Using the Scaling Equations to Define Experimental Matrices for Software Validation

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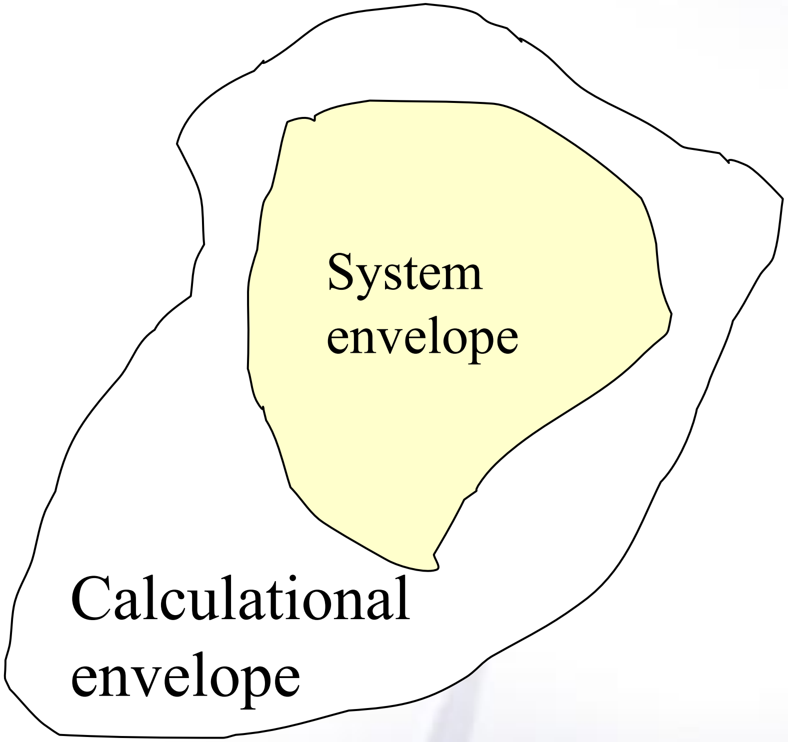
V&V30 Standards Committee

Presentation Content…

- ***Description of problem***
- ***System and numerical model calculational envelopes***
- ***Process***
- ***Importance of validation data from scaled facilities***
- ***Scaling methodologies***
- ***Observations***

Analysis Needs: Licensing Nuclear Systems…

- ***The Evaluation Model is the set of numerical models used to calculate the behavior of a reactor system for steady-state and transient scenarios.***
- ***The needs are set by the operational and accident envelopes of the system.***
- ***Can only be satisfied if calculational envelope of the numeric models is demonstrated to either match or encompass the system operational and accident envelopes.***



Calculational envelope =

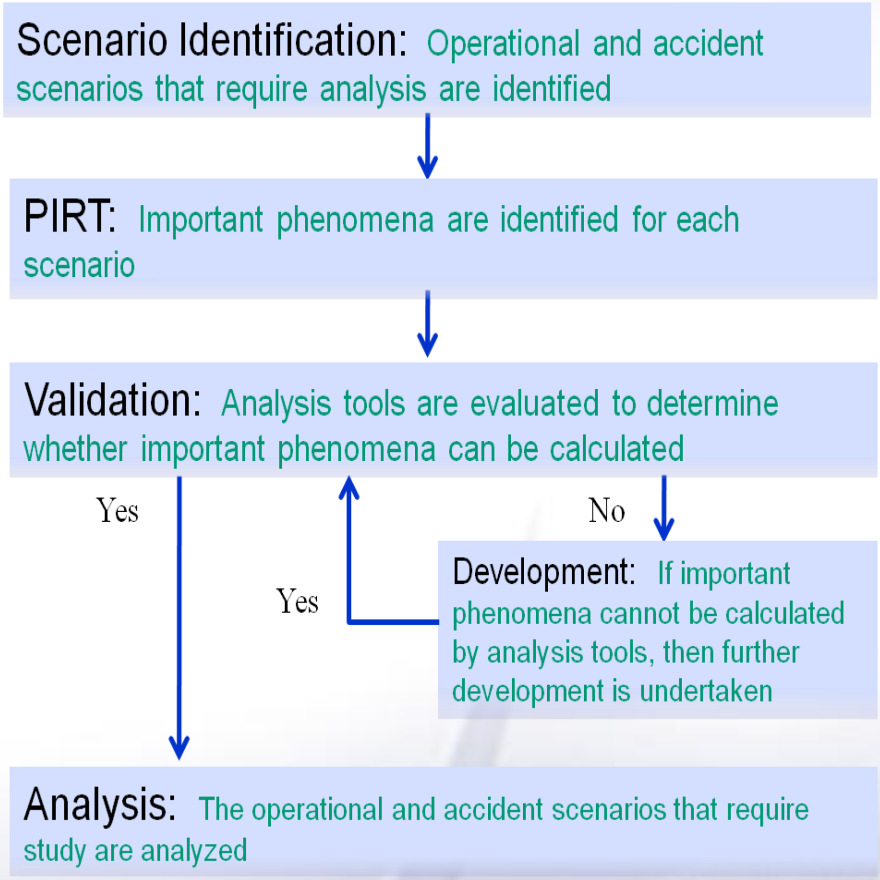
Domain of qualification

Numeric Model Calculational Envelope…

- ***Defined by physics in software***
- ***Confirmation that software physics models properly calculate the key phenomena (verification and validation [V&V])***
- ***Successful V&V can only be achieved if an adequate, high-fidelity data matrix and/or exact analytical solution set are available to benchmark the calculational results***

Validation of Numeric Models Focuses on Key Phenomena for Selected Scenarios…

- ***Validation must show numerics models capable of calculating ALL key phenomena with reasonable agreement to experimentally-generated validation data***
- ***Therefore, data are required for all key phenomena***
- ***The data are the standard used to determine whether additional development are required.***
- ***Once the numerics models are validated, analysis of the plant behavior may proceed.***
- ***Hence defining the experimental matrix and designing the experiments to achieve these objectives is crucial.***



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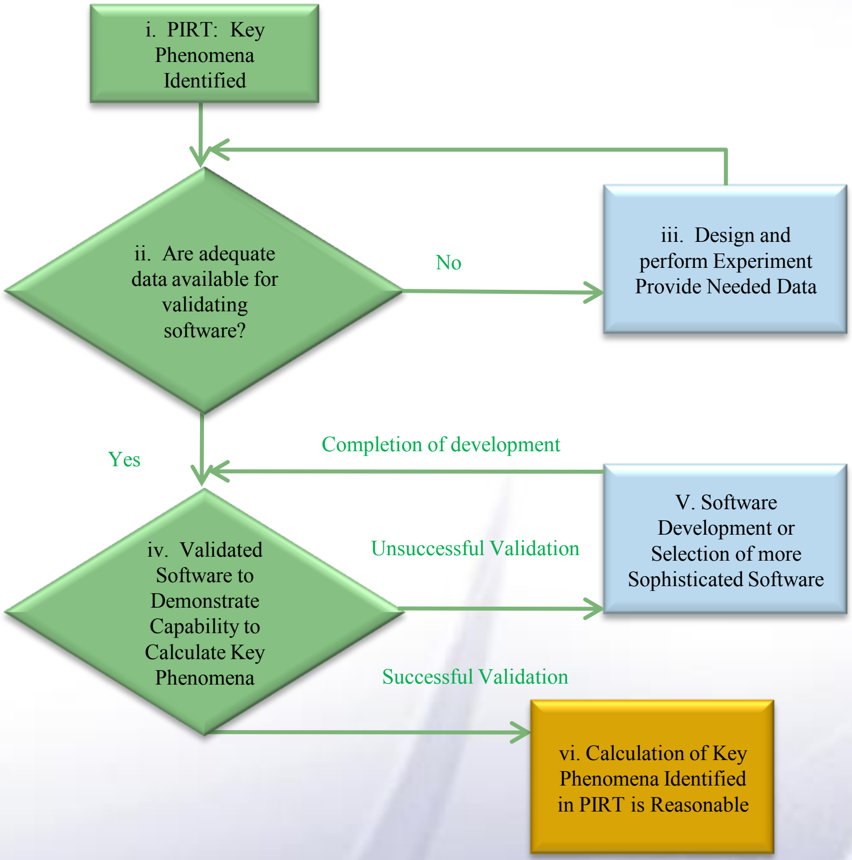
Fulfilling Data Needs…

- Experiments designed and performed must provide adequate data to perform validation calculations
- Data sometimes available in literature
- Some data may be available from international partners
- Balance of data needs must be obtained by designing and performing experiments



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Experiments Using Scaled Systems…

- ***To license a nuclear plant, the licensee must show that the plant will not violate the requirements imposed by the regulatory agencies.***
- ***Some scenarios which must be considered preclude testing the full-scale system at the scenario conditions, e.g.:***
  - ***Design basis events (DBEs)***
  - ***Beyond design basis events (BDBEs)***
- ***Scaled experiments designed and built specifically to generate data to validate numeric models these scenarios are very important.***

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Experiment Design (1)…

- *All experiments should be scaled to the prototype plant using an accepted approach.*
- *Most of the defining work is based on the needs set by light water reactor licensing requirements—and thus consider two-phase steam-water systems at state conditions ranging from 17 MPa to atmospheric pressure, subcooled to slightly superheated temperature conditions with depressurization time scales determined by critical mass fluxes and the defined leak size.*
- *The traditional scaling approach is based on achieving the same power/volume ratio as the prototype with selected parameters designed to be equivalent which are dependent on the scenario under investigation. For slow depressurization rates, other key ingredients are consideration of $[gD]^{1/2}$ to give scaled flow regime transitions in horizontal piping.*

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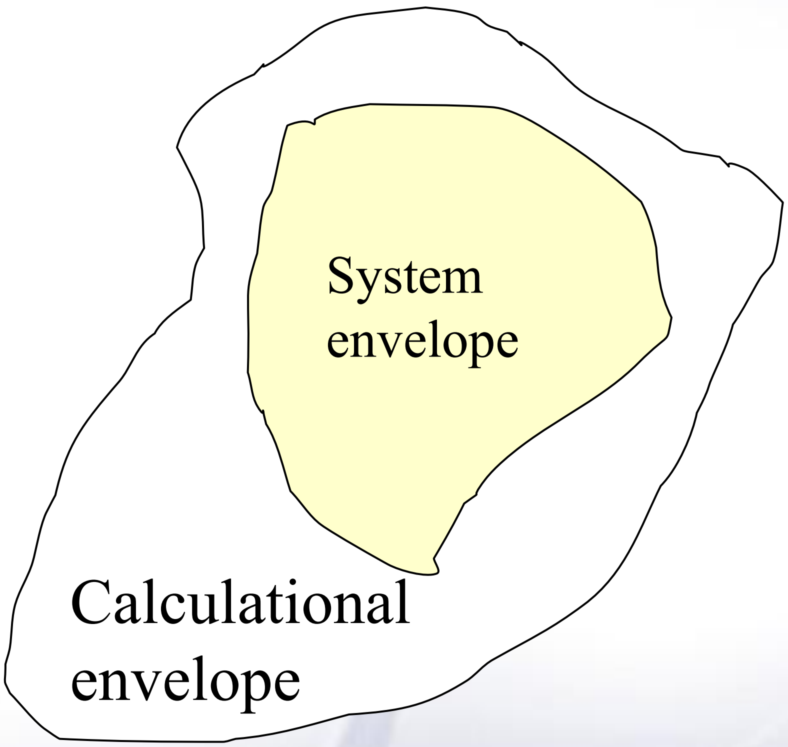
Experiment Design (2)…

- ***Power/volume scaling—preserves:***
  - ***Vertical dimensions***
  - ***Time***
  - ***Velocity***
  - ***Heat generation in the flow direction—including phenomena associated with heat transfer, e.g., flashing, evaporation, and condensation***
- ***Examples of experiments using this type of scaling approach have been constructed and used.***



Experiment Design (3)…

- ***Component experiments generally designed to be "as-large" as practical*.***
  - ***Components such as fuel assemblies are usually tested at full scale.***
  - ***Experience has demonstrated that other components may be scaled successfully if around 1/3-scale.***
  - ***Experiments should be designed at various scales so their data may be compared; if the experiments are well scaled then the data sets from two or more facilities should complement one another and show reasonable agreement.***
  - ***"Stream-tube approach" is used, i.e., facility designed to duplicate a portion of the prototypical system flow within a stream-tube. In the prototype the stream-tube does not have solid walls—but in the scaled facility there are solid walls.***

****Discussion on LBLOCA, including PIRT rankings taken from:***
Levy, S., 1999, Two-Phase Flow in Complex Systems, Wiley-Interscience

Scaling Isolates Key Nondimensional Quantities

- ***Key variables that have significant contributions are isolated using the non-dimensionalized scaling equations derived from transport equations.***
- ***For operational and off-normal system envelopes.***
- ***This approach yields guidance for both experimental design and the specification of data point frequency for experiment.***

$$q^* = \Pi_{core,NC} = q''_0 L / \rho_{c,0} w_{c,0} \bar{C}p - loop)_0 (\bar{T}_c - \bar{T}_{sc})_0$$

$$where,\ w_{c,0} = \left(\frac{\beta g \dot{q}_c L}{\bar{\rho}_c a_c \bar{C}_{p-c} \Pi_F}\right)^{1/3}$$

$$T^* = \frac{T - T_{LP,0}}{T_{UP,0} - T_{LP,0}}$$

$$X^* = X / L$$

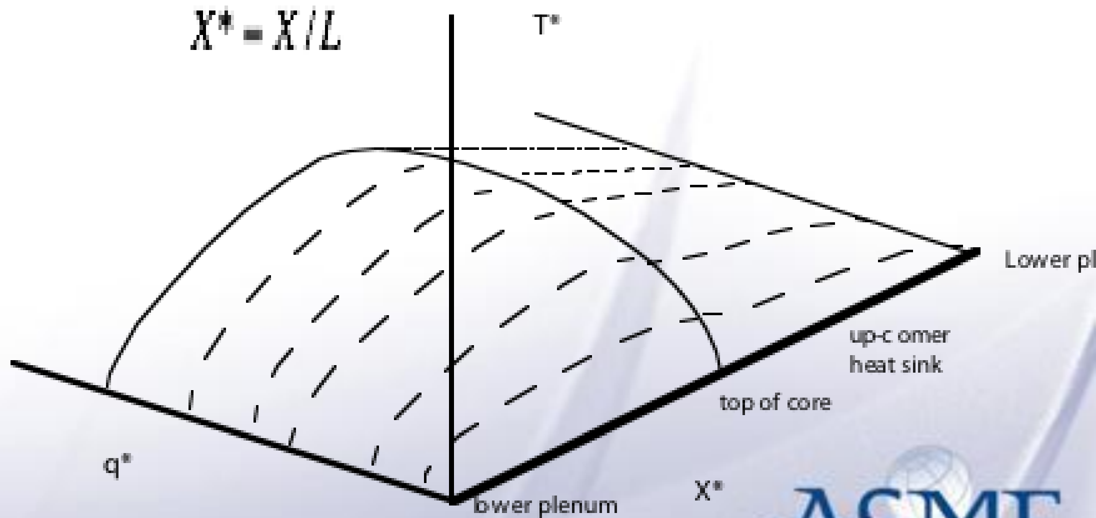
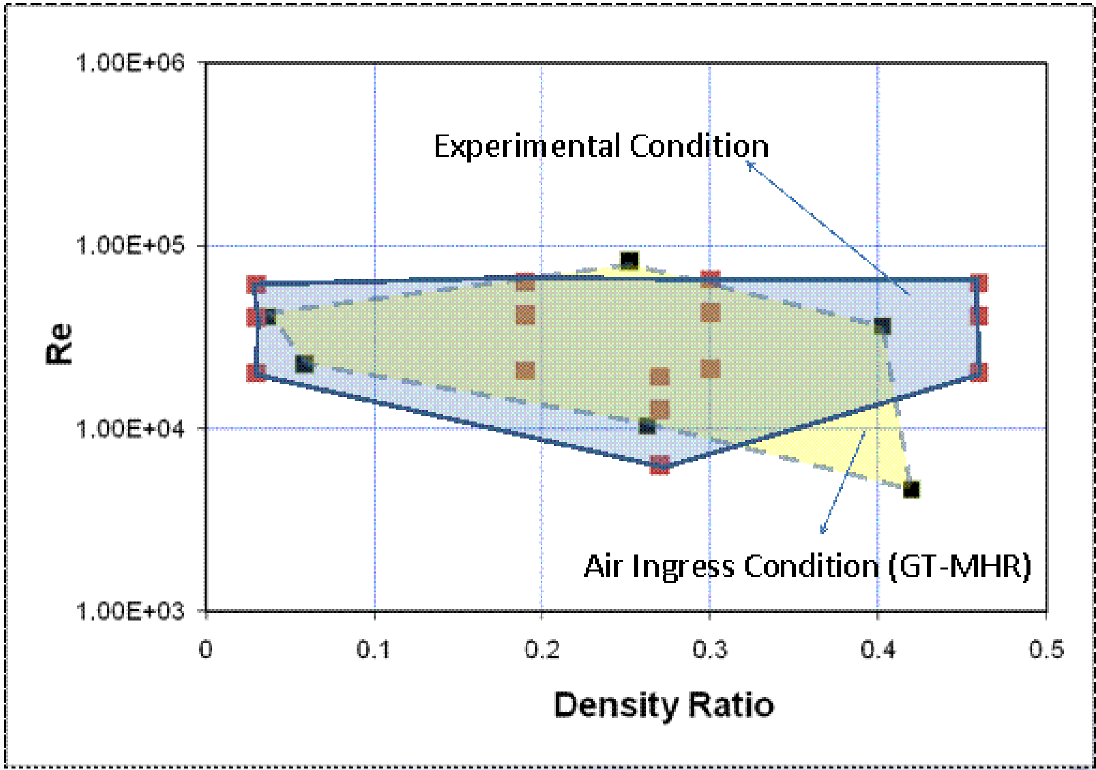


Figure courtesy of Glenn McCreery, Ph.D.

So Experiment Design Must Be Quite Rigorous…

- *Designed to capture key phenomena*
- *Scaled to provide direct link between subscaled experimental facility and prototypical plant*
- *Low, quantified uncertainties*
- *Experiment design should consider decomposition of behavior in system component to lowest level that can be modeled by software to ensure each component is properly being calculated by software physics*



Courtesy C. Oh

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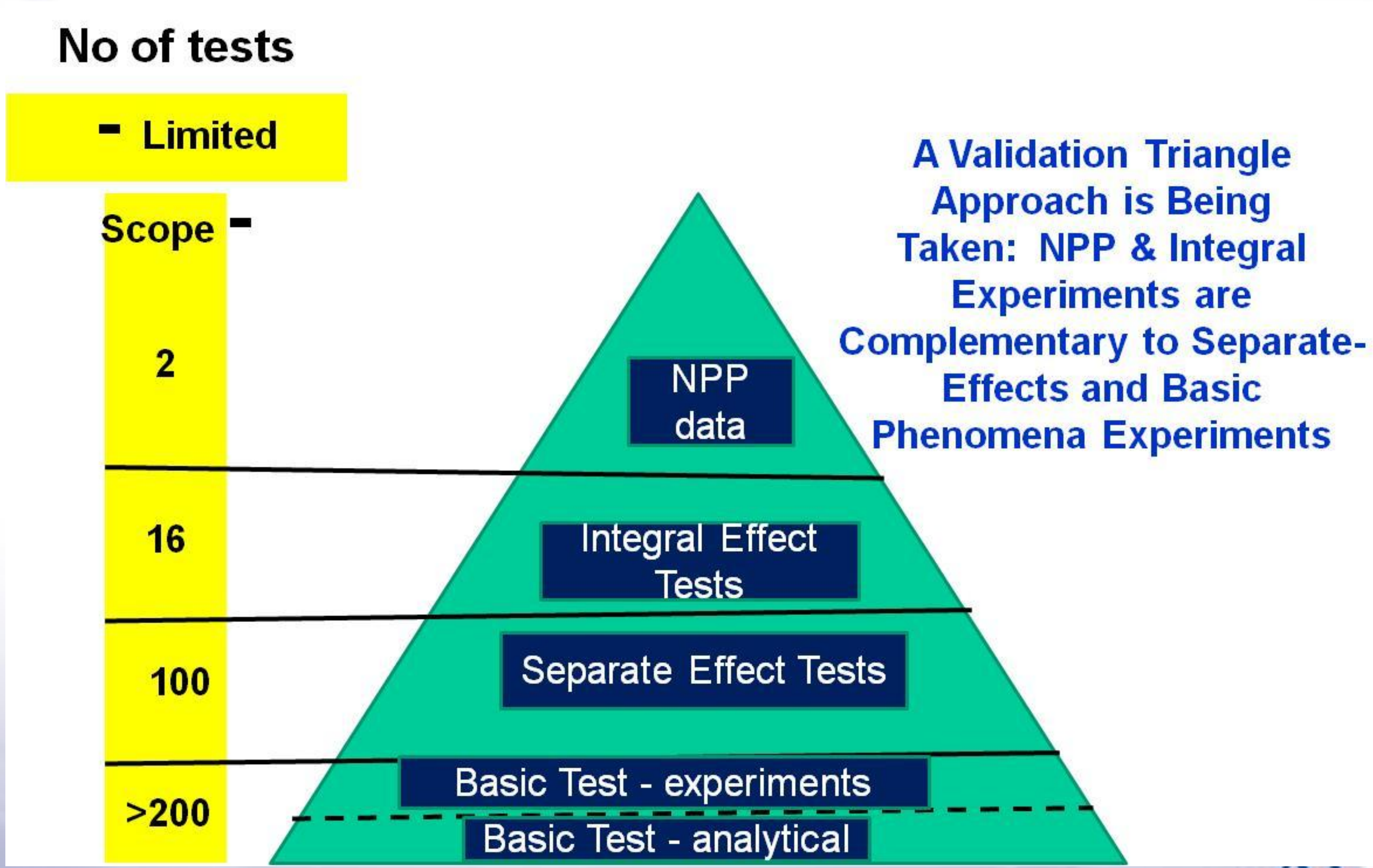
Validation is an In-Depth Activity…



Experiment Design (4)…

- *In the early 90s an alternate approach for scaling was developed by Zuber: the Hierarchical Two-Tiered Scaling (H2TS) Methodology. Zuber's H2TS methodology has been used as the basis for:*
  - *Reduced height, reduced pressure facilities*
  - *That is, facilities used to simulate even SBLOCAs using less than full-height at operating pressures substantially less than prototypical pressures.*
  - *Timing is not preserved.*
- *Experiments have been constructed using this scaling approach—especially at universities*

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Experiment Design (5)…

- ***As stated in Levy, 1999, Zuber's objectives in formulating the H2TS methodology were to:***
  - ***Have a method that is systematic, auditable, and traceable***
  - ***Develop a scaling rationale and similarity criteria***
  - ***Assure that important processes have been identified and addressed properly and provide a means for prioritizing and selecting processes to be addressed experimentally***
  - ***Create specifications for test facilities design and operation (test matrix, test initial and boundary conditions) and provide a procedure for conducting comprehensive reviews of facility design, test conditions, and results***
  - ***Assure the prototypicality of experimental data for important processes and quantify biases due to scale distortions or to nonprototypical test conditions***

Ref: (a) Zuber, N., 1991, An Integrated Structure and Scaling Methodology for Severe Accident Technical Issue Resolution, NUREG/CR-5809, November, Appendix D-A, "Hierarchical, Two-Tiered Scaling Analysis."

(b) Discussion on H2T@ taken from: Levy, S., 1999, Two-Phase Flow in Complex Systems, John Wiley & Sons

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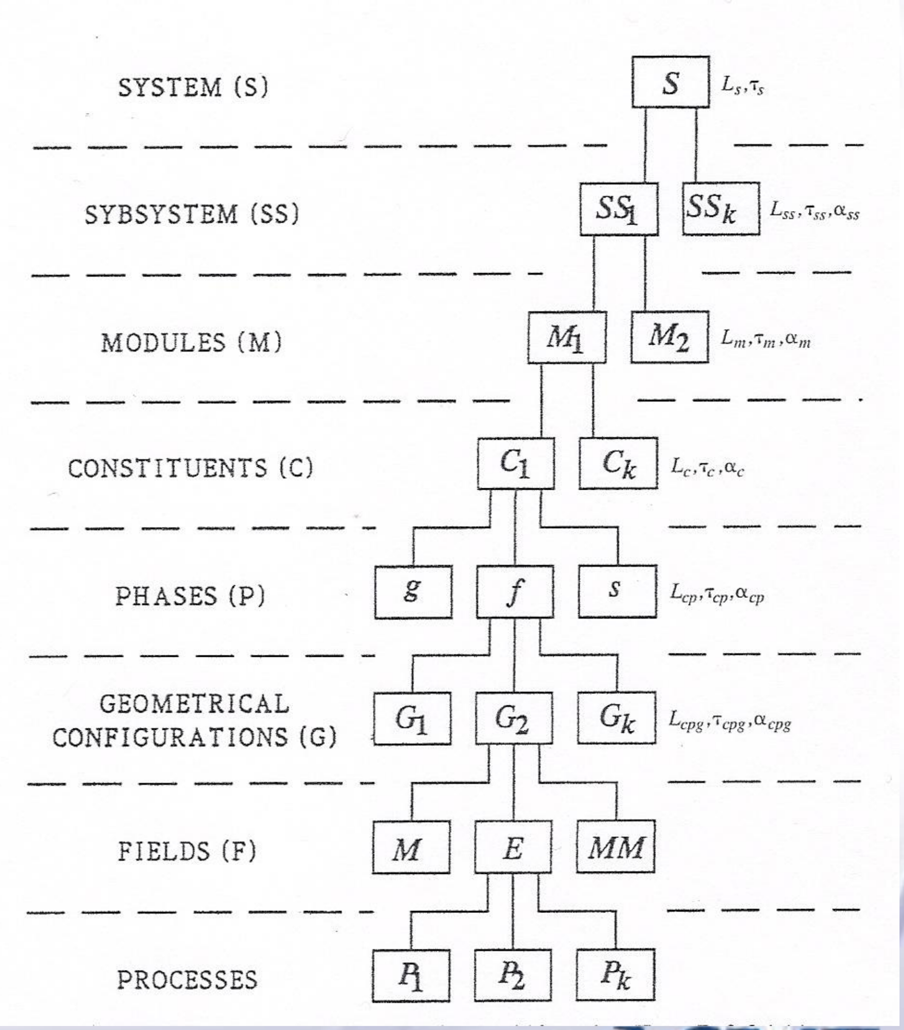
Zuber's H2TS Scaling Methodology (1)…

- ***Decomposes and organizes the system***
  - ***Starting with the whole system***
  - ***Working downward through subsystems, components, until reaching the transfer processes***
- ***Scale measures are assigned at each level.***
- ***Lowest level transfer processes characterized by rate of transfer—a temporal scale and transfer area (spatial scale)***



Zuber's H2TS Scaling Methodology (2)…

- ***A volume fraction also used to account for other constituents such as phases and/or geometries.***
- ***The applicable temporal, spatial, and volume fractions are identified for each level.***
- ***At the phase level the possibility of any state is accounted for, e.g., vapor, liquid, etc***

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Summary…

- ***A rigorous process is used to design experiments that will provide validation data for systems analysis numerical models.***
- ***Traditionally a form of power-to-volume scaling has been used for designing LWR-validation experiments.***
- ***For Generation III+ and Generation IV systems Zuber's H2TS scaling methodology is more commonly used.***
- ***Experiments built to create experimental data matrix that is the foundation of numeric model validation matrix.***

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