
- INEL, OSU and NEXANT-Bechtel Design team

MASLWR Design Concept



MASLWR Simple Schematic



MASLWR Normal Operating Parameters

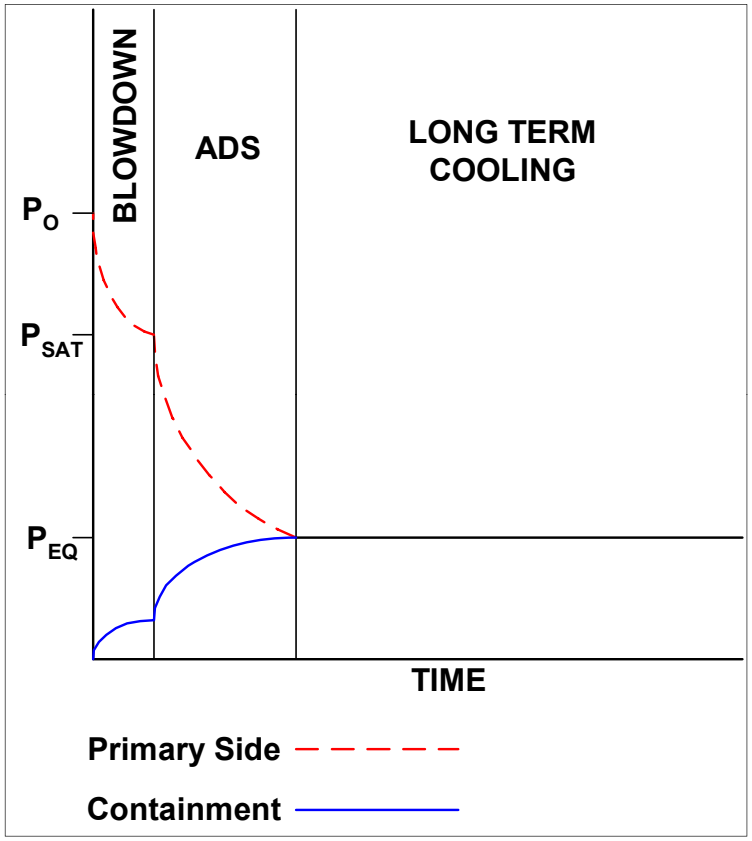
Primary Side	
Reactor Power (MW)	150.00
Primary Pressure (MPa)	7.60
Primary Mass Flow Rate (kg/s)	597.00
Reactor Inlet Temperature (K)	491.80
Reactor Outlet Temperature (K)	544.30
Saturation Temperature (K)	565.00
Reactor Outlet Void Fraction	0.00%
Secondary Side	
Steam Pressure (MPa)	1.50
Steam Outlet Quality	1.00
Steam Temperature (K)	481.40
Saturation Temperature (K)	471.60
Feedwater Temperature (K)	310.00
Feedwater Flowrate (kg/s)	56.10

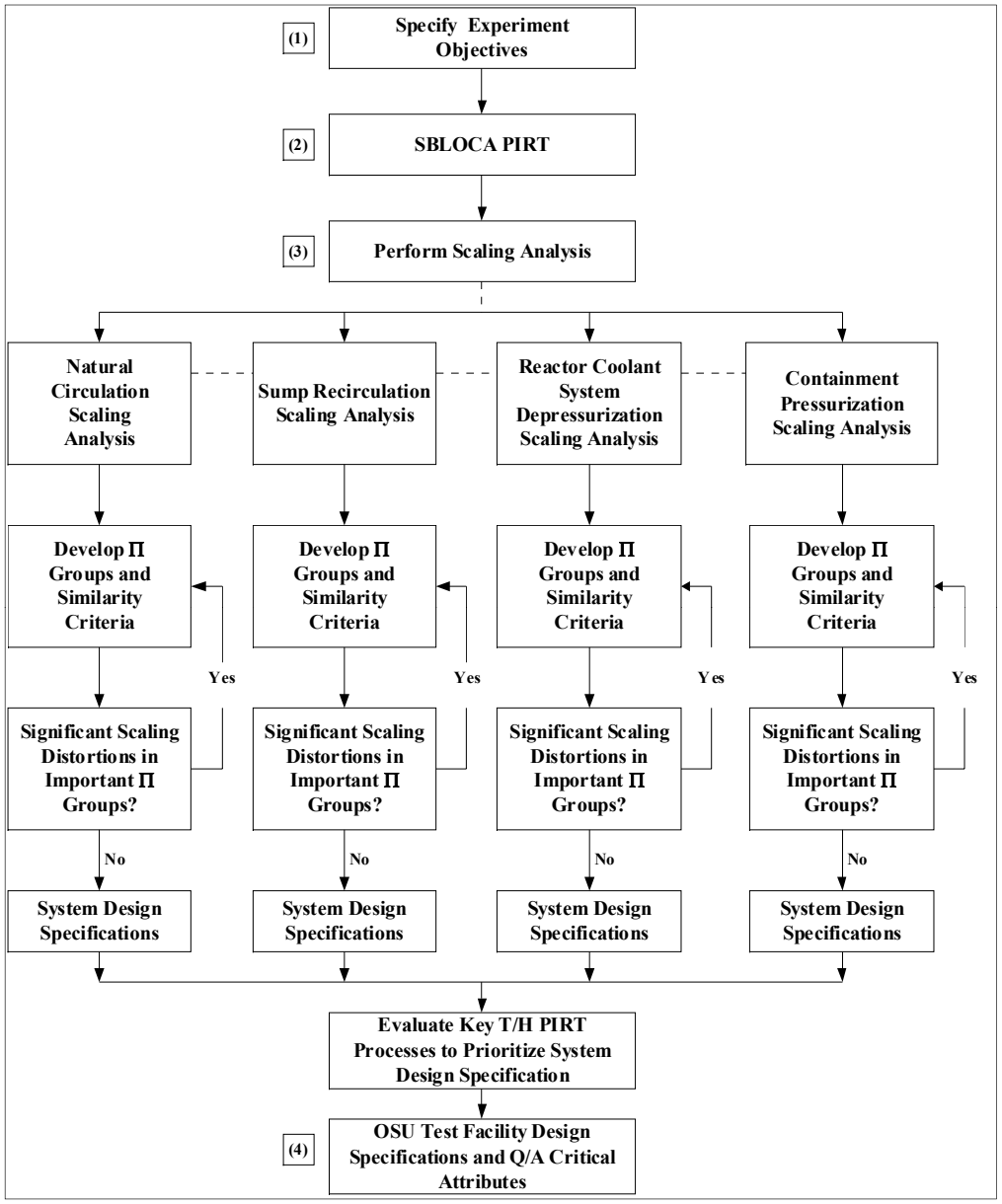
MASLWR Passive Safety Systems

- Two, independent, small diameter, steam vent valves (SVV)
- Two, independent, small diameter, Automatic Depressurization System (ADS) valves
- Two, independent, small diameter, Sump Recirculation Valves (SV)
- A high-pressure containment vessel with an internal pressure suppression pool, and
- An external cooling pool that serves as the ultimate heat sink for the high-pressure containment and reactor decay heat.

MASLWR SBLOCA Behaviour

- BLOWDOWN PHASE:
  - Begins with the opening of the break and ends with the ADS initiation.
  - Subcooled blowdown into the containment suppression pool.
- ADS BLOWDOWN PHASE:
  - Begins with the opening of the ADS valve and ends when the containment and reactor system pressures are equalized
  - Saturated blowdown into containment suppression pool.
- LONG TERM COOLING PHASE:
  - Begins with the equalization of the containment and reactor system pressures and ends when stable cooling is established.
  - Stable Cooling: Natural circulation cooling established within containment and natural circulation cooling established in exterior pool.



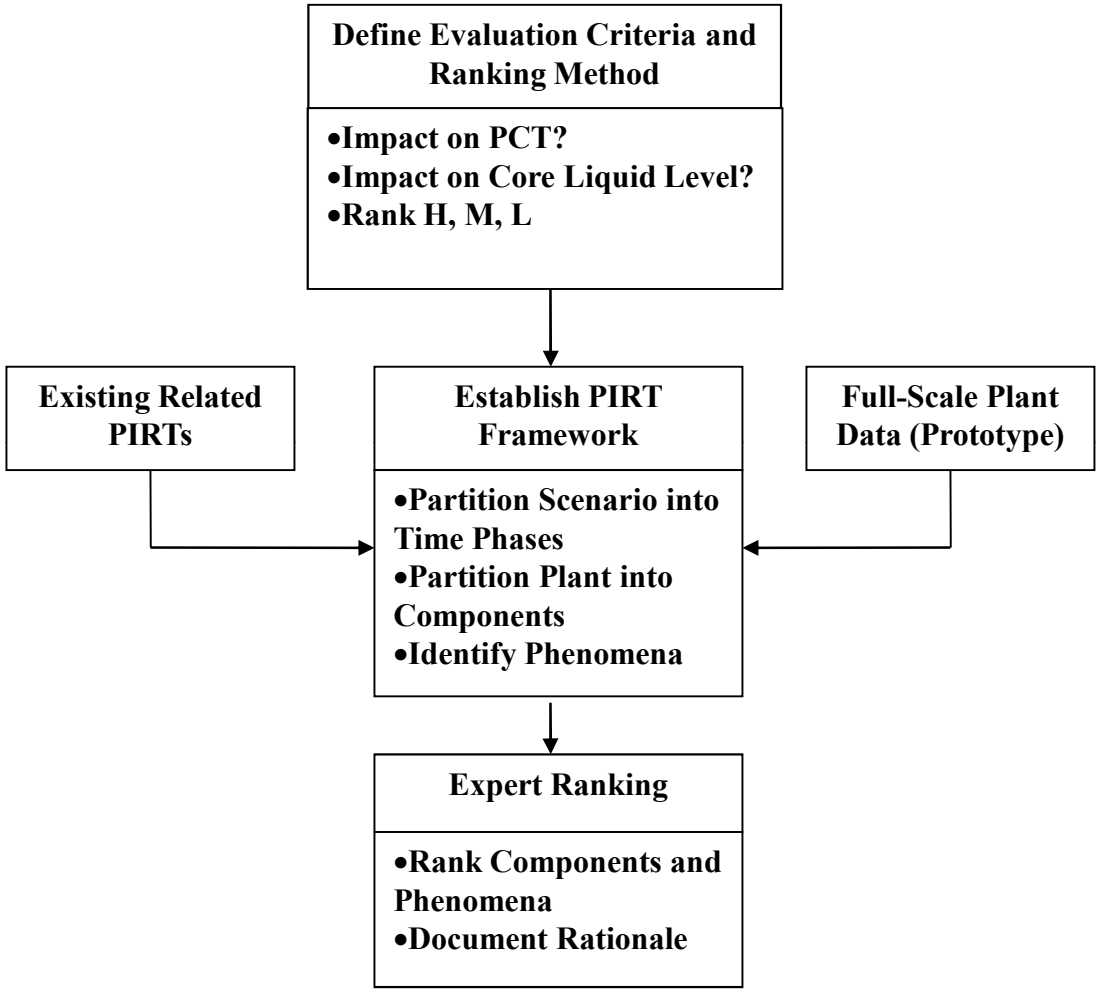


Scaling Analysis Flow Chart for MASLWR

- Scaling Analyses for Four Operational Modes:
  - Natural Circulation
  - Sump Recirculation
  - RCS Depressurization
  - Containment Pressurization

Phenomena Identification and Ranking Tables

(PIRT Development Method)



Phenomena Identification and Ranking Tables

(Evaluation Criterion and Ranking Scale)

- Evaluation Criterion
  - How does this particular phenomenon in this particular component impact the fuel's Peak Cladding Temperature (PCT) during this phase of the scenario?
- Ranking Scale
  - High (H): Phenomenon significantly impacts the PCT during a specific phase of the scenario.
  - Medium (M): Phenomenon has a moderate impact on the PCT during a specific phase of the scenario.
  - Low (L): Phenomenon has little impact on the PCT during a specific phase of the scenario
  - Plausible (P): Phenomenon has not been previously assessed in other designs or its impact on PCT is not well understood or modeled by computer codes. For purposes of test facility scaling, these phenomena were considered highly ranked.
  - Inactive or Not Applicable (I): Phenomenon cannot physically impact the PCT during a specific phase of the scenario.

MASLWR SBLOCA PIRT *(1 of 3)*

System	Period			Component	Period			Process/Phenomenon	Period		
	1	2	3		1	2	3		1	2	3
Vent Valves	H	H	H	Valves	H	H	H	Mass Flow (Choked/Nonchoked)	H	H	H
				Piping	M	M	H	Line Flow Resistance	M	M	H
ADS	I	H	H	Valves	I	H	H	Mass Flow (Choked/Nonchoked)	I	H	H
				Piping	I	M	H	Line Flow Resistance	I	M	H
				Sparger	I	H	M	Condensation	I	H	M
								Energy Release	I	H	M
								Mass Release	I	H	M
Passive Cont. Cooling Sys. (PCCS)	P	P	H	External Cont. Cooling Pool	I	I	H	Natural Convection Heat Transfer	I	I	H
								Thermal Stratification	I	I	L
				Containment Shell	P	P	H	Internal			
								Pressure	L	M	H
								Buoyancy Driven Flow	P	P	P
								Heat Transfer	L	L	H
								Wall - condensation rate	L	L	H
								Noncondensible Gas Mass Fraction	L	L	H
								Wall			
								Thermal Capacitance	L	L	H
								Thermal Conduction	L	L	H
Passive Safety Recirculation System	L	L	H	Sump	L	L	H	ADS Heat-up of Sump	I	L	M
								Condensation (Surface of Pool)	L	I	I
								Thermal Stratification	L	L	L
								Recirculation (Flow Resistance)	I	I	H
								Resupply from Containment	L	L	H

Period 1 - Blowdown
Period 2 - ADS Operation
Period 3 - Long Term Cooling

H - Significantly Impacts PCT
M - Moderately Impacts PCT
L - Little Impact on PCT

I - Inactive during the transient Phase
P - Plausible

MASLWR SBLOCA PIRT *(2 of 3)*

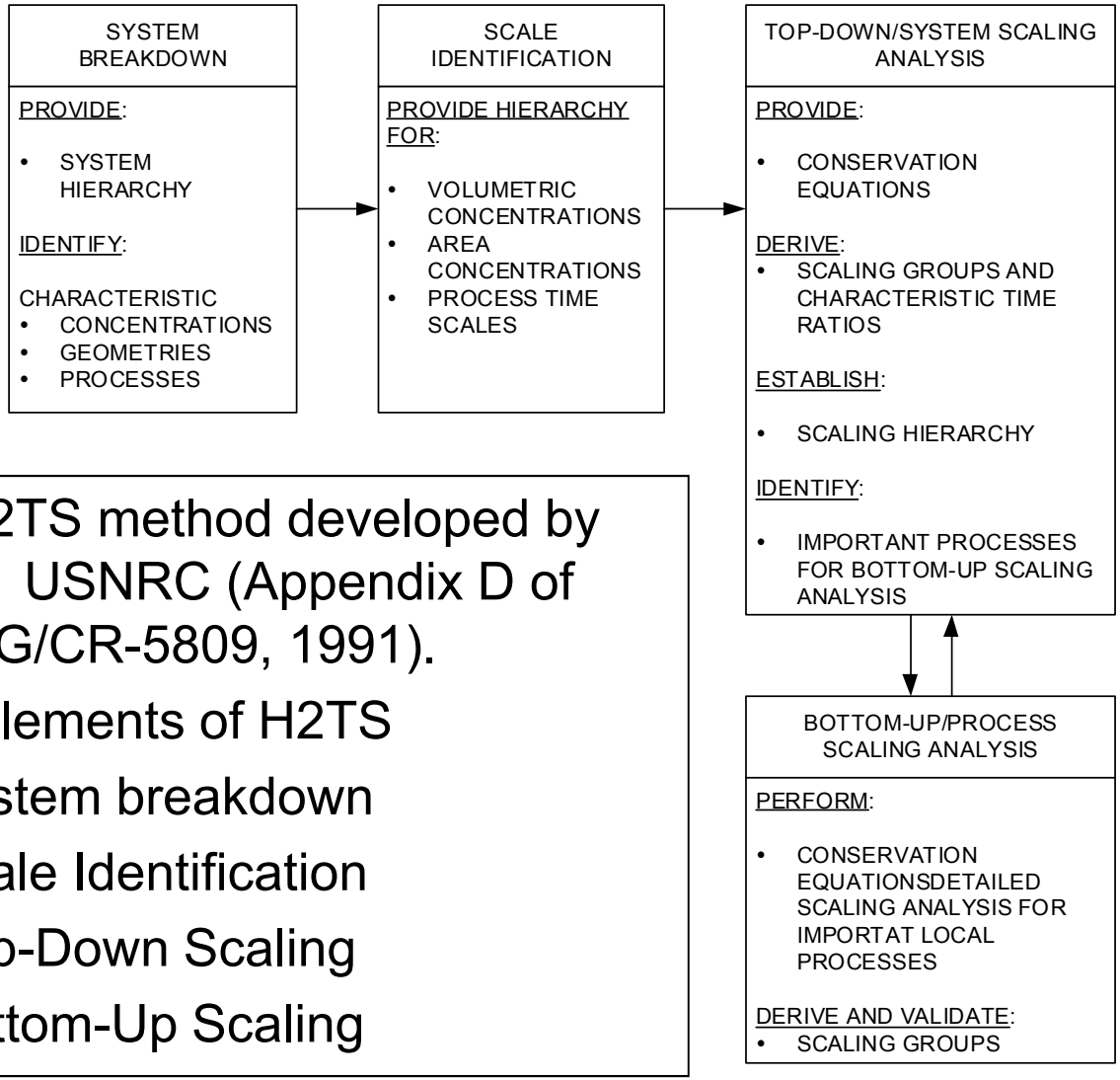
System	Period			Component	Period			Process/Phenomenon	Period		
	1	2	3		1	2	3		1	2	3
Primary Coolant System	H	H	H	Hot Leg Riser	H	H	H	Flashing	M	H	L
								Flow Resistance (wall/control rod tubes)	M	M	M
								Riser Inventory/Circulation/Level	H	H	H
				SG Tube Annulus	H	H	H	SG Tube Condensation	H	H	H
								Flow			
								Entrainment/De-entrainment	L	L	I
								CCF	I	I	I
								Flow Resistance	H	L	L
								Multidimensional Flow	L	L	L
								Level	L	L	H
								Flashing	H	H	L
								Stored Energy Release- Hot wall effect	M	M	H
Reactor System	H	H	H	Vessel - Control Rods	H	L	L	Reactivity Change	H	L	L
				Vessel - Core Subchannels	H	H	H	Flow			
								Interfacial Drag	L	H	L
								Mass Flow	H	H	H
								Flow Resistance	H	H	H
								Two_phase Mixture Level	H	H	H
								Flashing	M	H	L
				Vessel - Downcomer	H	H	H	Flow			
								Entrainment/De-entrainment	L	L	I
								CCF	L	L	L
								Flow Resistance	H	M	H
								Multidimensional Flow	L	L	L
								Level	L	L	H
								Flashing	M	H	L
								Stored Energy Release- Hot wall effect	M	M	H

Period 1 - Blowdown — *H - Significantly Impacts PCT* — *I - Inactive during the transient Phase*
Period 2 - ADS Operation — *M - Moderately Impacts PCT* — *P - Plausible*
Period 3 - Long Term Cooling — *L - Little Impact on PCT*

MASLWR SBLOCA PIRT *(3 of 3)*

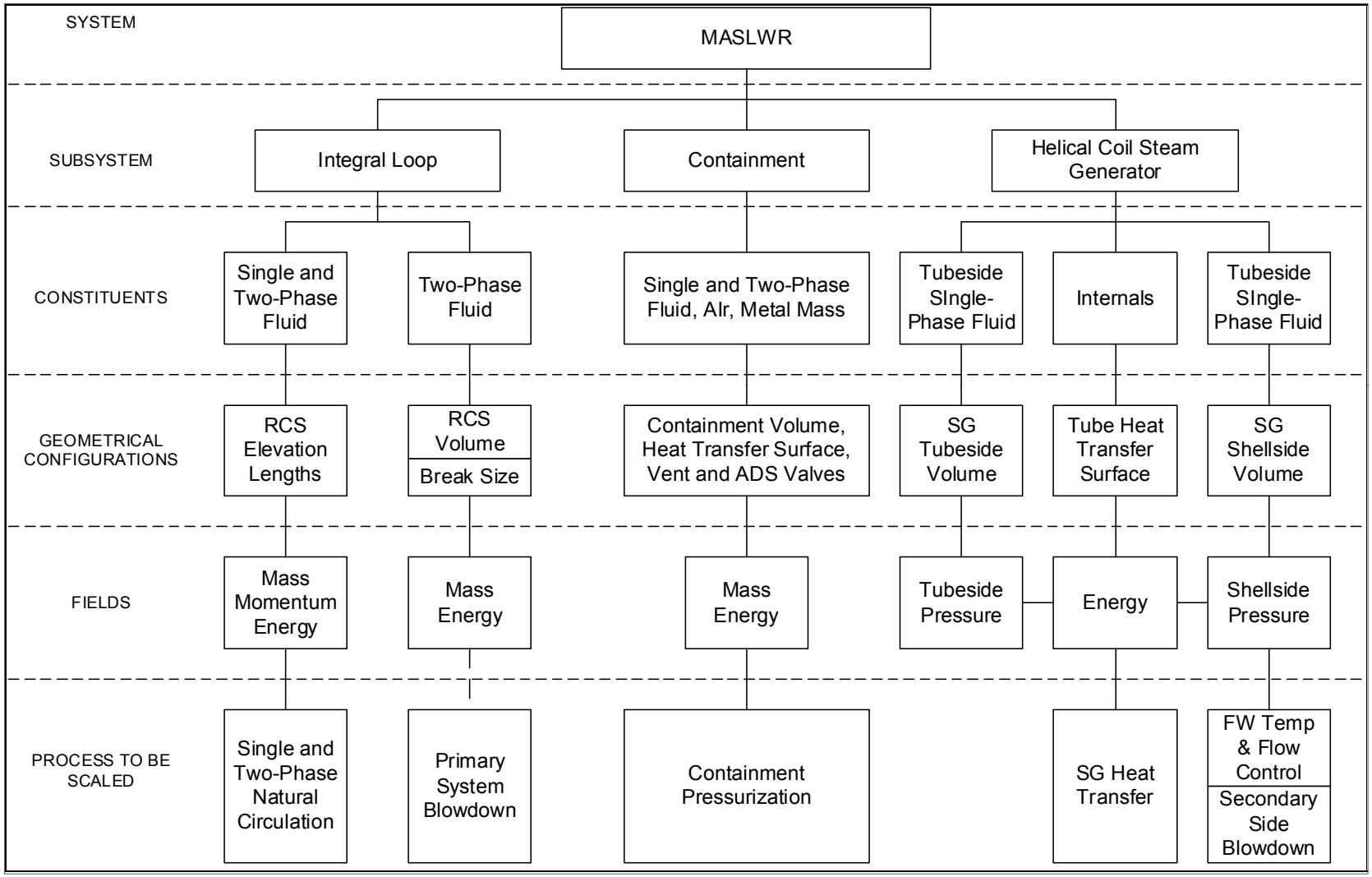
System	Period			Component	Period			Process/Phenomenon	Period		
	1	2	3		1	2	3		1	2	3
Reactor System (continued)	H	H	H	Vessel - Fuel Rods	H	H	H	Fuel Heat Transfer			
								Conduction	H	H	H
								Gap Conductance	H	H	H
								Stored Energy Release	H	H	L
								Cladding Convective Heat Transfer			
								Subcooled Liquid	H	L	L
								Subcooled Boiling	H	L	L
								Nucleate Boiling	L	L	H
								CHF by DNB	L	L	H
								Film Boiling	L	L	H
								Forced Convection to vapor	L	L	H
								Reactivity			
								Void	H	I	I
								Moderator temperature	H	I	I
								Fuel temperature (Doppler)	H	I	I
								Decay Heat	H	H	H
				Vessel - Guide Tubes	L	L	L	Film Draining	L	L	I
								Stored Energy Release	L	L	L
				Vessel - Lower Plenum	H	H	H	Flow transient			
								Flow Resistance	H	L	H
								Flashing	M	H	L
								Stored Energy Release	M	M	H
				Vessel - Structures	L	L	L	Stored Energy Release	L	L	L
				Vessel - Upper Head	H	H	L	Flow Transient			
								Entrainment/De-entrainment	L	L	L
								Stored Energy Release	H	H	L
								Flashing	M	H	L
Steam Generator/Heat Exchanger	L	L	H	Tubes	L	L	H	Heat Transfer with FW Available	H	H	H

Hierarchical Two-Tiered Scaling (H2TS) Methodology

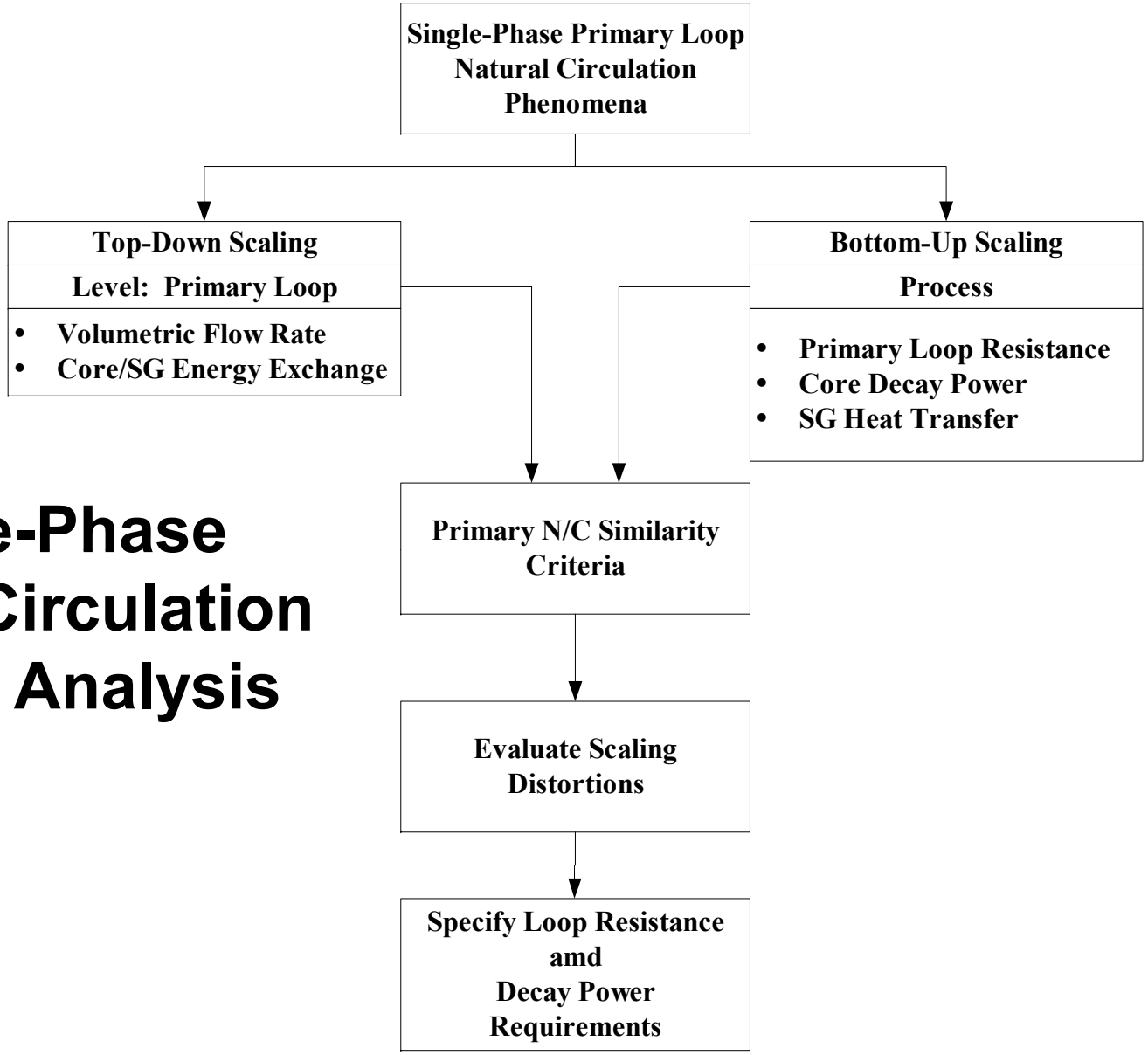


- The H2TS method developed by Zuber, USNRC (Appendix D of NUREG/CR-5809, 1991).
- Four Elements of H2TS
  - System breakdown
  - Scale Identification
  - Top-Down Scaling
  - Bottom-Up Scaling

HIERARCHICAL TWO-TIERED SCALING (H2TS) METHODOLOGY
(MASLWR System Breakdown)

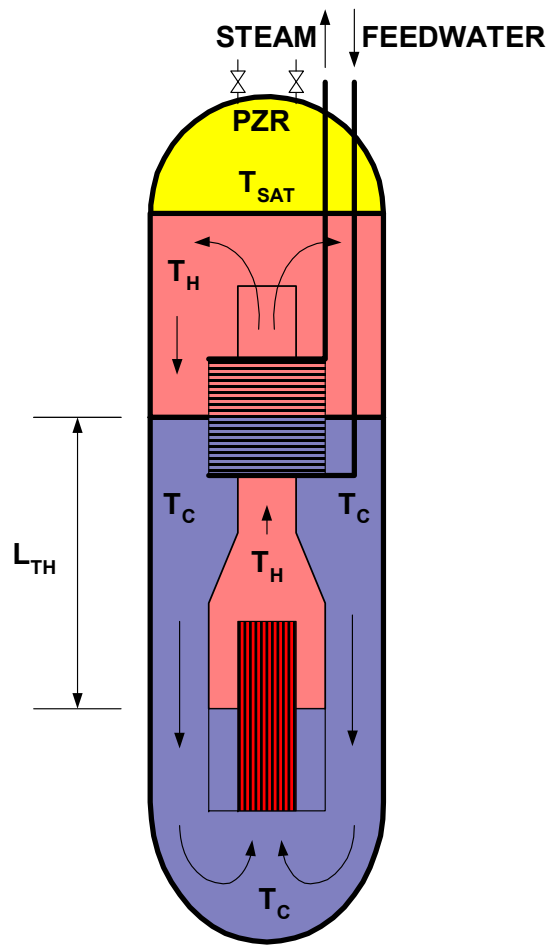


Single-Phase Natural Circulation Scaling Analysis



Single-Phase Natural Circulation Scaling Analysis
(MASLWR Control Volume & Assumptions)

- Obtain Mass, Momentum and Energy Integral Balance Equations
- Simplifying Assumptions:
  - 1-D flow along the loop axis, fluid properties were uniform at every cross-section.
  - Boussinesq approximation was applicable.
  - Incompressible fluid
  - T_C is constant
  - Form losses, primarily in the core and steam generator regions, dominate the loop resistance.



Single-Phase Natural Circulation Scaling Analysis
(Governing Equations)

Loop Momentum Balance:

$$\sum_{i=1}^{N}\left(\frac{l_i}{a_i}\right)\cdot\frac{d\dot{m}}{dt}=\beta g\rho\left(T_H-T_C\right)L_{th}-\frac{\dot{m}^2}{\rho_l a_c^2}\sum_{i=1}^{N}\left[\frac{1}{2}\left(\frac{fl}{d_h}+K\right)_i\left(\frac{a_c}{a_i}\right)^2\right]$$

Loop Energy Balance:

$$C_{vl}M_{sys}\frac{d\left(T_M-T_C\right)}{dt}=\dot{m}C_{pl}\left(T_H-T_C\right)-\dot{q}_{SG}-\dot{q}_{loss}$$

Single-Phase Natural Circulation Scaling Analysis
(Dimensionless Initial and Boundary Conditions)

Characteristic Time Ratio:

$$t^{+} = \frac{t}{\tau_{loop}}$$

Dimensionless Ratios:

$$\dot{m}^{+} = \frac{\dot{m}}{\dot{m}_o}$$

$$\dot{q}_{SG}^{+} = \frac{\dot{q}_{SG}}{\dot{q}_{SG_o}}$$

$$\dot{q}_{loss}^{+} = \frac{\dot{q}_{loss}}{\dot{q}_{loss_o}}$$

$$\left(T_M - T_C\right)^{+} = \frac{\left(T_M - T_C\right)}{\left(T_M - T_C\right)_o}$$

$$\left(T_H - T_C\right)^{+} = \frac{\left(T_H - T_C\right)}{\left(T_H - T_C\right)_o}$$

$$\left\{\sum_{i=1}^{N}\left[\frac{1}{2}\left(\frac{fl}{d_h}+K\right)_i\left(\frac{a_c}{a_i}\right)^2\right]\right\}^{+} = \frac{\sum_{i=1}^{N}\left[\frac{1}{2}\left(\frac{fl}{d_h}+K\right)_i\left(\frac{a_c}{a_i}\right)^2\right]}{\sum_{i=1}^{N}\left[\frac{1}{2}\left(\frac{fl}{d_h}+K\right)_i\left(\frac{a_c}{a_i}\right)^2\right]_o}$$

Single-Phase Natural Circulation Scaling Analysis
(Dimensionless Balance Equations)

Loop Momentum Balance Equation:

$$\Pi_L \frac{d\dot{m}^+}{dt^+} = \Pi_{Ri}\left(T_H - T_C\right)^+ - \Pi_{Fl}\left(\dot{m}^+\right)^2 \left\{ \sum_{i=1}^{N} \left[\frac{1}{2}\left(\frac{fl}{d_h} + K \right)_i \left(\frac{a_c}{a_i} \right)^2 \right] \right\}^+$$

Loop Energy Balance Equation:

$$\frac{1}{\gamma} \frac{d\left(T_M - T_C\right)^+}{dt^+} = \Pi_T \dot{m}^+ \left(T_H - T_C\right)^+ - \Pi_{SG} \dot{q}_{SG}^+ - \Pi_{loss} \dot{q}_{loss}^+$$

Characteristic Time Constant:

$$\tau_{loop} = \sum_{i=1}^{N} \frac{l_i}{u_i} = \sum_{i=1}^{N} \tau_i = \frac{M_{sys}}{\dot{m}_o} = \frac{M_{sys}}{\rho_l u_{co} a_c}$$

Single-Phase Natural Circulation Scaling Analysis
(Dimensionless Groups – Characteristic Time Ratios)

Loop Reference Length Number:

$$\Pi_L = \sum_{i=1}^{N} \frac{l_i}{l_{ref}} \frac{a_c}{a_i}$$

where:

$$l_{ref} = \frac{M_{sys}}{\rho_l a_c}$$

Loop Richardson Number:

$$\Pi_{Ri} = \frac{\beta g \left(T_H - T_C\right)_o L_{th}}{u_{co}^2}$$

or

$$\Pi_{Ri} = \frac{\beta g \dot{q}_{co} L_{th}}{\rho_l a_c C_{pl} u_{co}^3}$$

Loop Resistance Number:

$$\Pi_{Fl} = \sum_{i=1}^{N} \left\{ \frac{1}{2} \left(\frac{fl}{d_h} + K \right)_i \left(\frac{a_c}{a_i} \right)^2 \right\}$$

Ratio of Specific Heats:

$$\gamma = \frac{C_{pl}}{C_{vl}}$$

Loop Energy Ratio:

$$\Pi_T = \frac{\left(T_H - T_C\right)_o}{\left(T_M - T_C\right)_o}$$

SG Heat Transport Number:

$$\Pi_{SG} = \frac{\dot{q}_{SGo}}{\rho_l u_{co} a_c C_{pl} \left(T_M - T_C\right)_o}$$

Loop Heat Loss Number:

$$\Pi_{Loss} = \frac{\dot{q}_{loss,o}}{\rho_l u_{co} a_c C_{pl} \left(T_M - T_C\right)_o}$$

Single-Phase Natural Circulation Scaling Analysis
(Steady-State Solution)

Dimensionless Loop Momentum Balance Equation:

$$\Pi_L \underbrace{\cancel{\frac{d\dot{m}^+}{dt^+}}}_{=0} = \Pi_{Ri} \underbrace{\left(T_H - T_C\right)^+}_{=1} - \Pi_{Fl} \underbrace{\left(\dot{m}^+\right)^2 \left\{ \sum_{i=1}^{N} \left[\frac{1}{2} \left(\frac{fl}{d_h} + K \right)_i \left(\frac{a_c}{a_i} \right)^2 \right] \right\}^+}_{=1}$$

Steady-State

Steady-State Loop Momentum Balance Equation:

$$\Pi_{Ri} = \Pi_{Fl}$$

Solving for Velocity at Core Inlet:

$$u_{co} = \left(\frac{\beta \dot{q}_{co} L_{th} g}{\rho_l a_c C_{pl} \Pi_{Fl}} \right)^{1/3}$$

Single-Phase Natural Circulation Scaling Analysis
(Scale Ratios)

Time Scale Ratio:

$$\tau_{loop,R} = \left(\frac{\rho_l C_{pl}}{\beta}\right)_R^{1/3} \left(\frac{a_c \Pi_{Fl} l^2}{\dot{q}_{co}}\right)_R^{1/3}$$

Fluid Velocity Scale Ratio:

$$u_R = \left(\frac{\beta}{\rho_l C_{pl}}\right)_R^{1/3} \left(\frac{\dot{q}_{co} l}{a_c \Pi_{Fl}}\right)_R^{1/3}$$

Loop Length Scale Ratio:

$$l_R = \left(L_{th}\right)_R$$

Loop Energy Scale Ratio:

$$\left[\frac{\left(T_H - T_C\right)_o}{\left(T_M - T_C\right)_o}\right]_R = 1$$

SG Power Scale Ratio:

$$\left(\frac{\dot{q}_{SGo}}{\dot{q}_{co}}\right)_R = 1$$

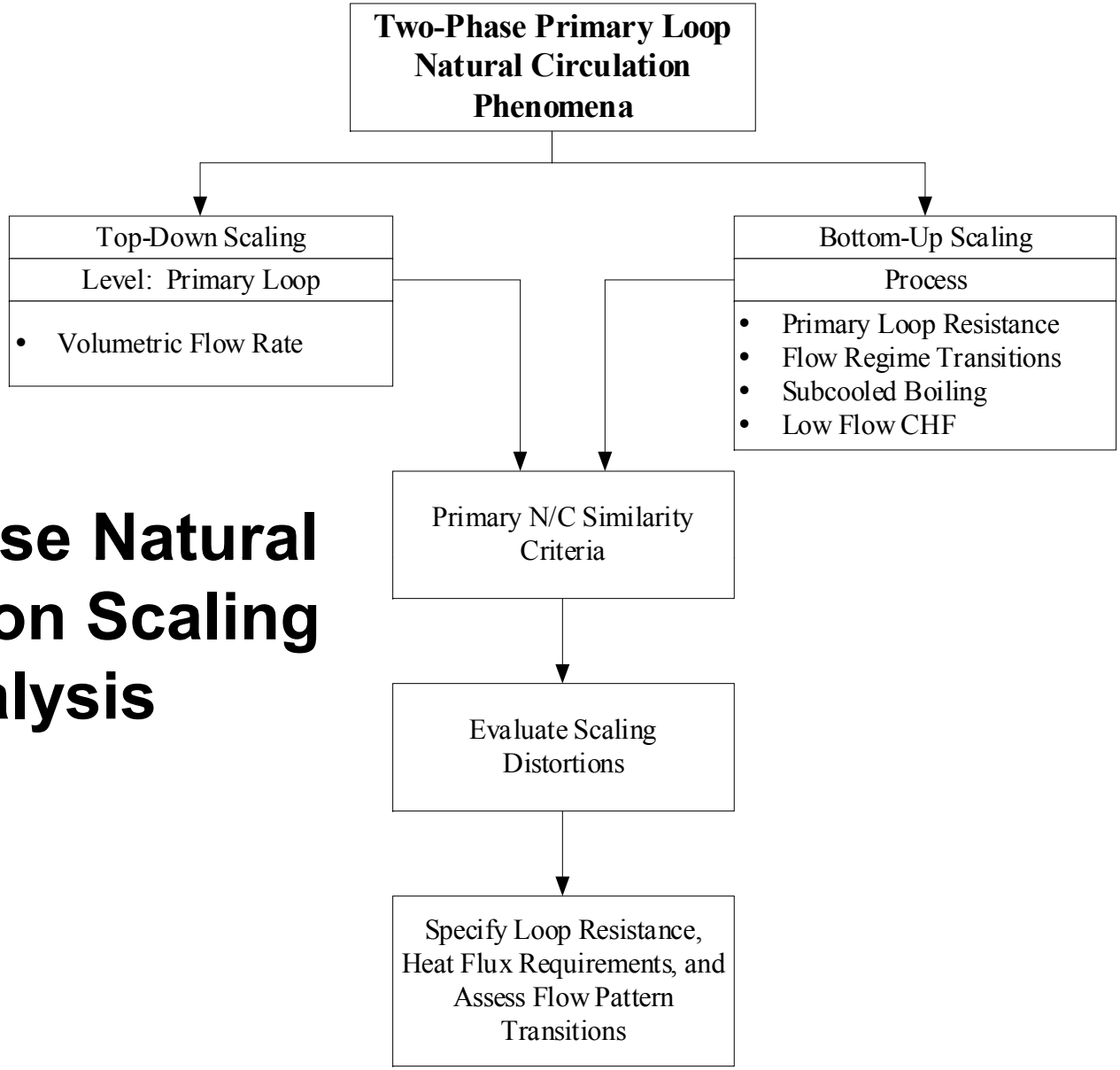
Heat Loss Scale Ratio:

$$\left(\frac{\dot{q}_{loss,o}}{\dot{q}_{co}}\right)_R = 1$$

Flow Area Scale Ratio (Kinematic Similarity):

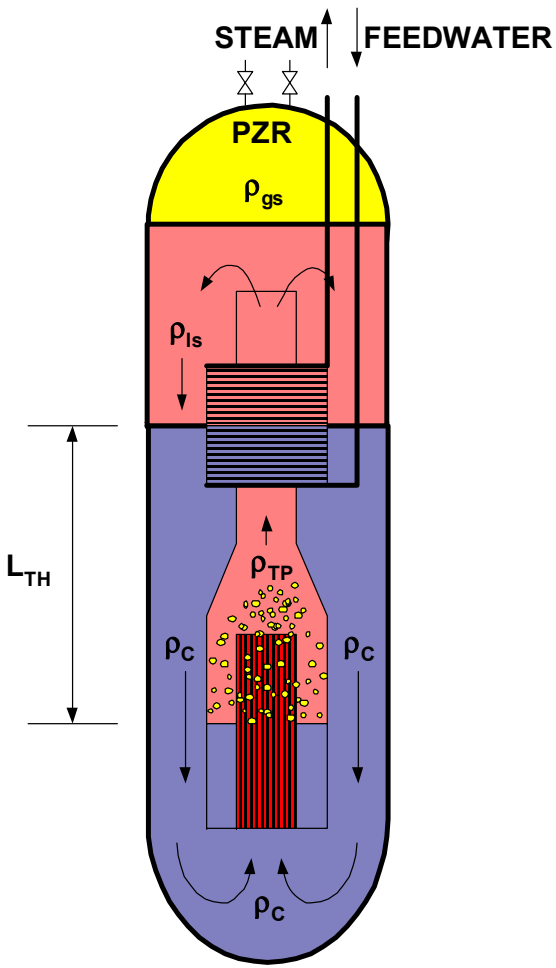
$$\left(\frac{a_i}{a_c}\right)_R = 1$$

Two-Phase Natural Circulation Scaling Analysis



Two-Phase Natural Circulation Scaling Analysis
(MASLWR Control Volume & Assumptions)

- Obtain Mass, Momentum and Energy Integral Balance Equations
- Simplifying Assumptions:
  - Constant core inlet enthalpy
  - Uniform fluid properties at every cross-section,
  - Homogeneous flow in the two phase region,
  - Chemical Equilibrium – no chemical reactions,
  - Thermal Equilibrium – both phases at the same temperature,
  - The sum of convective accelerations due to vaporization and condensation are negligible,
  - Viscous effects included in determination of form losses only.
  - Form losses, primarily in the core and steam generator regions, dominate the loop resistance.



Two-Phase Natural Circulation Scaling Analysis
(Governing Equations)

Loop Momentum Balance:

$$\sum_{i=1}^{N}\left(\frac{l_i}{a_i}\right)\cdot\frac{d\dot{m}}{dt}=g\left(\rho_l-\rho_{TP}\right)L_{th}-\frac{\dot{m}^2}{\rho_l a_c^2}\left\{\sum_{SP}\left[\frac{1}{2}\left(\frac{fl}{d_h}+K\right)_i\left(\frac{a_c}{a_i}\right)^2\right]+\frac{\rho_l}{\rho_{TP}}\sum_{TP}\left[\frac{1}{2}\left(\frac{fl}{d_h}+K\right)_i\left(\frac{a_c}{a_i}\right)^2\right]\right\}$$

Loop Energy Balance:

$$M_{sys}\frac{d\left(e_M-e_l\right)}{dt}=\dot{m}\left(h_{TP}-h_l\right)-\dot{q}_{SG}-\dot{q}_{loss}$$

Equilibrium Vapour Quality at Core Exit:

$$x_e=\frac{h_{TP}-h_f}{h_{fg}}$$

Homogeneous Two-Phase Fluid Mixture Density:

$$\rho_{TP}=\frac{\rho_f}{1+x_e\left(\frac{\rho_f-\rho_g}{\rho_g}\right)}$$

Two-Phase Natural Circulation Scaling Analysis
(Dimensionless Initial and Boundary Conditions)

$$t^+ = \frac{t}{\tau_{loop}}$$

$$\dot{m}^+ = \frac{\dot{m}}{\dot{m}_o}$$

$$(\rho_l - \rho_{TP})^+ = \frac{(\rho_l - \rho_{TP})}{(\rho_l - \rho_{TP})_o}$$

$$(e_M - e_l)^+ = \frac{(e_M - e_l)}{(e_M - e_l)_o}$$

$$\dot{q}_{SG}^+ = \frac{\dot{q}_{SG}}{\dot{q}_{SG_o}}$$

$$\dot{q}_{loss}^+ = \frac{\dot{q}_{loss}}{\dot{q}_{loss_o}}$$

$$(h_{TP} - h_l)^+ = \frac{(h_{TP} - h_l)}{(h_{TP} - h_l)_o}$$

$$\left(\frac{\rho_l}{\rho_{TP}}\right)^+ = \frac{(\rho_l / \rho_{TP})}{(\rho_l / \rho_{TP})_o}$$

$$\left\{\sum_{SP}\left[\frac{1}{2}\left(\frac{fl}{d_h} + K\right)_i \left(\frac{a_c}{a_i}\right)^2\right]\right\}^+ = \frac{\sum_{SP}\left[\frac{1}{2}\left(\frac{fl}{d_h} + K\right)_i \left(\frac{a_c}{a_i}\right)^2\right]}{\sum_{SP}\left[\frac{1}{2}\left(\frac{fl}{d_h} + K\right)_i \left(\frac{a_c}{a_i}\right)^2\right]_o}$$

$$\left\{\sum_{TP}\left[\frac{1}{2}\left(\frac{fl}{d_h} + K\right)_i \left(\frac{a_c}{a_i}\right)^2\right]\right\}^+ = \frac{\sum_{TP}\left[\frac{1}{2}\left(\frac{fl}{d_h} + K\right)_i \left(\frac{a_c}{a_i}\right)^2\right]}{\sum_{TP}\left[\frac{1}{2}\left(\frac{fl}{d_h} + K\right)_i \left(\frac{a_c}{a_i}\right)^2\right]_o}$$

Two-Phase Natural Circulation Scaling Analysis
(Dimensionless Balance Equations)

Loop Momentum Balance Equation:

$$\Pi_L \frac{d\dot{m}^+}{dt^+} = \Pi_{Ri,\rho}\left(\rho_l - \rho_{TP}\right)^+ - \left(\dot{m}^+\right)^2 \left[\Pi_{F1} \left\{ \sum_{SP} \left[\frac{1}{2}\left(\frac{fl}{d_h} + K\right)_i \left(\frac{a_c}{a_i}\right)^2 \right] \right\}^+ + \Pi_{F2}\Pi_\rho \left(\frac{\rho_l}{\rho_{TP}}\right)^+ \left\{ \sum_{TP} \left[\frac{1}{2}\left(\frac{fl}{d_h} + K\right)_i \left(\frac{a_c}{a_i}\right)^2 \right] \right\}^+ \right]$$

Loop Energy Balance Equation:

$$\frac{d\left(e_M - e_l\right)^+}{dt^+} = \Pi_e \dot{m}^+ \left(h_{TP} - h_l\right)^+ - \Pi_{SG}\dot{q}_{SG}^+ - \Pi_{loss}\dot{q}_{loss}^+$$

Characteristic Time Constant:

$$\tau_{loop} = \sum_{i=1}^{N} \frac{l_i}{u_i} = \sum_{i=1}^{N} \tau_i = \frac{M_{sys}}{\dot{m}_o} = \frac{M_{sys}}{\rho_l u_{co} a_c}$$

Two-Phase Natural Circulation Scaling Analysis

(Dimensionless Groups – Characteristic Time Ratios)

Loop Reference Length Number:

$$\Pi_L = \sum_{i=1}^{N} \frac{l_i}{l_{ref}} \frac{a_c}{a_i}$$

where:

$$l_{ref} = \frac{M_{sys}}{\rho_l a_c}$$

Loop Richardson Number:

$$\Pi_{Ri,\rho} = \frac{g(\rho_l - \rho_{TP})_o L_{th}}{\rho_l u_{co}^2}$$

Loop Liquid Phase Resistance Number:

$$\Pi_{Fl} = \sum_{SP} \left\{ \frac{1}{2}\left(\frac{fl}{d_h} + K\right)_i \left(\frac{a_c}{a_i}\right)^2 \right\}_o$$

Loop Two-Phase Resistance Number:

$$\Pi_{F2} = \sum_{TP} \left\{ \frac{1}{2}\left(\frac{fl}{d_h} + K\right)_i \left(\frac{a_c}{a_i}\right)^2 \right\}$$

Density Ratio:

$$\Pi_\rho = \left(\frac{\rho_l}{\rho_{TP}}\right)$$

Loop Energy Ratio:

$$\Pi_e = \frac{\dot{q}_{co}}{\dot{m}_o (e_M - e_l)_o}$$

SG Heat Transport Number:

$$\Pi_{SG} = \frac{\dot{q}_{SGo}}{\dot{m}_o (e_M - e_l)_o}$$

Loop Heat Loss Number:

$$\Pi_{Loss} = \frac{\dot{q}_{loss,o}}{\dot{m}_o (e_M - e_l)_o}$$

Two-Phase Natural Circulation Scaling Analysis
(Steady-State Solution)

Dimensionless Loop Momentum Balance Equation:

$$\Pi_L \cancel{\frac{d\dot{m}^+}{dt^+}} = \Pi_{Ri,\rho} \underbrace{\left(\rho_l - \rho_{TP}\right)^+}_{=1} - \underbrace{\left(\dot{m}^+\right)^2}_{=1} \left[\Pi_{F1} \underbrace{\left\{ \sum_{SP} \left[\frac{1}{2}\left(\frac{fl}{d_h} + K\right)_i \left(\frac{a_c}{a_i}\right)^2 \right] \right\}^+}_{=1} + \Pi_{F2}\Pi_\rho \underbrace{\left(\frac{\rho_l}{\rho_{TP}}\right)^+ \left\{ \sum_{TP} \left[\frac{1}{2}\left(\frac{fl}{d_h} + K\right)_i \left(\frac{a_c}{a_i}\right)^2 \right] \right\}^+}_{=1} \right]$$

Steady-State

Steady-State Loop Momentum Balance Equation:

$$\Pi_{Ri,\rho} = \Pi_{Fl} + \Pi_{F2}\Pi_\rho$$

Two-Phase Natural Circulation Scaling Analysis
(Steady-State Velocity at Core Inlet)

Velocity at Core Inlet:

$$u_{co}^3 + \phi_a u_{co}^2 + \phi_b u_{co} - \phi_c = 0$$

where:

$$\phi_a = \frac{\dot{q}_{co}\Delta\rho}{\rho_f a_c}\left(\frac{(\Pi_F + \Pi_{F2})\rho_g h_{fg} - \Delta\rho\Pi_{F2}h_{sub}}{\Pi_F\rho_g^2 h_{fg}^2 - (\Pi_F + \Pi_{F2})\rho_g h_{fg}\Delta\rho + \Pi_{F2}(\Delta\rho)^2 h_{sub}^2}\right)$$

$$\phi_b = \frac{\Delta\rho}{(\rho_f a_c)^2}\left(\frac{\Delta\rho\Pi_{F2}\dot{q}_{co}^2 + L_{th}g(\rho_f a_c)^2 h_{sub}\rho_g h_{fg}}{\Pi_F\rho_g^2 h_{fg}^2 - (\Pi_F + \Pi_{F2})\rho_g h_{fg}\Delta\rho + \Pi_{F2}(\Delta\rho)^2 h_{sub}^2}\right)$$

$$\phi_c = \frac{1}{\rho_f a_c}\left(\frac{L_{th}g\dot{q}_{co}\Delta\rho\rho_g h_{fg}}{\Pi_F\rho_g^2 h_{fg}^2 - (\Pi_F + \Pi_{F2})\rho_g h_{fg}\Delta\rho + \Pi_{F2}(\Delta\rho)^2 h_{sub}^2}\right)$$

and

$$\left\{\begin{aligned} \Delta\rho &= (\rho_f - \rho_g) \\ h_{sub} &= (h_f - h_l) \\ \Pi_F &= \Pi_{F1} + \Pi_{F2} \end{aligned}\right\}$$

Two-Phase Natural Circulation Scaling Analysis
(Steady-State Velocity with Saturated Liquid at Core Inlet)

Dimensionless Cubic Equation:

$$\Pi_z^3 + \psi_a \Pi_z^2 + \psi_b \Pi_z - \psi_c = 0$$

where:

$$\Pi_z = \frac{1}{N_{Zuber}} = \frac{\rho_g \dot{m}_o h_{fg}}{\rho_f \dot{q}_{co}}$$

$$\psi_a = \left(\frac{\Delta\rho}{\rho_f}\right)\left(\frac{\Pi_F + \Pi_{F2}}{\Pi_F}\right)$$

$$\psi_b = \left(\frac{\Delta\rho}{\rho_f}\right)^2\left(\frac{\Pi_{F2}}{\Pi_F}\right)$$

$$\psi_c = \left(\frac{\Delta\rho}{\rho_f}\right)\left(\frac{gL_{th}\rho_g^2 h_{fg}^2 a_c^2}{\dot{q}_{co}^2}\right)\left(\frac{1}{\Pi_F}\right)$$

Two-Phase Natural Circulation Scaling Analysis
Scaling Catastrophe Functions -Reyes (1994)

Criterion:

$$\beta^3\left(\Pi_{zp}^3 + \psi_{ap}\Pi_{zp}^2 + \psi_{bp}\Pi_{zp} - \psi_{cp}\right) = \Pi_{zm}^3 + \psi_{am}\Pi_{zm}^2 + \psi_{bm}\Pi_{zm} - \psi_{cm}$$

where:

$$\beta = \left(\Pi_z\right)_R$$

$$\beta = \left(\psi_a\right)_R$$

$$\beta^2 = \left(\psi_b\right)_R$$

$$\beta^3 = \left(\psi_c\right)_R$$

Two-Phase Natural Circulation Scaling Analysis
(Scale Ratios for Saturated Two-Phase Conditions)

Time Scale Ratio:

$$\tau_{loop,R} = \frac{l_R}{(L_{th})_R^{1/2}}$$

Fluid Velocity Scale Ratio:

$$u_R = (L_{th})_R^{1/2}$$

Power Scale Ratio:

$$(\dot{q}_{co})_R = a_{c,R}(L_{th})_R^{1/2}\left(\frac{\rho_f \rho_g h_{fg}}{\Delta\rho}\right)$$

Loop Resistance Scale Ratios:

$$(\Pi_{F1})_R = 1$$
$$(\Pi_{F2})_R = 1$$

SG Power Scale Ratio:

$$\left(\frac{\dot{q}_{SGo}}{\dot{q}_{co}}\right)_R = 1$$

Heat Loss Scale Ratio:

$$\left(\frac{\dot{q}_{loss,o}}{\dot{q}_{co}}\right)_R = 1$$

Flow Area Scale Ratio (Kinematic Similarity):

$$\left(\frac{a_i}{a_c}\right)_R = 1$$

Conclusions

- A *General Scaling Methodology* for the design of a single-phase or two-phase Natural Circulation Integral System Test Facility has been described.
  - Discussed the structure of a Phenomena Identification Ranking Table (PIRT)
  - Discussed the H2TS methodology to obtain the geometric dimensions and operating conditions for a N/C integral system test facility.