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Proceedings of the ASME 2016 Power and Energy Conference

Proceedings of the ASME 2016 Power and Energy Conference
PowerEnergy2016
June 26-June 30, 2016, Charlotte, North Carolina

PowerEnergy2016-59062

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ABSTRACT

As pipe networks age, build-up [scaling] and corrosion decrease pipe diameter and increase pipe roughness, leading to significant pressure drops and lower flow rates. When modeling the hydraulics of these systems, calibrating the pipes to account for additional scaling and/or fouling can be vital to accurately predicting the hydraulic behavior of the system.

An automated, multi-variable goal-seeking software was used to calibrate the raw water system of the Duke McGuire Nuclear Station (MNS). This calibration process involved three phases. The first phase was the testing of the automated, multivariable goal-seeking software on a previously calibrated system. The second phase was the calibration of a partial data set. The third phase was the calibration of a complete data set. The automated goal-seeking software was found to have varying degrees of success in each phase.

At the conclusion of the calibration process, the partial data calibration of two parallel systems at MNS yielded average overall calibration accuracies of 2.1% and 1% for flow rates, and 1.2 psig (8.4 kPa-g) and 1.7 psig (11.9 kPa-g) for pressures. The complete data calibration of one of these systems at MNS yielded an average overall calibration accuracy of 2.3% for flow rates, and 1.4 psig (9.5 kPa-g) for pressures.

ABBREVIATIONS

1A	Unit 1 A Train
1B	Unit 1 B Train
2A	Unit 2 A Train
2B	Unit 2 B Train
AHU	Air Handling Unit
CA	Auxiliary Feedwater System
EC	Engineering Change
KC	Component Cooling System
KD	Diesel Generator Engine Cooling Water System
KF	Spent Fuel Pool Cooling
MNS	McGuire Nuclear Station
NS	Containment Spray System
NV	Chemical and Volume Control System
PMTG	Purple Mountain Technology Group
RN	Nuclear Service Water System
SNSWP	Standby Nuclear Service Water Pond
YC	Control Area Chilled Water System

INTRODUCTION

McGuire Nuclear Station is located in Huntersville, North Carolina, USA off Lake Norman, midway in the chain of lakes created when the flood-prone Catawba River was dammed. Unit 1 began commercial operation in 1981 followed by Unit 2 in 1984. Figure 1 shows a photo of the station.

The Nuclear Service Water System (RN) is a safety-related, open loop cooling system that provides cooling water from Lake Norman or the Standby Nuclear Service Water Pond (SNSWP) to various station heat exchangers during all modes of operation. In addition, the system acts as an assured source of makeup water for several other safety-related systems, including the Auxiliary Feedwater System (CA). The CA system is provided as a backup for the Main Feedwater System and is designed to dissipate heat from the Reactor Coolant System when normal non safety-related systems are unavailable.

The RN system delivers water to each of the two power station Units (Units 1 and 2). Two trains (A and B) supply water to each Unit. Therefore, Unit 1 is supplied by the 1A and 1B trains. Unit 2 is supplied by the 2A and 2B trains. These systems share common intake and discharge piping, as well as one heat exchanger, but are otherwise independent from each other.

FIGURE 1. DUKE MCGUIRE NUCLEAR STATION

The A Train and B Train systems also share common supply and discharge piping, so in reality, all four systems have some level of interconnection.

Figure 2 shows a high level schematic of the RN B Train system. Note that there are 47 heat exchangers in the RN B Train system (23 heat exchangers in each Unit, plus one shared heat exchanger) counting the three major load heat exchangers in each Unit.

The original design configuration of the RN to CA assured supply placed the flow path downstream of the Diesel Generator Engine Cooling Water System (KD) heat exchanger, near the RN return header. This configuration resulted in high supply temperatures, low Net Positive Suction Head (NPSH), and air entrainment concerns to the CA pumps. Engineering changes (EC's) were developed to relocate the assured supply to upstream of the KD heat exchanger which alleviates these concerns.

Hydraulic models of the RN and CA systems were needed to evaluate the new flow and pressure conditions of these systems after implementation of the EC.

As previously mentioned, the RN system utilizes raw water from Lake Norman or the SNSWP, neither of which are chemically controlled. Over time, this raw water causes build-up (scaling) and corrosion which decreases pipe diameters and increases pipe roughness, leading to significant pressure drops and lower flow rates (see Figure 3).

After the model was developed from piping drawings, a benchmark (the MNS term for model calibration) was therefore required to ensure the model accurately reflected the current conditions in the plant.

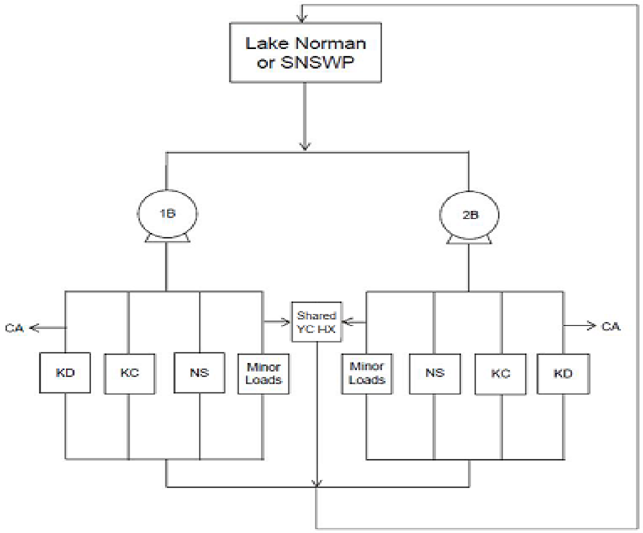

FIGURE 2. FLOW DIAGRAM OF THE (RN) NUCLEAR SERVICE WATER B TRAIN SYSTEM AT MCGUIRE NUCLEAR STATION

PREVIOUS MODELING WORK AND OBJECTIVES FOR THIS PROJECT

Previous computer hydraulic models of the 1A, 1B, 2A and 2B systems existed that had been built by Duke MNS staff. These models were built using the commercially available AFT Fathom software [1]. AFT Fathom is a steady-state, incompressible flow software that uses the Newton-Raphson iterative method. It allows the user to select from 10 different pipe friction models, the most popular of which is the Darcy Weisbach equation, which was used in this project.

The focus of this current project was the RN 1B and 2B systems. Previous calibration work by Duke MNS on the 2A system was manually iterated. This previous work on 2A was used by the software developer to test a new, automated calibration capability in the modeling software. This will be described in more detail in later sections. Note that other than this testing on the 2A system, all calibration effort in this project was on the 1B and 2B systems. Thus, discussion of the 1A and 2A systems will be limited in this paper.

All modeling and calibration work was required to be performed in accordance under a nuclear quality program [2-3]. Reference [4] provided the approved software nuclear validation and verification (V&V) for this project.

While the 1A, 1B, 2A and 2B models existed previously, only the 2A model was in compliance with reference [2-3]. Thus, before calibration was performed, the 1B and 2B models needed to be extensively modified, thoroughly reviewed and appropriately documented in order to comply with references [2-3].

This work was contracted to Purple Mountain Technology Group (PMTG) in partnership with Applied Flow Technology (AFT). AFT is the developer of the reference [1] software and creator of the new automated capability used for calibration.

Duke MNS managed this project with technical assistance from their onsite contractor AREVA INC.

FIGURE 3. RN PIPING TUBERCLES DUE TO RAW WATER SCALING INCREASE PIPE ROUGHNESS AND REDUCE PIPE DIAMETER

After each model development and documentation phase was completed, the calibration phase of the project was undertaken. The balance of this paper discusses the calibration of the RN 1B and 2B models.

The ultimate objective of this project was to deliver to Duke MNS an RN B Train model (which combined the originally separated 1B and 2B models) that was in compliance with references [2-3], and had been calibrated to Duke MNS operational field data in a manner also in compliance with said references. This objective was achieved.

OVERVIEW OF MODELS DEVELOPED FOR RN B TRAIN

The complete B Train RN model, consisting of both the 1B and 2B RN systems, was modeled in the reference [1] software (see the 2B system model in Figure 4) after individually modeling and then subsequently combining the 1B and 2B systems. The two systems are similar but not identical in design. Both systems take suction from a common source - the Standby Nuclear Service Water Pond (SNSWP) or Lake Norman - with approximately 2,100 feet of pipe common to both systems before they diverge into 1B and 2B trains. After diverging, each train has its own pump with several heat exchangers downstream of the train's pump. The two systems reconnect downstream where they share approximately 850 feet of common piping before discharging into the SNSWP or Lake Norman.

Each heat exchanger is classified in one of two ways: major load and minor load. *Major loads* are defined as being supplied by piping with a diameter of greater than 6”. *Minor loads* are defined as being supplied by piping with a diameter of less than 6”. Note that, while the NS (containment spray) heat exchanger is a major load heat exchanger, limitations in data collection prevented NS piping from being calibrated. The one exception to these definitions is the shared YC heat exchanger, which is supplied by 8” pipe, but is considered a minor load. In general, major load pipes are constructed from carbon steel (which makes them more likely to corrode and accumulate scaling), and minor load pipes are constructed from stainless steel (which makes them less likely to corrode and accumulate scaling).

MODEL CALIBRATION METHODOLOGY

The model calibration was performed by altering pipe roughness values and pipe ID reduction (i.e., wall scaling) values to ensure that the model reflected the configuration of the plant at the time field-recorded data was taken. The RN B Train was calibrated using multiple data sets that were taken during different plant operating configurations to improve the accuracy of the calibration. These data sets were calibrated concurrently for increased ease and efficiency of the calibration process. The calibration was completed using a combination of a new, automated goal seeking process (the Beta method), as well as some manual iteration.

Parameters varied

By increasing the pipe ID reduction value, the pipe inner diameter was decreased, and higher velocities were seen for a given flow rate. This, in turn, caused higher pressure drop because of the higher velocity.

The increased roughness value resulted in a higher friction factor and thus increased pressure drop based on conventional frictional pressure drop relationships.

From a hydraulic standpoint, the effect that an increased amount of pipe ID reduction and an increased pipe roughness value have on a pipeline is decreased flow and increased pressure drop through a given path.

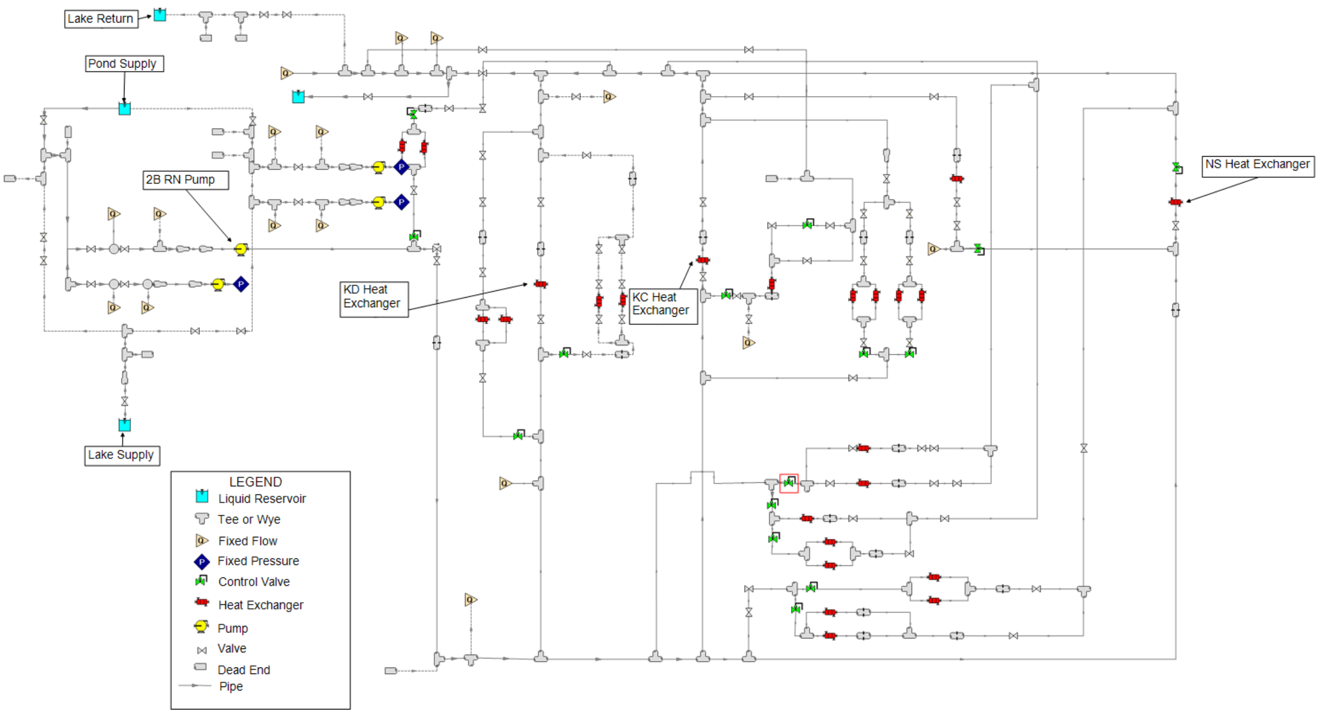

FIGURE 4. 2B RN SYSTEM HYDRAULIC MODEL WITH 280 PIPE ELEMENTS AND 24 HEAT EXCHANGERS. NOTE THAT THE SUPPLY AND DISCHARGE PIPING IS SHARED WITH THE 1B, 1A, AND 2A SYSTEMS

Mathematically, however, pipe ID reduction has a more significant effect on pipeline pressures and flows than does pipe roughness, so pipe ID reduction was first used to coarsely calibrate the model, and then roughness was used to more finely adjust the calibration.

Available data

Duke MNS collects flow and pressure data during plant outages. Duke MNS calls this test a “flow balance”. Typically, only partial data is collected, but for the purpose of this EC, a more complete set of data was collected, as well. The following defines a partial and complete data set:

- **Partial data set**- Flow balance data that contains flow and pressure data for major loads, but only flow data for minor loads
- **Complete data set**- Flow balance data that contains flow AND pressure data for major and minor loads

Calibration process

As discussed previously, the calibration process for this project involved varying pipe roughness values and pipe ID reduction values in order to bring model predictions as close as possible to field data. This project provided some special calibration challenges that were met partially with enhanced automation and partially with manual iteration.

The special challenges included:

- Calibrating the model to multiple data sets of field measurements with data from different operating conditions
- Uncertainty associated with measured field data
- A constantly changing system, due to lack of chemical control and periodic cleaning of parts of the system. This means it can be difficult to match data taken at different times.
- Achieving satisfactory calibration when the number of measured data points is different from the number of parameters to be varied
- Applying a new, automated method to the calibration process

Overview of goals and variables – Whether pursued by way of automatic searching algorithms or by manual iteration, the basic process of model calibration is a process of varying computer model input parameters (variables) in order to bring the model into agreement with desired outputs (goals).

In the RN B Train calibration, the *variables* were the pipe roughness and ID reduction values, and the *goals* were the measured pressures and flow rates.

The simplest calibration process would be when there is a single variable and single goal. This process would become in principle a "one equation and one unknown" situation. Ideally, a closed-form algebraic equation could be used. In practice, no such equation exists or it is impractical to use. Thus iteration is required. Whether manual or automated iteration is used, it is possible to find a unique variable that will achieve the goal. This unique solution is in accordance with the "one equation and one unknown" concept of basic algebra.

As the number of variables and goals increases, iteration becomes more complicated, but as long as the number of goals and variables remains equal, it remains possible to find a unique solution.

In practice, the model calibration process often results in a different number of goals and variables. In other words, it is similar to a "one equation and two unknowns" situation. In such cases, there is no unique solution which meets the goals but potentially an infinite number of possible solutions. The objective of the engineer performing the calibration is then to find appropriate variables that meet the goals that are best suited to handle anticipated future use of the final calibrated model.

Calibrating multiple data sets concurrently – Many piping systems do not always operate in the same manner and, in fact, can have many different operating configurations. The RN 1B and 2B systems are such systems. In general, the systems can draw from either the lake (Lake Norman) or the pond (SNSWP). Further, the systems can operate with water diverted for things such as strainer cleaning. When data is taken from these different operating configurations, the data will differ. This allows for a better model calibration to be performed but also greatly complicates the calibration process.

The RN 1B and 2B systems had multiple data sets which had to be matched. The standard process for doing this is quite tedious, even when using modeling software. It involves creating separate models of the system – one for each data set. Changes are made by the user to the variable for each model in order to match the measured data for that model. This back and forth process is tedious and error-prone.

Further, even if this process could be automated with searching algorithms, applying the algorithms to different models of the same physical system does not allow for automated correlation of the variables among the different models. For example, what good is a calibration which finds a pipe roughness in Model #1 which differs from the roughness for the same pipe in Model #2? If the pipe in the Model #2 is the same physical pipe as in Model #1, it must have the same roughness.

A workaround for this conundrum can be implemented when using modeling software if the software has the ability to run more than one model simultaneously in the same hydraulic computation.

Figures 5 and 6 illustrate this workaround. First consider a situation where flow rate data exists for a gravity flow pipe system (Figure 5). The system has particular liquid levels in the supply and discharge tanks (H_1 = 100 and H_2 = 80, respectively, with units of feet or meters irrelevant to this discussion). In such a case, the roughness in pipes P1 and P2 (the variables) can be varied until the predicted model flow rate agrees with the measured flow rate (the goal).

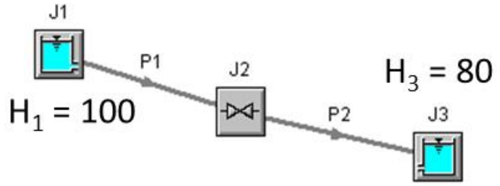

FIGURE 5. CALIBRATING A SINGLE DATA SET. GRAVITY FLOW PIPE SYSTEM WITH KNOWN, MEASURED FLOW RATE FOR KNOWN TANK HEIGHTS OF 100 AND 80.

Figure 6 illustrates a more complicated case and the workaround. Here there are two measured flow rates. The first is the same as in Figure 5. But now a second set of data is included for a situation where H_1 = 95 and H_3 = 82. Pipe P1 in the upper model and lower model are the same physical pipe – and thus must have the same roughness and ID reduction values regardless of the flow rate through the pipe. Tank J1 above and below is the same physical tank, just with different liquid levels.

The reference [1] modeling software allows multiple models to be run in the same hydraulic calculation. Further, its goal seeking capabilities allow for automatic varying of pipe friction and ID reduction in order to bring the model into the best possible agreement with the measured data. And finally, the automatic goal seeking feature has a special capability which allows users to link pipes from different data sets. In other words, the two P1 pipes in Figure 6 (which represent the same physical pipe under different flow conditions) can be linked to each other such that the roughness or ID reduction for each of the P1 pipes is automatically varied in sync with each other. Note that only one type of parameter can be varied at a time.

Expanding this concept, the entire RN system 1B or 2B model can be duplicated as many times as there are additional data sets and all kept within the same hydraulic calculation, with every pipe element linked among data sets as specified by the user.

Manual process – As discussed in the previous section, the process of performing calibration on a model the size of the 1B and 2B systems, with different data sets, is tedious. If the user has the data set in separate models, then the user must change back and forth between the various models manually updating the pipe roughness and/or ID reduction and keeping them all in sync. In cases where there are three data sets and thus three separated models, the tediousness grows exponentially.

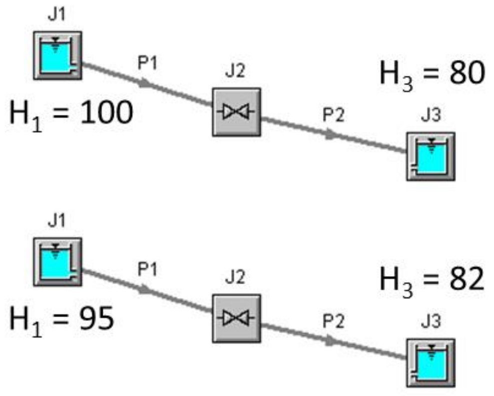

FIGURE 6. CALIBRATING MULTIPLE DATA SETS CONCURRENTLY. GRAVITY FLOW PIPE SYSTEM WITH UNKNOWN, TWO DIFFERENT MEASURED FLOW RATES FOR DIFFERENT KNOWN TANK HEIGHTS OF 100 AND 80 IN UPPER CASE 1, AND 95 AND 82 IN LOWER CASE

If the data sets are modeled within the same hydraulic model as opposed to separate models (see previous section on concurrent calibration), then some of the tediousness can be removed. However, the process remains error-prone as the user must be careful to make sure the manual updates to roughness and ID reduction are kept in sync among the various data sets.

New automated process (Beta method) – With the large number of variables and goals in this project, it was clear that an automated goal seeking process was needed.

However, the reference [1] software goal seeking used the Least Squares method and was best suited for a single variable or at best a small number of variables (2 or 3).

Research uncovered a method called the "Beta method" [5] which held promise for the type of multi-variable goal seeking needed on the RN system B Train project. Previous applications of the Beta method to aircraft test data correlation by Mundt and Quinn [6] showed it was suitable for applications of the size of the 1B and 2B hydraulic models.

The Beta method is essentially a method which organizes results from numerical optimization in order to match multiple variables and goals. It uses constrained optimization across a continuous design space where the objective function is the Beta parameter. The Beta parameter goes to zero as the goals are met by the searching algorithm. The numerical optimizer minimizes the value of Beta, thus providing matching of goals. Numerical optimization techniques like those used in the reference [1] software are discussed in detail by Vanderplaats [7].

The Beta method was implemented in the reference [1] software. It was first tested on several single variable test problems against the existing Least Squares method and it performed reliably and similarly. On several multi-variable test problems, the Beta method performed much better than the Least Squares method with more accurate results obtained in less time.

MODEL CALIBRATION RESULTS

The model calibration was performed in three phases: first, it was compared to a previous calibration performed manually, second, it was used on two systems with partial data sets, and finally, it was used on one system with a complete data set.

Testing of automated process to previous manually calibrated 2A system

Before this project started, Duke MNS personnel had completed a manual hydraulic calibration of the RN 2A system. This calibration had two data sets – one with a strainer in service and the second without it. This model development and calibration were performed in accordance with references [2-3] using the reference [1] software, version 6.0.

The 2A model was very similar to the 1B and 2B models, which were still in development at that time. In order to test the Beta method on an application similar to that expected for the 1B and 2B models, it was applied to the previous 2A model and compared to the previous calibration results.

This 2A model with two data sets had a total of 14 goals (consisting of a combination of pressure and flow measurements) and 9 variables (consisting of 9 unique roughness values). Thus, unique results were not expected due to the different number of goals and variables, and accordingly, different pipe roughness results were obtained by the Beta method each instance it was run with different initial roughness guesses. What was found was that, no matter what the initial starting point for the pipe roughness values, the Beta method consistently found roughness values that matched the flow and pressure data much better than the manual iterations in the best cases (on a percentage basis). In the worst cases, it matched the data from the hand iterations equally well. The process of obtaining these results with the Beta method took less than a day. This is compared to "many weeks" of previous manual iteration.

In summary, it appeared that the Beta method was suitable for use on the 1B and 2B model calibrations and it was recommended for use.

Experience on calibrating 1B and 2B system with partial data sets

After the testing phase, a partial model calibration was performed on both the 1B and 2B RN systems separately. During the calibration for each Train, only the major load heat exchanger pipes (with the exception of the NS heat exchanger pipes) were calibrated. To account for the flows to each minor load heat exchanger, a fictitious flow control valve was placed in each minor load flow path with each control valve set to the field-recorded flow. Therefore, flow to each minor load flow path was fixed, and the major load pipes could then be calibrated to ensure the total 1B and 2B RN systems model flow responded similarly to actual recorded flow from the plant.

In essence, the purpose of fictitious flow control valves was to concentrate the additional pressure loss from scaled pipes into a single modeling element. This was done because pressure data was not available and there was thus no way to properly identify the location of pressure loss from scaling.

In addition to the hydraulic data provided, Duke MNS provided initial estimated values for piping roughness and scaling factors for ID reduction, as well as suggested minimum and maximum scaling factors and roughness values to use as bounds to stay within during the calibration process. These bounds were roughly approximated according to visual data taken from observing sections of major load piping in the plant (e.g., see Figure 3).

The new automated goal seeking process (the Beta method) discussed previously in this paper was used to perform this calibration. Pipes with the same diameter within the same area of the model were linked (see the Model Calibration Methodology section), and pressure and flow goals were applied to the inlet and outlet pipes for the KD and KC heat exchangers, as well as the RN pump. The model of the Train being benchmarked was duplicated within the same hydraulic model as many times as tests were performed in the field. This was to allow for concurrent model calibration as discussed in a previous section. In this case, there were three concurrent models for the 1B Train and two for the 2B Train. Because only one variable per pipe can be varied at a time with the Beta method (i.e., pipe ID reduction and roughness cannot both be varied automatically in the same run), pipe ID reduction was initially manually calibrated to coarsely adjust the pressures and flows. This initial manual calibration provided the Beta method a more accurate starting point from which the roughness values could be adjusted using the Beta method to fine tune the results.

Difficulties in achieving a successful calibration during this partial model calibration process necessitated review of potential errors and/or problematic uncertainties in the model input and in the client-provided data. During this review, it was found that the valve position reported for the major load KC (component cooling) heat exchanger valve was preventing the model from allowing a sufficient amount of flow through this heat exchanger. Further communication with Duke MNS and the valve supplier led to the discovery that this valve position was being determined incorrectly in the provided data. This valve position was then adjusted in the model to more accurately reflect the position in the field.

Additional difficulties during the partial calibration process were encountered. During the beginning of calibration, the initial guesses at pipe roughness were adjusted in an attempt to achieve results within the desired range. However, after multiple rounds of iteration, flow and pressure results still remained too far from the acceptable range. These multiple iterations indicated that specific areas in the model were preventing the flow and pressure results from matching the plant hydraulic data. Therefore, the following adjustments to the model and Beta method goal seek set-up were required at these locations in the model to achieve a successful calibration:

- Increased roughness and wall scaling factors, beyond Duke MNS suggested upper limits throughout the model
- Removed heat exchanger discharge pressure goals, and set goals for supply pressure and flow rates
- Unlinked all pipes to allow each pipe roughness factor to vary independently from other pipes
- Some pipe roughness values were not varied at all

Tables 1 through 4 present the 1B and 2B partial model calibration results for both pressures and flows, respectively.

Using the previously stated methods and several rounds of iteration with the Beta method, results deemed acceptable by Duke MNS were achieved.

Experience on calibrating 2B system with complete data set coupled with previously partially calibrated 1B and 2B systems

After completing the 1B and 2B RN system partial calibrations, a complete set of pressure and flow data became available that allowed for the complete model calibration of the 2B RN system.

A similar process to that described for the 1B and 2B systems' partial model calibration was initially performed, with the following exceptions:

- The 2B RN system partial model calibration pipe wall scaling factors for ID reduction and roughness values from those pipes that were previously calibrated were used as the starting point for the complete calibration. In all other pipes, the Duke-provided initial values were used. Note that Duke MNS initially assumed that most minor load pipes were clean with no scaling and a minimum pipe roughness.
- Duke MNS did not observe scaling in the minor load pipes as was performed for the major load pipes. Therefore, engineering judgment was used on the scaling values based on preliminary calibration runs.
- Both the KD and KC heat exchanger valves required adjustment to achieve the field-recorded flows. These adjustments were made per the discussion in the partial model calibration section.
- Because flows and pressures were available for minor and major load pipes in the complete model calibration, all fictitious control valves in the 2B

system minor load flow paths were removed and each flow path was calibrated according to flows and pressures.

As in the partial model calibration, pipes in the same area of the model with the same diameter were initially linked to each other. The wall scaling for ID reduction in these pipes was then set as the unique variables, and the flow goal and supply pressure goal for each heat exchanger was entered. This amounted to 64 variables with 34 goals. As mentioned for the partial model calibration, it was determined that it was necessary to adjust both the KD and KC heat exchanger valve positions from the stated positions in order for the flow to these heat exchangers to match the field-recorded data. Because of uncertainty in these stated valve positions (reference the valve discussion in the previous discussion), this adjustment was deemed reasonable.

Also as observed in the partial model calibration, significant difficulties were experienced when using the Beta method to achieve the measured flows and pressures in the complete model calibration process. Similar manipulations to the model and Beta method goal seek set-up were used as those described in the partial model calibration section to achieve a successful calibration.

Despite several iterations using the Beta method to calibrate the complete 2B RN model, difficulties in achieving a successful calibration were still present. Manual iteration without the Beta method was then used to directly alter the model values by running the model without the Beta method capability and then manually adjusting the modeled pipe scaling and roughness values in an effort to match the measured flow and pressure data. This manual iteration yielded significantly closer results in the minor load piping than those obtained by the Beta method because changes in the scaling factors and roughness values in the minor load pipes did not significantly affect flows in the other major load pipes due to the drastically higher flows in the major load pipes. Tables 5 and 6 show the final pressure (Table 5) and flow (Table 6) results at the termination of this calibration process. Note that these are the abridged forms of the tables.

As can be observed from the complete model calibration results, model pressure results were within 2 psi of the field recorded pressures for all but three flow paths: 1) NV pump motor cooler, 2) KF motor AHU, and 3) KC pump motor cooler, and flows were within 5% of the field recorded flows for all but the KF pump motor AHU flow path.

Of interest from the results was the inability to achieve sufficiently high pressures in the NV motor cooler and KC pump motor cooler flow paths, despite maintaining scaling and roughness values at a minimum. The engineering drawings were referenced and it was determined that some minor errors existed in the model as tees and area changes were modeled in such a way as to add more resistance than actually existed in these areas. With these modeling errors remedied, the model pressure increased by approximately 2 psi in these areas, which cut the deficit observed from the pressure measured in the field.

Due to time and plant operational constraints, Duke MNS and PMTG were unable to determine the cause of the remaining pressure deficit between the model predictions and the field-recorded data. Possible reasons for this deficit include out of calibration measurement devices, errors in the measurement process, or errors of a similar nature. The results were deemed sufficiently close to proceed with use of the calibrated model for hydraulic analysis of hypothesized scenarios. This determination was made for two reasons. First, these flow paths with calculated pressures outside of the established pressure calibration criteria are minor loads and are not critical to the analyses required to validate the EC design. Additionally, despite these pressure deficits, flows to these minor loads are significantly higher than the minimum required flow.

FUTURE WORK

Beta method

It is unclear what caused the difficulty of applying the Beta method to the full calibration of the 2B system. With the size of the model and large number of goals and variables, there are many possible explanations. It is suspected that the search method used while applying the Beta method would have influenced the quality of the results obtained by the program. The search methods available include: 1) The Modified Method of Feasible Directions 2) Sequential Linear Programming and 3) Sequential Quadratic Programming. While the Modified Method of Feasible Directions was used, time constraints prevented the exploration of using other search methods that may have improved the quality of the calibration. Additionally, another potential cause of the difficultly observed with the Beta method while calibrating the 2B RN system includes using a highly uneven number of goals (34) compared to variables (64).

Additional applications of the Beta method (which can vary approximately 44 types of variables) by PMTG on future projects and also by customers of the reference [1] software will provide further insight. Additional expertise will be gained and possibly the Beta method implementation or numerical control factors can be improved.

A Train calibration

While this project focused on the RN 1B and 2B systems, Duke MNS wants to repeat the efforts from this project to enhance their 1A and 2A system hydraulic models. As discussed previously, the 2A system model has been built and calibrated. However, some design changes have been made to the 2A system since the model was built, and new data was subsequently obtained. It is expected that a complete, combined model of the A train that satisfies references [2-3] will be developed in the future.

TABLE 1. FLOW RESULTS FOR 1B PARTIAL MODEL CALIBRATION

Flow Scenario	Parameter	Model Value		Flow Balance Value		Calibration Accuracy
		gpm	m^3/hr	gpm	m^3/hr	
Flow Balance-1 Major Loads	1B KD HX	1033.0	234.6	1046.0	237.6	-1.2%
	1B KC HX	5063.0	1150.0	4863.0	1104.5	4.1%
	1B RN Pump	11964.0	2717.4	11778.0	2675.1	1.6%
Flow Balance-2 Major Loads	1B KD HX	1029.0	233.7	1040.0	236.2	-1.1%
	1B KC HX	5048.0	1146.5	5148.0	1169.3	-1.9%
	1B RN Pump	12065.0	2740.3	12174.0	2765.1	-0.9%
Flow Balance-3 Major Loads	1B KD HX	1176.0	267.1	1154.0	262.1	1.9%
	1B KC HX	5812.0	1320.1	5606.0	1273.3	3.7%
	1B RN Pump	9140.0	2076.0	8910.0	2023.7	2.6%
Flow – Average Overall 1B Calibration Accuracy						**2.1%**

TABLE 2. PRESSURE RESULTS FOR 1B PARTIAL MODEL CALIBRATION

Flow Scenario	Parameter	Model Value		Flow Balance Value		Calibration Accuracy	
		psig	kPa-g	psig	kPa-g	psig	kPa-g
Flow Balance-1 Major Loads	1B RN Pump Inlet Pressure	-4.0	-27.6	-2.1	-14.5	-1.9	-13.1
	1B RN Pump Discharge Pressure	77.6	535.1	79.4	547.5	-1.8	-12.4
Flow Balance-2 Major Loads	KD HX Inlet Pressure	40.7	280.6	40.8	281.3	-0.1	-0.7
	KD HX Outlet Pressure	39.0	268.9	37.8	260.6	1.2	8.3
	KC HX Inlet Pressure	47.9	330.3	47.8	329.6	0.1	0.7
	KC HX Outlet Pressure	46.8	322.7	46.8	322.7	0.0	0.0
	1B RN Pump Inlet Pressure	-3.8	-26.2	-2.5	-17.2	-1.3	-9.0
	1B RN Pump Discharge Pressure	77.5	534.4	78.0	537.8	-0.5	-3.4
Flow Balance-3 Major Loads	KD HX Inlet Pressure	49.9	344.1	48.3	333.0	1.6	11.0
	KD HX Outlet Pressure	47.7	328.9	44.6	307.5	3.0	21.4
	KC HX Inlet Pressure	61.9	426.8	59.4	409.6	2.5	17.2
	KC HX Outlet Pressure	60.3	415.8	58.5	403.4	1.8	12.4
	1B RN Pump Inlet Pressure	0.0	0.0	1.1	7.6	-1.2	-7.6
	1B RN Pump Discharge Pressure	89.1	614.3	89.1	614.3	0.0	0.0
Pressure – Average Overall 1B Calibration Accuracy						**1.2**	**8.4**

TABLE 3. FLOW RESULTS FOR 2B PARTIAL MODEL CALIBRATION

Flow Scenario	Parameter	Model Value		Flow Balance Value		Calibration Accuracy
		gpm	m^3/hr	gpm	m^3/hr	
Flow Balance-1 Major Loads	2B KD HX	801.0	181.9	833.0	189.2	-3.8%
	2B KC HX	4931.0	1120.0	4893.0	1111.3	0.8%
	2B RN Pump	12070.0	2741.4	12096.0	2747.3	-0.2%
Flow Balance-2 Major Loads	2B KD HX	1089.0	247.3	1083.0	246.0	0.6%
	2B KC HX	5357.0	1216.7	5334.0	1211.5	0.4%
	2B RN Pump	12664.0	2876.4	12667.0	2877.0	0.0%
Flow – Average Overall 2B Calibration Accuracy						**1.0%**

TABLE 4. PRESSURE RESULTS FOR 2B PARTIAL MODEL CALIBRATION

Flow Scenario	Parameter	Model Value		Flow Balance Value		Calibration Accuracy	
		psig	kPa-g	psig	kPa-g	psig	kPa-g
Flow Balance-1 Major Loads	2B RN Pump Inlet	-5.6	-38.6	-3.1	-21.4	-2.5	-17.2
	2B RN Pump Discharge	78.9	544.0	78.5	541.3	0.4	2.8
Flow Balance-2 Major Loads	2B RN Pump Inlet	-6.9	-47.6	-3.1	-21.4	-3.8	-26.2
	2B RN Pump Discharge	76.3	526.1	76.5	527.5	-0.2	-1.4
Pressure – Average Overall 2B Calibration Accuracy						**1.7**	**11.9**

TABLE 5. ABRIDGED FLOW RESULTS FOR 2B COMPLETE CALIBRATION

Flow Scenario	Parameter	Model Value		Flow Balance Value		Calibration Accuracy
		gpm	m^3/hr	gpm	m^3/hr	
Flow Balance 1- Major Loads	2B KC HX	4661.2	1058.7	4503.3	1022.8	3.5%
	2B KD HX	977	221.9	969.1	220.1	0.8%
Flow Balance 1-Minor Loads	2B NV Pump Speed Reducer & Bearing Oil Flow Element	50.5	11.5	51.5	11.7	-2.0%
	2RNFE-6760 (2B NV Pump Motor Cooler Flow Element)	100	22.7	98.2	22.3	1.8%
	2B1 KC Pump Motor Cooler Flow Element	77.3	17.6	79.6	18.1	-2.8%
	2B2 KC Pump Motor Cooler Flow Element	88.1	20	87.4	19.8	0.8%
	B YC Chiller Condenser Flow Element	767.2	174.3	795.3	180.6	-3.5%
	2B KF Pump Motor AHU Inlet Isolation Valve	33.1	7.5	31.5	7.2	4.9%
	2B NS HX Flow Element	3904.4	886.8	3901.8	886.2	0.1%
	2B RN Pump Flow Element	11566.9	2627.2	11429	2595.8	1.2%
Flow Balance 2- Major Loads	2B KC HX	5229.7	1187.8	5089.3	1155.9	2.8%
	2B KD HX	1097.7	249.3	1067.7	242.5	2.8%
Flow Balance 2- Minor Loads	2B NV Pump Speed Reducer & Bearing Oil Flow Element	56.9	12.9	56.5	12.8	0.8%
	2B NV Pump Motor Cooler Flow Element	112.7	25.6	111.2	25.2	1.4%
	2B1 KC Pump Motor Cooler Flow Element	86.8	19.7	88.3	20.1	-1.7%
	2B2 KC Pump Motor Cooler Flow Element	98.9	22.5	99.3	22.6	-0.4%

Flow Scenario	Parameter	Model Value		Flow Balance Value		Calibration Accuracy
		gpm	**m^3/hr**	**gpm**	**m^3/hr**	
Flow Balance 2- Minor Loads	B YC Chiller Condenser Flow Element	860.7	195.5	872.6	198.2	-1.4%
	2B KF Pump Motor AHU Inlet Isolation Valve	38.4	8.7	35.6	8.1	8.0%
	2B NS HX Flow Element	38.4	8.7	35.6	8.1	8.0%
	2B RN Pump Flow Element	8599.4	1953.2	8428.7	1914.4	2.0%
Flow-Average Overall 2B Calibration Accuracy(Includes All Values from Complete Table available upon request)						**2.3%**

TABLE 6.ABRIDGED PRESSURE RESULTS FOR COMPLETE MODEL CALIBRATION

Flow Scenario	Parameter	Model Value		Flow Balance Value		Calibration Accuracy	
		psig	**kPa-g**	**psig**	**kPa-g**	**psig**	**kPa-g**
Flow Balance 1- Major Loads	2B KC HX Supply Header	49.9	348.3	50.7	354.0	-0.8	-5.7
	2B KC HX Discharge Header	49.0	341.9	49.2	343.7	-0.3	-1.8
	2B KD HX Supply Header	48.9	341.5	49.7	346.8	-0.8	-5.3
	2B KD HX Discharge Header	46.7	326.1	47.2	329.3	-0.5	-3.3
Flow Balance 1- Minor Loads	2B RN Pump Suction Header	-2.8	-19.3	-2.3	-15.9	-0.5	-3.5
	2B RN Pump Discharge Header	81.8	571	81.8	571.4	-0.1	-0.3
	B YC Chiller Condenser Flow Element	43.8	305.9	45.2	315.9	-1.4	-10.1
	B VC/YC Chiller Condenser Discharge	35.1	245	37.1	258.9	-2.0	-13.9
	2B KF Pump Motor AHU Supply	28.8	201.1	27.1	189.4	1.7	11.7
	2B KF Pump Motor AHU Discharge	25.6	178.7	24.8	173.2	0.8	5.6
	2B NV Pump Oil Coolers Supply	57.4	400.7	57.3	400.0	0.1	0.7
	2B NV Pump Speed Reducer & Bearing Oil Flow Element	40.9	285.9	40.7	284.1	0.3	1.7
	2B NV Pump Motor Cooler Supply	53.9	376.5	57.5	401.7	-3.6	-25.2
	2B NV Pump Motor Cooler Flow Element	46.4	324.4	50.9	355.8	-4.5	-31.4
	2B KC Pump Motor Coolers Supply	45.6	318.4	51	356.3	-5.4	-37.9
	2B1 KC Pump Motor Cooler Flow Element	34.1	237.8	37.3	260.6	-3.3	-22.8
Flow Balance 2- Major Loads	2B KC HX Supply Header	61.8	431.5	60.7	423.8	1.1	7.7
	2B KC HX Discharge Header	60.7	423.8	58.8	410.6	1.9	13.3
	2B KD HX Supply Header	59.2	413.2	58.4	407.6	0.8	5.7
	2B KD HX Discharge Header	56.4	394.2	55.3	385.9	1.2	8.2
Flow Balance 2- Minor Loads	2B RN Pump Suction Header	1	7.1	1.4	9.8	-0.4	-2.7
	2B RN Pump Discharge Header	91.4	638.4	91.5	639.1	-0.1	-0.8
	B YC Chiller Condenser Flow Element	56.7	395.7	56.1	391.6	0.6	4.1
	B VC/YC Chiller Condenser Discharge	45.8	320	46.7	326.0	-0.9	-6
	2B KF Pump Motor AHU Supply	38.6	269.5	37.2	260.0	1.4	9.5
	2B KF Pump Motor AHU Discharge	34.6	241.6	31.2	217.9	3.4	23.7
	2B NV Pump Oil Coolers Supply	67.5	471.5	65.6	457.9	1.9	13.6
	2B NV Pump Speed Reducer & Bearing Oil Flow Element	47.1	328.9	46.6	325.2	0.5	3.6
	2B NV Pump Motor Cooler Supply	64.1	447.9	68	475.3	-3.9	-27.3
	2B NV Pump Motor Cooler Flow Element	54.9	383.1	59.8	418.0	-5.0	-34.9
	2B KC Pump Motor Coolers Supply	57.0	397.9	61.5	429.4	-4.5	-31.6
	2B1 KC Pump Motor Cooler Flow Element	42.6	297.4	44.6	311.4	-2.0	-14
Pressure-Average Overall 2B Calibration Accuracy (Includes All Values from Complete Table available upon request)						**1.4**	**9.5**

CONCLUSIONS

The Beta method, a new, automated process, was used along with manual iteration during various phases of calibration to assist in calibrating the Duke McGuire Nuclear Station raw water system. The Beta method was performed in three phases. In the first phase, the Beta method was used to calibrate a previously calibrated model. In the second phase, it was used on two systems with partial data sets. In the third phase, it was used on one system with extensive data collection.

During the first phase, the Beta method consistently found roughness values which matched the test data much better in the best cases. In the worst cases, it matched the data equally well. During the second phase, the Beta method was used to calibrate flows in a partial data set to an average overall accuracy of 2.1% and 1%, respectively, and pressures to an average overall accuracy of 1.2 psig (8.4 kPa-g), and 1.7 psig (11.9 kPa-g), respectively. During the third phase, difficulties with the Beta method were experienced due to a variety of reasons that will be explored. In this phase, manual iteration was used in conjunction with the Beta method to calibrate flows in a complete data set to an average overall accuracy of 2.3% and pressures to an average overall accuracy of 1.4 psig (9.5 kPa-g).

Duke does not currently have any plans to investigate the discrepancies discussed because the minimum requirements of the EC were met even with these discrepancies, and they were met with adequate margin above the required flow. Therefore, Duke is confident that the minor load piping will receive (at least) the minimum required flow and that these discrepancies do not need to be examined at this time in order to ensure the safe operation of the plant. Because the only requirement of the flow balance tests for the minor load piping was to record the flows through these pipes (i.e., the pressure measurements were performed for additional precision in support of the EC and were not a requirement in the flow balance tests), the minimum criteria were determined to have been met satisfactorily and, conservatively, with sufficient margin. Further, flow balances are routinely performed to monitor and trend flows through all flow paths to ensure that adequate flows are met.

Even without further investigation of these discrepancies, calibration of the raw water system at Duke MNS provided several benefits to the analysis of the EC. Within the limited time that the calibration was performed, errors in the hydraulic model input, as well as errors in field data, were discovered and corrected as a direct result of the calibration process. Additionally, results acquired from the calibrated model were more realistic and conservative (i.e. lower flows and pressures) than would be calculated from an uncalibrated model. These more conservative results provide additional certainty in asserting the suitability of the proposed EC. In the long term, the calibration performed will likely help those at Duke MNS to quickly pinpoint specific areas in their system that require additional attention. Such areas are indicated in the calibrated model by pipes with large scaling factors (which could indicate highly scaled pipes), or areas in the model that were unable to achieve the flows or pressures (which could indicate faulty measurement devices or other problems with data collection).

ACKNOWLEDGMENTS

The authors would like to acknowledge others who contributed to this project – David Jackson, Ben Keiser, John Rockey, Tom DeVincentis, Elijah Kempton, Norman Stambaugh, Ladreon Hare, James Smith, Dan Heacox, and Terry Pedersen.

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