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Simulation of a PWR Residual Heat Removal System for Component Fatigue Monitoring

E. Lyles Cranford III[1] and Mark A. Gray[1]

1) Westinghouse Electric Company, LLC

ABSTRACT

Fatigue monitoring is used in aging management programs to assess structural integrity of key components in nuclear power plants. The accuracy of the fatigue monitoring results is directly influenced by the accuracy of the input data stream. For fatigue monitoring of a component, the input data consists of local temperatures, pressures, and forces that act on the local stress model. The simulations that generate these local loadings are driven by time-dependent plant process parameters taken from existing plant sensors and control inputs. These simulations are "reactive models" that respond to the changing input stimuli, and simulate a system's thermal-hydraulic and mechanical characteristics in terms compatible with the local stress models. This paper discusses a method to model these complex systems by simplifying them into independent and dependent processes that, when combined effectively, represent the whole. The method is applied to create a simulation of a typical Pressurized Water Reactor Residual Heat Removal system that can predict the local thermal-hydraulic and mechanical loads acting on the auxiliary piping nozzles on the Reactor Coolant System main loop.

INTRODUCTION

As nuclear power plants continue to operate into the later term of their design life and also pursue life extension and license renewal, fatigue monitoring is a method used to assess component life in nuclear plant aging management programs. Nuclear plant component fatigue monitoring is typically accomplished through a multi-faceted approach, consisting of elementary transient cycle counting tasks as well as monitoring actual transients and/or fatigue usage at controlling component locations [1]. The latter is accomplished by models that provide the elements needed to calculate fatigue usage in a component in a manner consistent with the ASME fatigue calculation methods used in plant component design, but not necessarily using the same techniques as used in design. Fatigue monitoring models are made up of three basic elements. The first is the determination of a composite set of input loadings on the component. The second element is the calculation of component stresses at controlling locations from the input loadings. The third is the calculation of fatigue usage from the stress peaks and valleys determined from the stress histories.

Fatigue monitoring models resemble design analysis models for the second two elements. For the input loadings, design analysis approaches are not adequate for components where fatigue is limiting. Design transients typically model the temperature loads conservatively with respect to thermal shock stress. In addition, contributions of moment, pressure, and temperature loads are typically combined conservatively. Especially for piping moment loads, the phasing with the fluid temperature and pressure transients is not easily determined.

The goal of fatigue monitoring is to track the effects of actual loadings on component fatigue to accurately assess the component life. Therefore, conservatism inherent in the design analysis approaches is not desired in fatigue monitoring models. It is more desirable to use detailed load histories that account for the effects of actual plant transient loadings on the stress histories in the component. It is advantageous to predict local loading on components using plant computer data points that are already available and functions that transform the global plant computer data into the local component loads (Global-to-Local, or "GTL transformations"). Use of such techniques avoids installation of additional sensors in the plant to support the monitoring system.

This paper illustrates a method to break down a complex system into primary process models and combine the simplified models in a systematic fashion, to create an overall simulation that appropriately predicts component loadings as a function of plant computer inputs and system characteristics. The example used is a Residual Heat Removal System in a Westinghouse four-loop nuclear power plant. System characteristics were modeled to predict the loadings and stresses in the branch nozzles on the main reactor coolant loop piping. Modeling tools available in the WESTEMS™ diagnostics and monitoring software were used to develop the system simulations [2]. First the modeling tools used are described, and then the method used to develop the overall model is discussed. Results of sample testing of the effectiveness of the model are also provided.

PROBLEM DESCRIPTION

The Residual Heat Removal (RHR) system employed in four loop pressurized water reactor systems is a complex system of pumps, valves, and piping that shares common piping and nozzles at the reactor coolant loop piping interface. The figure below shows one example of such a system:

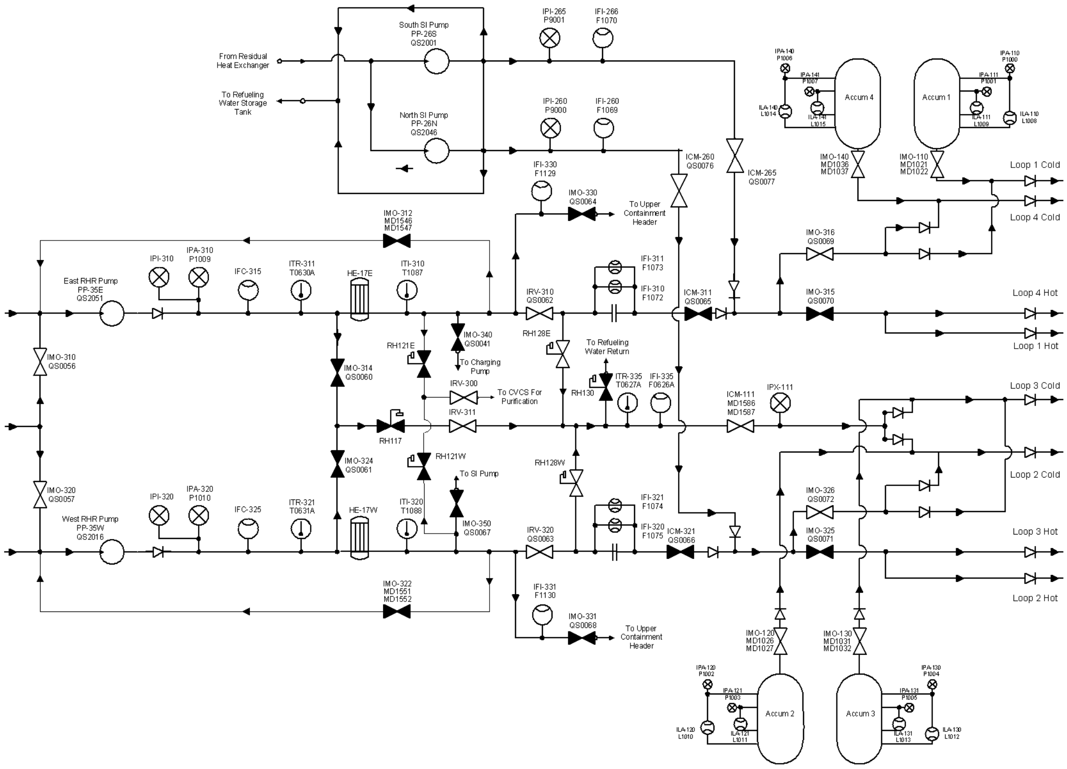


Figure 1 Residual Heat Removal System

The system's primary task is the removal of decay heat from the reactor's core. The system shares Reactor Coolant System (RCS) piping nozzles with the plant's emergency core cooling systems. Piping from the high pressure safety injection system and the plant's four accumulator tanks link up with the RHR system piping in common manifolds that lead to the primary coolant loop piping. The goal was to develop a structured method of simulating this and similar complex systems with enough accuracy to reasonably predict the local thermal hydraulic conditions at the RCS branch line nozzles.

There are no direct sensors that measure the local thermal hydraulic conditions at the RHR/RCS piping nozzles. There are process parameters that are used in the control of these systems that can be used to control certain boundary conditions in the simulation. One of the first steps in developing the simulation is to simplify the system down to only those elements that contain sensors and/or control system parameters. Certain assumptions are made in the development of the reduced system that is simulated. These include the following:

- The RHR feed into the Safety Injection (SI) is only used during low temperature operations; therefore it can be ignored as a feed source in the reduced system.
- The balance of the reduced system configuration is adequate only for the purpose of determining conservative thermal loads on the RCS loop piping nozzles.
- The available plant sensors that provide flow and temperature in a common header (segment 15 in figure 2) effectively account for heated RHR return flow from either RHR train.

The figure below shows the reduced model:

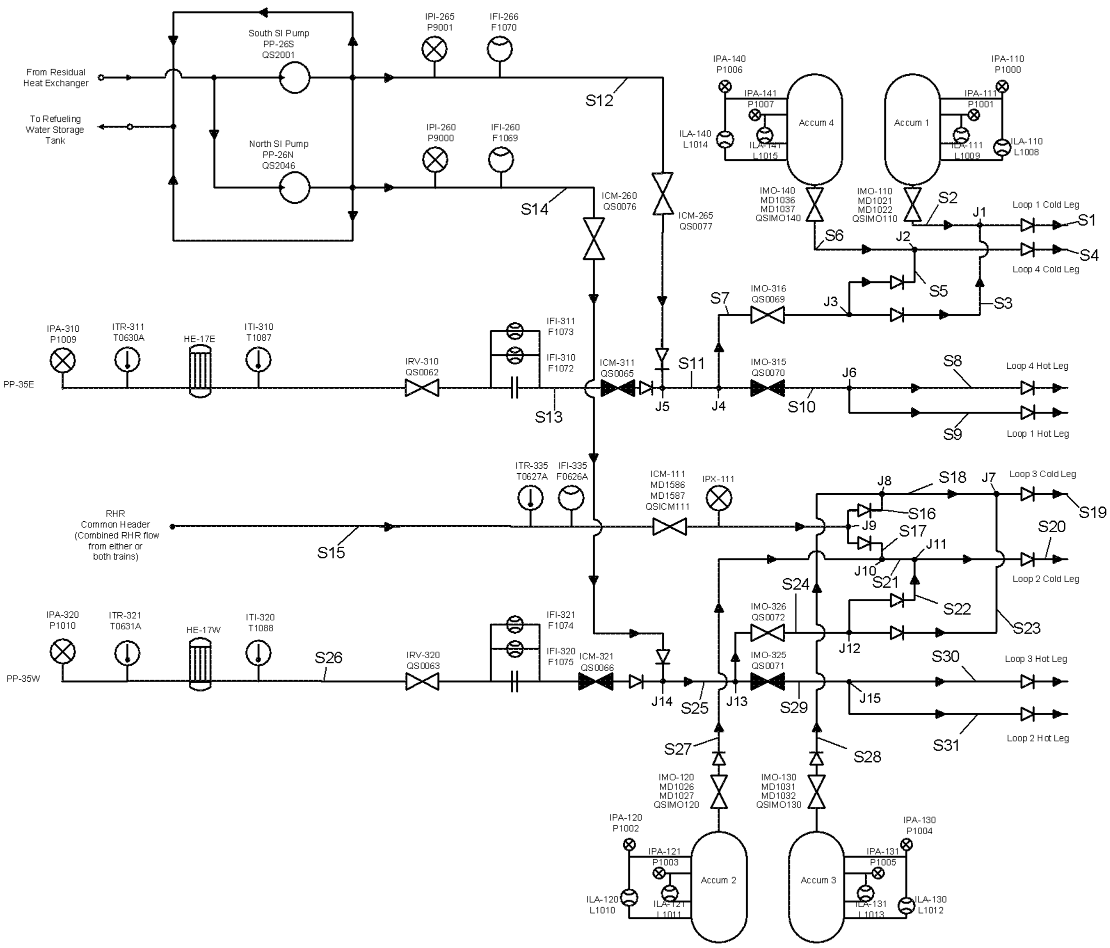


Figure 2 Reduced system based on available plant parameters

SIMULATION TOOLS

The simulation was created using the tools available in Westinghouse's Integrated Modeling System called WESTEMS™. WESTEMS™ provides a number of features that permit the simulation of a wide variety of plant equipment and piping systems. These tools are divided into the following types:

- Integrated Models
- Derived Value Functions
- Thermal Hydraulic Model Segments
- Stress Models

The Integrated Model technology is used to simulate all of the control systems, thermal hydraulics, heat transfer, and stress simulations in one integrated model [2, 3]. This technology can relate various physical processes in an organized structure that simulates the physics of actual systems and component reactions. The integrated model technology uses a programmable genetic algorithm with a sequenced instruction set developed by the user. The algorithm processes the instruction set through a three stage aging process to achieve its final states. With the aid of the other programmable functions, which include the Derived Value Function generator, the thermal hydraulic piping segment model, and the stress models, the Integrated Model feature can simulate virtually any of the sub-systems in the plant.

The Derived Value Functions (DVF) are a collection of more than 30 programmable functions that are used to simulate control logic and physical processes such as pressure, flow, and heat transfer coefficients. The DVF library provides a number of general algebraic or logical forms that may be configured to accept plant parameter data points or other previously calculated derived value functions. Derived Value Functions are used to synthesize parameters that represent time dependent values such as pressures, flows, temperatures, forces, and moments acting on various components and structures.

The Thermal Hydraulic Functions (THF) are simple thermal hydraulic piping models that are used in series with derived value functions to simulate more complex piping systems. The THF models are used to determine time dependent temperature loads on nozzles and intermediate sections of piping. The models are control-volume-based solutions that incorporate inlet and outlet boundary temperatures, inlet flow rate and heat losses to the environment. The total energy flux entering and leaving each control volume is calculated using a finite difference approximation method. An implicit form of the finite difference equations is used so that the complete system can be solved using matrix solution methods at each time step.

WESTEMS™ component stress (ASN) models evaluate stress and fatigue according to the requirements described in ASME B&PV Code Section III, NB-3200. The stress equations and limits in NB-3200 are general enough so that the inputs to the program can make it applicable for any edition of the Code. The structural stresses determined according to NB-3200 are based on stress intensity and stress intensity range due to mechanical loads (e.g., pressure, moment) and thermal transient loads. The stress component time histories for ASN models are calculated by applying time history mechanical and thermal load scale factors to unit stresses using the transfer function method. The stresses may also be adjusted by other input factors to develop Code equation stress histories. The transient stress histories are evaluated to determine the stress peaks and valleys, which are in turn used to calculate the applicable stress intensities and ranges of stress intensity required for the Code equations.

MODEL DEVELOPMENT METHOD

The following discussion describes the method that was developed for modeling these complex piping systems. The method used the tools described above: the thermal hydraulic piping models, the DVF mass balanced mixing functions, and DVF logic gates. To better communicate the method, the following are defined:

The building blocks:

Process Element Any single model or function that represents one or more physical or logical processes being modeled in WESTEMS™.

Attribute A single characterization that represents one or more physical or logical metrics being modeled in WESTEMS™.

THBC Thermal Hydraulic Boundary Conditions, which are the time-based set of parameters characterized by the following physical attributes:

- Temperature (F)
- Pressure (psig)
- Flow (gpm or CFM)

Piping Segment A section of piping with two ends with each end characterized by its THBC parameters. Therefore, the total minimum number of attributes required to define a piping segment is six. There are no limits on maximum. The number of process elements that define the piping segment depends on the number of valves and THBC parameters coming into and out of the piping segment. There must be enough process elements to completely define each of the piping segment thermal hydraulic boundary conditions.

Junction The intersection of two or more piping segments where pressure, temperatures, and flows are the result of combining two or more sets of THBC. The junction attributes have to be calculated based on the contributions of the two or more intersecting piping elements. There are no limits to the number of segments that make up a junction.

Boundaries Special junctions where all of the thermal hydraulic conditions are known. They are used in the sequencing process to establish the segment solution sequence.

The actions:

Mapping The identification and enumeration of the piping segments and junctions that make up the piping system model. The process starts with the identification of all junctions, starting at the final solution end of the system to be modeled and working backwards. The segment map is the ordered list of segments with the inlet junctions on the left and the outlet junctions on the right. In a segment map, each segment is only listed once;, junctions are listed as many times as they occur. A junction map is the opposite of a segment map. As the name implies, junction maps are junction centered. The junctions are only listed once and segments are listed multiple times. These two structures are used to develop the sequencing of the segments for the final solutions.

Sequencing The piping system simulation is solved by WESTEMS™ using sequential logic. The sequencing step is a methods-based approach to organize the solution order of a large number of elements.

Pressure Balancing The process of formulating the downstream pressure solution for each segment and junction based on the combined input pressures.

Flow Balancing The process of formulating the downstream flow solution for each segment and junction based on the combined input flow values.

Thermal Modeling The process of determining the extent of the thermal hydraulic models necessary to account for heat losses to the environment and mixing of two flow streams that are at two different temperatures.

Segment Mapping

The modeling process starts with the decomposition of the reduced piping model into elementary piping elements called segments. Each segment is assigned a unique number. Each segment must have an inlet junction and an outlet junction. The best approach to segment mapping is to start with the final solution location (i.e., at the RCS piping branch line nozzle intersections) and work backwards. During the mapping process, locations that have known thermal hydraulic boundary conditions (THBC's) are designated as boundary junctions (indicated by the gray background in the table below).

Table 1 Segment Map Legend

Object	Color
Junction	
Boundary	
Segment	

Table 2 Sample Segment Map

Inlet Junction	Name	Outlet Junction
Junction 01	Segment 01	Loop 1 CL
Accumulator 1	Segment 02	Junction 01
Junction 03	Segment 03	Junction 01
Junction 02	Segment 04	Loop 4 CL
Junction 03	Segment 05	Junction 02
Accumulator 4	Segment 06	Junction 02

Junction & Segment Sequencing

The process of sequencing the segments (piping elements) and junctions identified in the segment mapping session is performed in two steps. Starting with the segment map, the first step is to use the segment map to rewrite the junctions in an ascending order of dependencies. The resulting list then has the junctions in the required sequential solution order. The second step uses the junction sequencing to identify the segment solution sequence. When this task is completed, then both the junctions and segments have solution sequence numbers assigned.

The junction and segment map sequencing is accomplished by first determining a solution order for the junctions. This is accomplished by converting the segment map into a junction map as shown in the table below:

Table 3 Sample Junction Map

Junction Sequence	Incoming Segments		Junction	Outgoing Segments	
1	Segment 13	Segment 12	Accu-RHR-J05	Segment 11	
2		Segment 11	Accu-RHR-J04	Segment 07	Segment 10
3		Segment 07	Accu-RHR-J03	Segment 03	Segment 05
4	Segment 05	Segment 06	Accu-RHR-J02	Segment 04	
5		Segment 10	Accu-RHR-J06	Segment 08	Segment 09
6		Segment 15	Accu-RHR-J09	Segment 16	Segment 17
7	Segment 17	Segment 27	Accu-RHR-J10	Segment 21	

Now the junctions have a solution order number assigned, which is used to assign a solution order to the segments. This is accomplished by starting with the uppermost left hand segment and assigning solution numbers: first to the incoming segments, using a conventional approach from left to right and down to the next row, and then over to the outgoing segments, looking for any that were not yet assigned. Applying this to the sample shown above would yield the following:

Segment Sequence	Segment
1	Segment 13
2	Segment 12
3	Segment 11
4	Segment 07
5	Segment 05
6	Segment 06
7	Segment 10
8	Segment 15
9	Segment 17
10	Segment 27
11	Segment 03
12	Segment 04
13	Segment 08
14	Segment 09
15	Segment 16
16	Segment 21

Pressure Balancing

Pressure balancing charts are used to develop logic for the derived value function models. Pressure balancing is accomplished by arranging the available plant sensors and valve status data in these balancing charts. Figure 3 shows a sample of this process:

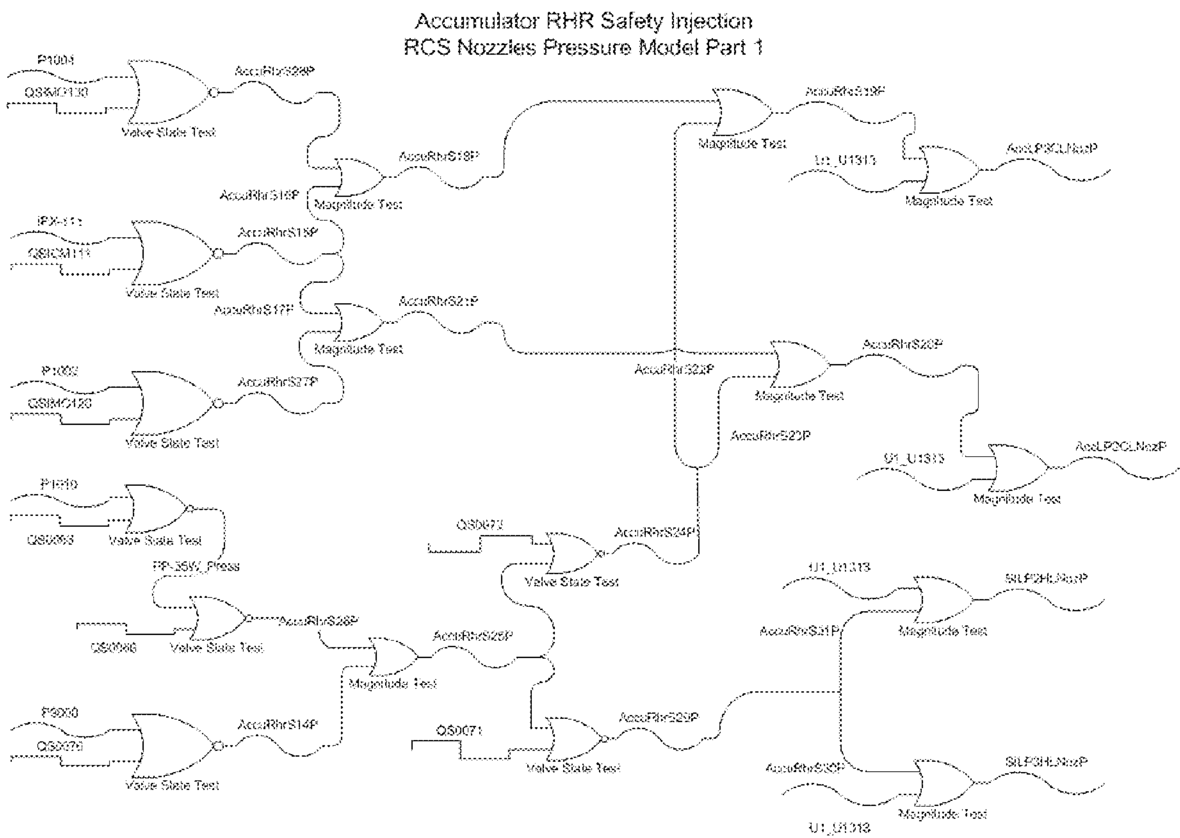


Figure 3 Pressure Balancing Chart

Manifolds, junctions where two or more piping segments join, are indicated as magnitude tests in the pressure balancing chart. Each logic symbol in the pressure balancing chart will become a derived value function in the final simulation.

Performing the Flow Balancing

Flow balancing is performed using a similar process as pressure balancing, by arranging the available plant sensors and valve status data in balancing charts. However, the flow balancing uses the pressures previously developed in the pressure balancing charts to determine if the indicated flows from sensors are allowed to pass into the downstream segments. Each logic symbol on the flow balancing chart will become a derived value function in the final simulation. The sequence of the solutions will be provided by the segment sequencing table developed earlier. Figure 4 shows a sample of this:

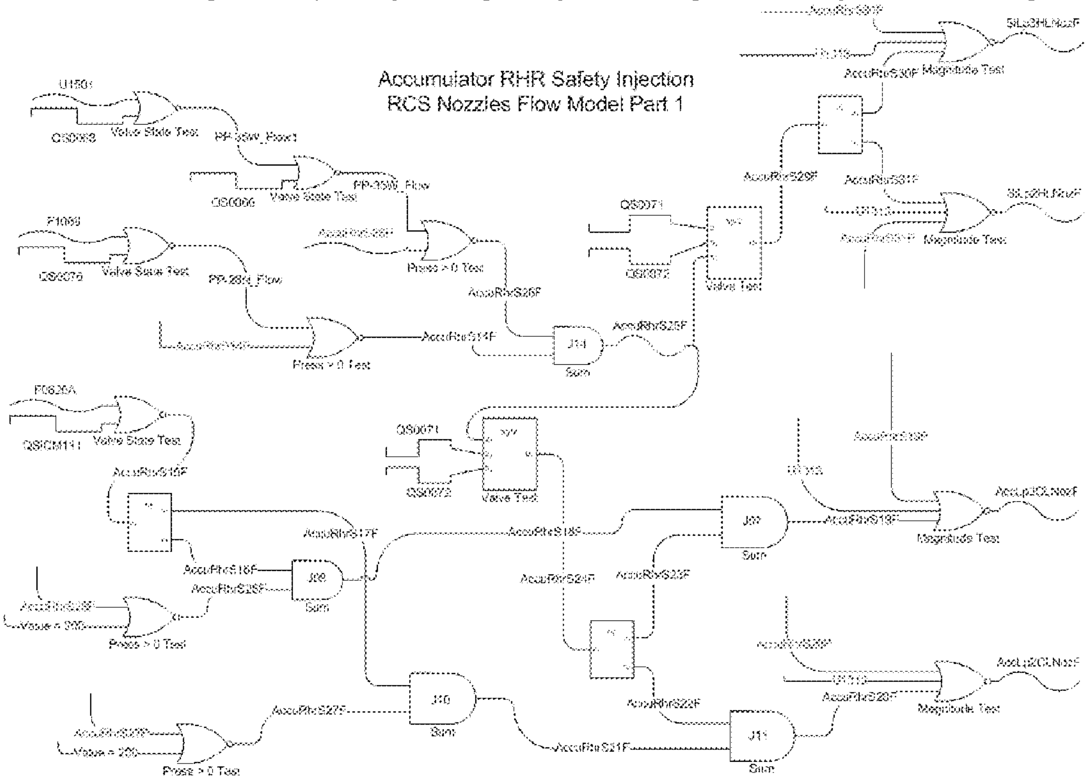


Figure 4 Sample Flow Balancing Chart

Implementation Phase

The final step in construction of the simulation is to build the models in the sequence developed for the segment sequences. This process starts with building of the pressure model derived value solutions, then the flow model derived solutions, and finally the thermal hydraulic model solutions can be configured to use the flows and pressures from the derived value functions. Initial temperatures are provided by the various boundary junctions.

TESTING

The completed simulations are tested using both idealized design transient input parameters and actual plant parameter data. Design input data are used to test the simulations' response to design events that may never be experienced. It is necessary to test these scenarios to guarantee that the simulation will accurately predict the local thermal hydraulic responses. When testing with plant data, it is desirable to test as much data as possible. The figure below shows the RCS Cold Leg RHR return nozzle's temperature response (at the nozzle safe end) to RHR startup, when flow is initiated through the system to the RCS nozzles. The test cycled the RHR system twice, achieving the results shown in:

As expected, the model predicted a cold water shock due to the existing inventory in the piping prior to reaching the temperature of the water exiting the RHR heat exchangers.

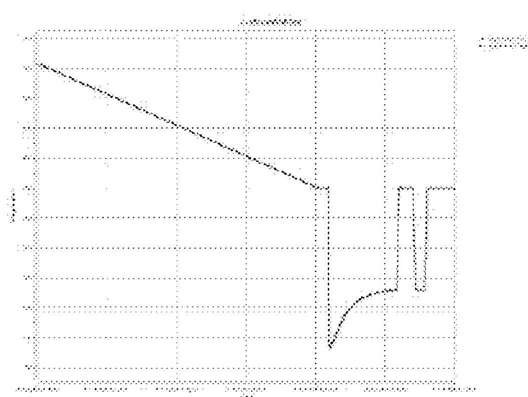


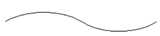
Figure 5 Nozzle Temperatures RHR System Startup Test

CONCLUSION

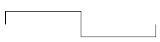
The problem and solution described in this paper demonstrates a systematic method to simplify and simulate complex systems in a manageable algorithm. The methodology described is adaptable to numerous simulation problems. The method provides a framework for a standard approach to system modeling within a monitoring system. This type of standardization is beneficial in the development of plant monitoring system models. One benefit is that multiple system models can share common solution utilities in the automation process. Another benefit is that multiple models within a system share a common framework, so that modifications or improvements to the system can be more efficiently applied. The method also allows for traceability of the simulation models when the need arises to debug or change the model inputs or characteristics. These benefits have been realized in the use of this method in the development of plant fatigue monitoring systems, as demonstrated by the favorable testing results presented for the specific problem described.

NOMENCLATURE

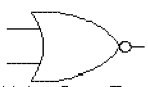
Analog Values are represented by:



Digital Values are represented by:



Valve State Test use a digital values for the valves and analog for the process parameter and use the following symbol:

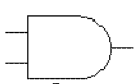


Valve State Test

Magnitude Test is used to determine what value will be used as the downstream outlet value. The symbol used is:

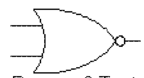
Magnitude Test

Summing Function combines all inputs into one output. The summing function uses the following symbol:



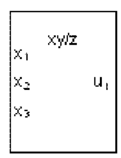
Sum

Value Greater Than Zero Test Uses the following symbol:



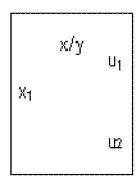
Press > 0 Test

Complex Manifold or Multiple Valve Test symbol is used to address more than one variable output magnitude, which is determined by two or more digital inputs. The following symbol is used to represent this type of logic:



Valve Test

Function generator is used to adjust the magnitude of analog parameters as required to account for tees and similar piping configurations where the process value's magnitude is affected. The following symbol is used:



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