Using GOTHIC™ and RAVEN to Explore Thermal-Hydraulic System Response

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INTRODUCTION

GOTHIC has been used together with RAVEN to demonstrate the capabilities of the codes to work in unison using a sample Reactor Water Storage Tank (RWST) backleakage model. GOTHIC is a versatile and generally applicable software package developed by Zachry Nuclear Engineering. GOTHIC is capable of performing a wide range of complex thermal hydraulics analysis problems relevant to the nuclear industry. The RAVEN code, developed at the Idaho National Laboratory, is a generic software driver that can perform parametric or probabilistic analysis using an existing analsysis code. With RAVEN performing the input sampling, optimization, response surface tracking, and reduced order surrogate modeling, GOTHIC can now more easily use advanced analysis techniques such as uncertainty quantification and propagation, goal-seeking optimization, and investigating system response for a high number of input variations.

MOTIVATION AND BACKGROUND

The current US fleet of nuclear power plants is in the process of extending its lifetime beyond the original design basis and reducing costs throughout the industry in order to deliver the nuclear promise. To advance these causes while maintaining the paramount safety of the plant, engineers and plant managers will need to leverage modern software and algorithmic tools to more efficiently and effectively assess plant response. The Risk Informed Safety Margin Characterization (RISMC) approach aims to provide insights to decision makers through a series of simulations of the plant dynamics for differing input conditions (e.g. probabilistic analysis and uncertainty quantification). These insights will provide the best possible information for making informed safety margin management decisions. GOTHIC and RAVEN are two tools that can be used together to facilitate this transition.

GOTHIC and RAVEN Background

GOTHIC is a thermal hydraulics software package that has wide adoption across many areas of nuclear analysis. It solves the conservation equations for mass, momentum and energy for multicomponent, multi-phase flow in lumped parameter and/or multi-dimensional geometries. GOTHIC has several features that make it well suited to working together with RAVEN including: input modification through text files, output data files in flexible format, the ability to start and stop runs from command line interface, and a flexible and computationally efficient solution scheme that enables a large number of cases to be run within a manageable time frame. This analysis was performed using the latest released version, GOTHIC 8.3(QA)[1].

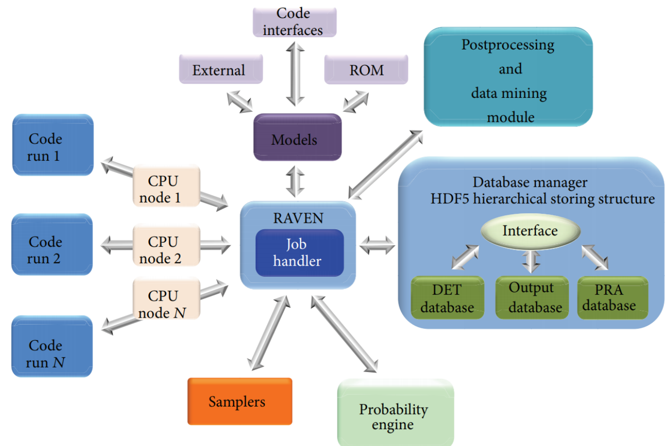

Fig. 1. RAVEN statistical framework[3]

RAVEN is a software framework that can perform parametric and stochastic analysis based on the response of complex modeling and simulation tools. RAVEN has the flexibility to be paired with almost any analysis code as long as the parameters being perturbed are accessible by input files or via python interfaces. RAVEN is capable of investigating system response and exploring input spaces using various sampling schemes such as grid, Latin hypercube, or Monte Carlo. However, the key value of RAVEN comes from the system feature discovery capabilities such as: constructing limit surfaces, separating regions of the input space leading to system failure, and using dynamic supervised learning techniques[2]. The general structure of how the RAVEN code operates is shown in Figure 1.

RWST Backleakage Sample Problem

This paper applies some of the methodologies from the RISMC approach as well as pairing GOTHIC with RAVEN using a Reactor Water Storage Tank (RWST) backleakage analysis as a sample problem.

Following a design-basis Loss of Coolant Accident (LOCA) the inventory in the RWST is used to provide emergency cooling inventory to the faulted primary cooling system. Once the RWST is depleted, the sump fluid is isolated and recirculated to provide decay heat cooling. However, there is a possibility for the sump fluid to leak back through the closed valves and enter the RWST above the waterline. Plants are required to evaluate the possible dose consequences of this backleakage. If the sump fluid is hot enough to flash to steam when it reaches the above-water inlet to the RWST, the dose released to the environment is potentially much higher and more difficult to analyze. GOTHIC is used

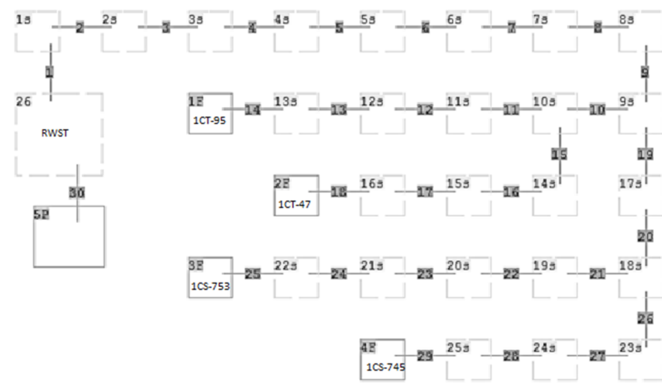

Fig. 2. Noding diagram for GOTHIC backleakage piping model

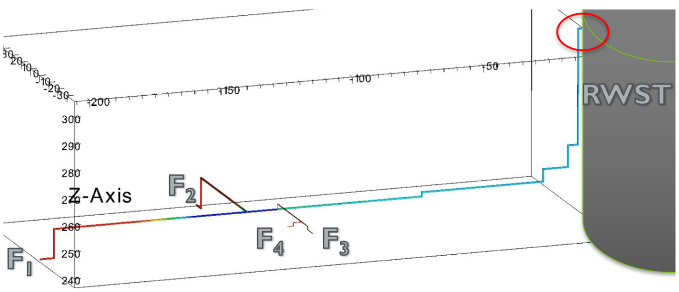

Fig. 3. Isometric view of leakage pathways with horizontal bends and elbows removed for clarity

to model the fluid mixing and heat losses in the RWST piping to evaluate the potential for hot sump fluid to travel back toward the RWST and the resulting temperature of that fluid when it enters the RWST. Higher leakage rates generally lead to higher temperatures at the RWST entrance. However, the complexity of the multiple leakage pathways mixing the cold fluid that was previously in the pipes with the hot fluid coming from the sump creates a system response that is highly non-linear. Figure 2 shows the GOTHIC noding diagram and Figure 3 shows an isometric view of the 4 leakage pathways and the above-water entrance to the RWST.

ANALYSIS AND RESULTS

Constructing limit surfaces is a technique that can be used to classify areas in the problem input space into two types. The space of inputs that lead to the system passing safety criteria, and those that lead to failure. For the RWST backleakage problem the concern is keeping the maximum fluid temperature at the entrance to the RWST below the boiling point. In this case we will use 98.89°C (210°F) as the upper limit with any case that predicts temperature below that as passing. Initially the problem was solved using dimensionality reduction and semi-automated iteration using only GOTHIC. The analysis has been repeated using RAVEN as a software driver for GOTHIC to provide independent confirmation of the two methods and assess potential advantages in accuracy, efficiency, or flexibility using the GOTHIC-RAVEN approach.

GOTHIC Approach

The system contains four valves which can each have independent leakage characteristics. Using a four dimensional brute force grid search technique would require many thousands of cases to fully characterize the input space with any usable fidelity. We therefore needed to find ways to reduce the dimensionality of the input space to make things more manageable.

First, it was assumed that multiplying all the flows by a scaling factor will always increase the peak temperature at the RWST inlet for scaling factors greater than 1.0 and always decrease the peak temperature for factors less than 1.0. This is reasonable since the same flow ratios will produce roughly the same mixing timings and lower total flow will give the water more time to cool before reaching the RWST. This does not immediately reduce the input dimensionality, but it does make it much easier to find and visualize the limit surface. The second assumption is that since two of the valves are close together in the piping system and there is very little difference in the results whether flow comes from one or the other. We will add them together and consider them as a single input in the space when constructing the surface. With these assumptions we can reparametrize the input space into the following terms:

$$F_T = F_1 + F_2 + F_3 \tag{1}$$

$$\alpha = \frac{F_1}{F_1 + F_2} \tag{2}$$

$$\beta = \frac{F_3}{F_1 + F_2 + F_3} \tag{3}$$

Where F_1, F_2, and F_3 are the flows through each leakage pathway and F_T is the sum of flow through all the leakage pathways. α and β are non-dimensional parameters used to reparametrize the inputs.

The specific forms of α and β were selected to generate the full range of possible flow ratios by varying each over the range 0 to 1. We can then use a grid of α and β values and iterate the parameter F_T to find the limiting total flow that produces output temperature just below boiling. This technique generates the limit surface in Figure 4

The advantage of this technique is that it generates a grid which can be easily evaluated to determine if any measured leakage configuration is likely to lead to boiling at the inlet to the RWST. The plant can use this grid when testing backleakage rates during an outage to quickly determine if the plant was ever in a potentially unsafe configuration when one or more valves is found to exhibit off-nominal behavior. One disadvantage with this approach is that it scales rather poorly. As the grid resolution increases many more cases are needed but not all of them are providing useful information.

RAVEN-GOTHIC Approach

The RAVEN-GOTHIC interface for this project uses a python wrapper script to facilitate the transfer of information between the two codes. The script perturbs the GOTHIC inputs by modifying a GOTHIC command file (.gcf) with the

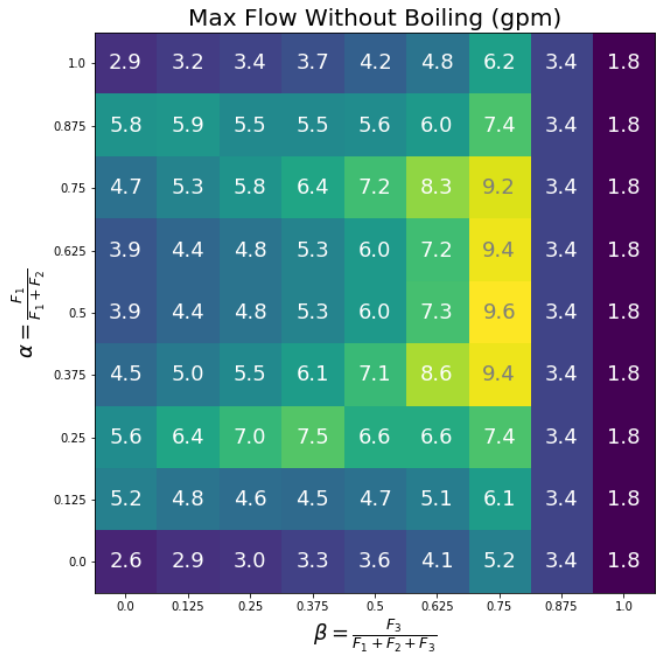

Fig. 4. Limit Surface of the maximum total flow that precludes boiling at the entrance to the RWST over non-dimensional parameters α and β in the original GOTHIC only approach

information generated for each case by RAVEN. It then executes the .gcf from the command line to modify and run the GOTHIC base model. Upon case completion, the wrapper script modifies the GOTHIC output data so that it will be in the form expected by RAVEN.

With this framework in place RAVEN can be used as a driver to perform a wide range of functions including forward sampling, adaptive sampling, generating reduced order models, data mining, and plotting, all using GOTHIC as the back-end analysis code. The limit surface search method from RAVEN was applied to the backleakage problem with a K-nearest neighbor algorithm acting as a reduced order model to accelerate the search. The temperature output results from the GOTHIC case runs are shown in Figure 5 and a scatter plot showing passed and failed cases from both the GOTHIC-evaluated cases and the reduced order model-evaluated cases is shown in Figure 6.

The visualization in Figures 5 and 6 turns out to be too cluttered to convey much information but it does at least communicate some of the complexity. Figure 7 shows an attempt to map the surface more clearly. The points just underneath the limit surface are mapped into two dimensions where position represents the portion of the total flow that comes from each valve and color represents the total flow rate. The corner points represent flow through only a single valve and the edges represent flow through two valves. Points in the middle represent some mixture of flow between all three valves. This figure shows the behavior of the surface across the different flow configurations much more clearly. The surfaces for both the original GOTHIC results from Figure 4 and the

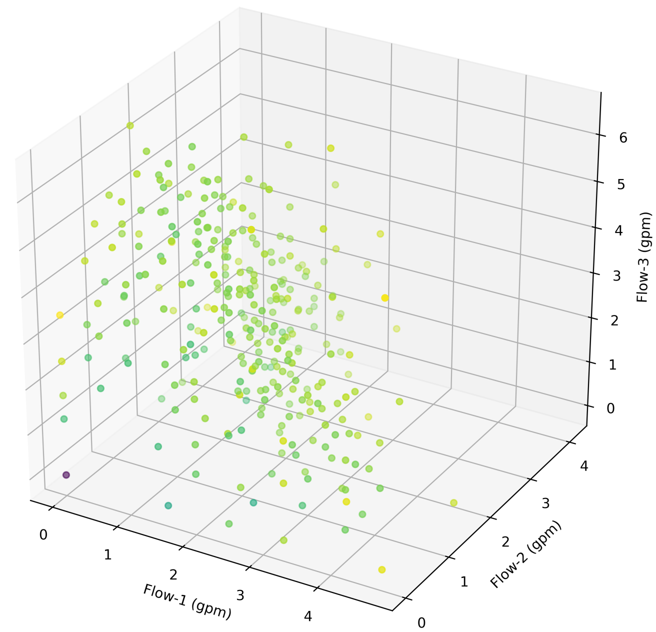

Fig. 5. Output peak temperature at RWST backleakage entrance from coldest (purple) to hottest (yellow) from RAVEN-GOTHIC limit surface search to find the limit surface boundary where the maximum RWST inlet temperature of 98.89°C (210°F) is reached over the three independent leakage flowrates

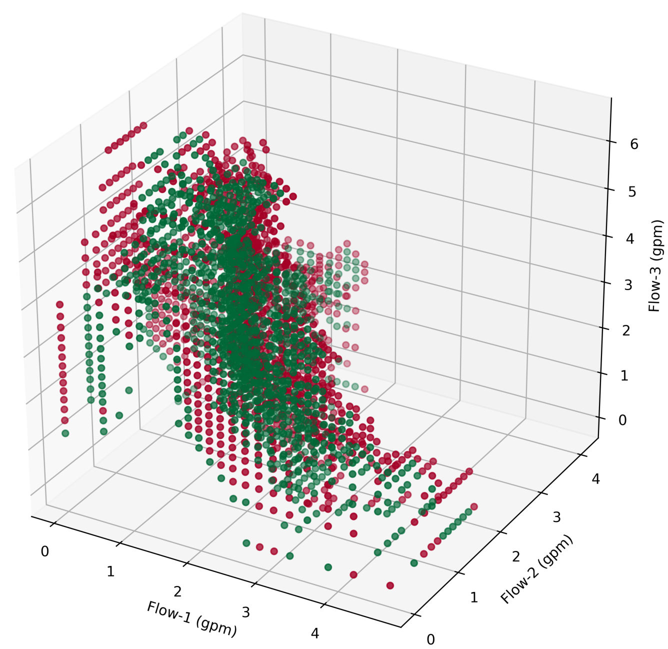

Fig. 6. Scatter plot from GOTHIC-RAVEN limit surface search with pass(green) and fail(red)

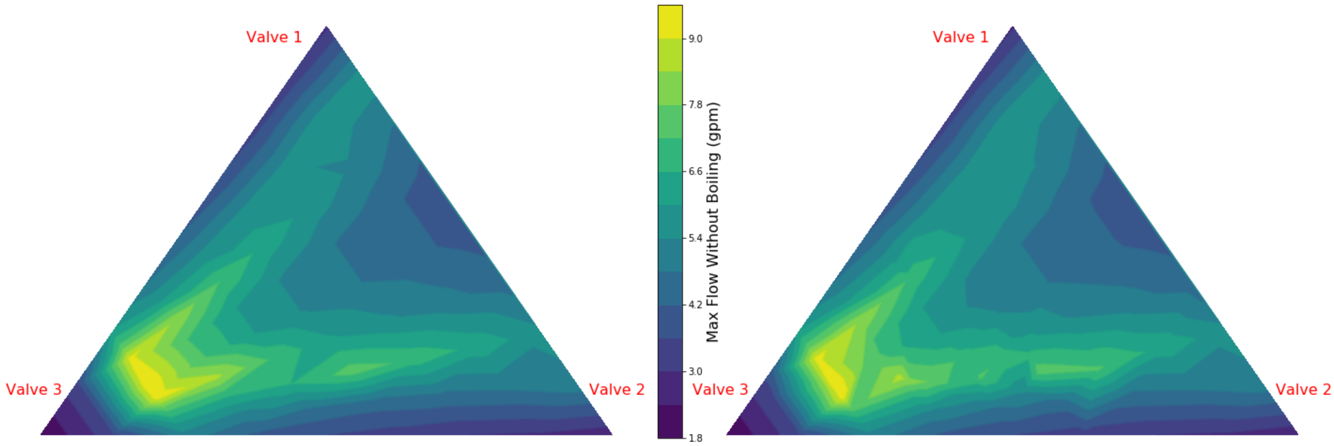

Fig. 7. Comparison of the GOTHIC iterative limit surface search(left) to the GOTHIC-RAVEN fully automated limit surface search(right). Corner points represent flow through a single valve, edge points - flow through two valves, and points within the triangle - some flow through all three valves

GOTHIC-RAVEN data from Figure 5 are presented to show any differences between the results. As expected, the two surfaces are very similar with the GOTHIC-RAVEN surface showing a bit more "noise" probably because of the random sampling of points rather than the grid-based sampling of the original which creates a smoothing effect.

CONCLUSION

This paper has demonstrated the process for using GOTHIC and RAVEN to determine the complex response of a thermal-hydraulic system over a range of input conditions. Also we have shown some techniques that can be used to simplify the visualization and understanding of the data that such a process can produce.

One limitation of this class of analysis is the amount of processing power and time applied to resolve the system response. As the physics of the underlying model become more complex and/or more input variables are investigated, the required number of cases and the processing time become large. A code with flexible spacial and temporal precision and high computational efficiency, like GOTHIC, is therefore well suited to leverage these techniques to solve a wide variety of problems.

There are many potential uses for this type of analysis including, multi-variable optimization, estimating total system reliability using Monte-Carlo methods, sensitivity studies, dynamic PRA, and dynamic event tree generation. The nuclear industry should look to take better advantage of these tools moving forward to help deliver the nuclear promise.

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