FLASHback: RELAP at Fifty

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Abstract

The first thermal-hydraulic systems code to gain wide acceptance in the nuclear community was the FLASH code, originally developed at Bettis Atomic Power Laboratory in 1966. This was followed shortly afterwards by the RELAPSE code by a team at the Idaho National Laboratory (INL). Since that time, the vision that inspired the FLASH and RELAPSE codes has continued to evolve at the INL. This paper describes a FLASH-emulating metamodel and presents a benchmark against an equivalent RELAP5-3D simulation.

Keywords: FLASH, RELAP5-3D, validation

Introduction

Nuclear safety analysts use mathematical modeling to investigate the capacity of a light water reactor (LWR) nuclear power plant's emergency core cooling system (ECCS) to maintain core integrity during a loss-of-coolant accident (LOCA). While processes involved in LWRs are many, the primary analytical challenge relates to the coexistence and interactions of liquid and vapor water, i.e., two-phase flow. Over the range of conditions present during hypothetical transients and accidents, the related fluid flow and heat transfer phenomena can vary substantially. In the interest of devising credible analysis techniques for such problems, in the early 1960s the U.S. Atomic Energy Commission sought to translate their previously sponsored experimental and theoretical research into digital computer codes. The first broadly-distributed nuclear safety analysis code was FLASH, developed at Bettis Atomic Power Laboratory (Ref. 1).

When introduced in 1966, the FLASH code calculated flows, coolant inventories, pressures and temperatures in a nuclear power plant primary system during a LOCA in a pressurized water reactor (PWR). Starting with calculations of the rate of coolant flow through assumed leaks, it calculated inflow from a refill system (i.e., pumped safety injection), inventory of water in the reactor vessel, flow through the core and loops, core power, and heat transfer from the fuel to the coolant. It also calculated the fuel temperatures in both a hot and average channel of the core. The FLASH code took root in the desert of Eastern Idaho and before the end of 1966 the staff at the Nuclear Reactor Testing Station (today the Idaho National Laboratory (INL)) released an incrementally improved version named RELAPSE. Since that time, the vision that inspired the FLASH and RELAPSE (Ref. 2) codes has continued to evolve at the INL. Multiple generations of developers and users have put their fingerprints into this effort. The compilation of changes, both small and large, now exists as the international recognized nuclear safety analysis software RELAP5-3D (Ref. 3).

To recognize fifty years of development, this paper reviews the original FLASH model as the basis for a FLASH-like thermal-hydraulic metamodel that has been programmed in the MATLAB mathematics

environment. Subsequently, a LOCA benchmark is presented comparing the performance of this FLASH metamodel against an equivalent RELAP5-3D simulation of a lumped-parameter reactor coolant system (RCS) with a top-sided break location.

The FLASH Fluid Model

The architecture of the FLASH code is best described as a very simple "node and branch" design. This approach assumes that the spatial elements (nodes) are capable of energy and mass storage only. The nodes are connected by branches that model resistances and contributions to flow. Thus, the conservation-of-momentum is written for each branch, while the conservation-of-energy and -mass are written for each node. This aligned well with the state-of-knowledge at that time. Notably, while there was a good understanding of the properties of water and steam as separate entities, there was relatively little understanding of two-phase properties of water coolant. To address the possibility of their coexistence, early computer models made two key assumptions that allowed them to apply what they did know about water and still get reasonable answers. These were 1) water and steam move as a homogeneous mass and 2) the temperature of water and steam appearing together are equal (i.e., in equilibrium). With these assumptions, the governing equations and associated closure models describing the a control volume thermal-hydraulic state need only to consider the mass, momentum, and energy transport of a single phase-homogenized fluid, which means a single equation for each conserved property.

For application on early digital computers, the developers of FLASH needed an efficiently-constructed model that incorporated only the content necessary to accomplish its objective. That objective for LWR LOCA simulation is to estimate the loads that might threaten system integrity. Those loads are realized depending on the physical phenomena present; however, those of interest for design-basis LWR system integrity are primarily hydrodynamic and thermal, i.e., pressure and temperature. Ideally, the derived governing equations provide an explicit expression of these figures-of-merit.

Pressure and temperature are not only measures of hydrodynamic and thermal loads; they are also two intensive fluid properties. By the state postulate of thermodynamics, the state of a system in thermodynamic equilibrium is completely specified by two independent, intensive properties. With pressure and temperature as independent variables, the task of solution closure is simplified since we can directly evaluate any fluid physical property that might appear in a dependent process model or correlation.

With the figures-of-merit (almost) resolved, the derivation of the governing equations begins by considering mass conservation in a nuclear power plant reactor coolant system (RCS). For the lumped parameter system conceptualized in FLASH, the expression of relating mass balance between in-flows ($\dot{m}_{in}$) and out-flows ($\dot{m}_{out}$) to storage (M) is:

$$\frac{dM}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

Unlike pressure and temperature, mass is an extensive property; however, by reformulating the mass conservation equation as a volume conservation equation, an expression in terms of another intensive property, specific volume, can be derived. This volume equation relates the system volume (V) to the system mass (M), the ratio of which is specific volume (v):

$$\frac{dV}{dt} = 0 = \frac{d}{dt}(Mv) = M\frac{dv}{dt} + v\frac{dM}{dt} = M\frac{dv}{dt} + v(\dot{m}_{in} - \dot{m}_{out})$$

The derivation of the total lumped, stagnate system energy equation (E_o) is similar, but it includes the contribution from core power and structure stored energy ($\dot{Q}_{net}$):

$$\frac{dE_o}{dt} = (\dot{m}h_o)_{in} - (\dot{m}h_o)_{out} + \dot{Q}_{net}$$

The total energy of the system is approximated as the product of system mass and internal energy:

$$E_o \approx Me \rightarrow \frac{d}{dt}(Me) = M\frac{de}{dt} + e\frac{dM}{dt} = M\frac{de}{dt} + e(\dot{m}_{in} - \dot{m}_{out})$$

This outcome reflects a translation from a model based on the extensive properties of mass (*M*) and energy (*Me*) to one based on the intensive properties of specific volume (*v*) and internal energy (*e*), but this is only halfway to our goal. The next step is to translate this model to the preferred set of intensive properties that relate to physical and measurable loads: pressure (*P*) and temperature (*T*).

Incorporating water and steam properties into our mass and energy balance completes the governing equations. In doing so properly, the dependent terms in the governing equations become directly relatable to phenomena desired in the final model, those essential in PWR LOCA simulation. In the 1960s, water and steam property data were fairly well characterized for the ranges of pressures and temperatures required in nuclear power systems (P < 2500 psia/ 17 MPa and T < 620 F/ 325 C). In fact, the 1967 ASME standard (Ref. 4) is still commonly used in nuclear safety analysis while new standards regularly appear every ten years or so. As such, relations among intensive properties were readily available to translate the basic fluid model into its final form.

The first state relation applied is the relationship between temperature and enthalpy (*h*). Outside of phasic transitions (e.g., liquid to steam), changes in enthalpy are directly proportional to temperature via the fluid's specific heat (c_p). As will be evident through the model closure process, while temperature is directly measurable, enthalpy is a better measure of thermal load as it impacts energy storage and release dynamics in the fluid.

To translate the expression for specific volume and internal energy to pressure and enthalpy, specific volume and internal energy are defined using their partial derivatives (state relations) with respect to pressure and enthalpy:

$$dv = \left(\frac{\partial v}{\partial P}\right)_h dP + \left(\frac{\partial v}{\partial h}\right)_P dh$$

$$de = \left(\frac{\partial e}{\partial P}\right)_h dP + \left(\frac{\partial e}{\partial h}\right)_P dh$$

Substituting the above into the specific volume/mass balance and the internal energy/energy balances equation completes the derivation of a mathematical model relating dynamic change in our nuclear power RCS (or any thermodynamic system) in terms of pressure and enthalpy

$$M\left(\frac{\partial v}{\partial P}\right)_h \frac{dP}{dt} + M\left(\frac{\partial v}{\partial h}\right)_P \frac{dh}{dt} = -v(\dot{m}_{in} - \dot{m}_{out})$$

$$M\left(\frac{\partial e}{\partial P}\right)_h \frac{dP}{dt} + M\left(\frac{\partial e}{\partial h}\right)_P \frac{dh}{dt} = \dot{m}_{in}(h_{o,in} - e) - \dot{m}_{out}(h_{o,out} - e) + \dot{Q}_{net}$$

The last step is to calculate the partial derivatives. When the fluid is single-phase, the property partial derivatives in the coefficient matrix could be approximated by solutions for incompressible fluid (i.e., subcooled liquid) or ideal gas (i.e., superheated steam); however, given the availability of data, these are best determined from fluid property tables with the derivatives evaluated numerically using property finite difference approximations. When the mixture becomes saturated, another step is required and that is to evaluate the equilibrium quality (x_{eq}), which is defined as:

$$x_{eq} = \frac{h - h_f}{h_{fg}}$$

The saturated mixture specific volume can then be written in terms of the pressure (through the saturation properties) and the mixture enthalpy:

$$v = v_f + \frac{v_{fg}}{h_{fg}}(h - h_f)$$

Differentiating the above relation gives the partial derivatives of the saturated mixture specific volume as a function of the partial derivatives of the saturation properties:

$$\left(\frac{\partial v}{\partial h}\right)_P = \frac{v_{fg}}{h_{fg}}$$

$$\left(\frac{\partial v}{\partial P}\right)_h = \frac{\partial v_f}{\partial P} + x_{eq}\frac{\partial v_{fg}}{\partial P} - \left(\frac{v_{fg}}{h_{fg}}\right)\left[\frac{\partial h_f}{\partial P} + x_{eq}\frac{\partial h_{fg}}{\partial P}\right]$$

For the internal energy partial derivatives, the thermodynamic relationship is used $e = h - Pv$. Solving for the internal energy and differentiating gives the following partial derivatives:

$$\left(\frac{\partial e}{\partial h}\right)_P = 1 - \frac{Pv_{fg}}{h_{fg}}$$

$$\left(\frac{\partial e}{\partial P}\right)_h = -\frac{\partial v_f}{\partial P} - x_{eq}\frac{\partial v_{fg}}{\partial P} + \left(\frac{v_{fg}}{h_{fg}}\right)\left[\frac{\partial h_f}{\partial P} + x_{eq}\frac{\partial h_{fg}}{\partial P}\right]$$

While the partials with respect to pressure can be directly computed from steam table data, the partials with respect to enthalpy must be evaluated numerically, as mentioned for single-phase fluid.

To solve, the developers of FLASH applied a standard linear, state-space model. The form of the solution has the two governing equations put into matrix form using the state variable vector, u=[P ; h]. The matrix form for the governing equations is:

$$A\frac{du}{dt} = b$$

where the coefficient matrix and source vector are given as:

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

$$b = \begin{bmatrix} \dot{m}_{in}\left(h_{o,in} - e\right) - \dot{m}_{out}\left(h_{o,out} - e\right) + \dot{Q}_{net} \\ -v(\dot{m}_{in} - \dot{m}_{out}) \end{bmatrix}$$

A simple Forward Euler time integrator was then used to advance the solution of the set of equations through time.

FLASH Metamodel Model Closure

The derived governing equation described the reasoned formulation of physical laws for a simple control volume with mass and energy exchange with its environment. While arguably elegant in it generality, it is useless without context. This context addresses all practical elements of the selection of governing equations, how the rational model is solved and the model closure relations that reflect the analysis objective. In the following, the closure models presented generally align with those appearing in the original FLASH code. Since the objective of the FLASH metamodel described here is for a simulation of a specific scenario and plant configuration used in a benchmark with RELAP5-3D, additional simplifications and upgrades have been made in the spirit of the original developers' desire for efficient modeling targeting a specific application. Since the fuel heat transfer models are significantly different between FLASH and RELAP5-3D, a fuel model was not included in the FLASH metamodel.

Water/Steam properties

While modern thermal-hydraulic models includes momentum among the governing equations, that was not so in FLASH. Since in that model momentum was only used to establish rates of mass and energy moving across a dimensionless control volume boundary, its application is better described as a constitutive relation – specifically, a relation for mass flow either into or out of the control volume.

Central to the phenomenological description is the form of the momentum equation, which in most general terms (and assuming HEM) appears as

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

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

The primary quantity desired from a hydraulic analysis is the differential pressure between adjoining control volumes or across an interface between a control volume and its environment. In this lump parameter representation, friction and the rate of change of momentum are not meaningful. As such, the

momentum equation becomes a form of the Bernoulli equation, a simple mechanical energy balance, such as

$$\Delta P = \frac{1}{2}\rho K\left(\frac{\dot{m}}{\rho A}\right)^2 + \rho g(\Delta z + H) + \frac{1}{2}\rho\Delta\left(\frac{\dot{m}}{\rho A}\right)^2$$

where *K* is an empirical form loss coefficient, ρ is the fluid density, *g* is the gravitation constant, *Δz* is the elevation change, *H* is the work addition such as that from a pump, and *ΔP* is the corresponding pressure drop. Because for model closure mass flow is the desired quantity, the fluid velocity appears as the ratio of the mass flow rate and the product of density and area.

Generally, the dependent parameters will be known based on the initial state of the problem. Unrecoverable pressure losses resulting from form are commonly treated empirically (i.e., user-defined) in large-scale simulation. For certain configurations, such as for an abrupt area change, formulas are available.

Subcooled critical flow ($\mathbf{m_{out}}$)

The subcooled critical flow model used in FLASH was very simple; it was little more than an extension of the mechanical energy expression in the previous equation, modified by a calibration factor. In lieu of rehashing that method, an alternative model for sub-cooled critical flow is given that is of the same vintage as that used in FLASH. This is the Fauske Equilibrium Rate Model (ERM) (Ref. 5). The key difference in the ERM is the "ERM mass flux" term, which is defined as

$$G_{ERM} = \frac{h_{fg}}{v_{fg}}\sqrt{\frac{1}{NTc_{pf}}}$$

where G_{ERM} = mass flux (kg/s/m^2), h_{fg} = vaporization enthalpy (J/kg); v_{fg} = change in specific volume (m^3/kg); *T* = absolute temperature (K); c_f = specific heat of the liquid (J/kg-K). *N* is a non-dimensional correction parameter to account for non-equilibrium or other effects (i.e., yes, another calibration term). To account for the sub-cooling, an additional single phase pressure drop term is included giving the critical flow rate to be:

$$G_{cr} \cong C_D\sqrt{2[P - P_{sat}(T)]\rho_f + G_{ERM}^2}$$

In the above expression, *T* is the system temperature which is determined using the property look-up table for the current system pressure and mixture enthalpy. Thus, *Psat(T)* is the saturation pressure for the current lumped system pressure. In my experience, the "right" value for *N* is the value that provides continuity with the two-phase flow model. That is just a calibration exercise, which I found to be 1/0.64 for alignment with the common equilibrium models, including Moody.

Two-phase critical flow ($\mathbf{m_{out}}$)

The equilibrium two-phase critical flow models relate the velocity (*u*) at the choked location to the thermodynamic enthalpy of the fluid at the upstream point of entry into a pipe or orifice. The basic

expression for mass flux can be rearranged in terms of enthalpy by pulling density out of the square root radical. Consequently, the common equilibrium models express critical mass flux as

$$G_{cr} = C_d \rho''' \sqrt{2 * (h_0 - x h_g - (1-x) h_f)}$$

where a discharge coefficient, C_d, is included to calibrate for nonequilibrium effects. In addition, h_f and h_g are liquid and vapor specific enthalpy at critical pressure, x is equilibrium quality, and ρ''' is a mixture density expressed by

$$\rho''' = \frac{1}{\left[\frac{x}{\rho_g} + \frac{(1-x)S}{\rho_f}\right] * \sqrt{\left(x + \frac{1-x}{S^2}\right)}}$$

where S is the slip, i.e., the ratio of phasic velocities (u_g/u_f) and ρ_f and ρ_g are liquid and vapor density, respectively. Since the choke plane properties are unknowable in FLASH's simple fluid model, an iterative search must be made to find the maximum mass flux with respect to changes in pressure at the choked location, that is

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

Several equilibrium two-phase critical flow models derived from this basic approach. Individual models are distinguished based on assumptions for describing slip. FLASH assumed the Moody model (Ref. 6) where

$$S = \left(\frac{\rho_f}{\rho_g}\right)^{1/3}$$

This result is based on an assumption that the mass flux is maximized with respect to the slip ratio. The homogeneous-equilibrium model (HEM) and Fauske model (Ref. 5) are the common alternatives. The HEM assumes no slip (S=1) and the Fauske model is based on maximizing mass flux with respect to the slip ratio. This is

$$S = \left(\frac{\rho_f}{\rho_g}\right)^{1/2}$$

Selection among these different models is an option in the FLASH metamodel.

Boiloff (m_{out})

For long-term cooling after a LOCA, coolant boiloff is important. Basically, it just $\dot{m} = \dot{Q}_{net}/h_{fg}$; however, it is inherent in the FLASH metamodel model. As energy is added to the system, energy storage translates into a pressure increase. If there is a leak path, then from the mechanical energy equation above, the expression for mass flow is

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

Break plane conditions ($h_{o,out}$)

In order to solve the energy balance in control volumes, the correct enthalpy must be assigned to all incoming and exiting flows. This 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. The original FLASH code estimated a froth level and matched that with the elevation of adjacent flow paths to calculate a quality. To emulate this function for the target benchmark case of a top-sided leak adjacent to a control volume, a "critical transition mixture mass ratio" is evaluated that is defined as the ratio of the initial vessel mass to the remaining system mass at the time when "the control volume adjacent to the break" has emptied. This is a departure from the FLASH approach is meant to align with RELAP5-3D that applies upstream-donoring of void fraction; that is, it projects the volume void fraction to the junction in the direction of flow. As such, the break plane void fraction is defined as

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

Where α_f is the break liquid fraction, M_{tot} is the total vessel mass normalized, and M_{cr} is the critical transition mixture mass ratio. Since $\alpha_f + \alpha_g = 1$, the break void fraction is simply.

$$\alpha_g = 1 - \alpha_f$$

Void and liquid fraction are used in the calculation of break enthalpy by their relationship to equilibrium quality (note for homogeneous flow assumption, velocity terms cancel):

$$x = \frac{\alpha_g \rho_g u_g}{\alpha_g \rho_g u_g + \alpha_f \rho_f u_f}$$

$$h_0 = h_f + x h_{fg}$$

Reactor power (Q_{net})

The reactor power closure model in FLASH is a full implementation of a six group point reactor kinetics model, such as that described in Ref. 7. The reactor power model for the FLASH metamodel is further simplified by assuming coincident shutdown with the beginning of the simulation. Consequently, the necessary components of reactor power are shutdown reactivity, decay heat, and actinide power. Fission power is obtained by solving the neutron kinetic equations after a large negative insertion of reactivity. Assuming a single group of delayed neutrons, the power is given by (see Ref. 8, Eqn 3-65, translated to power from neutron flux)

$$P_f(t) = P_o \frac{\beta_{eff}/\Lambda}{\beta_{eff}/\Lambda - \rho\left(\beta_{eff}/\Lambda\right)} e^{-\lambda_i t}$$

where ρ is reactivity in dollars ($), i.e., normalized by β_{eff}. By extension, for six groups of delayed neutrons, the power is

$$P_f(t) = P_o\left[\sum_{i=1}^{6}\gamma_i \frac{\beta_{eff}/\Lambda}{\beta_{eff}/\Lambda - \rho\left(\beta_{eff}/\Lambda\right)} e^{-\lambda_i t}\right]$$

where γ_i are yield fractions for each delayed neutron group. Actinide decay power is evaluated as a function of time (*t*), duration of operation (*T*), and fissions-per-capture (*R*) as arguments. The formula are

$$P_{Np239} = 0.419R\frac{4.91x10^{-4}}{4.91x10^{-4} - 3.41x10^{-6}}(1 - \exp(-3.41x10^{-6}T))\exp(-3.41x10^{-6}t)$$

$$-\frac{3.41x10^{-6}}{4.91x10^{-4} - 3.41x10^{-6}}(1 - \exp(-4.91x10^{-4}T))\exp(-4.91x10^{-4}t)$$

$$P_{U235} = 0.474R(1 - \exp(-4.91x10^{-4}T))\exp(-4.91x10^{-4}T)$$

Dependent parameters are specified in any one of the ANSI/ANS decay heat standards (e.g. Ref. 9).

Accumulator injection (m_{in})

In 1966, accumulators had yet to become a standard safety feature of PWR ECCS; but, some form of pumped injection was provided for long-term cooling. Safety analysis using FLASH, therefore, only required the capability for simulating a simple pumped injection ECCS and no explicit model for an accumulator. That would not come about until RELAP5/MOD0 in 1979. The pumped safety injection in FLASH, referred to as a Fill System, only required table entries of pump head and flow. Theoretically, an accumulator model could be constructed that could emulate accumulator performance.

The importance of accumulator performance is well established. As such, instead of using a table, which would otherwise require an offline analysis of the fluid behavior, the RELAP5-3D model was implemented with some simplifications. Since the hydraulic solution in that model uses pressure, temperature and velocity as independent variables, it is conveniently formed for implementation in the FLASH metamodel. Pressure and velocity appear together in the mechanical energy equation, solving for velocity gives

$$\mathrm{v_{exit}} = \left[2\left(P_{acc} - P_{exit} + \rho_{acc} g L_{liq}\right)/\rho_{acc}\right]^{1/2}$$

The gravity head term is found by tracking the liquid level in the accumulator. The accumulator liquid level is found from

$$L_{acc} = \frac{V_{liq}}{A_{acc}}$$

where

$$V_{liq}(t) = V_{liq,0} - \int_0^t \dot{W}_{liq}\, dt$$

The FLASH metamodel only solves for v_{exit} when $\left(P_{acc} - P_{exit} + \rho_{acc} g L_{liq}\right) > 0$. For the complete solution of accumulator conditions, volumetric flowrate is preferred to velocity since it relates directly to the change in the accumulator gas volume.

$$\dot{W}_{gas} = -\dot{W}_{liq} = A_{acc} v_{exit}$$

The accumulator energy equation is cast in terms of the gas temperature, T_g,and volume, V_d,

$$M c_v \frac{dT_g}{dt} = -P_{acc} \frac{dV_d}{dt} + \dot{Q}_D$$

where M is the nitrogen mass, c_v is nitrogen specific heat, and $\dot{Q}_D$ is the net heat transfer rate to the gas from all sources. Differentiating the ideal gas law (i.e., *d(PV) = RdT*) provides a relationship between the time derivative for pressure and the time derivative of temperature. Substituting into the above gives

$$P_{acc}\left(1 + \frac{R}{c_v}\right)\frac{dV_d}{dt} + V_D \frac{dP_{acc}}{dt} = \frac{R}{c_v}\dot{Q}_D$$

where *R* is the ideal gas constant. Since the liquid is incompressible, the change in dome volume term is equivalent to the volumetric flow rate at the exit, $A_L v_L$. The pressure equation becomes

$$P_{acc}\left(1 + \frac{R}{c_v}\right) A_L v_L + V_D \frac{dP_{acc}}{dt} = \frac{R}{c_v}\dot{Q}_D$$

The expression for the FLASH metamodel is straight forward by recognizing that this has the general form and solution of:

$$\frac{dP}{dt} = -aP + b$$

$$P(t) = Ce^{-a\Delta t} + \frac{b}{a}$$

where Δt is the timestep,

$$a = \frac{\left(1 + \frac{R}{c_v}\right)\dot{W}_{gas}}{V_D} \quad \text{and} \quad b = \frac{R}{c_v}\frac{\dot{Q}_D}{V_D}$$

Since $\frac{R}{c_v} = k - 1$ where $k = \frac{c_p}{c_v} = 1.4$, then

$$a = \frac{1.4\dot{W}_{gas}}{V_D} \quad \text{and} \quad b = \frac{0.4\dot{Q}_D}{V_D}$$

The solution for *b* requires an expression for the rate of energy input into the gas space, $\dot{Q}_D$, which is from heat convection from the accumulator walls, ceiling and liquid surface (i.e., $\dot{Q}_D = hA\Delta T$). As such, it is primarily dependent on the temperature difference between the wall and the gas. The heat transfer coefficients have the form (see Equations 3.5-153 and 3.5.155 in Ref. 1).

$$h_i = \frac{C_i k_n}{\delta}(GrPr)^{\frac{1}{3}}$$

where C_i is a constant dependent on geometry type and defined in Ref. 1, $k_n$is the thermal conductivity, δ is vessel diameter, and Gr and Pr are the Grashof and Prandlt numbers. This accumulator heat transfer model does require nitrogen properties. For the target benchmark problem, all nitrogen properties with the exception of kinematic viscosity (appears in *Gr*) were treated as a constant determined from the initial pressure and temperature.

Surface areas for two vessel surface types were considered: 1) horizontal surfaces and 2) vertical walls. The area of the horizontal surfaces is just $A_{acc,h} = 2 * \pi D_{acc}^2/4$ (two-times for both the liquid surface and the ceiling). The area of the vertical walls is

$$A_{acc,v} = \pi D_{acc} L_D$$

$$L_D = \frac{V_D}{A_{acc,h}}$$

$$A_{acc,v} = \pi D_{acc}\frac{V_D}{A_{acc,h}} = \pi D_{acc}\frac{\left(\frac{4A_{acc}}{\pi}\right)^{0.5} V_D}{D_{acc}A_{acc,h}} = 2\left(\frac{\pi}{A_{acc}}\right)^{0.5} V_D$$

Since kinematic viscosity is a strong function of pressure, a simple correlation was derived from property table data,

$\nu = 1.29/P^{0.991}$ m^2/s, where pressure is given in Pa

With the dependent parameters defined from initial conditions, Ref. 1, and above, the final FLASH metamodel rate of energy equation is

$$\dot{Q}_D = h\left(1.333A_{acc} + \left(\frac{\pi}{A_{acc}}\right)^{0.5} V_D\right)(T_w - T_g)$$

where

$$h = 0.15 * 0.029\left(9.8 * 0.73 * 0.0033|T_w - T_g|\frac{P^{0.99}}{1.26}\right)^{1/3}$$

and the gas temperature is calculated from that appearing as Eqn. 3.5-207 in Ref. 1,

$$T_g^{n+1} = T_g^n e^{\left(\frac{R}{C_v}\ln\frac{V_D^n}{V_D^{n+1}} + \Delta t\frac{R}{C_v P^n V_D^n}\dot{Q}_D^n\right)}$$

The wall temperature was initialized to the initial gas temperature and assumed not to change for the duration of simulations.

Benchmark to RELAP5-3D

As a software verification and validation (V&V) exercise, a RELAP5-3D model was created to align with the FLASH metamodel described in the previous sections. The scope of the exercise was to assess the RELAP5-3D prediction of several system performance figures-of-merit (e.g., pressure, temperature, flows, etc.) against the FLASH metamodel for a scenario involving the depressurization and refill of a vessel followed by long-term boiloff. This scenario addresses several phenomena relevant in LOCA analysis: critical flow, ECCS delivery, pressurizer flashing

Figure 1 presents a generic nodalization scheme of the input models used in the assessment with the RELAP5-3D component types identified within parentheses. This model includes a pressure vessel, an accumulator, a containment boundary condition, and interior connections. For the assessment, transient initiation involves the instantaneous opening of a valve to the low pressure (containment) boundary condition. In the RELAP5-3D model the vessel is represented by a two-volume PIPE component. It is attached to the containment, a TMDPVOL component, through a single junction. An accumulator, represented by ACCUM component, is attached to the volume center of the lower vessel.

As previously noted, to align the FLASH metamodel and RELAP5-3D model the critical transition mixture mass must be determined. This is done by executing the RELAP5-3D calculation first. The results from that calculation (i.e., the normalized mass fraction at the moment the top volume void fraction is less than 0.01) are used as the critical transition mixture mass in the FLASH metamodel. This was found to be 0.46, at the low end of the range determined experimentally. Figures 2 – 6 present the results from the two models from a 5” top-sided break for RCS pressure, normalized inventory, accumulator pressure, accumulator flow, and accumulator temperature. The two-sided coverage of the code-to-code error was found to be within 2% for the accumulator flow and temperature and less than 1% for the other figures-of-merit.

Conclusions

The FLASH code represents the foundation of today’s two-phase thermal-hydraulic systems codes. Whereas the physical models incorporated into FLASH were simplified to function on the computers of the 1960s, its underlying technical basis has remained valid despite the expansion of thermal-hydraulic knowledge since. In comparison to its modern descendent, constrained to the same modeling framework as its predecessor, the FLASH metamodel demonstrate remarkable alignment with RELAP5-3D.

Demonstrating this agreement makes a significant contribution to the software V&V effort. As verification, the physical models of FLASH and RELAP5-3D can be directly inspected side-by-side as theory and source code (both MATLAB and FORTRAN). In doing so, the comparisons provide independent verification of closure relationships that describe critical flow, reactor decay power, and other key processes. Further, the alignment of results of the two codes provides evidence that the numerical representations and computation advancement are appropriate for the event that is typically regarded as the most limiting design-basis accident.

Lastly, revisiting FLASH provides a unique connectivity to the community of RELAP code developers. No doubt the longevity of the RELAP program can be attributed to that first well-conceived model from that original team of thermal-hydraulic code developers.

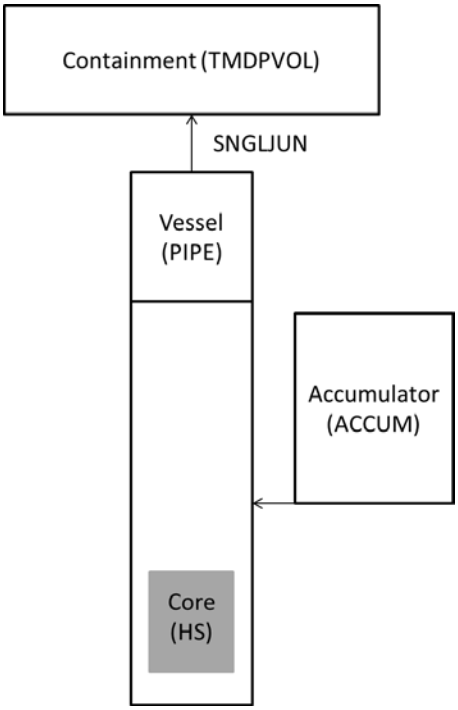

Figure 1 FLASH Metamodel and RELAP5-3D Model Nodalization

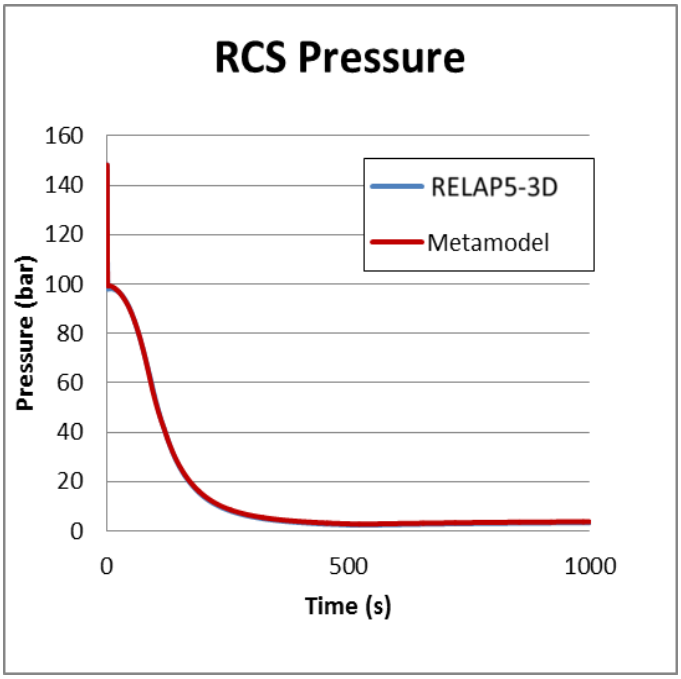

Figure 2 RCS Pressure, RELAP5-3D vs. Metamodel

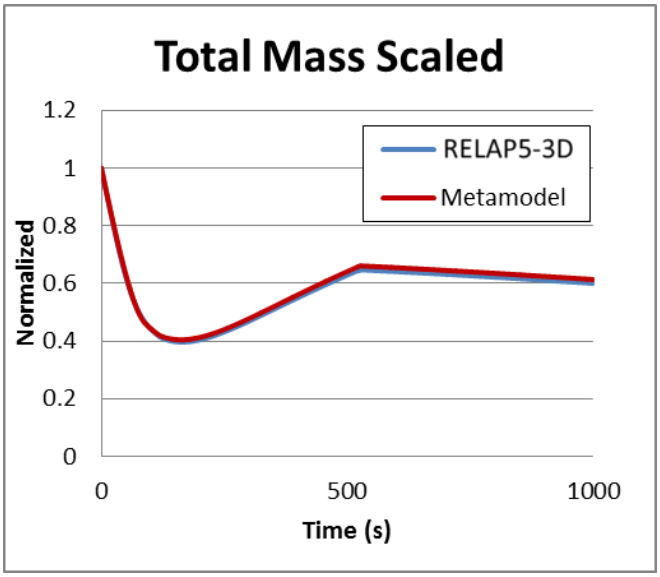

Figure 3 RCS Vessel Mass, RELAP5-3D vs. Metamodel

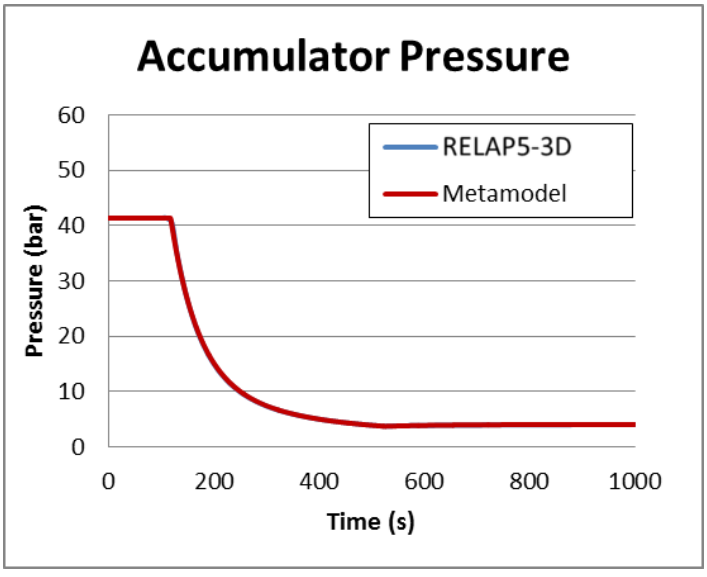

Figure 4 Accumlator Pressure, RELAP5-3D vs. Metamodel

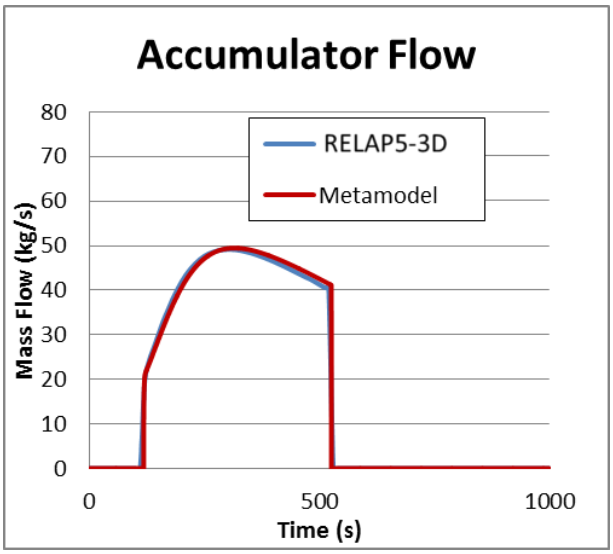

Figure 5 Accumulator Flowrate, RELAP5-3D vs. Metamodel

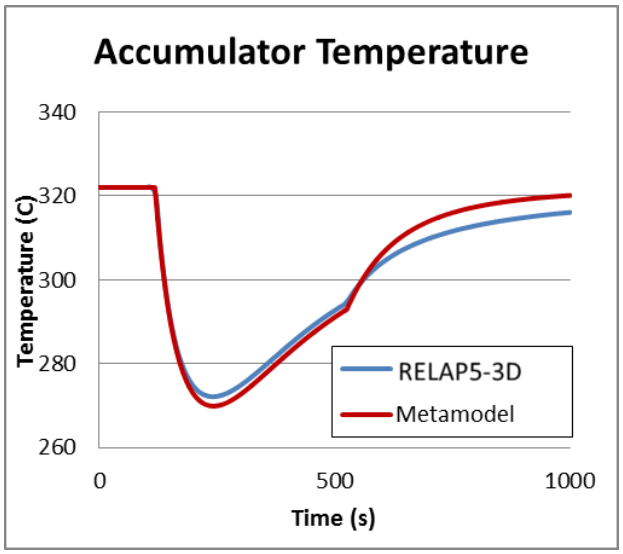

Figure 6 Accumulator Temperature, RELAP5-3D vs. Metamodel

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