FLASHback: RELAP at Fifty
(RELAP5-3D Commercial Grade Dedication at BWXT)

R. P. Martin, Methods Lead
BWX Technologies, Inc.
MMMMM DD, YYY

Outline

- Commercial Grade Dedication process for RELAP5-3D
- V&V process for RELAP5-3D per Regulatory Guide 1.203, Transient and Accident Analysis
- “FLASH” Model Genesis
- Benchmarks/Sensitivity Studies
- Conclusions

Software Quality Assurance References

- U.S. Regulations
  - 10 CFR 50, Appendix B, Criterion III, Design Control, and Criterion VII, Control of Purchased Products and Services
  - 10 CFR 21, requires that a commercial-grade item be “dedicated” – a point-in-time when the item is subject to reporting requirements
  - RG 1.203, “Transient and Accident Analysis”
  - DG-1305, “Acceptance Of Commercial-grade Design And Analysis Computer Programs For Nuclear Power Plants”
- Industry Guidance
  - ASME NQA-1
  - EPRI NP-5652, “Guideline for the Acceptance of Commercial-Grade Items in Nuclear Safety-Related Applications”
  - EPRI 1025243, “Guideline for the Acceptance of Commercial-Grade Design and Analysis Computer Programs Used in Nuclear Safety-Related Applications”

Commercial Grade Dedication

- Acceptance vs. Design
  - Acceptance of computer programs is the process of verifying critical characteristics
    - Method 1 – Inspections, tests, or analyses
    - Method 2 – Commercial grade surveys
    - Method 3 – Product inspections at manufacturer facility
    - Method 4 – Evaluation of historical performance
- Technical Evaluation
  - Identification of the safety function(s)
  - A failure modes and effects analysis (FMEA)
  - Identification of critical characteristics
  - Establishing acceptance criteria for each critical characteristic
  - Identification of the acceptance methods
  - Document

EPRI 1025243 – Critical Characteristics

Critical Characteristic	Acceptance Method	Acceptance Criteria
Physical: Physical media and contents provided for software installation	Method 1	Installation files must match preexisting software requirements and specification
Identification: Computer program name and version	Method 1	Program name(s) and version(s) from the INL-provided product list must align with preexisting software requirements.
Identification: Host computing environment	Method 1	RELAP5-3D is provided for compiling and executing under a UNIX, LINUX, or Windows operating system using Intel-based or Intel-compatible chip set. Host operating environment identifiers must be compatible with product specifications.
Performance / Functionality: Completeness and consistency	Method 1	Installation files must match preexisting software requirements and design specifications.
Performance / Functionality: Applicability and correctness	Method 1	Applicability is derived from application-specific phenomena identification and ranking table(s) (PIRT) conclusions matched against a qualitative code assessment. Correctness is based on verification that the documentation addressing the models and correlations associated with the PIRT conclusions align with the source code translation.
Performance / Functionality: Accuracy of output (Correlation between the expected and desired outcome)	Method 1	The collective assessment from a sample of well characterized problems from the INL's Developmental Assessment suite is expected to demonstrate a high standard of accuracy, consistent with criteria appearing in RG 1.203.

EPRI 1025243 – Critical Characteristics

Critical Characteristic	Acceptance Method	Acceptance Criteria
Dependability: Built-In Quality – Adherence to coding practices	Method 1 & 4	Coding practice applied by the INL is expected to be compatible with ASME NQA-1 expectations.
Dependability: Built-In Quality – Code Structure (complexity, conciseness)	Method 1 & 4	RELAP5-3D code structure is expected to demonstrate logical organization and hierarchy of data and data processing.
Dependability: Independent reviews & verifications	Method 1	Documented record of independent review demonstrates continuous improvement
Dependability: Testability & thoroughness of testing	Method 1 & 4	Per RG 1.203, for more important phenomena, constitutive model fidelity shall be within the accuracy of the validation data; however, if this is not possible, acceptance is allowable under conditions that account for modeling uncertainties in safety-related applications.
Dependability: Error Reporting and Notifications to Customers	Method 1	RELAP5-3D vendor is expected to practice a policy for user notification of user problems, errors and changes.
Dependability: Support and maintenance	Method 1 & 4	RELAP5-3D vendor is expected to be actively maintaining RELAP5-3D and guarantee limited user support
Documentation	Method 1 & 4	Code Manuals must accompany the provided RELAP5-3D product and adequately describe the software, provide traceability from theory to source code to code use, and guide users through model development and applications.

CGD Acceptance Documentation

Document Name	Document Description
10 CFR 830, Subpart A	DOE QA requirements
DOE O 414.1C	DOE QA guidance implementing 10 CFR 830
INL Software Quality Assurance	Laboratory software quality plan (Align with DOE O 414.1C/D and NQA-1-2008)
RELAP5-3D Development Software Management	Vendor software quality plan
RELAP5-3D Development Software Configuration Management Plan	Vendor software quality plan
RELAP5-3D Code Manuals: Volume 1-5	Vendor software manual
RELAP5-3D Developer Guidelines and Programming Practices	Vendor software manual
RELAP5-3D Software Requirements Specification	BWXT software requirements
RELAP5-3D Software Design Specification	BWXT subroutine map and summary
Critical Characteristic, FMEA, and Installation of RELAP5-3D	BWXT critical characteristics verification
RELAP5-3D Software Quality Assurance Summary Report	BWXT/Vendor document supporting critical characteristics verification

Failure Modes and Effects Analysis

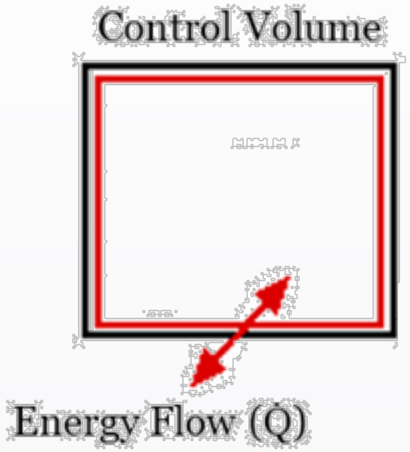
#	Failure	Prevention Action	Mitigation Action
1.	Product handling error (interface error)	**Accompanying documentation identifies desired product. Purchaser perform technical and legal verification.**	**Document receipt that confirms correctness of delivery.**
2.	Erroneous software input (interface error)	Erroneous code input relates to the correctness and handling of the design inputs used to create software input. **Design inputs are the responsibility of the purchasing organization**	Quality program measures mandate actions for reporting, correcting, and verifying remediation. **Design inputs are the responsibility of the purchasing organization**
3.	Improper software input preparation/ incomplete software input (interface error)	Incomplete or improper software input is addressed through **vendor-supplied code documentation and application-specific guidelines**	Incomplete or improper software input is addressed through **vendor-supplied code documentation and application-specific**
4.	Results sufficiency (conceptual error)	Conceptual errors are those resulting from computer program usage outside its intended range or when the computer program is syntactically correct, but the programmer or designer intended it to do something else. **Provided documentation and its automated input checking feature informs the user of limitations.**	Sufficiency of software output depends on the application criteria. **RG 1.203 documents the evaluation model development process and provides such acceptance criteria for 10 CFR 50.34 compliance.**
5.	Incorrect computation (arithmetic error)	Incorrect computation reflects a specific software-development-related failure such that output is either unavailable or incorrect. As a general preventive measure, **vendor software development abides by guidance appearing in a documented standard**	
6.	Improper software results post-processing (interface error)	Improper use of software results may **be prevented through provided documentation guiding the user on the proper interpretation of results.**	Improper use of software results is mitigated through purchasing organization QA program.

Software Quality Assurance Summary Report

- A technical foundation and roadmap intended to support a QA process leading to the promotion of an externally-acquired software to safety-related status
- Addresses software QA characteristics discussed in NUREG-1737, *Software Quality Assurance Procedures for NRC Thermal Hydraulic Codes*
- Includes an application-specific mapping of the developer's software quality assurance program to that of the purchasing organization
- Subsections of the SQASR include content useful in software development records
  - Elements of Software QA (i.e., planning, requirements, coding, acceptance testing, etc.)
  - Employs PIRT insights for identifying application-specific SRS, SDS, SVVP and SVVR per Regulatory Guide 1.203

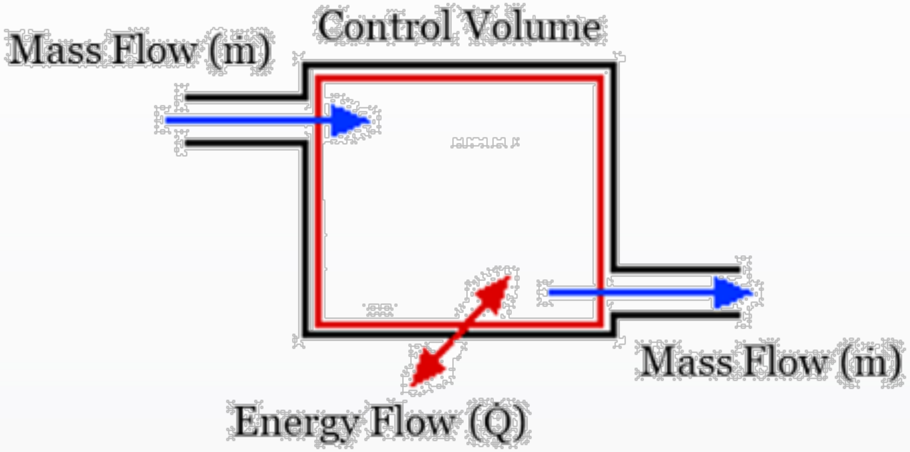
RELAP5-3D RG 1.203 V&V

- V&V Phenomena/Process Decomposition
  - System



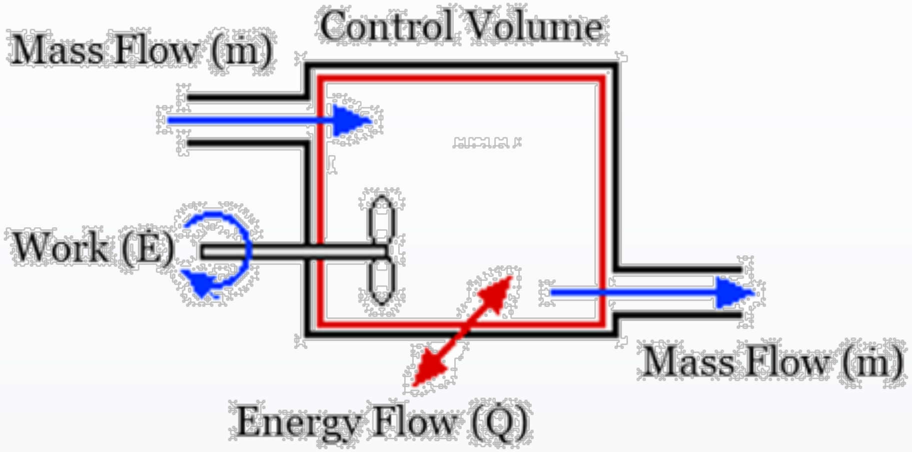
RELAP5-3D RG 1.203 V&V

- V&V Phenomena/Process Decomposition
  - System
    → Subsystem



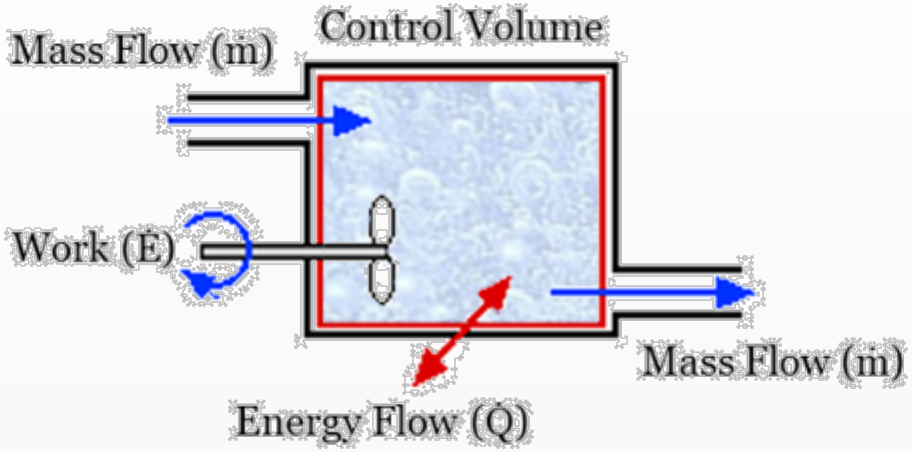
RELAP5-3D RG 1.203 V&V

- V&V Phenomena/Process Decomposition
  - System
    → Subsystem
      → Module



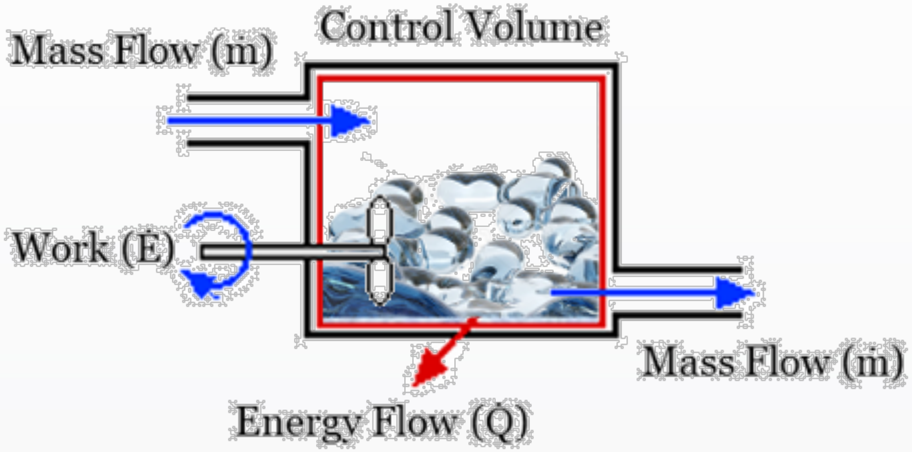
RELAP5-3D RG 1.203 V&V

- V&V Phenomena/Process Decomposition
  - System
    - → Subsystem
      - → Module
        - → Constituent



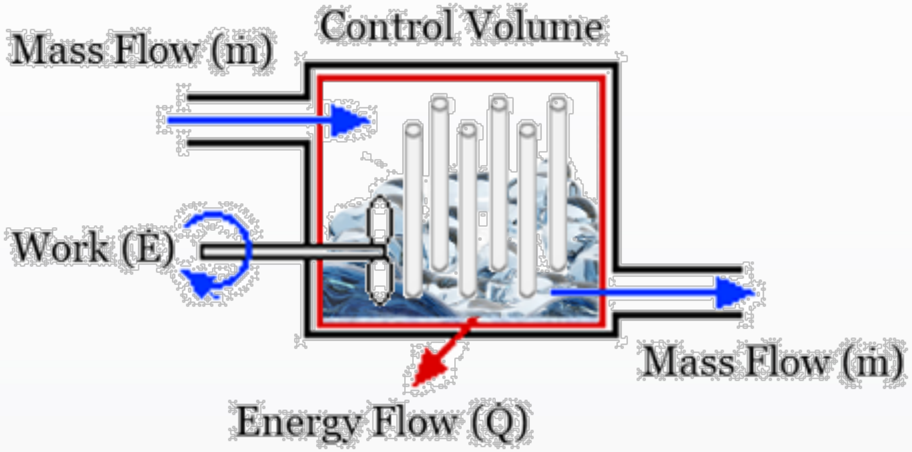
RELAP5-3D RG 1.203 V&V

- V&V Phenomena/Process Decomposition
  - System
    - → Subsystem
      - → Module
        - → Constituent
          - → Phase



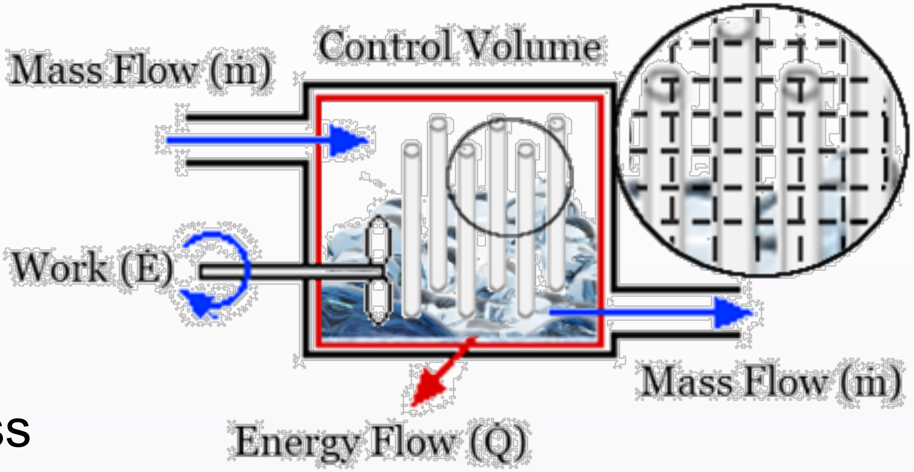
RELAP5-3D RG 1.203 V&V

- V&V Phenomena/Process Decomposition
  - System
    → Subsystem
      → Module
        → Constituent
          → Phase
            → Geometry

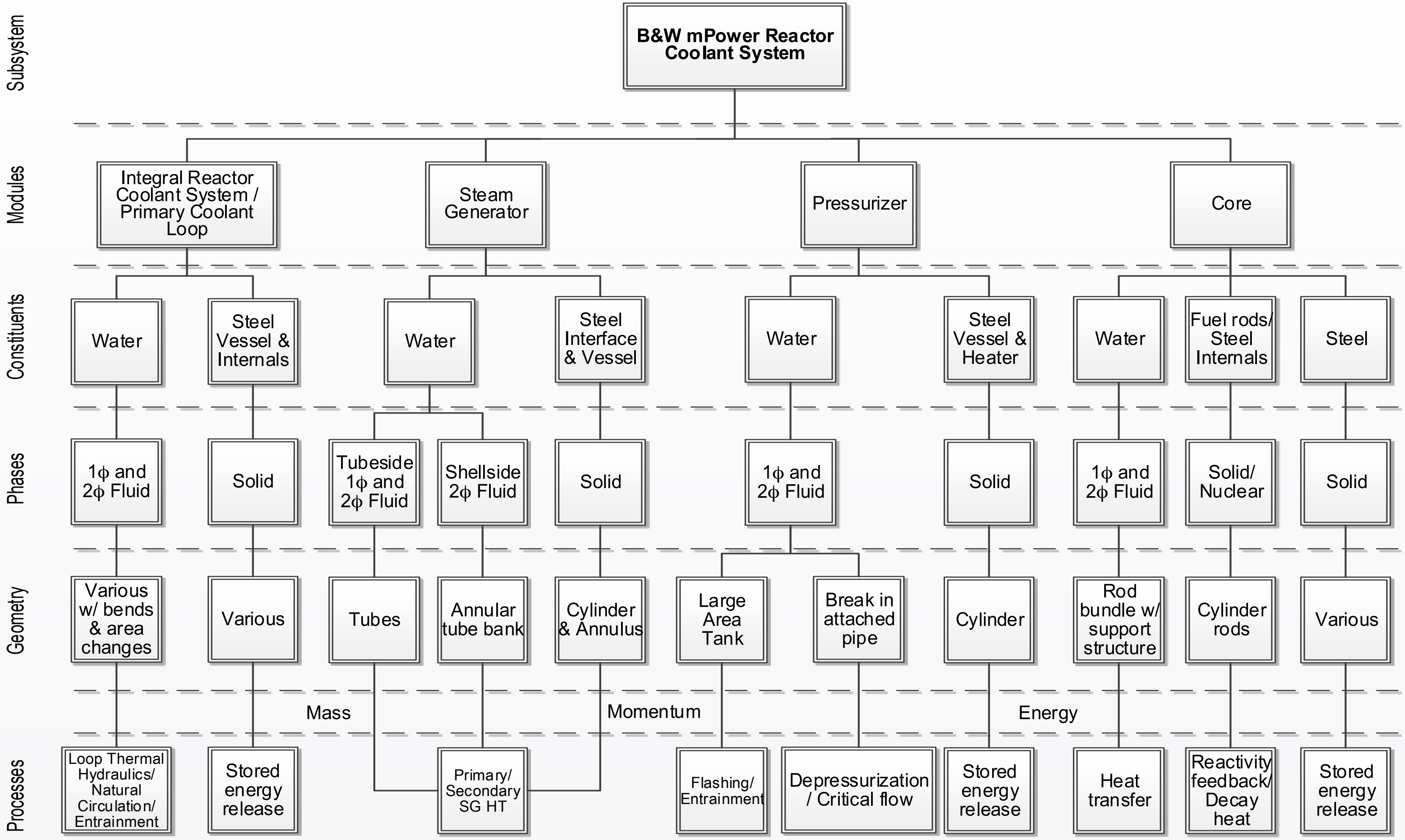


RELAP5-3D RG 1.203 V&V

- V&V Phenomena/Process Decomposition
  - System
    - → Subsystem
      - → Module
        - → Constituent
          - → Phase
            - → Geometry
              - → Process



LWR/SMR Phenomena Decomposition



Subsystem

B&W mPower Reactor Coolant System

Modules

- Integral Reactor Coolant System / Primary Coolant Loop
- Steam Generator
- Pressurizer
- Core

Constituents

- Water
- Steel Vessel & Internals
- Water
- Steel Interface & Vessel
- Water
- Steel Vessel & Heater
- Water
- Fuel rods/ Steel Internals
- Steel

Phases

- 1ϕ and 2ϕ Fluid
- Solid
- Tubeside 1ϕ and 2ϕ Fluid
- Shellside 2ϕ Fluid
- Solid
- 1ϕ and 2ϕ Fluid
- Solid
- 1ϕ and 2ϕ Fluid
- Solid/ Nuclear
- Solid

Geometry

- Various w/ bends & area changes
- Various
- Tubes
- Annular tube bank
- Cylinder & Annulus
- Large Area Tank
- Break in attached pipe
- Cylinder
- Rod bundle w/ support structure
- Cylinder rods
- Various

Mass Momentum Energy

Processes

- Loop Thermal Hydraulics/ Natural Circulation/ Entrainment
- Stored energy release
- Primary/ Secondary SG HT
- Flashing/ Entrainment
- Depressurization / Critical flow
- Stored energy release
- Heat transfer
- Reactivity feedback/ Decay heat
- Stored energy release

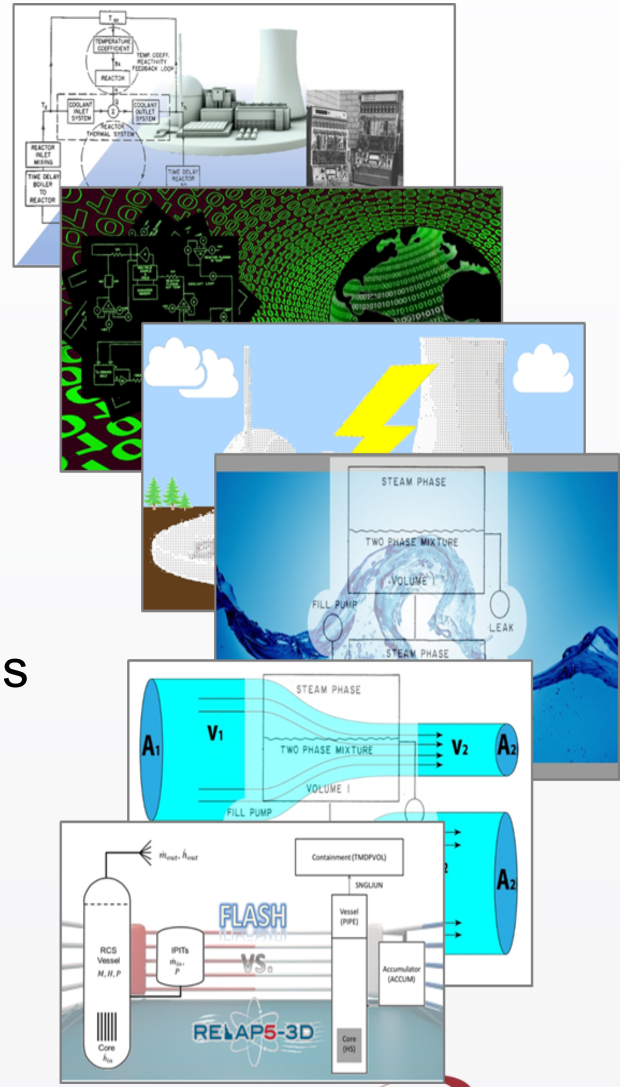
Software V&V Plan

- Failure Modes and Effects Analysis (1)
- Verification (13 Critical Characteristics)
- Essential Functionality and Installation Testing (60)
- System-, Subsystem-, Module- Performance Tests (2)
- Module-, Constituent- and Phase- Performance Tests (6)
  - Pump performance
  - Core boil-off and decay heat
  - Water Properties
  - Critical flow/RCS depressurization
  - Passive heat structures
  - Accumulator injection
- Integral-Effects Tests (14)
- Separate-Effects Tests (21)
- Testing of BWXT mPower Evaluation Model-Specific Features (3)

“FLASH” Model Genesis

- Building a simple thermohydraulic model addresses 4/6 Module-, Constituent-, and Phase- scale phenomena
  - examining the evolution of systems from non-equilibrium conditions to steady-state. Performance trends are largely dependent on the properties and nature of the specific module, constituent, and phase
- Two Governing Equations plus Five closure relations
  - Bernoulli-type mechanical energy equation
  - Critical flow
  - Fluid exit state
  - Decay heat
  - Accumulator model
- Originally, considered Reyes/Hochreiter 1998 AP600 scaling paper, then realized that it was basically FLASH

FLASH History

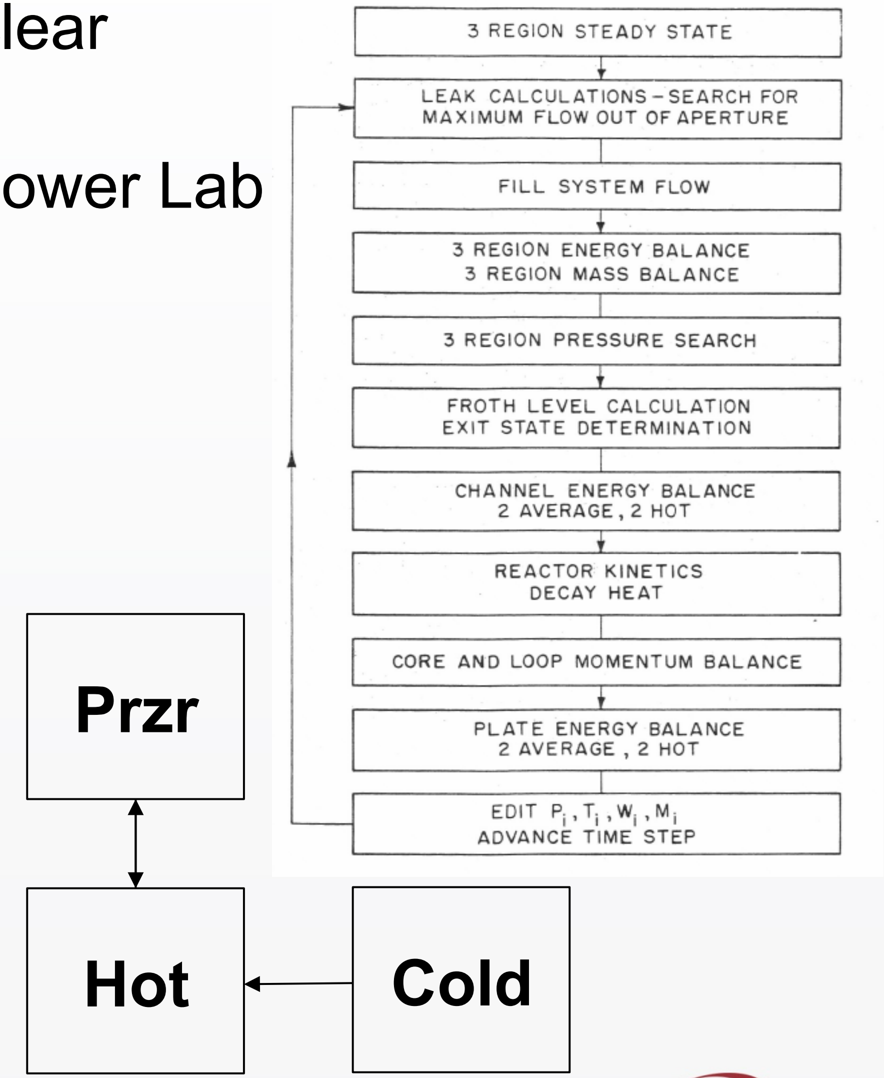


- Origins of Nuclear Science-Based Forecasting
  - Bettis begins to develop analog computers for process simulation
- Nuclear Goes Digital
  - AEC invests in digital computing
  - IBM develops FORTRAN
- Nuclear Safety On Demand
  - Safety review emphasizes LOCA in mid-1960s
  - AEC invests in FLASH development at Bettis
- Early Nuclear System Modeling (2 parts)
- FLASH Model Closure (5 parts)

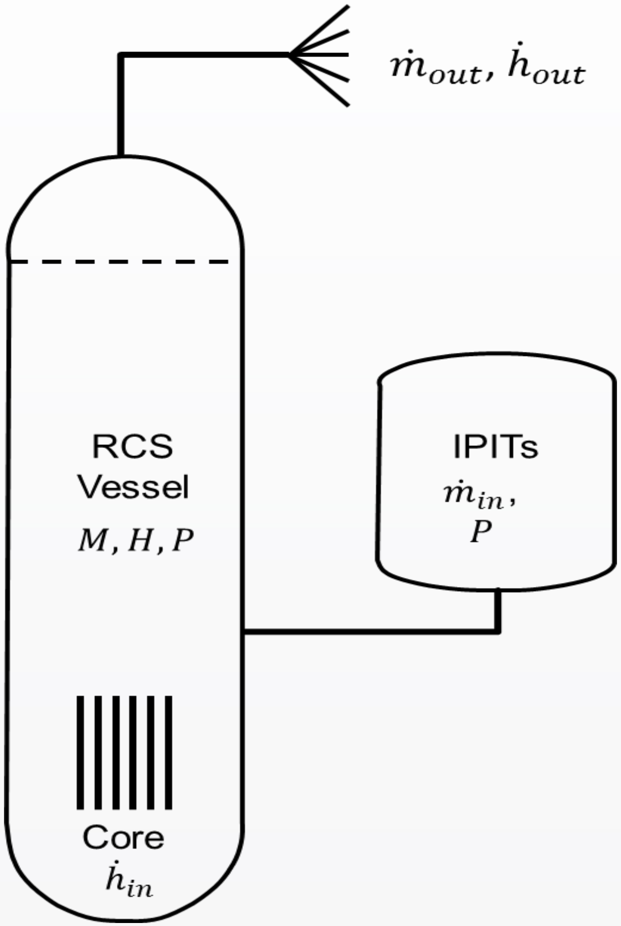
FLASH

The first broadly-distributed nuclear safety analysis code

- Developed at Bettis Atomic Power Lab
- 3 volume system
- Fill via table
- Choke flow model
- Secondary side as constant heat transfer coefficient
- HEM field equations
- Plate fuel, heat in only
- Explicit numerics



Benchmark Illustrations



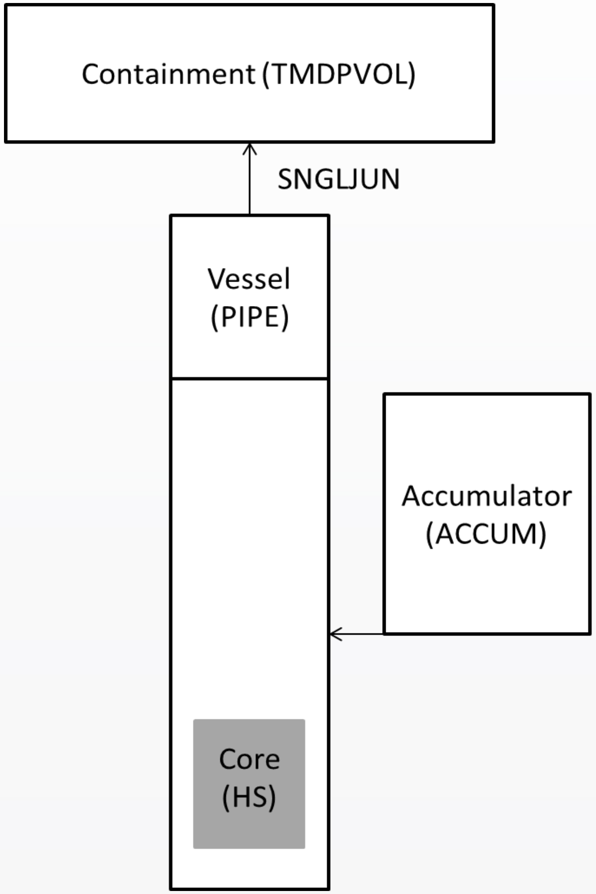
$\dot{m}_{out}, \dot{h}_{out}$

RCS
Vessel
M, H, P

IPITs
$\dot{m}_{in},$
P

Core
$\dot{h}_{in}$

FLASH



Containment (TMDPVOL)

SNGLJUN

Vessel
(PIPE)

Accumulator
(ACCUM)

Core
(HS)

RELAP5-3D

"FLASH" Model Genesis
TH Model Governing Equations

- Mathematical expression depends on the objective of the simulation
- Ideally, the derived governing equations provide an explicit expression of these figures-of-merit
  - Pressure and temperature, hydrodynamic and thermal loads
  - With intensive fluid properties, system state known

- $dM/dt = m_{in} - m_{out}$

$M dv/dt = -v(m_{in} - m_{out})$

- $dE_{o}/dt = (m h_{o})_{in} - (m h_{o})_{out} + Q_{net}$

$M de/dt = Q_{net} - e(m_{in} - m_{out})$

TH Model Governing Equations

- Intensive form
  - $dv=\left(\frac{\partial v}{\partial P}\right)_h dP+\left(\frac{\partial v}{\partial h}\right)_P dh$
  - $de=\left(\frac{\partial e}{\partial P}\right)_h dP+\left(\frac{\partial e}{\partial h}\right)_P dh$
- Final set

$$A=M\begin{bmatrix}\left(\frac{\partial e}{\partial P}\right)_h & \left(\frac{\partial e}{\partial h}\right)_P \\ \left(\frac{\partial v}{\partial P}\right)_h & \left(\frac{\partial v}{\partial h}\right)_P\end{bmatrix}$$

$$b=\begin{bmatrix}m_{in}\left(h_{o,in}-e\right)-m_{out}\left(h_{o,out}-e\right)+Q_{net} \\ -v\left(m_{in}-m_{out}\right)\end{bmatrix}$$

Momentum

- $$\begin{bmatrix} time \;\; rate\ of\ change \\ momentum \end{bmatrix} = [\Delta Pressure] + [Work] + [Body] + [Friction]$$

$$+[Form\ Loss] + [Acceleration]$$

- $\Delta P = 1/2\ \rho K(m\ /\rho A\ )\uparrow 2\ + \rho g(\Delta z + H) + 1/2\ \rho\Delta(m\ /\rho A\ )\uparrow 2$
- Form loss model needs closure

$$K_e = \left(1 - \frac{A_1}{A_2}\right)^2 \quad \text{or} \quad K_c = \left(1 - \frac{A_2}{A_1}\right)^2$$

- Leak path flow

$$\frac{\rho_g}{2}\left(\frac{\dot{m}}{\rho_g A}\right)^2 = (P_{vessel} - P_{exit}) \quad \text{or} \quad \dot{m} = AG = A\sqrt{2\rho_g(P_{vessel} - P_{exit})}$$

Critical Flow

- Subcooled - Fauske Equilbrium Rate Model
  - $G{\downarrow}ERM = h{\downarrow}fg\ /v{\downarrow}fg\ \surd 1/NTc{\downarrow}pf$
  - $G{\downarrow}cr \cong C{\downarrow}D\ \surd 2[P-P{\downarrow}sat\ (T)]\rho{\downarrow}f + G{\downarrow}ERM{\uparrow}2$
- Saturated - HEM-Moody-Henry/Fauske
  - $G{\downarrow}cr = C{\downarrow}d\ \rho''\ \surd 2*(h{\downarrow}0 - xh{\downarrow}g - (1-x)h{\downarrow}f\ )$
  - $\rho{\uparrow}'' = 1/[x/\rho{\downarrow}g\ + (1-x)S/\rho{\downarrow}f\ ]*\surd(x+1-x/S{\uparrow}2\ \ )$
  - $S=1$ or $S=(\rho{\downarrow}f\ /\rho{\downarrow}g\ ){\uparrow}1/2$ or $S=(\rho{\downarrow}f\ /\rho{\downarrow}g\ ){\uparrow}1/2$

$$\left.\left(\frac{\delta G}{\delta P}\right)\right|_{s} = 0 \qquad \text{and} \qquad \left.\left(\frac{\delta^2 G}{\delta P^2}\right)\right|_{s} < 0$$

Fluid Exit State

- To align the break enthalpy prediction to reality requires a model for segregating the conditions of the control volume adjacent to the break and that of the bulk.
- The point-in-time when the break plane transition from two-phase to vapor-only is modeled to occur when the adjacent volume has completely voided.
  - D'Auria and Frogheri, 2002 –Transition Mixture Density, 40-65%

$\alpha_f = \frac{M_{tot} - M_{cr}}{1 - M_{cr}}$ and $\alpha_g = 1 - \alpha_f$

$x = \frac{\alpha_g \rho_g u_g}{\alpha_g \rho_g u_g + \alpha_f \rho_f u_f}$ and $h_0 = h_f + x h_{fg}$

Core Heat

- The point reactor kinetics equations are

$$\frac{d\phi(t)}{dt} = \frac{[\rho(t) - \beta]\phi(t)}{\Lambda} + \sum_{i=1}^{N} \lambda_i C_i(t) + S$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda}\phi(t) - \lambda_i C_i(t) \qquad i = 1,2,3,\ldots,N$$

$$\psi(t) = \Sigma_f \phi(t) \qquad P_f(t) = Q_f \psi(t)$$

- Decay heat $\frac{d}{dt}\gamma_{\alpha j}(t) = \frac{F_\gamma a_{\alpha j}}{\lambda_{\alpha j}} F_\alpha \psi(t) - \lambda_{\alpha j}\gamma_{\alpha j}(t)$ $\quad j = 1,2,\ldots N_\alpha \quad \alpha = 1,2,3$

$$P_\gamma(t) = \sum_{\alpha=1}^{3}\sum_{j=1}^{N_\alpha} \lambda_{\alpha j}\gamma_{\alpha j}(t)$$

- Actinide $\frac{d}{dt}\gamma_U = F_U \psi(t) - \lambda_U \gamma_U(t)$

$$\frac{d}{dt}\gamma_N = \lambda_U \gamma_U(t) - \lambda_N \gamma_N(t)$$

$$P_\alpha(t) = \eta_U \lambda_U \gamma_U(t) + \eta_N \lambda_N \gamma_N(t)$$

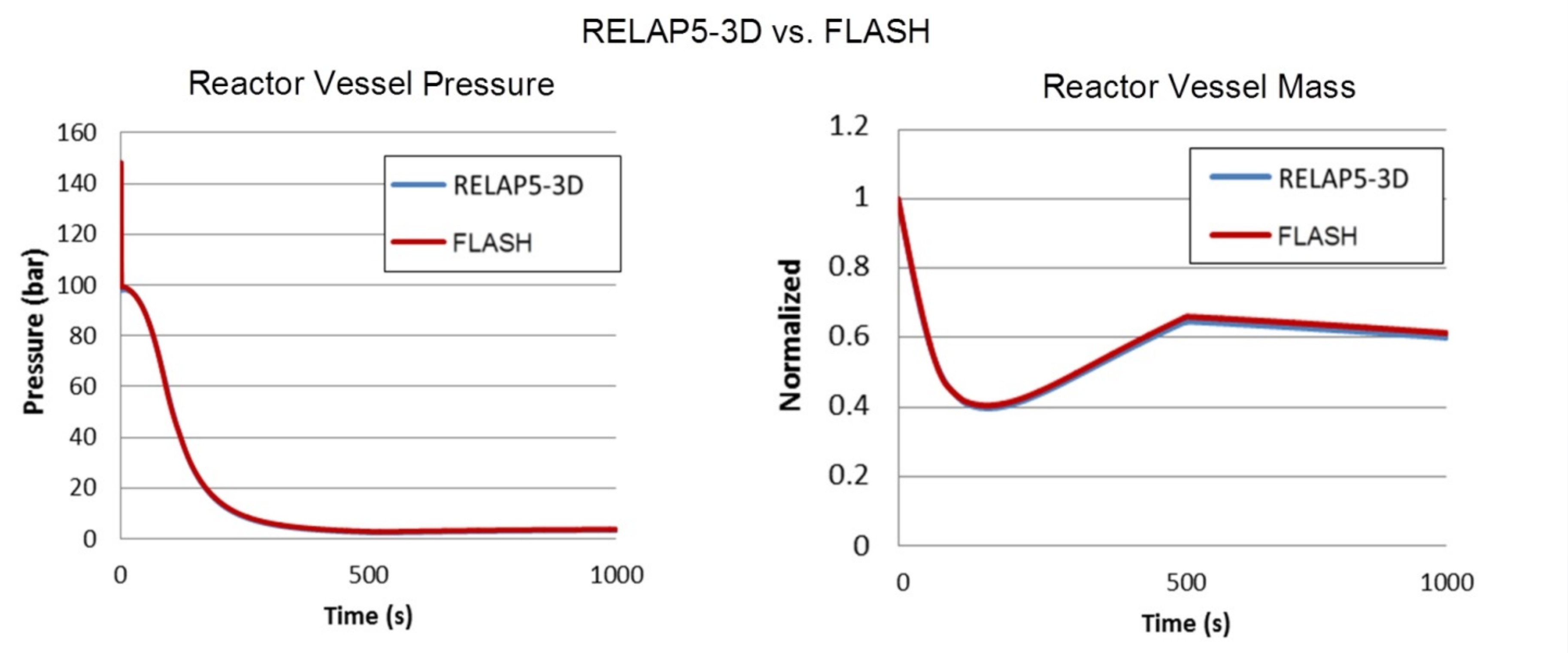
Accumulator (Fill)

- Pressure and accumulator exit velocity appear together in the mechanical energy equation
  - $v_{exit} = [2(P_{acc} - P_{exit} + \rho_{acc} g L_{liq})/\rho_{acc}]^{1/2}$
  - Gravity head term ($\rho g L$) is found by tracking the liquid level
- Accumulator energy equation
  - $Mc_v \frac{dT_g}{dt} = -P_{acc}\frac{dV_d}{dt} + Q_{gD} \rightarrow T_g^{n+1} = T_g^n e^{(R/C_v \ln V_D^n / V}$
- The pressure equation becomes
  - $P_{acc}(1 + R/c_v) A_L v_L + V_D \frac{dP_{acc}}{dt} = R/c_v \, Q_D$
- Final closure from requires simplified fluid properties
  - $\nu = 1.29/P^{0.991}$ (kinematic viscosity)
  - $h = 0.15*0.029\left(\frac{9.8*0.73*0.0033 (T_w - T_g)}{P^{0.99}/1.26}\right)^{1/3}$

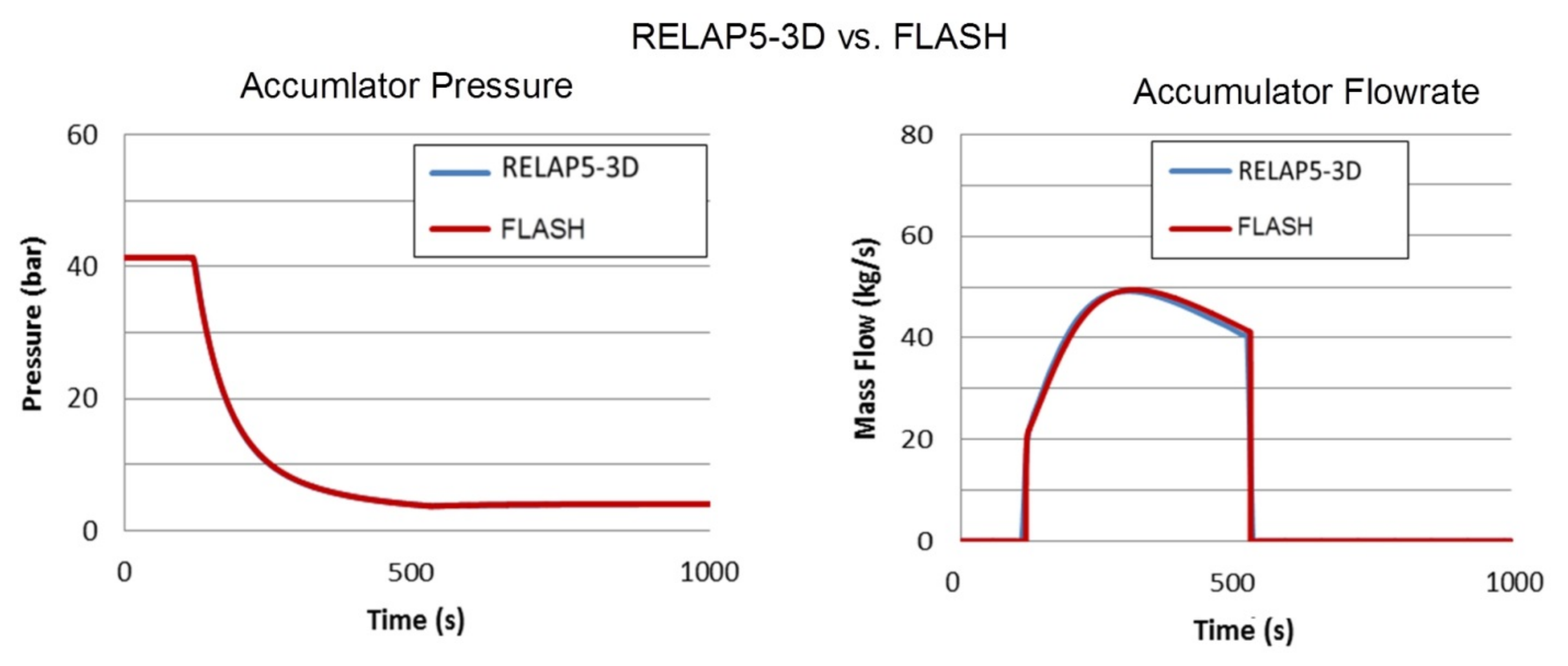
“FLASH” Performance

- To align RELAP5-3D and the FLASH model, The critical transition mixture mass was calculated from RELAP5-3D
  - Converged when top volume < 10% total volume (M_{cr} =46%)
- 5” top-sided break for vessel pressure
  - normalized vessel inventory
  - accumulator pressure
  - accumulator flow
  - accumulator temperature
- Break flow study
- Nodalization study
- Pressurizer study

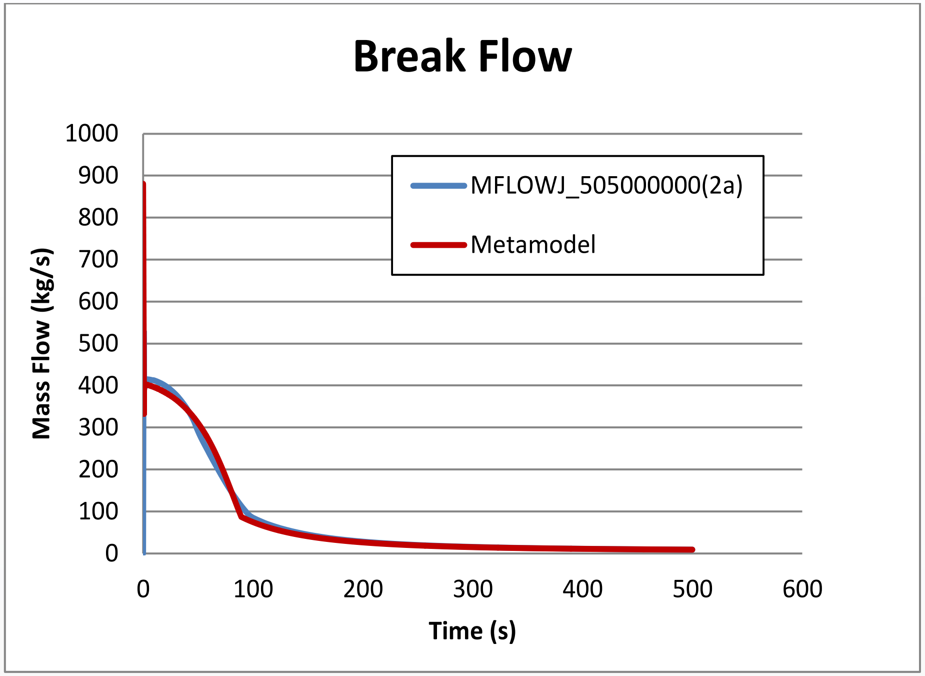
“FLASH” Performance

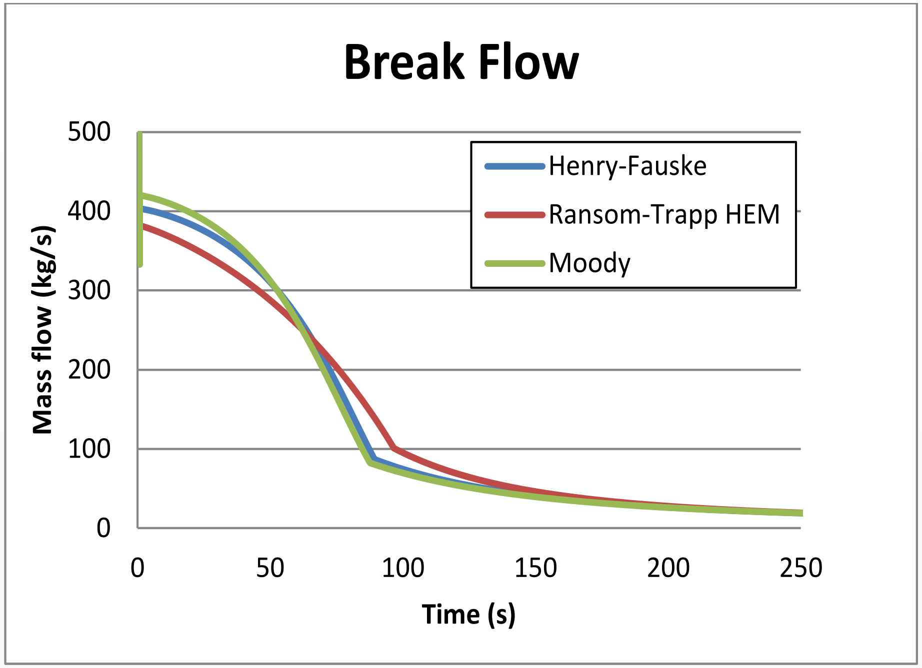


“FLASH” Performance



Break Flow Study

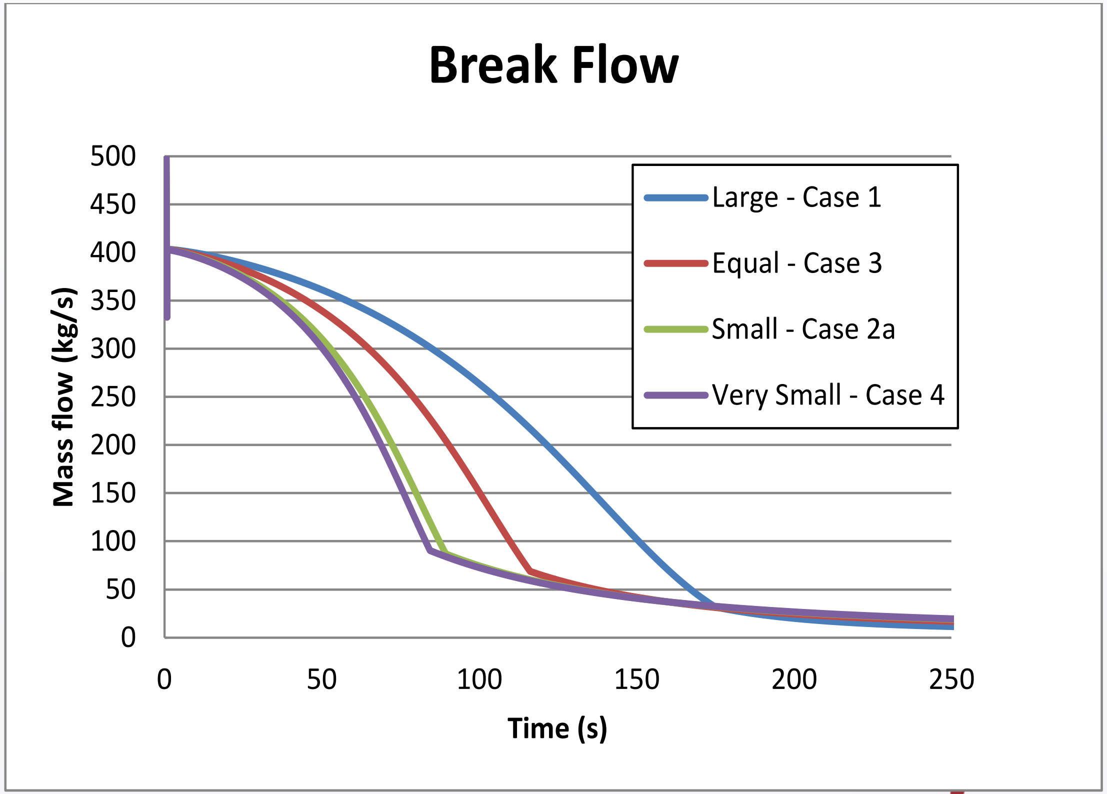




- Metamodel
  - Henry-Fauske
  - HEM
  - Moody
- R5-3D
  - Ransom-Trapp HEM

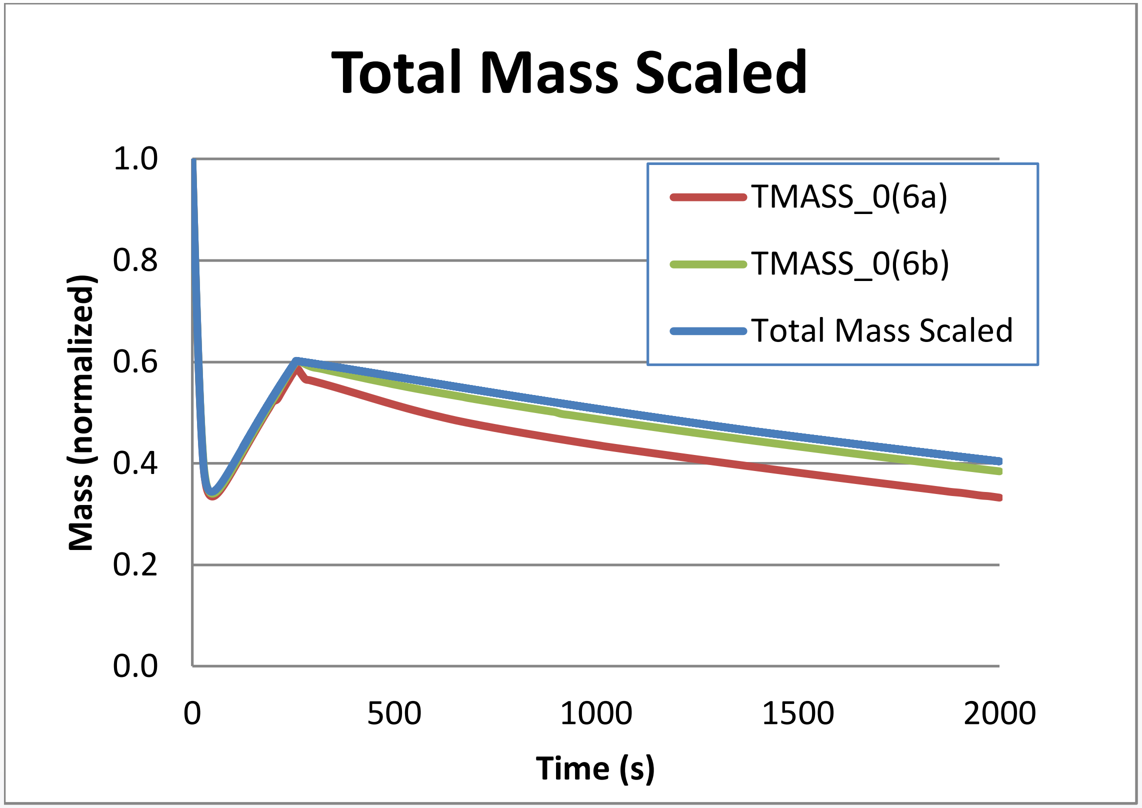
Nodalization Study

- Metamodel - Large
  - 10/90 Split
- Metamodel - Equal
  - 50/50 Split
- Metamodel - Small
  - 90/10 Split
- Metamodel - V. Small
  - 96.5/3.5 Split



Pressurizer Study

- Metamodel
- Base R5-3D case
- R5-3D with
  - more axial resolution
  - bundle drag
  - vertical stratification



Conclusion

- The “FLASH” model demonstrates remarkable alignment with its modern descendent, RELAP5-3D
- As verification,
  - the physical models of FLASH and RELAP5-3D can be directly inspected side-by-side for closure relationships that describe critical flow, reactor decay power, and other key processes.
  - the alignment of results of the two codes provides evidence that the numerical representations and computation advancement are appropriate (i.e., solution by alternative method).
- Revisiting FLASH provides a unique connectivity to the community of RELAP code developers.
  - Underlying technical basis of simplified “FLASH” model has remained valid despite the expansion of thermal-hydraulic knowledge since the 1960s