PICKERING NGS EMERGENCY WATER SUPPLY SYSTEM EMERGENCY START FLOW SIMULATION AND EXPERIMENT

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Abstract

A proposed modification to the OPG Pickering Nuclear Generation Station Emergency Water Supply (EWS) system was analyzed using the Industry Standard Toolset code GOTHIC [1] to determine the acceptability of the proposed system configuration during pump start-up. The new configuration of the system included a vertical dead-ended pipe, initially filled with air. The simulation demonstrated that no significant water hammer effects were predicted and tests performed with the new configuration confirmed the analysis results.

1. Introduction

The Pickering Nuclear EWS System is a seismically qualified, manually operated system. Following a Design Basis Earthquake (DBE) or other common mode event, EWS can be placed in service to inject strained lake water directly to the Primary Heat Transfer System (PHTS), boilers, and reactor building air conditioning units to provide an emergency heat sink function.

Manual operation of EWS first requires the start of the Emergency Power Generators (EPGs), energizing the Emergency Power System (EPS), manual EWS pump start, and manual operation of EWS valves. These actions are required to be completed within 40 minutes of the start of the event. An overview of the EWS piping system layout is shown in Figure 1.

A proposed modification to the EWS system poised configuration was to pre-open a large valve (V1) on each of the four Units to significantly reduce the time and effort required to put EWS in service in an emergency situation. However, opening V1 adds a long, vertical, and initially empty dead-leg pipe to the system on each Unit. This introduced new concerns for water hammer in the system due to the filling of the air pocket.

The simulation analysis described in this paper describes the EWS pump start procedure when V1 is pre-opened. The primary focus was to determine if there is significant water hammer pressure generated during the start of the EWS pumps when V1 was pre-opened. Another issue was that since there would be a large section of pipe to fill, the pump may experience run-out conditions, thus potentially impacting the pump operation during an event. As a potential solution to the above, the analysis also examined the response if the strainer inlet valves were pre-throttled to provide backpressure to the pumps and limit overall system pressure.

The simulation results were used as an input for OPG to decide whether or not to proceed with changing the valve configuration, and conducting a field test. The results gave good confidence that significant water hammer would not occur, and the field test was performed. The results of the test are presented in this paper and show good agreement with the simulations.

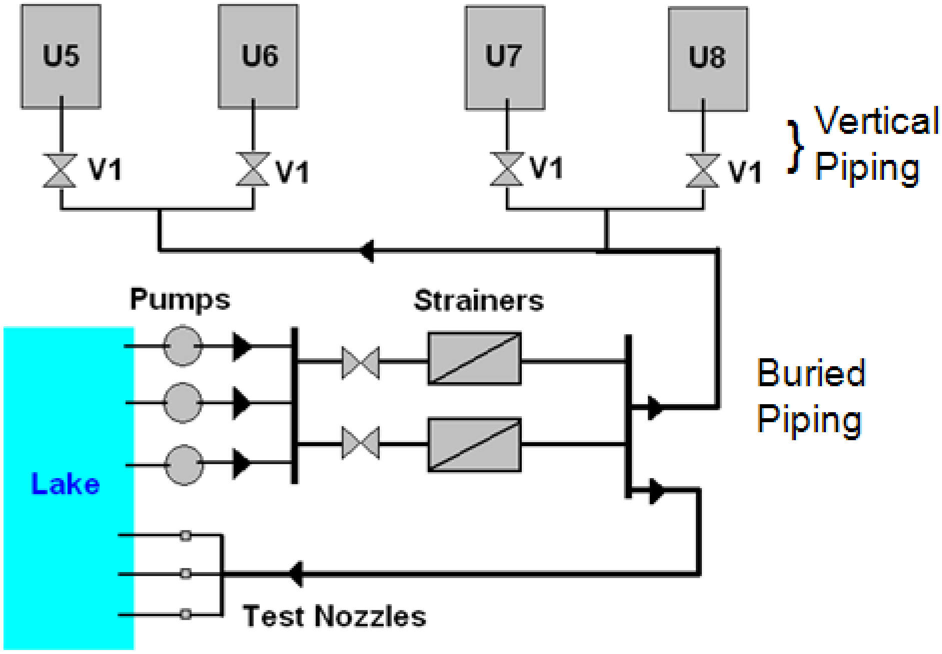

Figure 1 Pickering NGS EWS piping configuration overview

2. Simulation of EWS Response

Prior to a field test being performed with valve V1 pre-opened, GOTHIC version 7.2a was utilized to help provide confidence that the test can be executed without risk to the EWS piping system. The system modeling included the following:

- Multiple EWS injection pumps which take water from the lake,
- Strainer inlet valves which start in a throttled position to limit system pressure,
- A loop back to the lake through test nozzles and throttled-open valves to provide an open flow path back to the lake for testing and start-up,
- A long run of low elevation buried piping which connects the EWS pumphouse at the lake to the reactor buildings, which ends shortly before valve V1, and
- A vertical run of piping from ground level to the next closed valve.
- The vertical section of piping is initially air-filled, and the buried piping is water-filled.

2.1 Simulation Methodology

A GOTHIC 7.2a model was constructed to represent the system hydraulics and air pocket, and was used to produce a transient simulation of the pump start, valve opening, and system response. GOTHIC was chosen based on its capability to model multiple fluids in various phases, bulk flows, wave propagation, and pipe network components. The model included two EWS pumps, test nozzles (which provide an open flow path for testing and start-up), valves, and single unit load. The layout of the GOTHIC model is shown in Figure 2. A single unit is included in the model to simplify the model and to better understand the results.

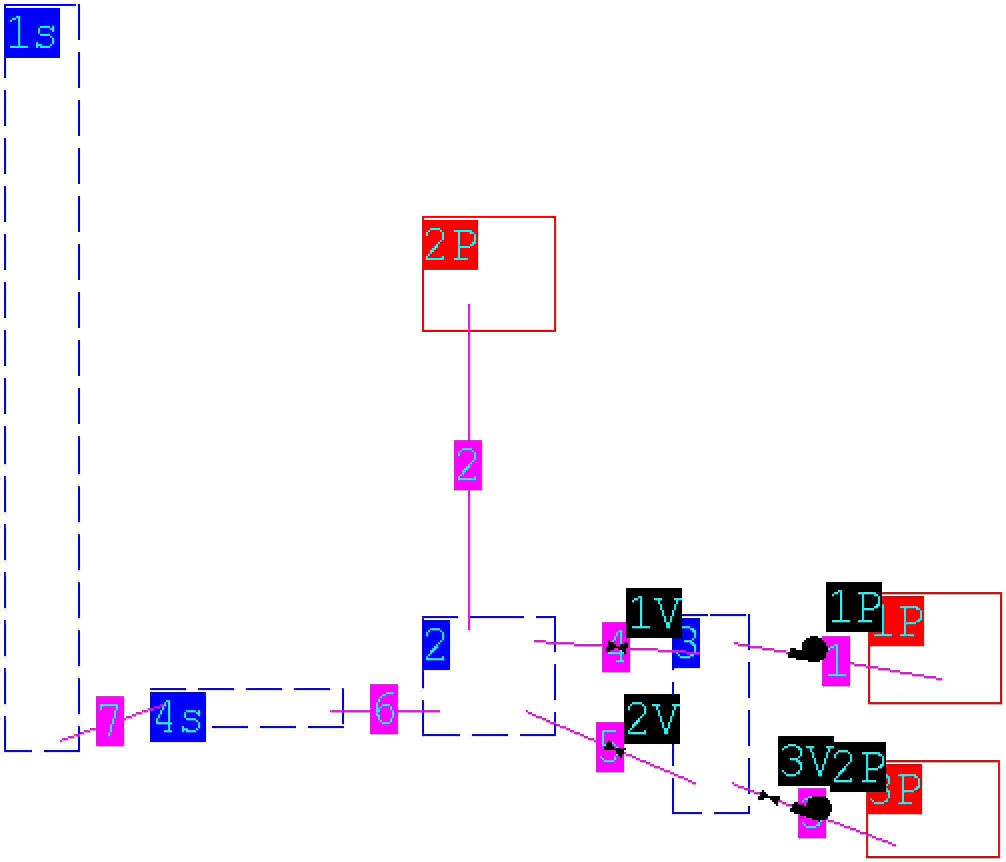

Figure 2 Overview of the GOTHIC EWS injection model

The EWS Pumps (1P and 2P in Figure 2, each 50% duty) are connected in parallel to a common discharge header (volume 3). The modeled pump characteristics were created based on the EWS injection pump head curve. The pump start transient is approximated by opening a simulated discharge valve with linear opening resistance characteristic over 0.5 seconds.

The pump discharge header discharges to two 18” parallel strainer pipes to the strainer discharge header (volume 2), on which the 12” nozzle pipes are connected, as well as the 30” buried pipe to each of the four units. The dimensions and characteristics of the piping were obtained from OPG piping drawings.

The strainer inlet valves are gate valves which are throttled to a resistance of K = 1400 Pa/Pa. This corresponds to an opening of roughly 3.5% [1]. These valves have a non-linear resistance coefficient, as specified in [1]. The resistance of the test nozzles is equivalent to a minor loss coefficient of K = 200, which was derived from OPG specifications and [1].

Resistances of strainers and headers are considered to be negligible. This is considered valid since the throttled strainer valves and nozzles provide several orders of magnitude larger resistance. This is also conservative for water hammer since less resistance results in increased velocity, and higher water hammer pressure. Both the pump suction and nozzle discharge boundary conditions are set to 101.3 kPa(a). The lake water temperature is set to 5 ºC, which is considered conservative due to the density at this temperature.

The EWS piping system is considered to be drained to the 255’ 9” level, such that the 90 metre large diameter piping (16”-30”) in the yard is initially filled with water (subdivided volume 4s, 45 sub-volumes), and the 13 metre vertical run of pipes up to the EWS unit valve station is filled with air at atmospheric pressure (subdivided volume 1s, 26 sub-volumes). The top of the vertical pipe is assumed closed, and leak tight. It is conservatively modeled as a straight section of vertical pipe with a diameter of 10”. The buried piping volume and vertical pipe were discretized using a subdivided volume to allow modeling of the pressure waves and air pocket filling due to pump starts and valve opening.

Two models were constructed. Model 1 looks at sequentially starting two pumps, two test nozzles in their normal position, and no strainer inlet throttling. This model simulates the conditions where the pump discharge has very little resistance, and could result in the largest water hammer scenario. Model 2 looks at sequentially starting two pumps with strainer inlet nozzles throttled, and two test nozzles in their normal position. This model simulates the conditions where the pump discharge is largely throttled, and therefore the greatest static pressure increase is expected to be when the discharge valves are fully-opened.

Model 1 has two steps:

1. t = 0 s, start the first pump. Let the system stabilize for 30 seconds.
2. t = 30 s, start the second pump (over 0.5 seconds).

Model 2 has three steps:

1. t = 0 s, start first pump with valves strainer inlet valves throttled. Let the system stabilize for 30 seconds.
2. t = 30 s, start the second pump (over 0.5 seconds) with strainer inlet valves throttled. Let the system stabilize for 30 seconds.
3. t = 60 s, open strainer inlet valves fully over a period of 30 seconds.

The total simulation time is 100 seconds, with a time step of 0.001 seconds. Each modeling step is 30 seconds long to allow pressures and flow to stabilize. This is expected to be much faster than operator field action. The 2nd pump flow is started by opening the discharge valve over a period of 0.5 seconds to prevent numerical instability. The first pump is not controlled in this manner since there is a gradual fill time at the beginning.

3. Field Test of EWS Response

Once the results of the simulations determined that no significant water hammer effects were expected, a field test of the system was conducted.

3.1 Field Test Methodology

The field test of the EWS system was done by starting the first pump, waiting for the system pressure to stabilize, then starting the second pump. During this time the strainer inlet valves would remain throttled, the system would gradually fill, and the water column in the vertical piping would rise. Water from the pumps would be continuously discharged from the test nozzles to the lake. After the second pump was started and the system had stabilized, the strainer inlet valves were opened which removed line resistance (and pressure loss) and caused a subsequent increase in the vertical piping pressure.

4. Results

4.1 Simulation Results

The resulting pressures in the vertical pipe from Model 1 (strainer inlet valves not throttled) are shown in Figure 3 and Figure 4. PR1s1 represents the base of the vertical column (which quickly is submerged in water) and PR1s26 represents the top of the vertical column which remains air-filled as the air is compressed.

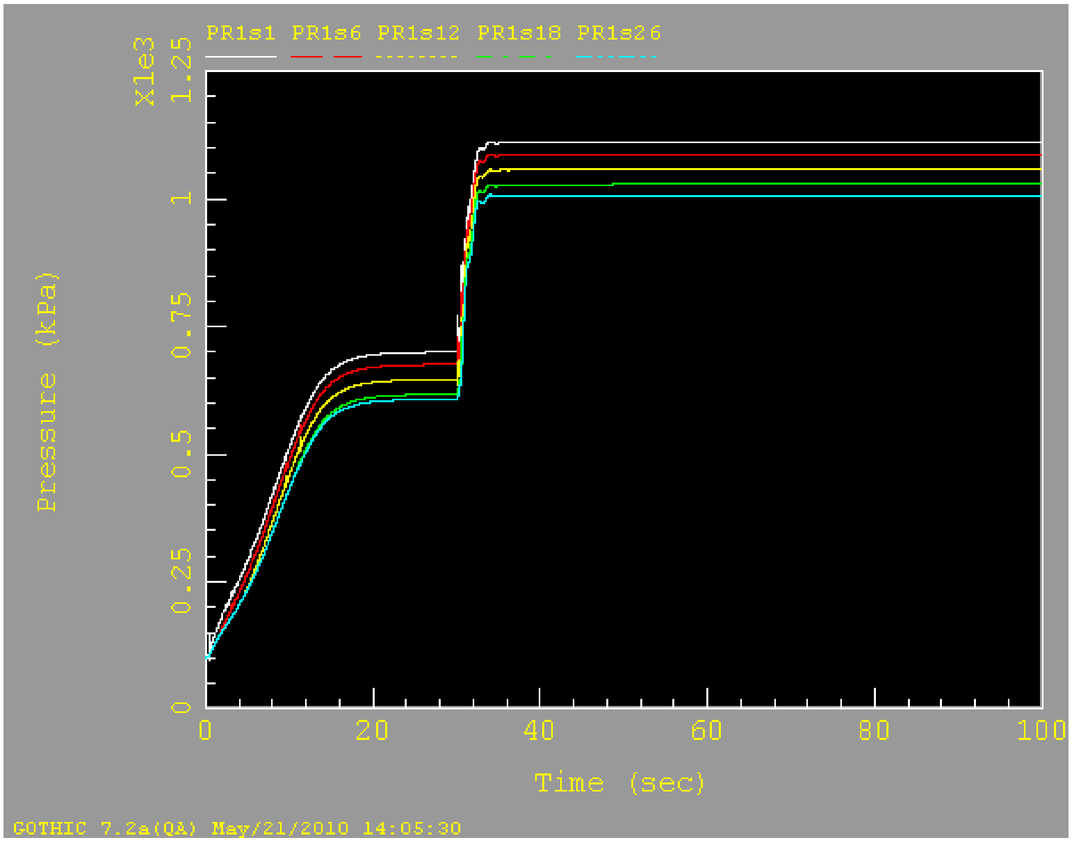

Figure 3 Pressures in Vertical Pipe (Model 1) (PR1s1 is bottom of pipe, PR1s26 is top of pipe)

The pressure in the discharge headers from Model 1 (strainer inlet valves not throttled) are given in Figure 5 and Figure 6. Since GOTHIC models pumps with an instant start, there could be several seconds of numerical instability once the pumps begin operating and before they have reached steady-state. However, in reality these large pressure spikes do not occur (as seen in Section 4.2). The numerical instability does not exist in reality because the pump has a finite run-up time. In the GOTHIC model, the issues associated with an instant pump start were addressed by opening the pump discharge valve over a short, finite duration (0.5 seconds).

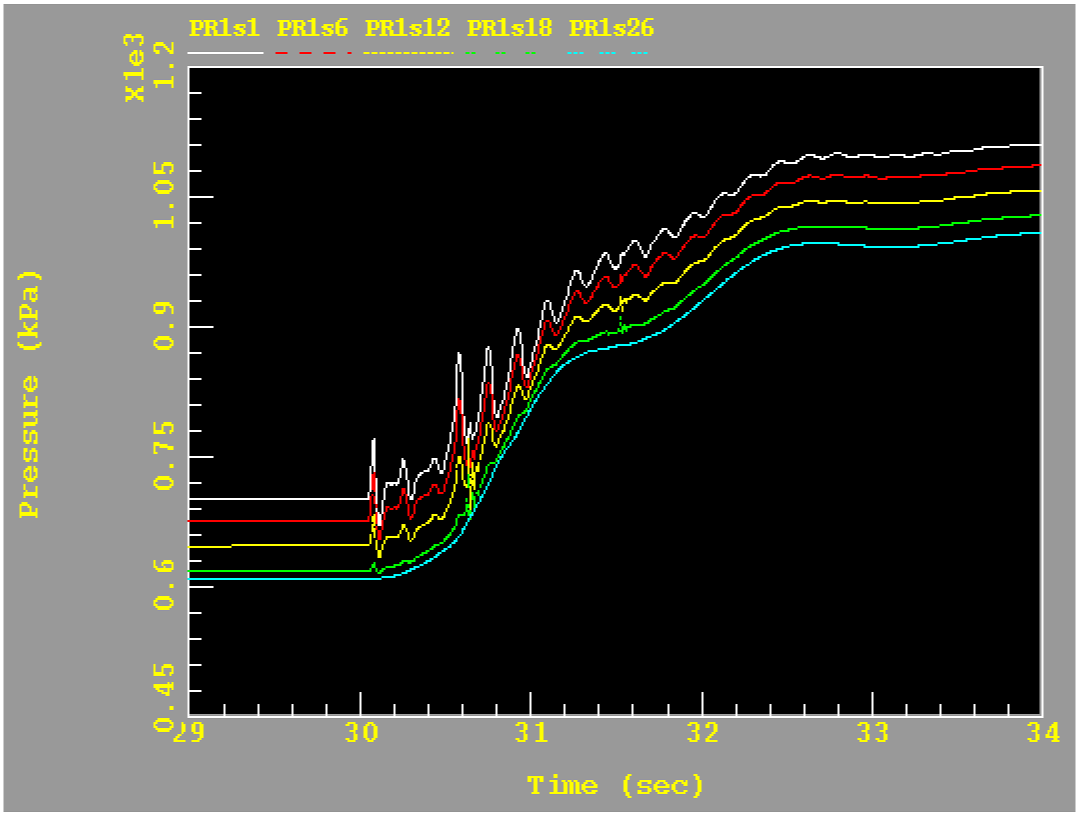

Figure 4 The pressure in the vertical pipe after second pump start (Model 1)

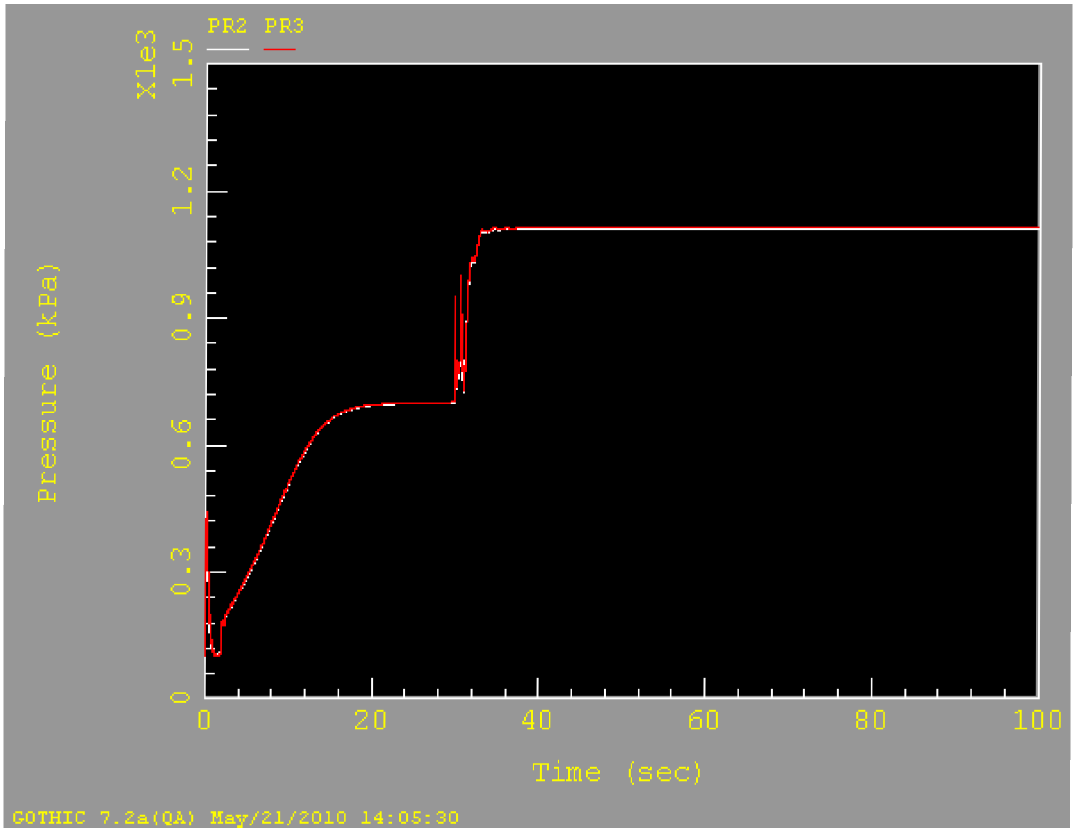

Figure 5 Header Pressures (Model 1) (PR2 = Strainer Discharge Header Pressure, PR3 = Pump Discharge Header Pressure)

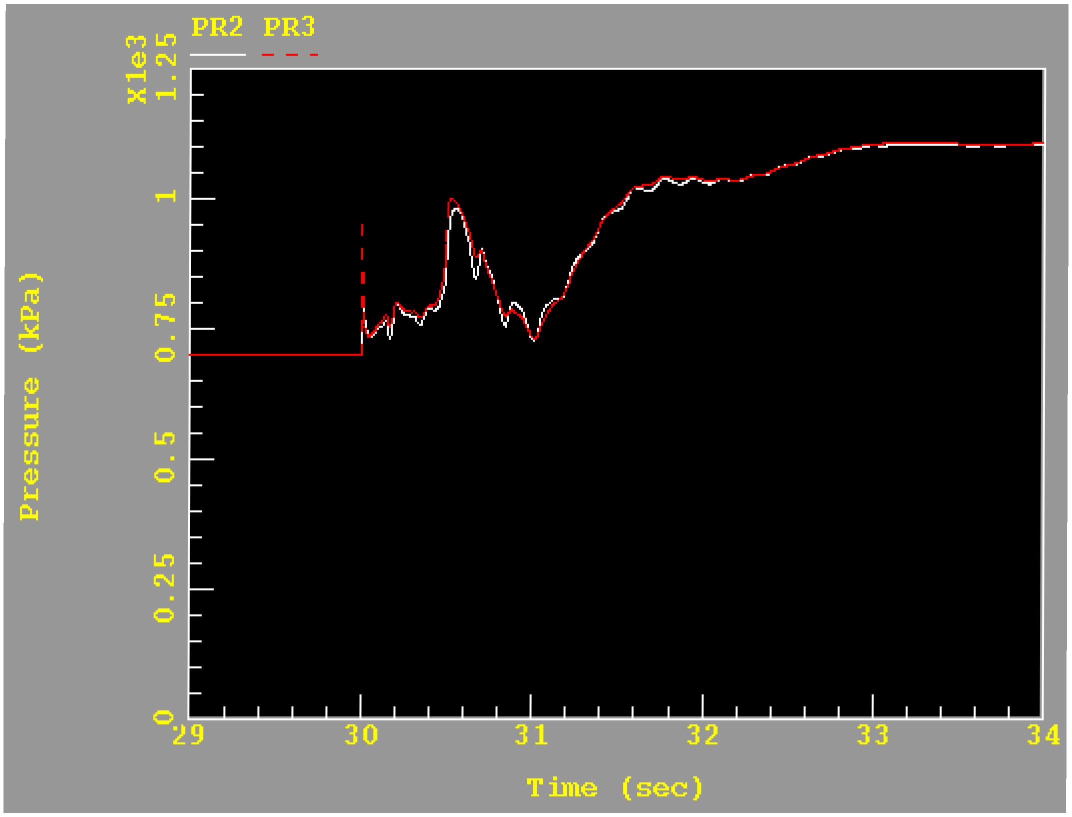

Figure 6 Header Pressures after second pump start (Model 1) (PR2 = Strainer Discharge Header Pressure, PR3 = Pump Discharge Header Pressure)

The resulting pressures in the vertical pipe from Model 2 (strainer inlet valves throttled) are shown in Figure 7.

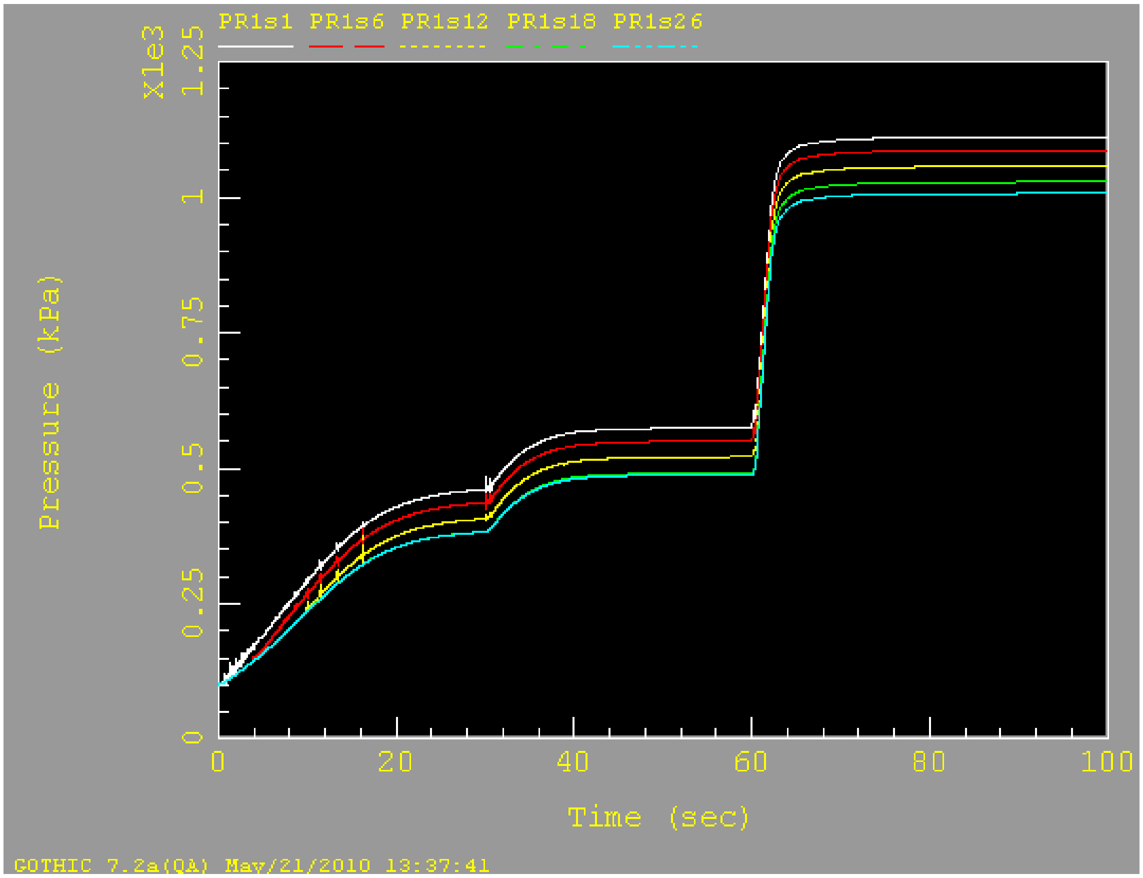

Figure 7 Pressures in Vertical Pipe (Model 2) (PR1s1 is bottom of pipe, PR1s26 is top of pipe)

Figure 8 and Figure 9 provide zoomed views of the pressure in the vertical pipe at 30 and 60 seconds, respectively, in Model 2.

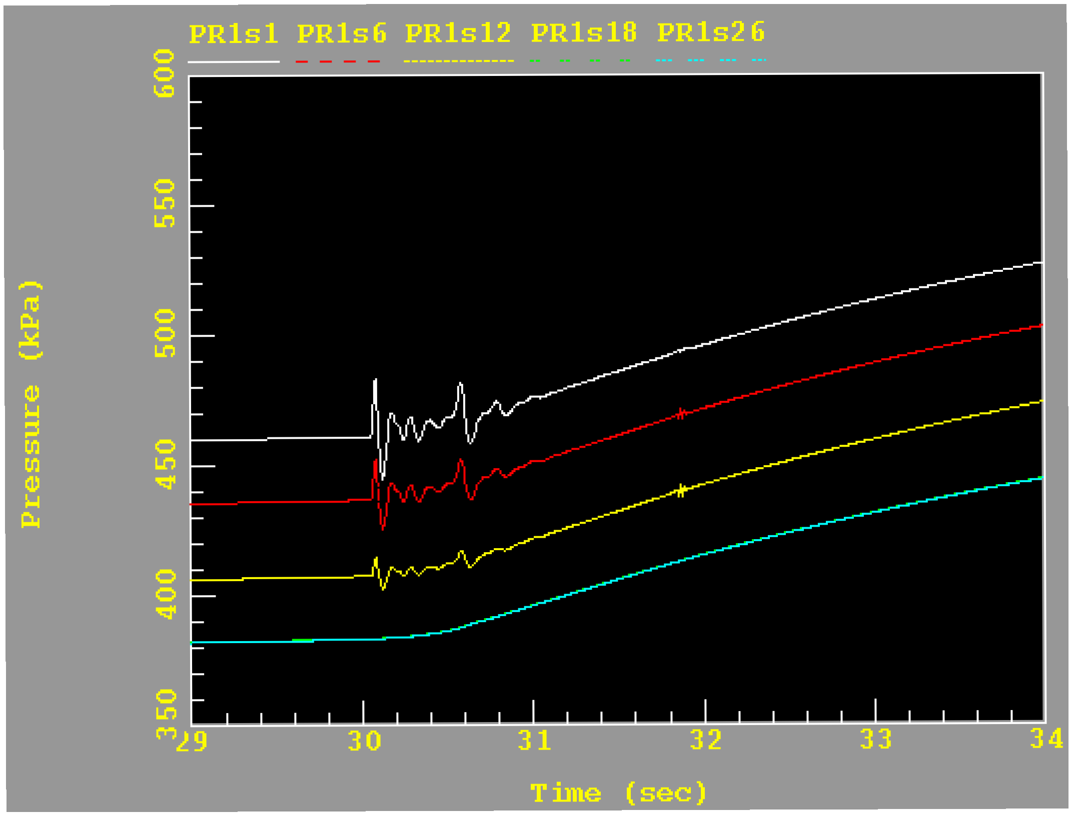

Figure 8 The pressure in the vertical pipe after second pump start (Model 2)

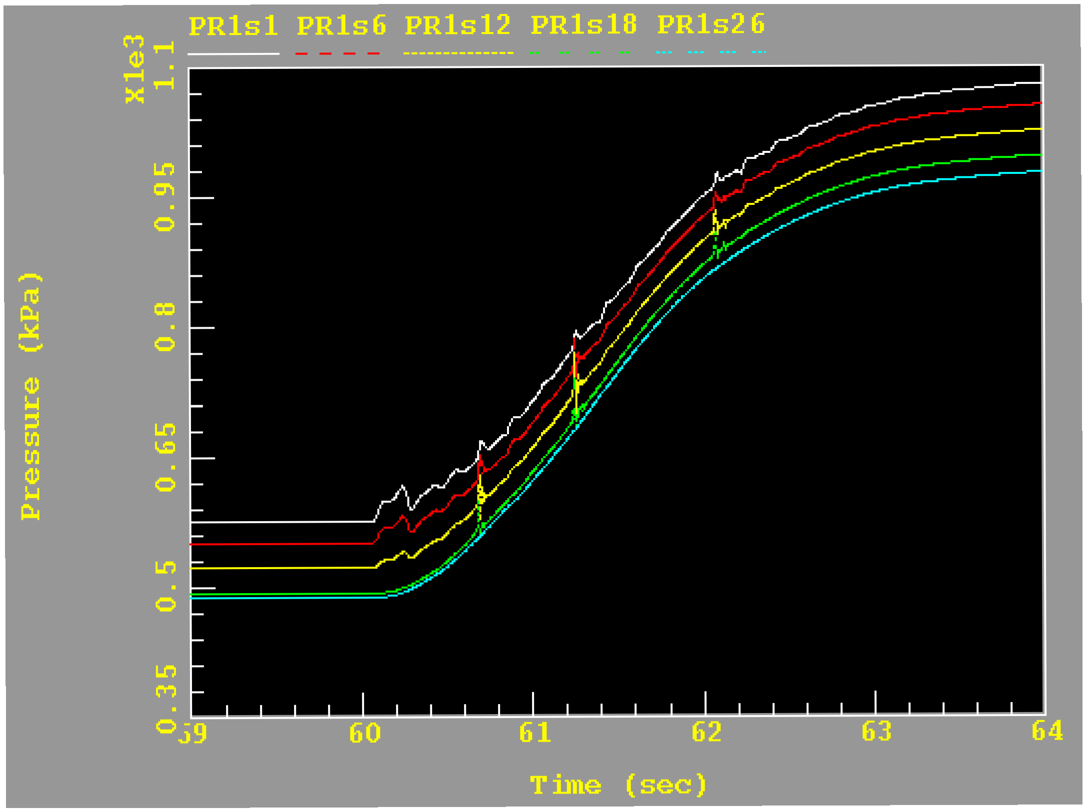

Figure 9 The pressure in the vertical pipe after strainer inlet valves opened (Model 2)

The pressure in the discharge headers is given in Figure 10. The effect of throttling the strainer inlet valves is seen in the overall magnitude of pressure between the pump and strainer discharge headers, as well as the reduced magnitude of the transient pressure spikes after the start of the second pump at 30 seconds.

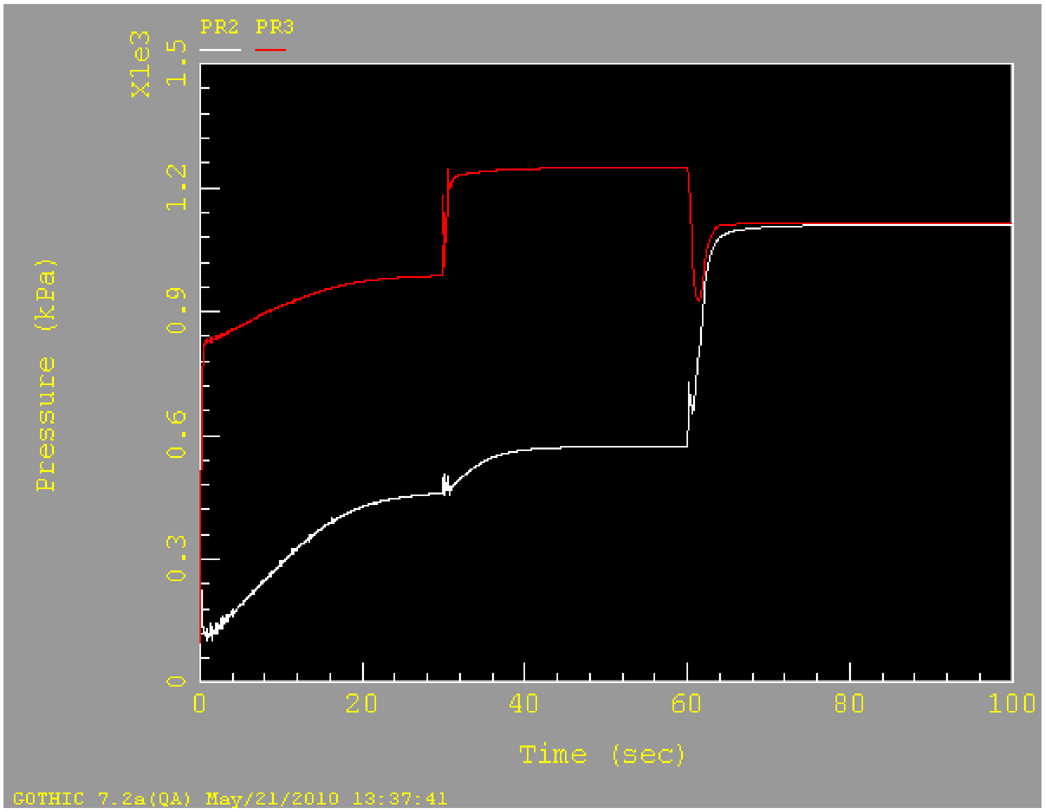

Figure 10 Header Pressures (Model 2) (PR2 = Strainer Discharge Header Pressure, PR3 = Pump Discharge Header Pressure)

4.2 Field Test Results

Field test pressure data was read on local pressure gauges, and the readings were recorded on video as the test was conducted. The procedure of the test was similar to Model 2, in that each pump was started sequentially, then the throttled strainer inlet valves were opened. A summary of the test results is given below:

1. The first pump was started. The pressure increased slowly and smoothly at the top of the air-filled column and at the pump discharge header as the system filled (~50 seconds). No pressure spikes were observed.
2. The second pump was then started (~150 seconds), which experienced a much faster increase in pressure (~2 seconds, small pressure transient of +100 kPa which dampened out after about 4 cycles) was observed at the top of the vertical piping.

3. Once the system had stabilized with two pumps operating, the throttled strainer inlet valves were fully opened (~300 seconds). It was determined after the test that the valves were throttled too far open, which resulted in a minimal increase in pressure once fully opened.
4. As-left throttled position has since been changed to better mitigate the system pressure transient.

The pressure of the strainer discharge header and pressure at the top of the vertical piping was recorded on video, and the pressure data were manually translated to a plot. The results for the strainer discharge pressure are shown in Figure 11 and Figure 12, and the results for the top of the vertical piping are shown in Figure 13 and Figure 14.

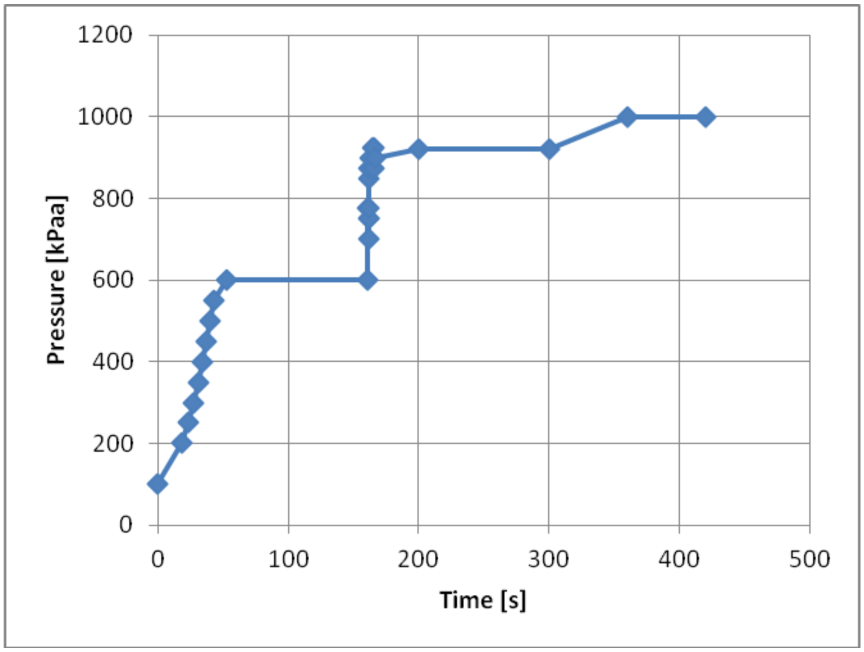

Figure 11 Field test results for strainer discharge pressure

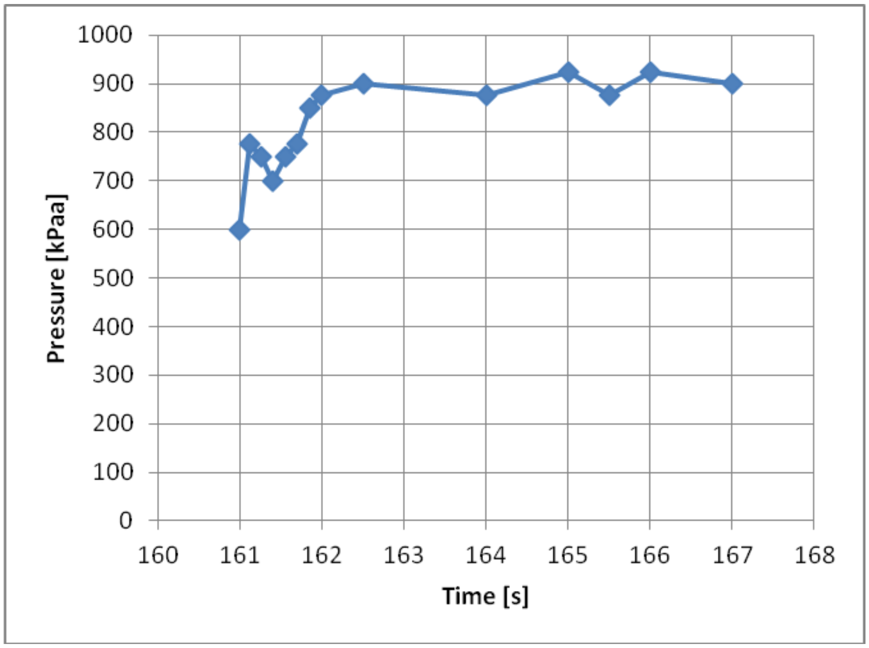

Figure 12 Field test results for strainer discharge pressure, after second pump start

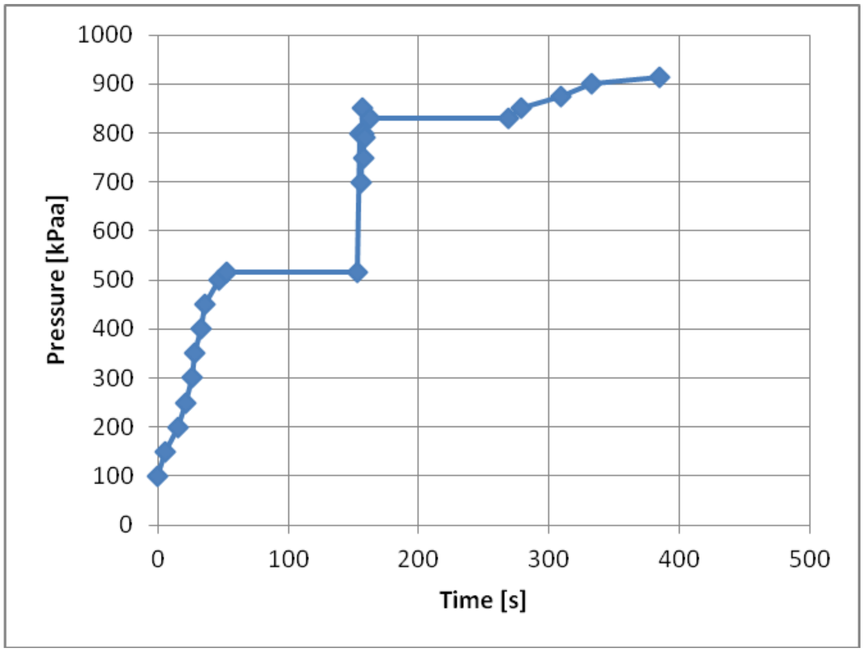

Figure 13 Field test results for top of vertical column

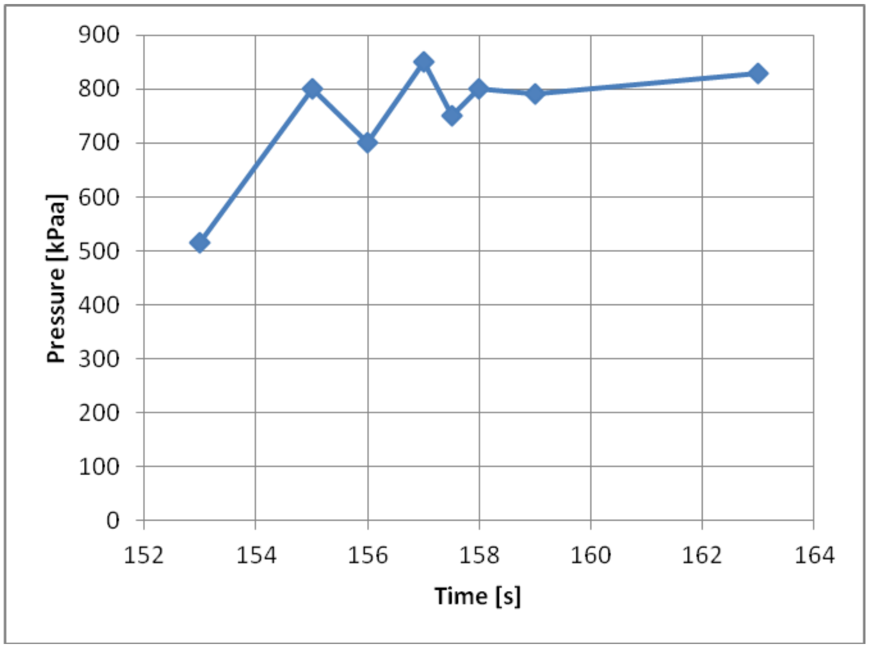

Figure 14 Field test results for top of vertical column, after second pump start

5. Discussion

The results of the field tests closely resemble the simulated results in that there is a initial steady pressure increase with very little system pressure oscillation when the first pump is started and the system begins to fill and pressurize. Once the second pump is started, pressure oscillations are observed in the strainer discharge and at the top of the vertical piping where the air pocket is compressed. The air pocket provides a less rigid boundary condition compared to a solid end (i.e., water-filled up to a closed valve).

The values of the field test do not exactly match simulated results for the following reasons:

1. Strainer inlet valve resistance was much lower than estimated in the simulations. This was evident when the valves were fully opened and resulted in very little change to system pressures.
2. Readability and conversion of the data, as well as the result videos broken into several files resulted in approximations for both pressure and time. Normal, small system pressure fluctuations were recorded as the time-averaged value.
3. Geometry of piping was simplified for modeling purposes.

The results of the field test (with initial strainer inlet valve throttling) align very closely with the results of Model 1 which has no throttling, as opposed to Model 2 which has significant throttling. The strainer inlet valves have since been throttled more in the closed direction.

The simulated response in Figure 4 clearly shows pressure waves which are indicative of a propagative flow system response. The propagation time of the water-filled piping is defined in [3].

$$t_p = \frac{L}{V}$$

Where L is the distance from the pump to the top of the water column, and V is the speed of sound in water. The measured test and simulation periods of the reflecting propagating waves corresponds well to the theoretical reflection time (twice the propagation time):

$$t_p = 2\frac{L}{V} = 2\frac{\sim 100m}{1500\,\frac{m}{s}} =\sim 0.13\,\text{seconds (~7.5 Hz)}$$

The pumps take some time to run-up to full speed and pressure (0.5 seconds was used in the simulation) and it only takes 0.13 seconds for the pressure to reflect back to the pump and interfere with the steadily increasing pressure. The test results for the top of the air column show fluctuating pressure amplitude on the order of 100 kPa, compared to the steady state increase in pressure of about 300 kPa. This is a factor of 3, compared to the factor of 4 for the simulations. If the pump start-up was instantaneous, or the buried piping was much longer, then a much higher pressure spike would be expected.

In addition, both the simulation results (Figure 4, Figure 6, Figure 8, and Figure 9) and test results (Figure 12 and Figure 14) show another prominent pressure oscillation with a period ranging from 0.5-3 seconds (0.3 - 2 Hz). This suggests a separate, bulk flow system response between the fluid column and the air pocket.

Due to the complexity of the system, it is not possible to classify the overall system response as either bulk or propagative flow regimes, but a combination of the two [3]. Reference [3] defines a system as primarily bulk flow if the propagative time is much smaller than the forcing function time. Near the start, the system is gradually filling because of the relatively small capacity of the pumps and is primarily a bulk flow system. After the start of the second pump and subsequently fast rise in pressure, the mixed flow regime of both bulk and propagative flows is seen. This is true in both the simulated and experimental results.

6. Conclusion

A proposed modification to the Pickering EWS system was modeled using GOTHIC. GOTHIC was able to model the mixed flow regime and thereby provide a convenient tool for assessment. The model accurately represented the multiple fluid phases, system hydraulics and air pocket response, and successfully produced a transient simulation of the pump start, valve opening, and system response that matched test conditions. The resulting simulation results demonstrated that no significant water hammer effects were predicted and was confirmed by the tests performed with the new configuration.

The conclusions of the simulation and test results are:

1. The relatively short time for propagative waves to travel through the system compared to pump start-up time resulted in no large pressure transients.
2. The air pocket at the top of the vertical column does provide some resistance to peak pressure. Results of both the test and simulation show that the air pocket caused a gradual deceleration of the incoming water, thus reducing the peak transient pressure.
3. The main EWS pumps do not have enough capacity to cause an initial pressure spike when the first pump is started. Both simulation and test results showed that there was a considerable time of system filling after the start of the first pump.
4. Strainer inlet throttling helped to significantly reduce the magnitude of pressure pulsation in the piping system.
5. The test nozzles contribute to the damping of the pressure pulsations, since after a pressure wave reaches the discharge headers some of the energy is rejected to the lake. The piping friction also makes a significant contribution to the damping of the dynamic system response.

7. References

[1] “GOTHIC Containment Analysis Package User Manual”, Version 7.2a, Electronic Power Research Institute, NAI 8907-02, January 2006.

[2] Donald S. Miller, “Internal Flow Systems”, British Hydromechanics Research Association, 1990.

[3] Frederick J. Moody, “Introduction to Unsteady Thermofluid Mechanics”, John Wiley & Sons, 1990.