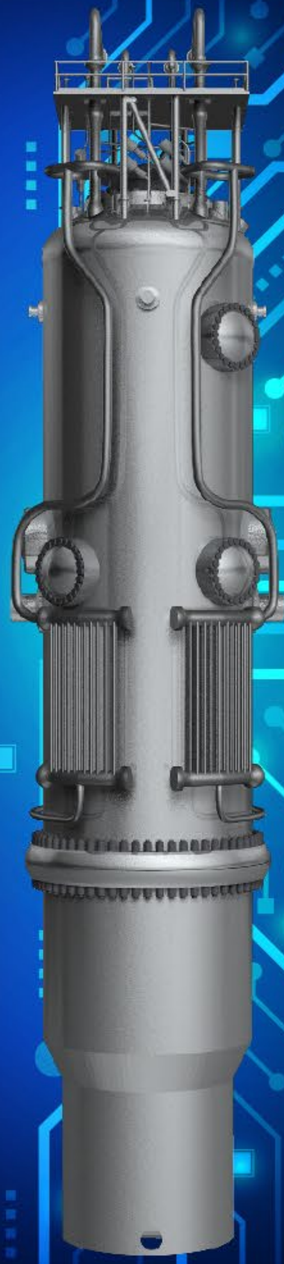
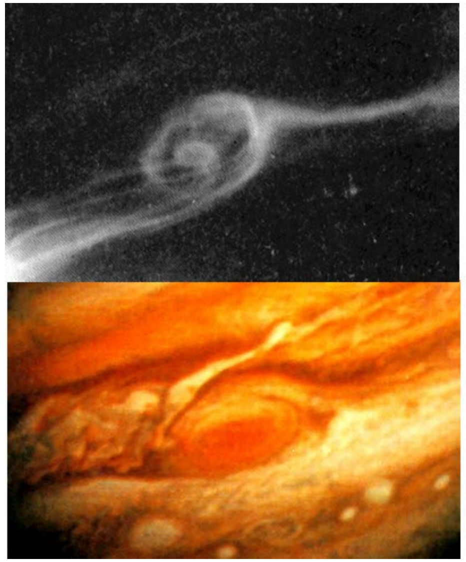
Nuclear Reactor Scaling in the United States

Dr. Jose N. Reyes, Jr
Chief Technology Officer and Co-founder, NuScale
Professor Emeritus, Oregon State University



Scaling Analysis

- Scaling Analysis is the method by which we quantitatively measure and/or establish the degree of similarity among objects or processes at different temporal, spatial, or dimensionless phase space intervals.
- Provides information about the system being examined without having to solve the governing equations. That is, it yields a set of “dimensionless” parameters that can be used to:
  - Correlate and graph experimental data.
  - Reduce the number of variables that must be experimentally investigated
  - Identify operational limits and transitions in phenomena.
- Provides a method to design an experiment such that a physical phenomenon observed at one spatial, temporal or phase space scale will be similar when observed at a different spatial, temporal or phase space scale.
- It is generally not possible to preserve similitude between a scaled experiment and a full scale prototype. Always some distortions that need to be quantified.



Woods (1968); Summer thermoclines in the Mediterranean Sea. Vortex Width: **0.3 m**

NASA Voyager 2 (1979); Great Red Spot of Jupiter. Vortex Width: **2.5×10^7 m**

Kelvin-Helmholtz Wave-Induced Shear Instabilities at Fluid Interfaces

NUSCALE

Evolution of Scaling Analysis Methods – Early Methods

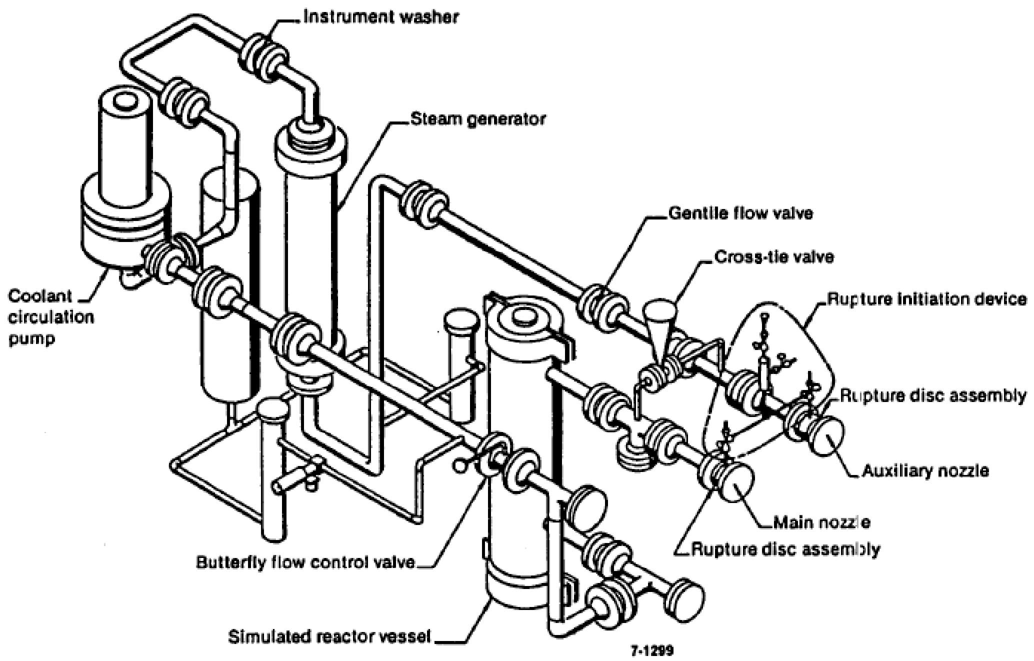
- **Buckingham-π Theorem (1914)** is a method of dimensional analysis that reduces the number of variables in a physical problem to a set of independent, dimensionless groups called π terms. The theorem states that if there are "n" physical variables and "k" fundamental dimensions (like mass, length, and time), then there will be p=n-k dimensionless groups.
- **Dimensional Analysis of Governing Equations.** For example, using a characteristic length, L, and flow velocity, U, to cast the Navier-Stokes Momentum equation in dimensionless form yields two important dimensionless groups, the Reynolds number (ratio of inertial to viscous forces) and the Froude number (ratio of inertial forces to gravitational forces).

$$\mathrm{Re} = \frac{UL}{\nu}; \quad Fr^2 = \frac{U^2}{gL}$$

- The methods of Buckingham-π and Dimensional Analysis of the governing equations has been successfully used to design **Separate Effects Tests. (SET).** However, for complex **Integral Effects Tests (IET),** these simple approaches are insufficient.
- The first IET used to assess emergency core cooling system (ECCS) effectiveness in a nuclear reactor was the Semiscale test facility which implemented simple **Linear Scaling** (1971) rather than a phenomena based scaling method.

Evolution of Scaling Analysis Methods- Linear Scaling (1969-1971)

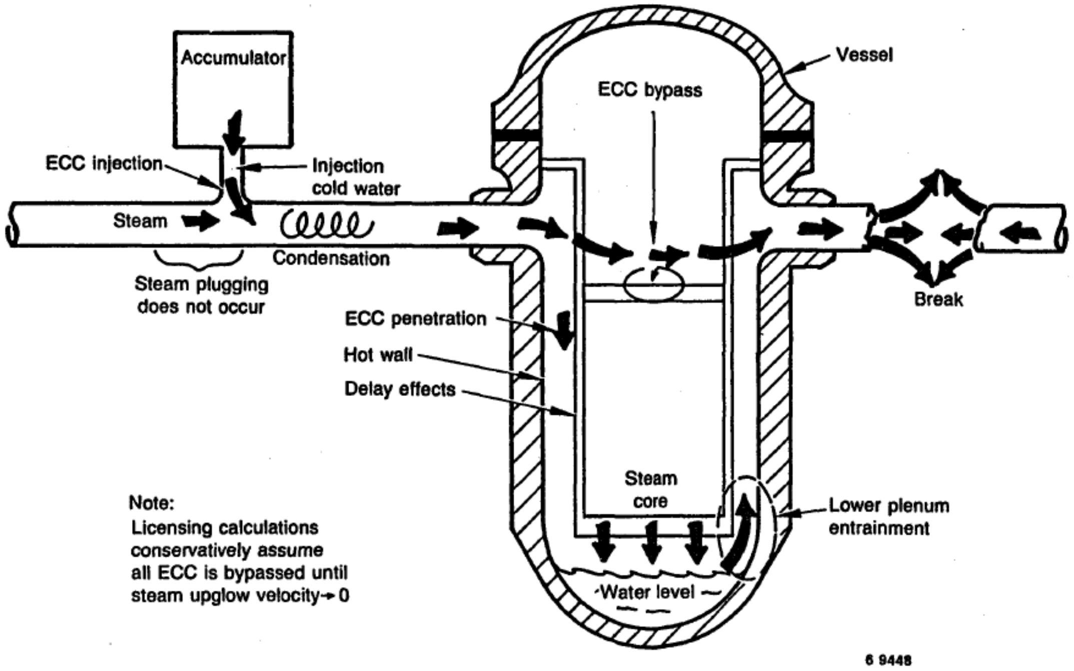
- **Linear Scaling:** All linear dimensions of the test facility are directly reduced by a fixed scale factor relative to the prototype plant.
- Advantage: Loop fluid transport time and acoustic wave propagation times are reduced by the known scale factor. Thus timing of events are directly scaled.
- Distortions:
  - Accelerations in the model are scaled by the inverse of the time factor.
  - Therefore rate controlled phenomena (such as flashing and flow regime development and transition) are distorted in time relative to the prototype.
  - Model will have very small geometric characteristics. Heating surfaces (downcomer surface, heater rods, steam generator tubes) must be reduced to small diameters leading to distortions in heat transfer processes.
- Linear Scaling of original Semiscale reactor vessel resulted in significant distortions. Single Loop (800 Series, 1969-1971).



Semiscale “non-scaled” system for double-ended cold leg break tests

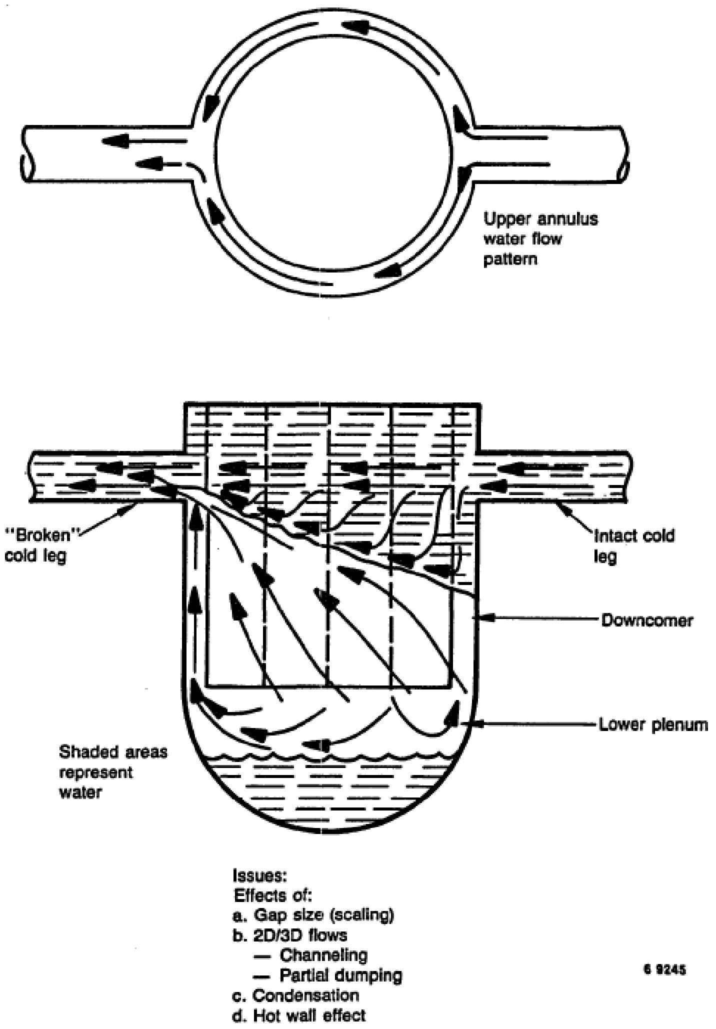
The ECCS Controversy - *Semiscale 800 Series Hypothetical LOCA tests*

- In 1971, several tests were conducted in the Semiscale test facility by the Aerojet Nuclear Company (ANC) in Idaho to investigate the hypothetical LOCA.
- Test 845 Cold Leg Injection– All injected Emergency Core Coolant bypassed the core and was ejected through the simulated pipe break. **NO CORE COOLING**
- Tests 848 and 849 Lower plenum injection. Similar results, nearly all of the coolant bypassed the core. **NO CORE COOLING**.
- These test results caused increased public and regulatory awareness to the LOCA and influenced the 1972 ECCS Hearings.
- The hearings contributed to the political decision made in 1973 to split the Atomic Energy Commission into a new agency for research and development (ERDA/DOE) and the Nuclear Regulatory Commission for safety review functions.



The ECCS Controversy - *Semiscale 800 Series Hypothetical LOCA tests*

- **It was determined that the Semiscale 800 Series tests were not representative of a full scale plant:**
  - The 1/15 linear scale experiments; 1 MW cylindrical core ~23 cm (9 in) height by ~23 cm (9 in) diameter; full power heat flux, 300^{o}C (575^{o}F), 15 MPa (2180 psig), Break area/system volume 0.0023m^{-1} (0.0007 ft^{-1})
  - Downcomer annular gap was 1.27 cm (0.5 in.)
    - 15 times the surface area per unit volume resulted in atypical stored energy release rate causing an atypical "hot wall" delay.
  - The resistance to flow through the core was 100 times too high and it was easier for the coolant to go out the break than into core.
  - Semiscale had only a single loop. Multi-dimensional effects could not be modelled.
- New "volume scaled" tests ranging from 1/30 scale to full scale were conducted throughout the 70's, 80's and early 90's (NUREG-0573, NUREG/IA-0127) **demonstrating the effectiveness of the ECCS and the importance of proper test facility scaling**.



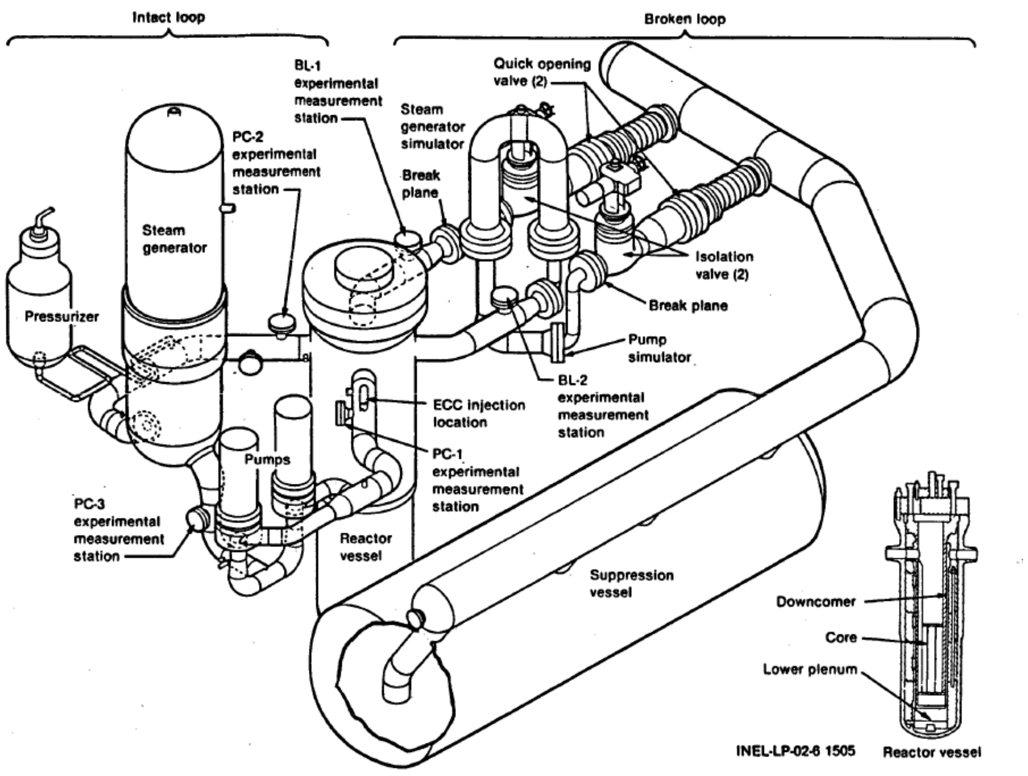
Evolution of Scaling Analysis Methods – Power to Volume Scaling (1970's)

Power to Volume (P/V) Scaling: Each component in the test facility is designed with a reduced fluid volume scaled by the ratio of the test facility power to the power of the prototype. The P/V scaling method was conceived and developed in the LOFT program in the early 1970s. (Reference 4.21).

Advantages:

- For full-height facilities with idealized P/V scaling, the time scale, fluid mass and energy distributions, velocities, accelerations, and lengths are preserved relative to the prototype. Therefore, the volumetric heat generation rates in the core, and the volumetric heat removal rates in the steam generators are preserved.

- *L. J. Ybarrondo et al., "Examination of LOFT Scaling" (74-WA/HT-53) ASME Annual Meeting, New York, NY, November 17-22, 1974*.



Loss of Fluid Test (LOFT) Primary Systems

Evolution of Scaling Analysis Methods - Power to Volume Scaling

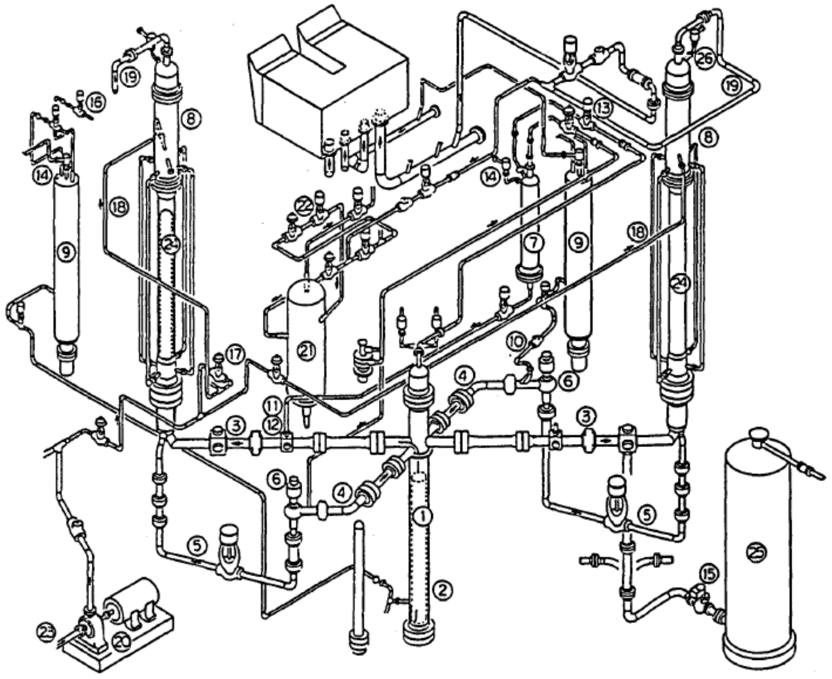
Distortions:

- Cannot simultaneously maintain the length, elevation, area, volume and pressure drop relationships required by strict volume scaling. P/V facilities typically have very large L/D ratios (i.e., tall and skinny).
- Cannot preserve loop piping pressure drops without deviating from strict P/V scaling. Pipe diameters oversized and horizontal lengths shortened to preserve piping hydraulic resistances (and corresponding pressure drop) while maintaining the correctly scaled pipe fluid volume.
- Overly large structural surface area to fluid volume ratio which can cause excessive heat transfer to the fluid or system heat loss depending on the transient type and time into a transient.
- Flow regimes and flow transitions may not be preserved as they are affected by pipe diameter which may be greatly reduced in facilities with very large L/D ratios. (Reference 4.23).
- Similarly, the upper head, the plena (upper and lower) as well as the downcomer in very large L/D facilities will be distorted. The downcomer has a narrow gap and very large surface to volume ratio. These distortions will affect processes such as ECC bypass, mixing, liquid entrainment and de-entrainment in the upper plenum, liquid carry over to the steam generators and steam binding which are important during the refill and reflood period of a large break LOCA.

Evolution of Scaling Analysis Methods - Ishii-Kataoka Scaling (1983)

Ishii-Kataoka Natural Circulation Scaling: Scaling criteria developed for a natural circulation (N/C) loop under single phase and two-phase flow conditions. Not limited to P/V scaling, it offered flexibility in choosing the height scale and time scale depending on forced flow or natural circulation flow.

- Single-Phase N/C: The 1-D, area-averaged, continuity, integral momentum, and energy equations were normalized to obtain the geometrical similarity groups, the friction number, Richardson number, characteristic time constant ratio, Biot number, and the heat source number.
- Two-Phase N/C: For a two-phase flow case, the 1-D drift-flux model was used to obtain the phase change number, subcooling number, drift-flux number, and the friction number.
- After TMI, “rigid” P/V scaling was abandoned to address SBLOCA phenomena. Flow regimes, counter-current flow and critical flow from a small break in a horizontal pipe obey Froude number scaling rather than P/V.
- ROSA-IV in Japan, BETHSY in France, MIST in the US and others, had hot legs and other horizontal components scaled according to Froude number to avoid severe scale distortion effects on T/H processes important to small breaks.
- *M. Ishii and I. Kataoka, "Similarity Analysis and Scaling Criteria for LWR's Under Single-Phase and Two-Phase Natural Circulation,“ Argonne National Laboratory, ANL-83-32, NUREG/CR-3267, March 1983.*



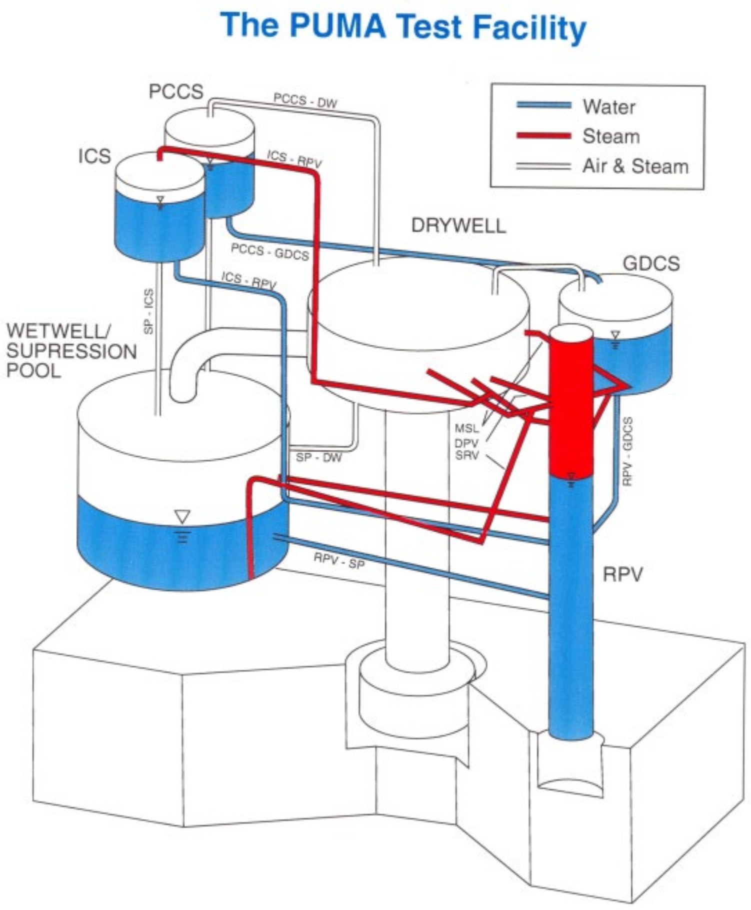
ROSA-IV Test Facility: Full-Height, 1/48 Volume, Power and Flow Areas

Ishii 3-Level Scaling

Ishii 3-Level Scaling: Provides an integrated, tiered approach, for integral system scaling.

- Level 1: Integral System Scaling
- Level 2: Mass and Energy Inventory and Boundary Flow Scaling
- Level 3: Local Phenomena Scaling
- Used to design the PUMA integral system test facility at Purdue University. It simulated a simplified boiling water reactor (SBWR) design. Assessed the performance of passive safety systems and to understand phenomena during LOCAs.
- PUMA is a scaled-down model, 1/4 the height and has components with 1/400 the volume of the actual reactor. It operated at 1/2 time scale and 1/200 power.

- *M. ISHII et al., "Scaling for Integral Simulation of Thermal Hydraulic Phenomena in SBWR During LOCA," Proceedings of Seventh International Meeting on Nuclear Reactor, Thermal Hydraulics (NURETH-7), September 1995, Saratoga Springs, New York, p. 1272*

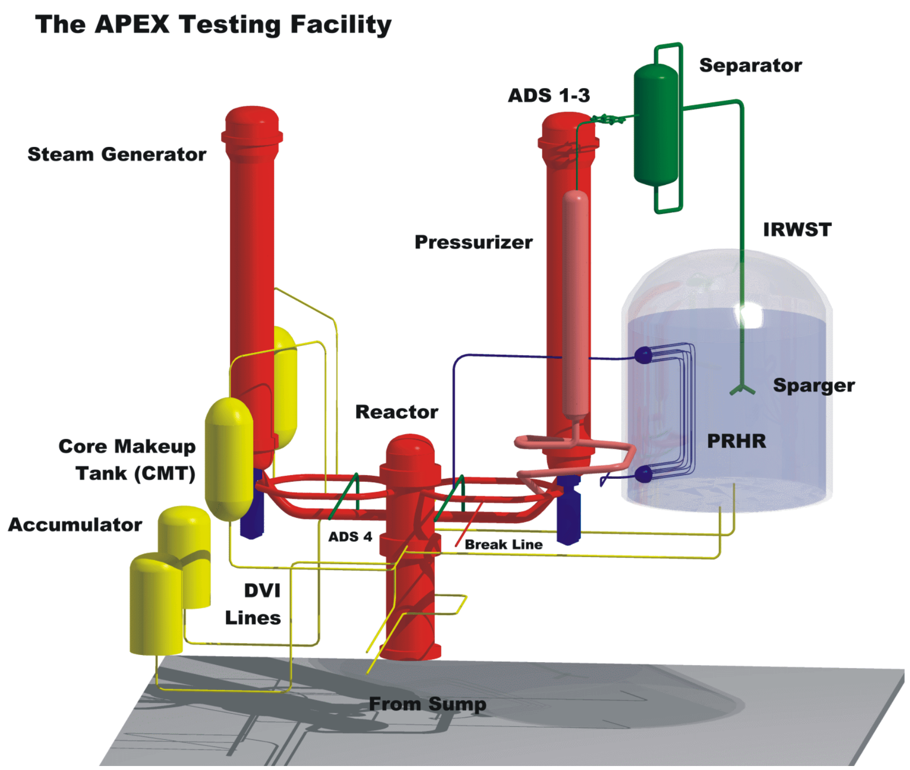


PUMA Test Facility: 1/4 Height, 1/400 Volume, 1/200 Power, 1/2 Time Scale

Hierarchical Two-Tiered Scaling (H2TS) Analysis

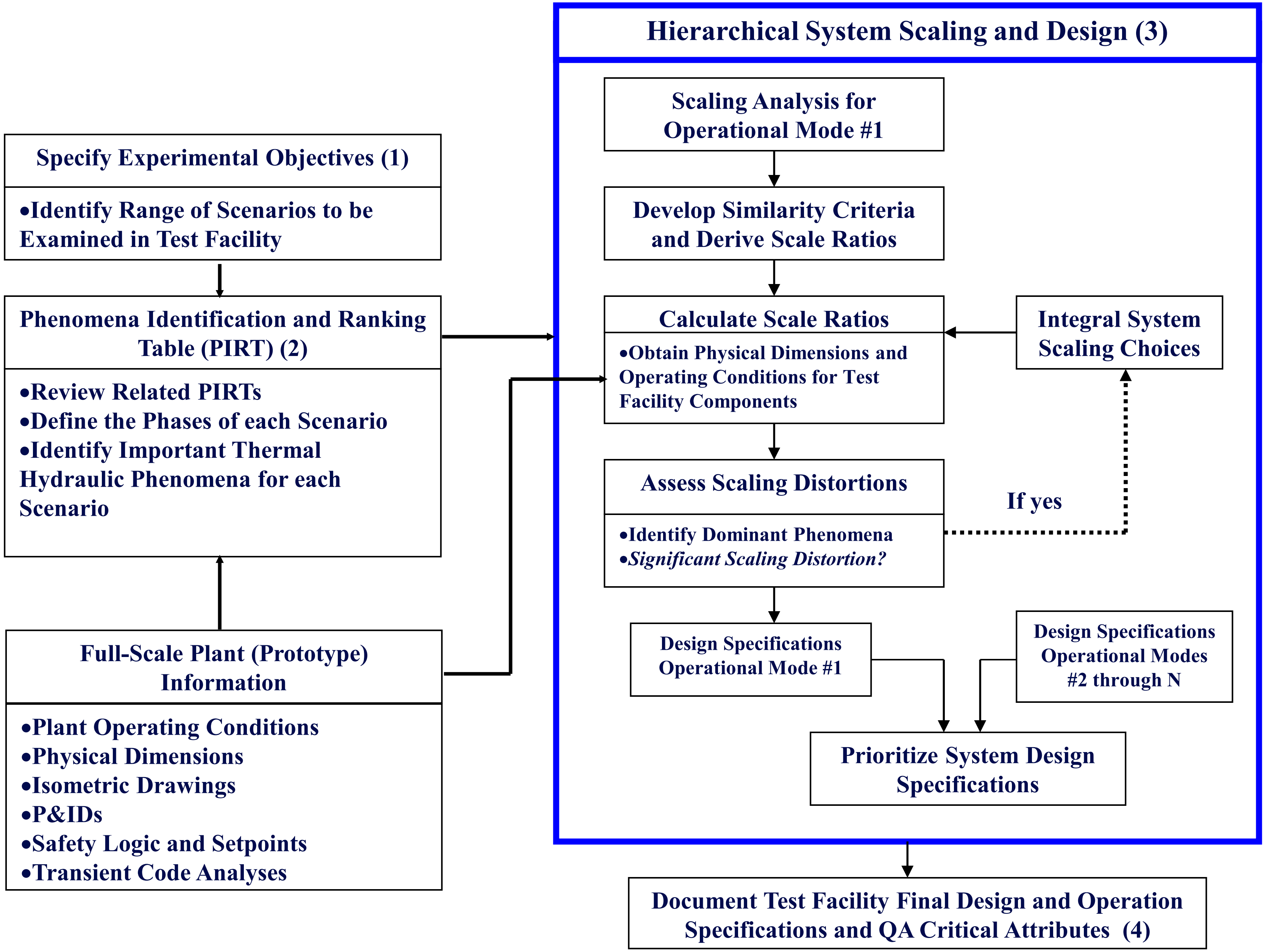
Zuber H2TS: Provides a Hierarchical Top-Down and Bottom-Up scaling analysis method for complex integral systems.

- <u>Top-Down</u> - *System-level analysis,* Analyzes the entire system's transient control equations to derive dimensionless groups (Π-groups) that describe system behavior. Provides a hierarchical framework and scaling criteria for the *system as a whole.*
- <u>Bottom-up</u> - *Phenomena-level analysis,* Identifies and ranks the most important physical phenomena governing the system's behavior. Provides closure for the top-down analysis by focusing on the necessary conditions for the important local phenomena to be scaled correctly.
- <u>Integration</u> - Insures that the scaled test facility can accurately replicate both the overall system response and the “most-important” thermal hydraulic phenomena.
- Used by Reyes to design the APEX test facility to assess AP600 passive safety system behavior and later AP1000 and Palisades nuclear reactor.
- *Zuber, N. 1991. A Hierarchical Two-Tiered Scaling Analysis, Integrated Structure and Scaling Methodology for Severe Accident Technical Issue Resolution, Appendix D. NUREG/CR-5809, USNRC, Washington, DC, USA.*

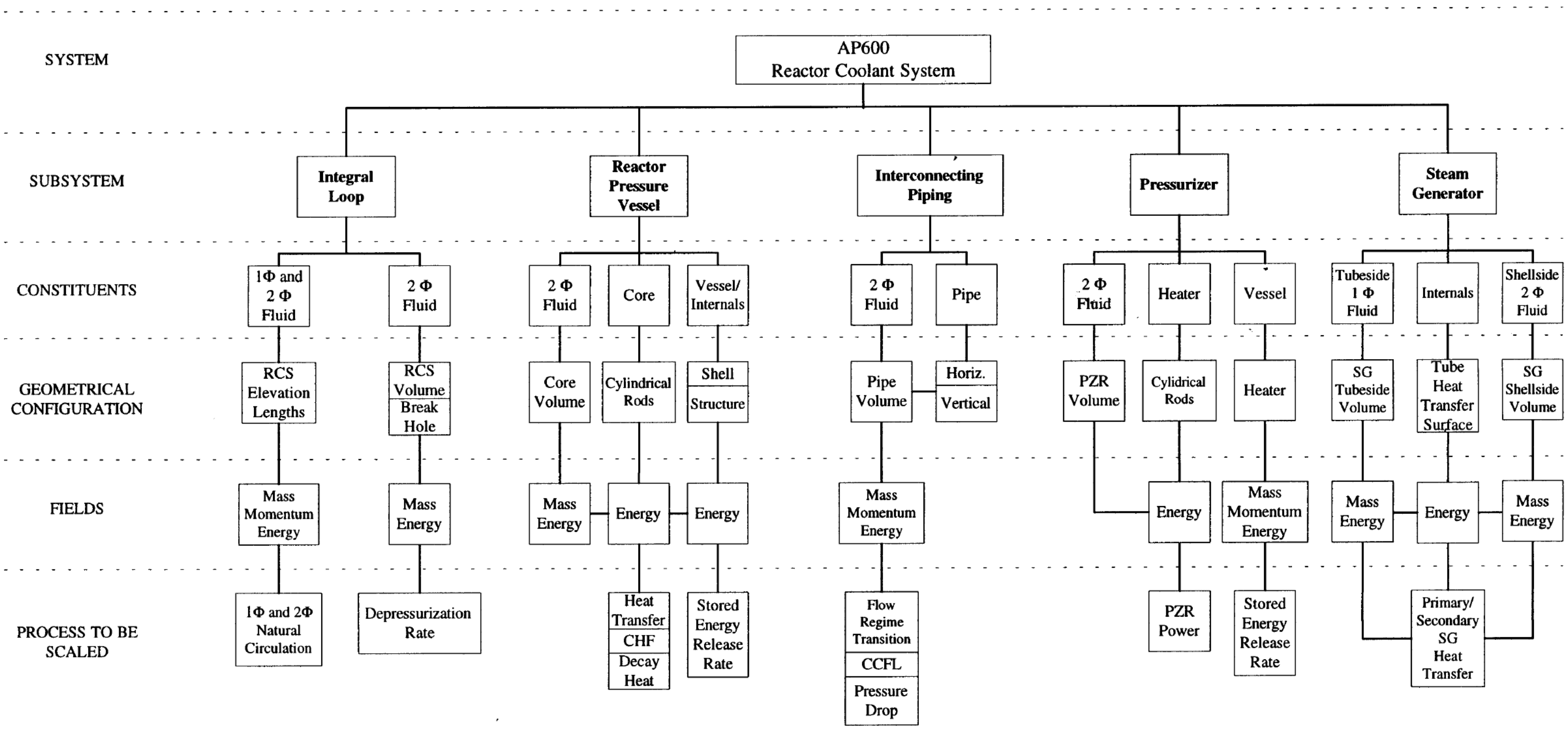


APEX Test Facility: 1/4 Height, 1/250 Volume, 1/2 Time Scale

General Scaling Methodology for APEX



HIERARCHICAL TWO-TIERED SCALING (H2TS) METHODOLOGY
(AP600 System Breakdown)



Fractional Scaling Analysis (FSA)

The Fractional Scaling Analysis (FSA) was formalized by Wulff, Zuber et al. [2005]. The FSA can be viewed as a refinement of the H2TS and it is based on the concept of the Fractional Rate of Change (FRC).

- Extends H2TS to apply to any tier in the hierarchical organization of system, subsystem, components, modules, processes - any level of complexity at which a system needs to be analyzed.
- The quantity of interest to scaling could be a single state variable or an aggregate of state variables. For an aggregate of interacting modules, an "effective" state variable can be defined. The aggregate of state variables expressed by the effective state variable could be acted upon by a single or an aggregate of agents-of-change.
- At each level, FSA identifies the relative importance of the processes involved, then for the most important processes, the FSA is used to determine the distortions following a procedure similar to the H2TS.
- Similarity criteria are derived by comparing the individual process effect metric. The evolution of a time-dependent process in two systems will be similar if the effect metrics are equal.

- *Wulff, W. Zuber, N., Rohatgi, U.S., Catton, I 2005. Application of fractional scaling analysis to loss of coolant accidents (LOCA). Proceedings 11th International Topical Meeting on Nuclear Thermal Hydraulics (NURETH-11), Popes' Palace Conference Center, Avignon, France, October 2-6.*

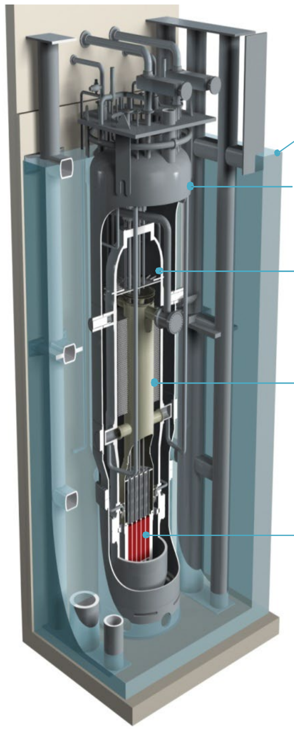
Dynamical System Scaling Analysis (2015)

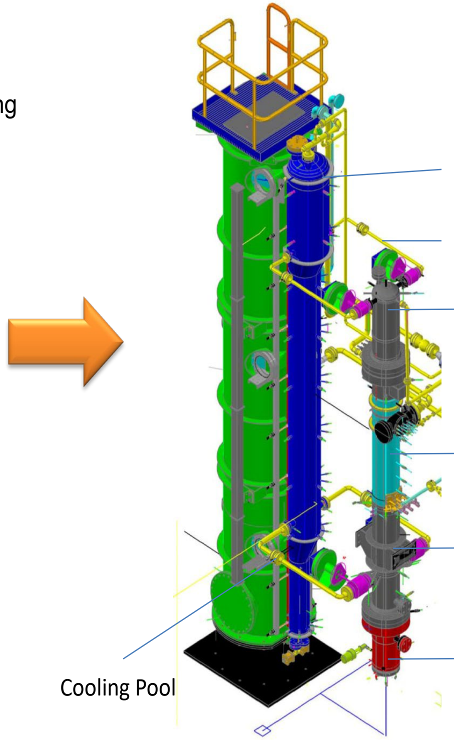
- **Dynamical System Scaling (DSS)** is a method to describe processes as geometric objects (points and curves) in a process "space-time" in which a suitable process metric can be developed, applied, and transformed.
- **Similarity Principle** - Process similarity, as with geometric similarity, can simply be viewed as an invariance of the "process metric" under coordinate transformations.
- NuScale Integral System Tests (NIST) facility designed using H2TS. Supported NuScale design certification.
- DSS used to analyze containment pressurization and mass transport during operation of reactor pressure vessel vent valves.

- *Reyes, J.N. "The Dynamical System Scaling Methodology," Proceedings of the 16th International Topical Meeting on Nuclear Thermal Hydraulics, NURETH-16 Conference, August 30-Sept 4, 2015, Chicago, Illinois.*

Parameter	Equation	Notes
Normalized Conserved Quantity:	$\beta(t) = \frac{1}{\Psi_o} \iiint_V \psi(\vec{x},t)\,dV$	Used to define the state of the system β, ω - a point on the process curve
Normalized Set of Agents of Change:	$\omega(t) = \frac{1}{\Psi_o} \sum_{i=1}^{n} \varphi_i = \sum_{i=1}^{n} \omega_i$	
Dynamical System Balance Equation:	$\frac{d\beta}{dt} = \omega = \sum_{i=1}^{n} \omega_i$	Used to describe the evolution of a process curve in β, ω space
Process Time:	$\tau = \frac{\beta}{\omega}$	Provides the natural time scale for parameterization of process curves
Transformation Law:	$d\tau = (1+D)\,dt$	Relates process time to reference time
Temporal Displacement Rate:	$D = \frac{d\tau - dt}{dt} = -\frac{\beta}{\omega^2}\frac{d\omega}{dt} = -\frac{\beta\ddot{\beta}}{\dot{\beta}^2}$	Ideal process scaling when $D_m = D_p$
	$D = \sum_{i=1}^{N} \Pi_i$	D is equal to the sum of the governing Pi-Groups for a specific process
Process Action:	$\tau_S = \int_{t_1}^{t_2} (1+D)\,dt$	Used to normalize the process coordinates
Normalized Coordinates:	$\tilde{\beta} = \beta;\ \tilde{\Omega} = \omega\tau_s;\ \tilde{t} = t/\tau_s;\ \tilde{\tau} = \tau/\tau_s$	Used to describe process curves in dimensionless phase space $\tilde{\beta}(\tilde{\tau}), \tilde{\Omega}(\tilde{\tau})$
Normalized Metric:	$d\tilde{\tau}^2 = \frac{(1+D)}{\tilde{\Omega}^2}\left[d\beta^2 + \frac{\beta^2}{D\tilde{\Omega}^2}d\tilde{\Omega}^2\right]$	Determines distances between points on normalized process curves to measure time-dependent distortion

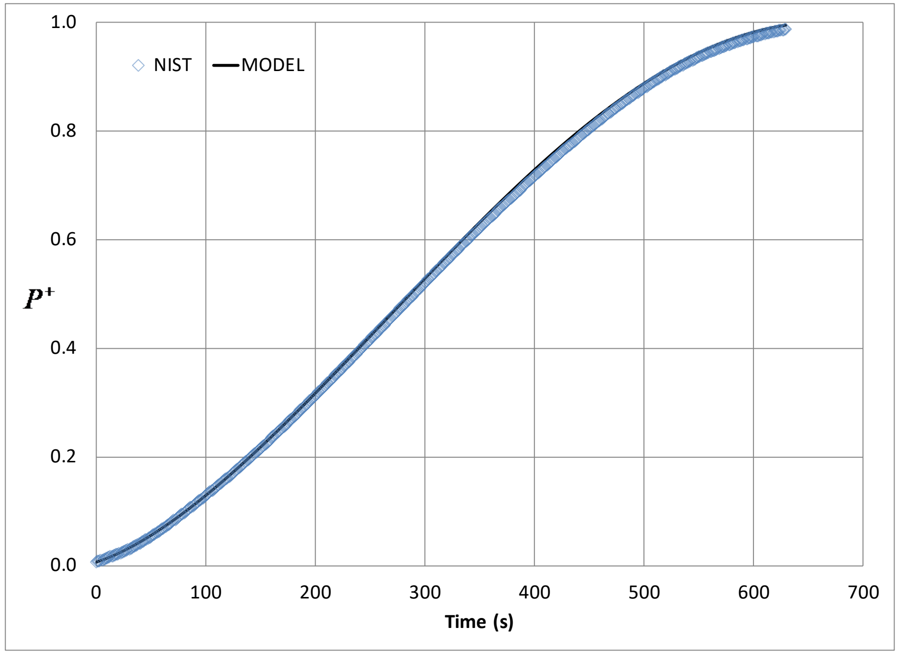
Semi-Empirical Model Comparison to NIST Data





NIST Test Facility: 1/3 Height, 1/253 Volume, 1:1 Time Scale

CNV Pressure

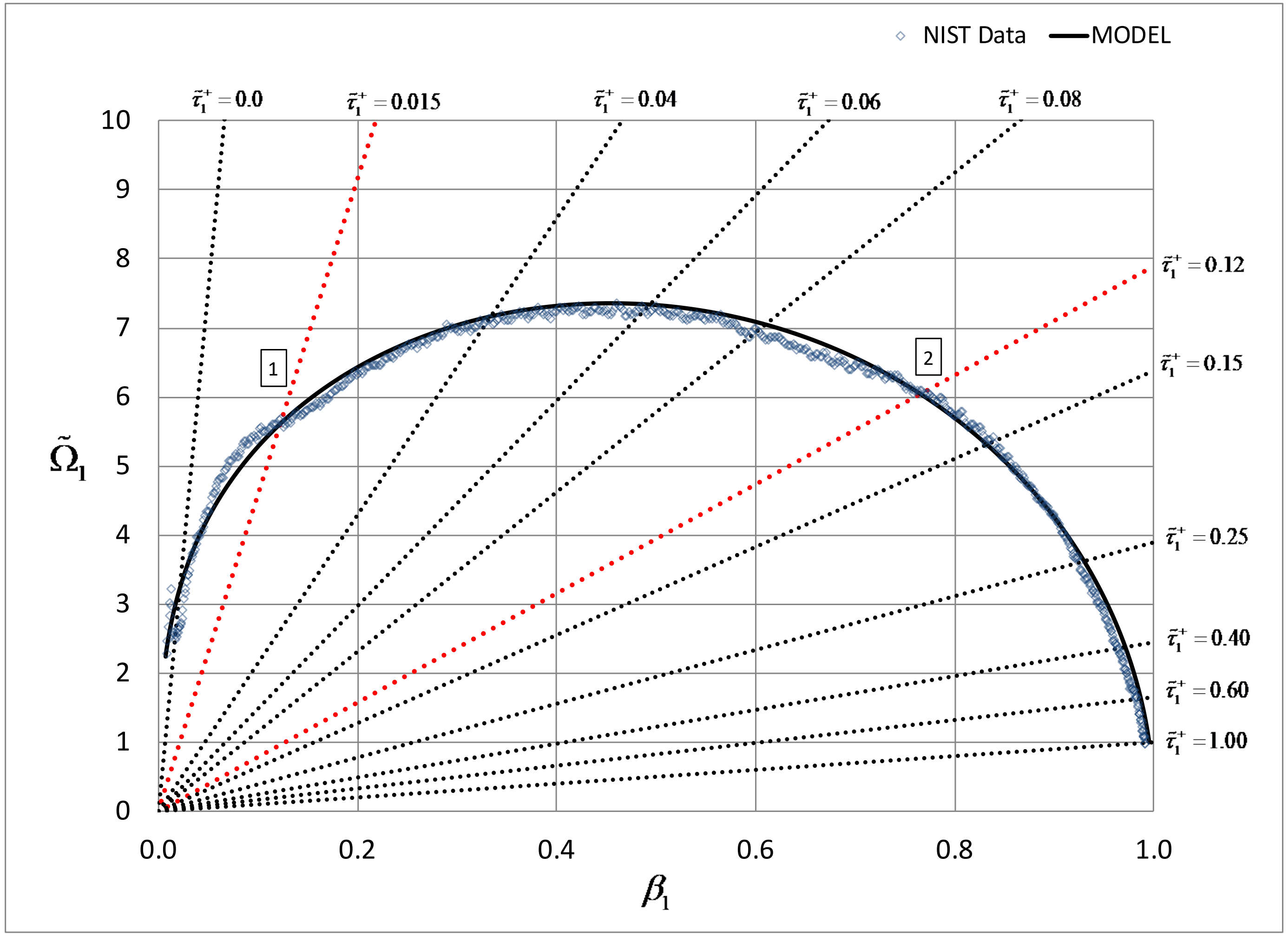


- **Pressurization due to reactor venting into containment (CNV) is a coupled mass and energy transport problem.**
- **The model comparison to data is very good.**
- **However, DSS approach is able to pick up subtle differences in local rates of change**

DSS Comparison of Model to Data

CNV Pressure - Normalized Coordinates

- Comparing the CNV pressurization data and the model predictions in dimensionless phase space $\beta_1 \tilde{\Omega}_1$ yields insights into the pressurization process. Where β_1 is the normalized CNV pressure and $\tilde{\Omega}_1 = \omega_1 \tau_s$ is the normalized pressurization rate, and τ_s is the process action.
- The inflection at point [1] is due to the transition from choked flow to unchoked flow.
- The inflection at point [2] identifies the transition to the minimum pressure difference between the CNV and the RPV. After this point the CNV and RPV pressures become tightly coupled and follow the same long-term cooling trend.



Scaling Methods in US Regulation

The Role of Scaling as Part of EMDAP (RG 1.203)

Evaluation Model Development and Assessment Process (EMDAP)

- ***Element 2, Development Assessment Base***
  - Step 6 - Perform scaling analysis and identify similarity criteria for IET/SET.
  - Step 8 - Evaluate effects of IET distortions and SET scale-up capability
- ***Element 4 – Assess Evaluation Model Adequacy***
  - Step 15 – Assess scalability of models.
  - Step 19 – Assess scalability of integrated calculations and data for distortions.

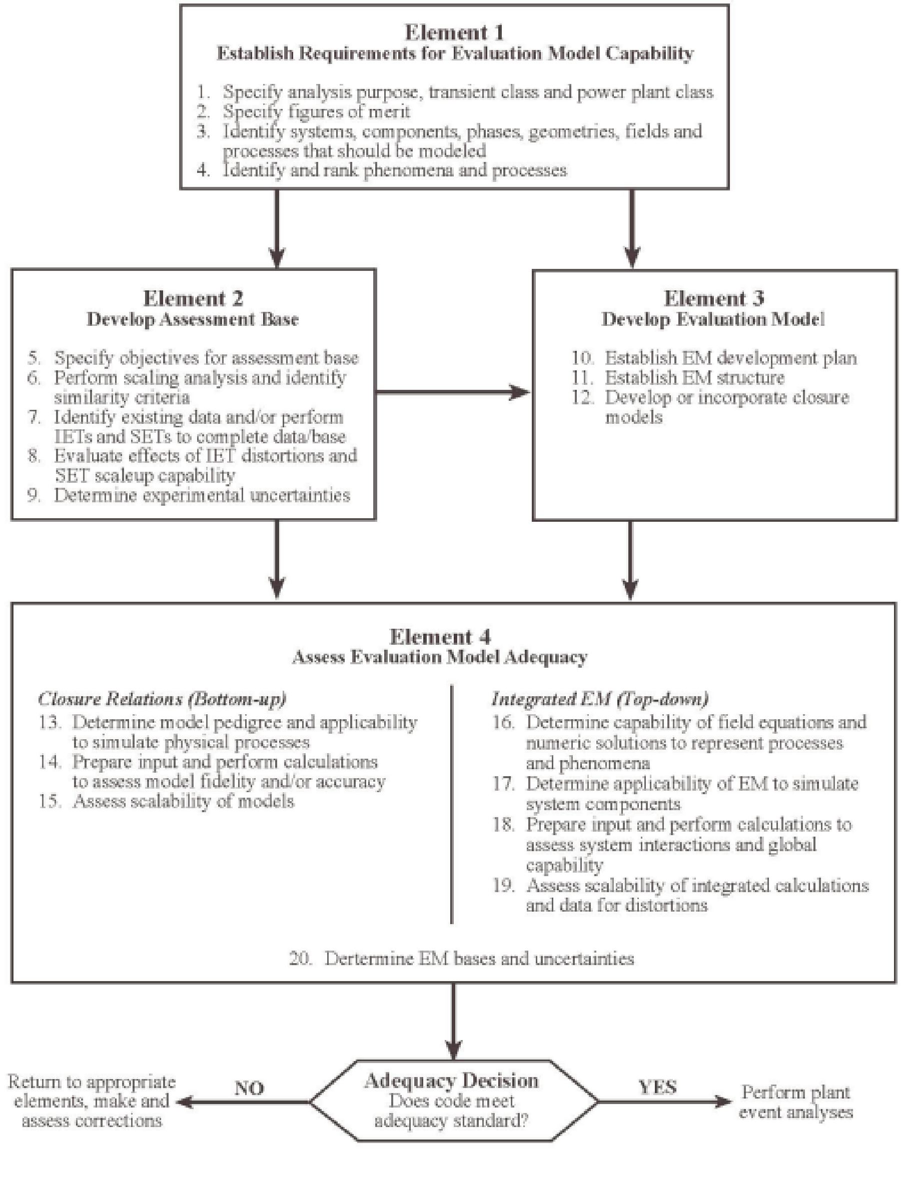


Figure 1. Elements of Evaluation Model Development and Assessment Process (EMDAP)

US SMR Vendors are Developing their Test Facilities

Nuclear Scaling and Application Workshop (NuSAW)

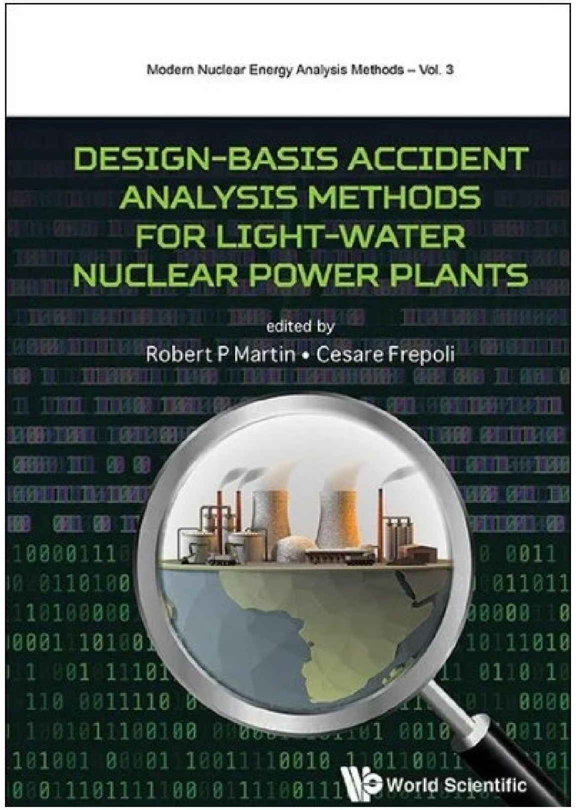
- A nuclear thermal hydraulic scaling specialist workshop was held at Oregon State University on August 1-3, 2023.
- Attended by ~35 participants
    - Westinghouse
    - NuScale Power
    - Kairos Power
    - TerraPower
    - X-Energy
    - Holtec SMR
    - NRC
    - INL
    - LANL
    - U-Michigan
    - UC Berkley
    - OSU
- The workshop offered an excellent opportunity to share research, insights, and perspectives with a diverse audience of professionals with a common interest in applying scaling analysis to their research fields.

Organizers: Professors Trevor Kent Howard, Qiao Wu
Honorary Chairman: Jose Reyes, Professor Emeritus

Value of having a Nuclear Scaling Analysis Community of Practice

Promote safety of nuclear power by:

- Developing state-of-the-art methods for performing separate effects and integral system scaling analyses.
- Validating new designs and safety analysis codes using data from well-scaled test facilities.
- Assuring scaling analysis knowledge transfer to the next generation of engineer and scientist.



Dr. José N. Reyes, Jr.

•••

Chief Technology Officer and Co-founder

•••

JReyes@NuScalePower.com

Acknowledgement and Disclaimer

This material is based upon work supported by the Department of Energy under Award Number DE-NE0008928.

This presentation was prepared as an account of work sponsored by an agency of the United States (U.S.) Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.