Quantitative Phenomena Identification and Ranking Table (QPIRT) for Bayesian Uncertainty Quantification

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Quantitative Phenomena Identification and Ranking Table (QPIRT) for Bayesian Uncertainty Quantification

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Abstract – Propagating parameter uncertainty for a nuclear reactor system code is a challenging problem due to often non-linear system response to the numerous parameters involved and lengthy computational times; issues that compound when a statistical sampling procedure is adopted, since the code must be run many times. The number of parameters sampled must therefore be limited to as few as possible that still accurately characterize the uncertainty in the system response. A Quantitative Phenomena Identification and Ranking Table (QPIRT) was developed to accomplish this goal. The QPIRT consists of two steps: a “Top-Down” step focusing on identifying the dominant physical phenomena controlling the system response, and a “Bottom-Up” step which focuses on determining the correlations from those key physical phenomena that significantly contribute to the response uncertainty. The Top-Down step evaluates phenomena using the governing equations of the system code at nominal parameter values, providing a “fast” screening step. The Bottom-Up step then analyzes the correlations and models for the phenomena identified from the Top-Down step to find which parameters to sample. The QPIRT, through the Top-Down and Bottom-Up steps thus provides a systematic approach to determining the limited set of physically relevant parameters that influence the uncertainty of the system response. This strategy was demonstrated through an application to the RELAP5-based analysis of a PWR Total Loss of main Feedwater Flow (TLOFW) accident, also known as ‘feed and bleed’ scenario.

I. INTRODUCTION

This work discusses the first phase of a Bayesian uncertainty quantification procedure that will incorporate data from SETs and IETs to estimate the dominant contributors to the uncertainty in a figure of merit (FOM). A screening procedure to eliminate irrelevant parameters from the analysis of a transient in a safety analysis code is presented. Due to the complexity of a safety analysis code, it is crucial to first narrow the focus to only the most important processes contributing to a FOM. Uncertainty propagation is then performed through those dominant controlling phenomena. Traditionally, Phenomena Identification and Ranking Tables (PIRTs) based on expert opinion have been used to guide selection of the “most important processes”. But in the present context, uncertainty propagation must be performed on the dominant processes as “viewed” by the safety code itself. Therefore a PIRT-like methodology must be applied to rank processes from the safety code’s point of view.

The goal of the current work is to develop a Quantitative PIRT (QPIRT), which determines the dominant processes directly from the code output. This gives a time and spatial history of the processes that the safety code considers to be controlling the response of the FOM.

The initial development of the QPIRT was presented in Reference 1, demonstrating the application to a LB-LOCA example1. This work builds on that approach, formalizing the QPIRT procedure to examine the entire system not just an individual component, then applying it to a PWR Total Loss of main Feedwater Flow (TLOFW), or “feed and bleed” scenario.

II. QPIRT METHODOLOGY OVERVIEW

The QPIRT process consists of two primary steps, with the overall goal of identifying parameters that significantly influence the FOM for a specific transient of interest. The first step, the Top-Down step, determines which physical processes dominate the value of the FOM,
by focusing on the governing equations used in the safety code (the two-fluid six equation model in RELAP5, for example). The second step, the Bottom-Up step then examines in detail the dominant processes identified by the Top-Down step by analyzing the specific correlations used in the safety code to model those processes. Specific “tunable” parameters for each correlation are then identified, as well as relationships to other processes. Together, the Top-Down and Bottom-Up steps ensure that only physically relevant parameters are chosen for uncertainty propagation.

The Top-Down step itself consists of several hierarchical length scales. This approach is similar to the hierarchical scales used in the Zuber Pi-group approach. The multiple scales are required because the physical phenomena governing the whole primary loop response may be different from the ones governing flow and heat transfer along the hot fuel rod within the core, for example. The multiple scales used in the QPIRT methodology consist of local (or cell volume) level, component, and system level. For each scale, the governing equations are cast in control volume balance form, as explained in the next section.

With the local level scale capturing phenomena directly impacting the FOM, the higher level scales are required to capture indirect effects from components throughout the rest of the system. The component level scale has results from each cell in a particular component volume averaged together. The system level scale then has results from individual component volumes averaged together over specific component groups (for example if there are several pipe component sections in the hot leg). The system level balance equations therefore ensure the dynamic behavior of the system as a whole is properly characterized.

III. TOP-DOWN BALANCE EQUATIONS

The Top-Down step focuses on control volume balance formulations of the governing equations in the safety code. The local level consists of identifying relevant ‘constituents’ (e.g. clad, fuel, coolant) involved in the transient and formulating appropriate balance equations consistent with the safety code. The equations will be problem dependent at the local level since the physical phenomena involved depend on the specific FOM of interest. For example, if clad oxidation rate is the FOM, different local level equations will be used than if max Peak Clad Temperature (PCT) is the FOM.

The following equation formulations will be given for cases where max PCT is the FOM, such as for the feed-and-bleed transients studied here. At the local level the four constituents involved are the clad, fuel, liquid phase and vapor phase.

### III.A Local Level Equations

At the local, or cell, level the following energy control volume balance equations are used. For the clad:

\[
\frac{d}{dt} [V (\rho cT)_C] = -\dot{Q}_{C-L} - \dot{Q}_{C-V} + \dot{Q}_{F-C} 
\]  

(1)

For the fuel:

\[
\frac{d}{dt} [V (\rho cT)_F] = \dot{Q}_{GEN} - \dot{Q}_{F-C}
\]  

(2)

The general control volume internal energy equation for either phase from the RELAP5 Manual (taken from RELAP5 Manual Vol. 1 Section 3.1.10.1.1) is:

\[
\frac{d}{dt} (\alpha_k \rho_k u_k V) = \sum_j (\alpha_k \rho_k u_k v_k) j
\]

\[
= \dot{Q}_V V + \dot{Q}_V
\]

\[
- \left[ P \frac{d\alpha_k}{dt} + \sum_j (PA\alpha_k v_k) j \right] + h_i V
\]

\[
+ D_k V
\]  

(3)

Note that the symbol \( V \) in Eq. (3) denotes the coolant cell volume, while the same symbol in Eq. (1) and (2) denotes the clad and fuel volumes, respectively. The summation terms in Eq. (3) are the sums of the convective internal energy flowing and flow work into and out of the control volume at the junction faces.

The processes in equations (1)-(3) will be defined in the subsequent sections.

### III.A.1 Clad Energy Equation

Equation (1) simply states that the time rate of change of the volume averaged internal energy of the clad is the balance of the heat transferred between the clad-to-liquid, clad-to-vapor and fuel-to-clad. Applying Newton’s law of cooling, the heat transfer processes can be expressed in terms of heat transfer coefficients:

\[
\frac{d}{dt} [V (\rho cT)_C] = -h_L S_{CO}(T_{CO} - T_L) - h_V S_{CO}(T_{CO} - T_V) + h_{gap} S_{gap}(T_{FO} - T_{CT})
\]

(4)

The heat transfer between the fuel and clad is represented by the heat transfer through the gap using the gap conductance \( h_{gap} \) and effective gap heat transfer area \( S_{gap} \). For cases where the FOM is the PCT, the outer clad
temperature, $T_{CO}$ is solved for from Eq. (4). First define the area heat transfer coefficients:

$$H_L = h_L S_{CO}, \ H_V = h_V S_{CD}, \ H_{GAP} = h_{GAP} S_{GAP}$$  \hspace{1cm} (5)$$

As well as the effective heat transfer coefficient acting on the outer clad:

$$H_{CO} = H_L + H_V$$  \hspace{1cm} (6)$$

Thus giving the outer clad temperature to be:

$$T_{CO} = \frac{H_{GAP}}{H_{CO}} (T_{FO} - T_{CI}) + \frac{H_L}{H_{CO}} T_L + \frac{H_V}{H_{CO}} T_V - \frac{1}{H_{CO}} \frac{d}{dt} [V(\rho_c T)_C]$$  \hspace{1cm} (7)$$

Equation (7) shows that the temperature values associated with each process as well as the fuel thermal capacitance are scaled by the effective heat transfer coefficient acting on the coolant side of the clad.

**III.A.2 Fuel Energy Equation**

Equation (2) compares the internal heat generation rate in the fuel with the heat transfer rate to the clad. Using the definitions defined previously, Eq. (2) is used to solve for the associated temperature for the fuel-to-clad heat transfer:

$$(T_{FO} - T_{CI}) = \frac{\dot{Q}_{GEN}}{H_{GAP}} - \frac{1}{H_{GAP}} \frac{d}{dt} [V(\rho_c T)_F]$$  \hspace{1cm} (8)$$

The fuel-to-clad heat transfer rate is thus associated with the temperature jump across the gap. Equation (8) examines the fuel’s contribution to that temperature jump by scaling the heat source term and fuel thermal capacitance by the effective heat transfer coefficient through the gap.

**III.A.3 Phase Temperature Energy Equations**

The heat transfer rate between the clad and phase were defined in Section III.A.1. The remaining processes on the right-hand-side (RHS) of Equation (3) are given as (using RELAP5 notation), for the liquid phase:

$$\dot{Q}_l V = [H_{If} (T_S (P_s) - T_l) - \frac{(1+\epsilon)}{2} \Gamma_w (h_{k_l} - h_l)] V$$  \hspace{1cm} (9)$$

$$D_S V = DISS_f V = V (\alpha_p v^2)_{FWF}$$  \hspace{1cm} (10)$$

$$h_l TV = -[\Gamma_{lg} h_{lg}^* + \Gamma_w h_l] V$$  \hspace{1cm} (11)$$

And for the vapor phase:

$$\dot{Q}_v = \left[ H_{iv} (T_S (P_s) - T_v) - \left(\frac{1+\epsilon}{2}\right) \Gamma_w (h_{k_v} - h_v) \right] V$$  \hspace{1cm} (12)$$

$$D_S V = DISS_f V = V (\alpha_p v^2)_{FWF}$$  \hspace{1cm} (13)$$

$$h_t TV = \left[ \Gamma_{ig} h_{lg}^* + \Gamma_w h_t \right] V$$  \hspace{1cm} (14)$$

In the interfacial heat transfer terms given by Eq. (9) and (12), the first term on the RHS in the bracket represents the interfacial heat transfer in the bulk fluid, while the second term represents the interfacial heat transfer in the region “near the wall”. Likewise, in the mass transfer terms given by Eq. (11) and (14), the first term on the RHS in the brackets models the mass transfer in the bulk fluid, while the second models the mass transfer “near the wall”.

The heat transfer rate with the clad and the bulk fluid interfacial heat transfer are used to define a total effective heat transfer coefficient acting on each phase. For the liquid this is given as:

$$\dot{H}_{l tot} = H_L + H_{lv} V$$  \hspace{1cm} (15)$$

And for the vapor phase:

$$\dot{H}_{v tot} = H_V + H_{lv} V$$  \hspace{1cm} (16)$$

Using the above definitions, Eq. (3) is solved for each phase temperature. The liquid phase temperature is given as:

$$T_L = -\frac{1}{\dot{H}_{l tot}} \frac{d}{dt} (\alpha_l \rho_l u_l V) - \frac{1}{\dot{H}_{l tot}} \sum_j [A_{\alpha_j} \rho_l u_l V_j] - \frac{V}{\dot{H}_{l tot}} \left[ \left(\frac{1+\epsilon}{2}\right) \Gamma_w (h_{k_l} - h_l) + V \frac{H_{If}}{\dot{H}_{l tot}} T_S (P_s) + \frac{H_l}{\dot{H}_{l tot}} T_{CO} \right.$$

$$- \left. \frac{PV}{\dot{H}_{l tot}} \frac{d}{dt} \sum_j \left( \frac{1}{\dot{H}_{l tot}} \sum_j \frac{\alpha_j}{\alpha_l} \right) \sum_j [P A_{\alpha_j} V_j] + \frac{V}{\dot{H}_{l tot}} \Gamma_{lg} h_{lg}^* - \frac{V}{\dot{H}_{l tot}} \Gamma_w h_l \right] V$$  \hspace{1cm} (17)$$

And for the vapor phase temperature:

$$T_v = -\frac{1}{\dot{H}_{v tot}} \frac{d}{dt} (\alpha_v \rho_v u_v V) - \frac{1}{\dot{H}_{v tot}} \sum_j [A_{\alpha_j} \rho_v u_v V_j] - \frac{V}{\dot{H}_{v tot}} \left[ \left(\frac{1+\epsilon}{2}\right) \Gamma_w (h_{k_v} - h_v) + V \frac{H_{If}}{\dot{H}_{v tot}} T_S (P_s) + \frac{H_v}{\dot{H}_{v tot}} T_{CO} \right.$$

$$- \left. \frac{PV}{\dot{H}_{v tot}} \frac{d}{dt} \sum_j \left( \frac{1}{\dot{H}_{v tot}} \sum_j \frac{\alpha_j}{\alpha_l} \right) \sum_j [P A_{\alpha_j} V_j] + \frac{V}{\dot{H}_{v tot}} \Gamma_{lg} h_{lg}^* - \frac{V}{\dot{H}_{v tot}} \Gamma_w h_l \right] V$$  \hspace{1cm} (18)$$

**III.A.4 Weighted Contributions**

As seen in each constituent’s energy equation, the various processes are scaled by the effective heat transfer
coefficient acting on that particular associated temperature value. The value of each term in the Eq. (7), (8), (17), and (18) (the equations that solve for each associated temperature value) is considered to represent the contribution onto the FOM from a particular physical phenomena. Each term is then scaled, or weighted by the sum of absolute value of each term in the equation, thereby defining the weighted contribution of each physical phenomenon on the FOM. For example, for the clad-to-liquid heat transfer process, the associated weighted contribution is:

\[ W_L = \left| \frac{\dot{h}_{ec}(T_{fo} - T_{co})}{\dot{h}_{co}} \right| + \frac{1}{\dot{h}_{co}} \frac{\partial}{\partial t} \left[ \rho \left( \rho u \right) \right] \]  

(19)

Weighted contributions for the remaining physical processes in the clad energy equation as well as in the other constituent energy equations are defined similarly.

The phase energy equations, however, complicate the weighted contributions because of the convective energy flow terms. Convective energy outflow terms are considered “effects” from the various heat transfer processes in a cell, not a “cause”. Therefore, the convective energy outflow terms are neglected from the weighted contribution denominator terms. This assumption can be justified using the method of characteristics.

III. B Component and System Level Equations

The component- and system-level balance equations are obtained by summing up all the local-level and component-level balance equations, respectively. To be general, the following system-level equations will represent the number of component groups in the system by just labeling the summation term with “ALL”. Also, from looking at Eq. (3), summing up around the entire system cancels out the inflow and outflow terms at all locations except at system-wide source and sink locations (for example, flow from the emergency core cooling system (ECCS) or flow out of a break). The source and sink flow terms will be represented by “Δ” to show it is the difference between the system wide inflow and outflow terms.

III.B.1 Phase Energy Equations

The system-level phase energy equations follow directly from the local-level phase energy equation, given by Eq. (3). After computing the component-averaged process values and then component-group averaged process values and summing up around the entire system, the system level phase energy equation is given by:

\[ \sum_{n} \frac{d}{dt} \left[ (\alpha_k \rho_k u_k) V_k \right] + \Delta \left[ (\alpha_k \rho_k u_k v_k)_{sys} \right] = \sum_{n} \left[ (\dot{Q}_{lw}) V_n \right] + \sum_{n} \left[ (\dot{Q}_{h}) V_n \right] - \sum_{n} \left[ \left( P \frac{d \alpha_k}{dt} \right) V_n \right] - \Delta \left[ (P \alpha_k v_k)_{sys} \right] + \sum_{n} \left[ (h_{i} \Gamma) V_n \right] + \sum_{n} \left( D_{i} V_n \right) \]  

(20)

The subscript n denotes a particular component group.

Unlike the local level equations, weighted contributions to a specific value are not computed for the system level energy equations. Instead, a normalized fractional contribution is computed by scaling each term in Eq. (20) by the sum of the absolute values of all the terms. Doing this allows the max possible value of a fractional contribution at any timestep to be 1. The largest magnitude fractional contribution terms are then considered to dominate the system average phase energy at that particular time.

III.B.2 Phase Momentum Equations

Since the system level equation results from summing up the various component groups in the system, the individual cell volume momentum equation will first be described. The different processes will be defined at the cell level with the corresponding system level processes defined just as in the system energy equation. The phase control volume balance momentum equation in a particular cell is:

\[ \frac{d}{dt} \left( \alpha_k \rho_k V_k \right) = \sum_{j} \left( \alpha_k \rho_k v_k \right)_{j} + \Delta \left[ P \alpha_k V_k \right] = F_{wk} + F_{formk} + F_{visc,sk} + F_{VMk} - \sum_{j} \left( \alpha_k \rho_k V_k \right)_{j} + \Gamma_{sk} V_k + \left( \alpha_k \rho_k \right) B_z \]  

(21)

Equation (21) is simply a force balance between all the forces acting on a particular phase in a cell volume. The first term on the LHS is the phase inertia and the second term is the acceleration of the phase at the control volume boundaries. The first three terms on the RHS of Eq. (21) are the wall friction, form loss, and interfacial friction forces, respectively. The fourth term is the virtual mass force acting on phase k. The fifth term is the pressure force acting at the boundaries of the control volume. The
sixth term is the momentum transfer due to mass exchange at the interface and the last term is the body force.

The system level phase momentum equation is set up just as the system level phase energy equation. Once the component group average values are computed and the component groups are summed up around the entire system, the system level phase momentum balance equation becomes (using the same notation discussed for the system level phase energy equations):

\[
\sum_{n}^{ALL} \frac{d}{dt} \left( (\alpha_k \rho_k v_k)_{n} V_n \right) + \Delta \left( (A \alpha_k \rho_k v_k v_h)_{sys} \right) = \sum_{n}^{ALL} [F_{wk}] + \sum_{n}^{ALL} [F_{form,k}] + \sum_{n}^{ALL} [F_{visc,k}] + \sum_{n}^{ALL} [F_{vM,k}] - \Delta \left( (PA \alpha_k)_{sys} \right) + \sum_{n}^{ALL} [(\Gamma v_{sk})_{n} V_n] + \sum_{n}^{ALL} ((\alpha_k \rho_k) B z)_{n}
\]

(34)

Fractional contributions are similarly computed for the system level phase momentum equation.

IV. FEED AND BLEED TRANSIENT MODEL

IV.A RELAP5 Model

The QPIRT methodology described above was applied to a total loss of main feedwater (TLOFW) accident with subsequent feed and bleed. The model represents a four loop PWR of nearly 3500 MWth nominal power. The core is modeled with three channels, a core averaged channel, a hot assembly channel, and a hot rod channel. The ECCS is modeled by including a safety injection (SI) line in each loop. The number of Power Operated Relief Valves (PORVs) to open was selected to be consistent with the PORV flow area of standard four loop PWR plants and similar power levels. From a literature search the flow area was chosen to simulate three PORVs being open \(^4,6\).

IV.B Results

The transient was simulated by forcing a shut off of the main feedwater flow to the secondary side steam generators five seconds after the start of the simulation. Thirty seconds later the reactor was tripped. PORV and safety relief valves (SRVs) pressure set points were set to be consistent with the literature\(^4,6\). Once the primary system pressure reaches those set point values, the rapid opening and closing of the PORVs and SRVs maintain the system pressure at the set point values, while the system continues to heat up. If there is no operator initiated bleed through the PORV the pressure set points control the depressurization rate. Thus, the system pressure remains high and there is no way for the ECCS to inject into the primary system through the SI lines once the primary system begins generating vapor and uncovering the core. Operator action was modeled as a RELAP5 TRIP function that forced the PORV to remain open after a certain point in time. This time was varied until a limiting case was found. The limiting case is defined as being the case with the last possible time for operator initiated bleed to occur without the max PCT going above the NRC limit of about 1478 K (2200 °F). Results showed that the max PCT crosses the limit if the PORVs are forced open 40 minutes after loss of main feedwater flow, the limiting case is therefore defined as operator initiated bleed occurring at 39 minutes.

IV. QPIRT ANALYSIS

Clad temperature results show that three distinct time phases occur during the TLOFW accident. These three time phases are explicitly labeled in Figure 1, which depicts the PCT results just for the limiting case of interest. Time Phase I spans from the start of the transient to about 50 minutes. Between about 50 minutes and nearly 75 minutes is Time Phase II, and Time Phase III occurs from nearly 75 minutes to the end of the transient. QPIRT results will be given in each time phase. The Top-Down local level analysis includes the dominant processes over a particular time phase that significantly influence the clad temperature, fuel temperature liquid phase temperature and vapor phase temperature. The system level analysis gives the processes that significantly influence the system wide phase energy and phase momentum during a particular time phase.

A significant process was considered to be any process whose weighted contribution or fractional contribution was at least 10%. This value was chosen arbitrarily just for this work and a sensitivity analysis to this threshold value is discussed later on in Section VI.

For the limiting case of interest the PCT occurs in cell 11 of the hot rod channel. Thus, all local level results are from this cell location in the hot rod channel.
Figure 1: Limiting Case Clad Temperature in Cell 11 Where max PCT Value Occurs. Time Phases are also labeled in the Figure.

V.A Local Level Top-Down Results

The Local Level Top-Down significant processes are given in Table I and the System Level Top-Down significant processes are given in Table II. The columns in Table I represent the significant processes that influence that particular constituent’s temperature. The analysis starts with the clad temperature. For example, in Time Phase I, the only significant process that influences the clad temperature is the heat transfer to liquid. Thus, in Time Phase I the Fuel and Vapor constituent processes can be ignored and the processes that influence the liquid phase temperature are examined. These significant processes were determined by computing the weighted contributions for each of the constituents. In the following sections the only plot shown for the weighted contributions will be for the clad temperature. This plot will be illustrative of how the significant processes are determined for the other constituents as well.

For convective energy flow terms, “bottom” means the flow goes through the bottom junction connected to the cell volume. “Top” therefore means the flow comes through the top junction and “cross-flow” means the flow comes through the junction connected to the adjacent hot assembly channel.

### TABLE I

Local Level Top-Down Results

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<tr>
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</thead>
<tbody>
<tr>
<td>I</td>
<td>Clad-to-liquid heat transfer</td>
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<td>Convective energy flow, interfacial heat transfer</td>
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<td>Internal heat generation, fuel thermal capacitance</td>
<td>Interfacial heat transfer, convective energy flow, liquid-phase thermal capacitance</td>
<td>Convective energy flow (both axial and cross)</td>
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<tr>
<td>III</td>
<td>Clad-to-liquid heat transfer</td>
<td>Irrelevant</td>
<td>Convective energy flow, interfacial heat transfer</td>
<td>Irrelevant</td>
</tr>
</tbody>
</table>

V.A.1 Clad Temperature Results

The weighted contributions to the clad temperature are shown in Figure 2. The weighted contributions were computed using Eq. (19) for each process. These results are used to determine the significant processes given in Table I for the Clad Temperature results. The Clad-to-Liquid heat transfer completely dominates the clad temperature value during Time Phases I and III, as shown by that particular weighted contribution value being near 1. Time Phase II corresponds to when that cell location in the hot rod channel has become uncovered. There are two interesting aspects of Time Phase II. The first is the significant influence of the Clad Thermal Capacitance on the clad temperature value. A Bottom-Up analysis of the clad material volumetric heat capacity shows a major spike in the value corresponding to a crystalline phase transition of the Zircaloy material. The second interesting point is the role of the liquid phase on the clad temperature. It is difficult to see but at the times corresponding to the major temperature drops in Time Phase II at about 54 minutes and 62 minutes, the Clad-to-Liquid heat transfer rate becomes again significant. Thus, even though Time Phase II is characterized by lack of liquid locally, these two specific time instances have had enough liquid enter the fluid cell to allow the heat transfer rate to increase significantly. Thus, the liquid temperature equation must still be analyzed in Time Phase II to determine what processes significantly influence its behavior.
V.A.2 Fuel Temperature Results

Because only two processes are involved in the fuel energy equation, the Top-Down results are very simple. The internal heat generation dominates Time Phases I and III while Time Phase II is characterized by a balance of the heat source with the fuel thermal capacitance.

V.A.3 Liquid Temperature Results

The early part of the transient shows that the liquid temperature is dominated by the energy brought into the fluid cell via convection and the heat transfer rate with the clad. The contributions of these two processes stay roughly constant during the natural circulation phase of the transient, up until the liquid flow rate drops off and vapor begins to show up in the fluid volume, as indicated by the presence of interfacial heat transfer. Time Phase III interestingly enough shows that the clad-to-liquid heat transfer rate is balanced by interfacial heat transfer and convective energy flow through the top junction. This represents that the local liquid flow field has not steadied out even though the clad temperature results are very smooth during Time Phase III. Eventually though, by about 150 minutes into the transient, the local liquid temperature weighted contributions steady out as a balance between the heat transfer with the clad and interfacial heat transfer.

The liquid is important in Time Phase II only during those few key moments when the liquid presence causes a sudden spike in the heat transfer rate at the clad. So even though these two points in time are very short and sudden the processes that contribute to the liquid temperature will be important to the PCT. The interfacial heat transfer in the bulk fluid is always significant during this time period. At the two points in time that correspond to the sudden clad temperature drop, the liquid phase energy transient term becomes significant. Several minutes before these points in time, the convective energy flow through the bottom and cross-flow junctions also become significant. Interestingly, the heat transfer rate with the clad has an insignificant effect on the liquid temperature at both of these times. The clad therefore does not control the liquid phase temperature during Phase II even though at two very important times the liquid phase temperature impacts the clad temperature. This result is very different from Phases I and III where the clad and liquid phase temperatures are linked together.

V.A.4 Vapor Temperature Results

Time Phases I and III show that the vapor temperature is dominated by the balance between interfacial heat transfer and convective energy flow from the bottom junction. The heat transfer rate with the clad is balanced by convective energy flow through the bottom junction for a majority of Phase II, but also with convective energy cross-flow as well. Cross-flow links the smaller hot rod channel with the larger hot assembly channel.

The convective energy flow terms represent energy brought into the local cell volume from another cell. This motivates the system level analysis by seeing what processes and component groups significantly influence the system level flow dynamics.

V.B System Level Top-Down Results

V.B.1 System Level Phase Energy Equation Results

Tables II shows the dominant physical phenomena that govern the system level phase energy equations. Since the same physical process can occur in multiple component groups at once, the locations where the particular process occurs is listed in the adjacent column in Table II.

The results from the system level energy equation relate directly to the known dynamics of the system throughout the transient. Early on in Time Phase I, there is an energy balance between the heat generated in the core and the heat transferred through the steam generators. However, once the secondary side of the steam generators dries out (since all feedwater was shutoff), the heat transfer through the primary side steam generators decreases dramatically, leading to an energy imbalance. This energy imbalance is captured in the system level liquid phase energy equation because the pressurizer energy transient term becomes significant once the heat transfer through the steam generators loses dominance. The pressurizer liquid energy transient term corresponds to the pressurizer filling up with liquid as the primary system heats up and the liquid expands. Once the pressurizer goes solid, liquid is ejected out the PORV. At this time more and more vapor begins to form in the primary system leading up to interfacial heat transfer and mass transfer terms becoming important. With the vapor phase, the primary dominant...
process is the convective energy outflow though the PORV. This makes sense and ties system level vapor energy equation to identifying when the PORV is opened to allow this to occur, which goes back to any uncertainty for when the operator can perform the action.

The system level energy equations results in essentially showing that the Bottom-Up step must be performed on the correlations in RELAP that model: wall-to-liquid heat transfer, interfacial heat transfer, and mass transfer. But it should be noted, the location where each process occurs is important because different components may be in different flow regimes even if the physical process occurring is nominally the same, which results in different correlations to investigate.

<table>
<thead>
<tr>
<th>TABLE II</th>
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<tr>
<td>System Level Energy Equation Top-Down Results</td>
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</table>

V.B.2 System Level Phase Momentum Equation Results

The same analysis was carried out for the system level phase momentum equations. Table III gives the significant processes that influence the system level phase momentum equations and is setup the same way as Table II.

At steady-state the pump provides the largest fractional contribution value, followed by the wall friction in the lumped loop steam-generator primary side tubes. Table III does not give the fractional contribution values, but it is important to note here that these two processes alone do not provide even half of the total fractional contribution (a value of 1). This shows that there will be a potentially substantial influence on the number of processes considered significant by the choice of the importance threshold value. The results in both Tables III and II are determined using an importance threshold value of 10%. The next section will go into further detail analyzing the influence of varying that value.

Once the accident sequence begins, the main feature from the results, as shown in Table III, is the balance between interfacial friction forces and buoyancy forces. This balance is the main influence on the liquid momentum equation, while several other processes contribute significantly to the vapor momentum equation. The pressure force from the PORV represents the PORV opening up and the system depressurizing, which again is consistent with the dynamics of the problem.

<table>
<thead>
<tr>
<th>TABLE III</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Level Momentum Equation Top-Down Results</td>
</tr>
<tr>
<td>Time</td>
</tr>
<tr>
<td>Phase</td>
</tr>
<tr>
<td>I</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>II</td>
</tr>
</tbody>
</table>
VI. IMPORTANCE THRESHOLD VALUE SENSITIVITY

As stated previously, the threshold value for significance was rather arbitrarily chosen as 10%. Lowering the threshold value will allow more processes to be considered significant at a cost of adding more pieces to the Bottom-Up step. Ideally, the threshold value should give a minimal number of processes that still captures a major portion of the dynamics of the system response. The system level equations were reanalyzed using multiple threshold values ranging from 1% to the already chosen value of 10%. There are two key pieces of information here, the “fidelity” of the results and the total number of processes considered significant. The “fidelity” of the results refers to checking if the chosen significant fractional contributions sum up close to one. Obviously the closer that value is to one, the more accurately the significant processes represent the total system dynamics.

As described in the previous section, the “fidelity” of the system level liquid momentum equation is very low at the steady-state condition (time equals zero). Reducing the threshold value raises the fidelity by capturing the influence of form loss and wall friction in the core. But to get the fidelity of the significant processes to be greater than 80% the threshold value has to be as low as 2%, giving a total of about 15 processes to analyze in the Bottom-Up step just at the steady-state condition. The liquid level energy equation shows the opposite behavior at the steady-state condition, with the higher threshold value basically capturing the entire dynamics of the system. The difference in fidelity between the two equations comes simply from the fact that the energy equation has only three really dominant terms, the heat transfer in the core and the two steam generators. The momentum equation on the other hand, balances the two pumps with the wall friction and form loss in multiple component groups.

As the accident progresses however, the opposite is true, as the fidelity of the higher threshold values in the liquid momentum equation improves while it worsens for the liquid energy equation. But, the vapor energy equation becomes more important through Time Phase II, as described in the local level results. Even though there a several points in time where the higher threshold values capture less than 20% of the liquid energy equation, the liquid phase is not as important during those times anyway. The fidelity of the higher threshold values are better for the vapor energy equation but are still only near 50% during the first half of Time Phase II. These results suggest that the threshold value of 10% might be too high to use to ensure that enough of the key significant processes are captures throughout the entire accident sequence.

VII. BOTTOM-UP STEP

The Bottom-Up step analyzes each of the dominant physical processes from the Top-Down step to find the specific correlations that govern the FOM response. The procedure is the same for both the local and system levels, and essentially involves examining the RELAP5 manual to see which correlations are used during each specific time phase. The number of important correlations required for a single Top-Down physical process will depend on the number of flow regimes a particular cell and component experiences during the transient. Examining the flow regime transitions will then be important, but for now the work focused on just examining the Top-Down physical processes. Table IV gives the correlations identified from the RELAP5 manual considered important for the corresponding physical process. The importance threshold value of 10% was used here for demonstration purposes. Eleven different physical processes were identified from the Top-Down step (this number comes from viewing heat transfer to liquid in multiple components to be the same process for example) used a total of 25 different correlations. Three of which are material properties, including the Gap conductance model, as well as decay heat and pump models used in RELAP5. These 25 correlations are then the starting point for a statistical sampling procedure to propagate uncertainties through to the FOM.
TABLE IV
Bottom-Up Identified Important Correlations

<table>
<thead>
<tr>
<th>Physical Phenomena</th>
<th>Name of Correlations Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall-to-Coolant Heat Transfer</td>
<td>Dittus-Boelter, Churchill-Chu, Chen, Chen-Sundaram-Ozkaynak, Modified Bromley</td>
</tr>
<tr>
<td>Interfacial Heat Transfer – Near Wall</td>
<td>Saha-Zuber + Lahey + wall-to-coolant heat transfer correlations</td>
</tr>
<tr>
<td>Interfacial Mass Transfer – Bulk</td>
<td>Same as the interfacial heat transfer – bulk correlations</td>
</tr>
<tr>
<td>Interfacial Mass Transfer – Near wall</td>
<td>Same as the interfacial heat transfer – near wall correlations</td>
</tr>
<tr>
<td>Choked Flow</td>
<td>Ransom-Trapp</td>
</tr>
<tr>
<td>Wall Friction Factor</td>
<td>Zigrang-Sylvester approximation to Colebrook-White</td>
</tr>
<tr>
<td>Interfacial Friction</td>
<td>Zuber-Findlay, Kataoka-Ishii, Wallis Correlation/Ishii-Chawla, EPRI</td>
</tr>
<tr>
<td>Material Properties</td>
<td>Clad Thermal Capacitance, Fuel Thermal Capacitance, Gap Conductance Model</td>
</tr>
<tr>
<td>Decay Heat Model</td>
<td>1973 ANS Standard</td>
</tr>
<tr>
<td>Pump</td>
<td>Farman-Anderson Pump Model</td>
</tr>
</tbody>
</table>

VIII. CONCLUSIONS

The QPIRT methodology provides a systematic approach for identifying the physical phenomena and correlations that dominate the FOM response. Starting with the Top-Down step, the important physical processes from multiple hierarchical levels are identified from the governing equations used in the safety analysis code. This ensures that the Bottom-Up step only chooses correlations that are physically relevant to the problem at hand.

The QPIRT is the first part in an uncertainty propagation methodology that uses the safety code itself to identify which correlations will be sampled in the subsequent statistical uncertainty quantification phase. In addition, the QPIRT aids in determining which SETs and IETs to use for calibration purposes since the dominant physical processes as viewed by the safety analysis code are known.

NOMENCLATURE

- \( V \) Volume
- \( \rho \) Density
- \( c \) Specific heat
- \( T \) Temperature
- \( \dot{Q} \) Heat transfer rate
- \( \alpha \) Phase fraction
- \( u \) Internal energy
- \( v \) Velocity
- \( P \) Pressure
- \( h \) Heat transfer coefficient
- \( S \) Surface area
- \( H \) Area heat transfer coefficient
- \( FWF \) RELAP5 liquid viscous dissipation coeff.
- \( FWG \) RELAP5 liquid viscous dissipation coeff.
- \( \varepsilon \) RELAP5 near wall boiling marker
- \( W \) Weighted contribution
- \( F \) Force term
- \( B_z \) Body force term

Subscripts
- \( C \) Clad
- \( L \) Liquid
- \( V \) Vapor
- \( F \) Fuel
- \( \text{gap} \) Gap
- \( \text{GEN} \) Internal heat generation
- \( k \) Generic phase
- \( W \) Wall
- \( i \) Interfacial term
- \( \text{CO} \) Outer clad position
- \( \text{CI} \) Inner clad position
- \( \text{FO} \) Outer fuel position
- \( S \) Saturation property
- \( f \) RELAP5 liquid term
- \( g \) RELAP5 vapor term

ACKNOWLEDGEMENT

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REFERENCES

1. J. Yurko, J. Buongiorno, “Quantitative Phenomena Identification and Ranking Table (QPIRT) for Reactor