Proceedings of 13th International Conference on Nuclear Engineering
"Nuclear Power – Meeting the Energy Challenge of the Environment "
Continental Grand Hotel, Beijing
Beijing, China
May 16-20, 2005

ICONE13-50297

VALIDATION OF A THERMAL HYDRAULIC COMPUTER CODE TO PERFORM TWO-PHASE MULTI-COMPONENT FORCE CALCULATIONS FOR STRUCTURAL EVALUATIONS

Joseph S. Miller/EDA, Inc.
6397 True Lane
Springfield, VA 22150
Phone: 703 597-2459, Fax: 703 313-9138
e-mail: JoeMiller@edasolutions.com

Kevin Ramsden/Exelon Nuclear
Mechanical Engineering, LLC
4300 Winfield Road
Warrenville, IL 60555
Phone: 630 657-3892 , Fax: 630 657-4328
e-mail: Kevin.ramsden@exeloncorp.com

ABSTRACT

This paper presents the results of piping load validation calculations using the thermal hydraulic computer program, RELAP5/M3.3. RELAP5/M3.3 is a computer program developed by the Nuclear Regulatory Commission (NRC) to perform two-phase multi-component hydraulic calculations.

RELAP5 was originally developed for the thermal-hydraulic evaluation of transients and loss of coolant accidents (LOCAs) in light-water nuclear power plants. RELAP5 uses a one-dimensional, two-fluid model, consisting of steam and water, with the possibility of the vapor phase containing a non-condensable component and the liquid phase containing a nonvolatile solute. RELAP5/M3.3 is the current version of the RELAP5 code series. The RELAP5/M3.3 code manual indicates that the program has not been validated to calculate forcing functions for structural evaluations. The evaluations presented in this paper provide the necessary comparisons to test data to validate RELAP5/M3.3 as a tool that can be used to develop forcing functions for structural evaluations.

In this paper, two cases are used to validate RELAP5M3.3 for use in analyzing fluid flow in piping systems and for producing the vector piping loads. The two cases are from the CE 908 test performed by Combustion Engineering and from the Altran Corporation waterhammer testing. Both tests were sponsored by EPRI.

The RELAP5/M3.3 calculated parameters such as pressure and calculated forcing functions are compared to measured pressure and forces from the CE 908 test performed in Windsor, Connecticut in 1979 through 1980. The CE908 test represents the high-pressure water slug discharge through a safety valve into a downstream piping configuration. The piping configuration represented a typical pressurized water reactor (PWR) safety/relief valve (S/RV) configuration.

The Altran Corporation waterhammer testing program performed a number of tests, covering simple column closure to waterhammer in more complicated geometries. A particularly desirable aspect for both the CE908 and the Altran Corporation waterhammer testing was that the support reaction loads were measured, which allows not only the RELAP5/M3.3 pressure, velocity and acceleration responses to be validated, but also the force time history generation methodology employed can be validated.

Nomenclature

LOCA - Loss of Coolant Accident
CE – Combustion Engineering
EPRI – Electric Power Research Institute

GL – Generic Letter
LOCA – Loss of Coolant Accidents
LWR – Light Water Reactor
NRC – Nuclear Regulatory Commission
PWR – Pressurized Water Reactor
SR/V – Safety Relief Valve
TBR – Technical Basis Report

Introduction

Development of RELAP5 (Ref. 4) was started in the 1980s to perform simulations of light water reactor (LWR) loss of coolant accidents (LOCAs). Many versions of RELAP5 have been developed over the last 25 years. RELAP5/M3.3, which is the version of RELAP5 used to perform the analyses presented in this paper, is a "best estimate" system code suitable for the analysis of all postulated accidents in Light Water Reactor (LWR) systems, as well as the full range of operational transients. The one-dimensional RELAP5/M3.3 code is based on a non-homogeneous and non-equilibrium model for the two-phase system that is solved by a fast, partially implicit numerical scheme to permit economical calculation of system transients.

For many years the nuclear community used RELAP5 to determine waterhammer type loads on piping structures containing a liquid mixture of steam and water with air. In the application of using RELAP5/M3.3 to model piping systems, it is stated in the RELAP5/M3.3 user manual (Ref. 4) that RELAP5/M3.3 was not validated to perform load calculations for piping systems. This paper is presented to provide the validation of RELAP5/M3.3 to perform analyses of complicated fluid flow systems and to provide the forces associated with fluid transient in the piping system.

Discussion

This paper compares RELAP5/M3.3 calculated forces to test data of thermal hydraulic load measurements from Altran Corporation testing that was performed to support the response to GL 96-06 (Ref. 1). Additionally, RELAP5/M3.3 calculated forces were compared to test data loads from CE 908, which was a test performed to validate piping restraints in support of utility responses to NUREG-0737 (Refs. 3 & 6). The Altran Corporation Test 2b was used to represent a low-pressure waterhammer event and the CE Test 908 was used to represent the high-pressure waterhammer event. Comparisons of the measured data to RELAP5/M3.3 calculated pressures and forces are provided for the two tests. The comparisons are presented in the following paragraphs.

Structural Loading Methodology

The development of the transient force time history as provided by RELAP5/M3.3 for application to structural analysis models is based on the general force equations for a container. The generalized force equation in one-dimensional form can be resolved for a piping segment as:

$$F = -\frac{1}{g}\frac{d}{dt}\iiint \rho A V dx$$

RELAP5/M3.3 employs a two fluid treatment, and with consideration of the vapor components of the flow, this equation becomes:

$$F = -\frac{1}{g}\frac{d}{dt}\iiint (\rho_l A V_l \alpha_l + \rho_g A V_g \alpha_g) dx$$

Where:

ρ=density

A= Area

V=velocity

α=void fraction

subscripts l and g refer to liquid and gas phases

x= distance along piping axis

g=gravitational constant

The integration of the two fluid force equations in one-dimensional form can be reduced to RELAP5/M3.3 XMGR variables as follows.

As related to RELAP5/M3.3 variables, for vapor

Wg = –Deriv(Sum(Velg x Voidg x Rhog x dL) x A/g)

where

Deriv is time derivative
Velg is velocity of gas, ft/s
Voidg is void fraction of gas
Rhog is density of gas, lb/ft^3
dL is length of piping node, ft
A is cross sectional area of pipe, ft^2
g is gravity constant

As related to RELAP5/M3.3 variables, for liquid

Wf = –Deriv(Sum(Velf x Voidf x Rhof x dL) x A/g)

Where

Deriv is time derivative,
Velf is velocity of liquid, ft/s
Voidf is void fraction of liquid
Rhof is density of liquid, lb/ft^3
dL is length of piping node, ft
A is cross sectional area of pipe, ft^2
g is gravity constant

Force = Wg + Wf.

A command program was written to develop these forces for RELAP5/M3.3's piping application using the XMGR processor, which is a plotting and analysis processor for RELAP5/M3.3. Use of the command processor simplifies the application of force calculations and removes the need for other software not supported by the RELAP5 development team.

RELAP5/M3.3 Validation for Low Pressure Waterhammer Applications

Altran Corporation performed testing that addressed GL 96-06 (Ref. 1). This testing was performed for EPRI and included some laboratory testing to quantify low pressure condensation induced waterhammer as well as to investigate the effects of thermal boundary layers and the presence of noncondensable gases on column closure waterhammer events. The Altran test data (Ref. 2) provides the benchmark data to perform a direct assessment of RELAP5/M3.3 capabilities.

Description of Altran Test Facility

The Altran Corporation test configuration 2b and test loop are shown in Figures 1 and 2. Detailed description of the test facility is presented in Ref. 2.

The Altran Corporation testing program performed a number of tests, covering simple column closure to more complicated geometries. A particularly desirable aspect of the Altran Corporation testing was that support reaction loads were measured, which allows not only the RELAP5/M3.3 pressure response to be validated, but also provided validation of the force time history generation methodology employed. Altran

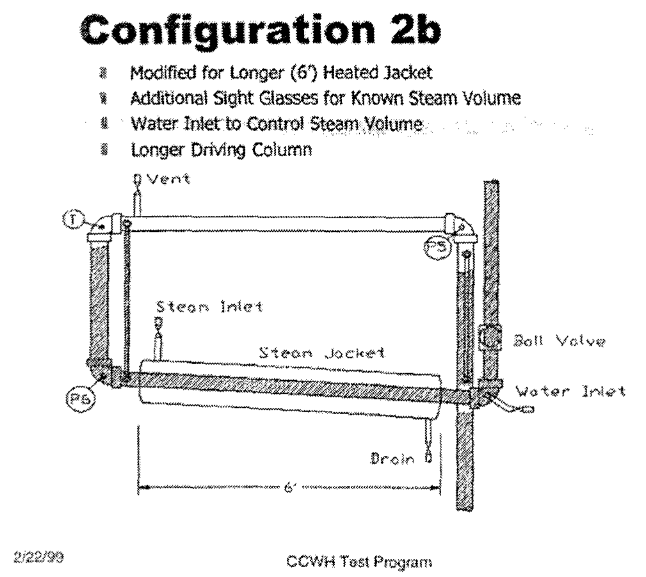

Figure 1 Altran Corporation Test Configuration 2b

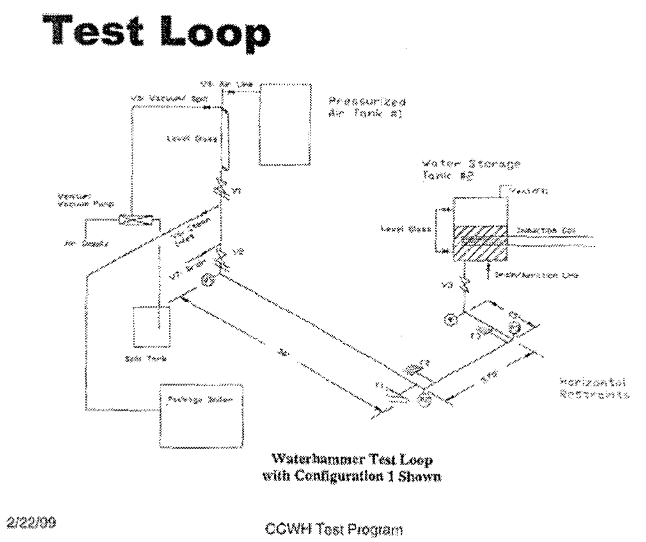

Figure 2 Altran Corporation Test Loop

Corporation test 240-2-75-2-E was selected for a validation case (Reference 2). It contains the following features.

1) Longer driving length.
2) More complex geometry, with longer horizontal runs in the void collapse region.
3) Support loads were measured and are available.
4) Driving pressure of 70 psig, yielding high void closure velocities on an open system.

Comparison of RELAP5/M3.3 to ALTRAN TEST DATA

A RELAP5/M3.3 model was prepared based on Figures 1 and 2 and information from Refs. 1 and 2. The RELAP5/M3.3 nodal diagram is shown in Figure 3. The RELAP5/M3.3 model was configured to employ the same key modeling features as those utilized in the similar waterhammer analysis performed by the utility. Specifically, a small amount of non-condensable was included in the liquid portions of the model (volume property mode=4, q=0.00001 for all volumes, except 104, where q=.000013 was used).

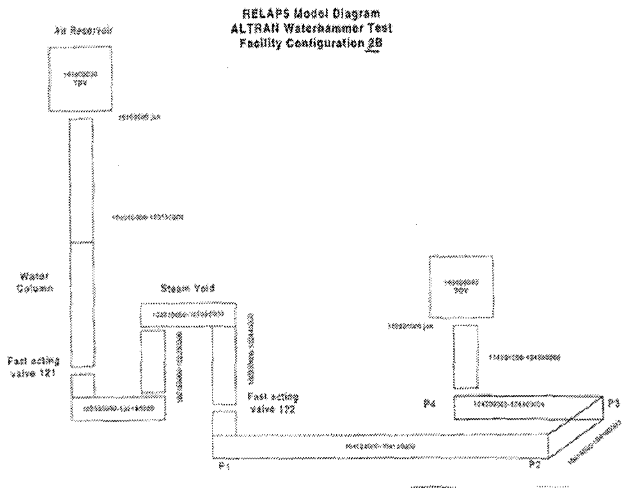

Figure 3 RELAP5/M3.3 Nodal Diagram of Altran Test 2b

RELAP5/M3.3 Hydraulic Response for Altran Corporation Test

The RELAP5/M3.3 model as described above was executed to completion for the test run. RELAP5/M3.3 predicted waterhammer pressures of approximately 780 psig. Ref. 2 contains data for 15 tests in the 2B configuration, with a 240" column, 70 psig driving head test data, and a range of measured air content. The mean of all tests was 771 psig, with a median of 793 psig. A Comparison of the predicted to measured pressure is provided in Figure 4. For the purpose of this comparison, the test data was plotted on the same figure as the calculated values. Figure 4 shows that the RELAP5/M3.3 model as configured generated pressure responses that were consistent and conservative with respect to the test data.

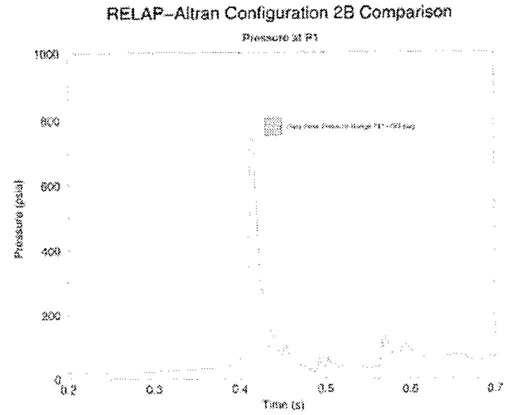

Figure 4 Altran Corporation Data and RELAP5/M3.3 calculated Value for P1

Structural Response Altran Corporation Case

The same methodology discussed earlier was applied to generate piping segment forces for the 2B test configuration. Command files were written in XMGR to calculate the wave and segment end loads. These loads were then compared to the forces measured in the test pipe supports.

The comparison of the support forces requires an understanding of the behavior of the structural system. The water-hammer load is of a very short duration, as evidenced in the pressure responses at various locations in the test apparatus. As can be seen, however, the support members experience force oscillations associated with structural induced oscillations for a number of cycles following the application of the pressure force. The single horizontal support can be compared directly to the force calculation during the passage of the pressure wave. The two supports that take load on the long axis of the experimental apparatus represent a different story, since the loading of one support involves the other one as well. This is also evidenced in the test data, as the interaction between the supports continues well beyond the application of the waterhammer load.

Due to this behavior, the comparison of experimentally measured support forces to analytically calculated segment loads will be limited to the first cycle in which the support is loaded. The comparison will be made on the single horizontal support, since it is less affected by the complex interactions observed in the longitudinal support pair. Figure 5 provides the force-time history calculated for support F1. The forces generated by post-processing of the RELAP calculation are compared to the test data in the Table 1.

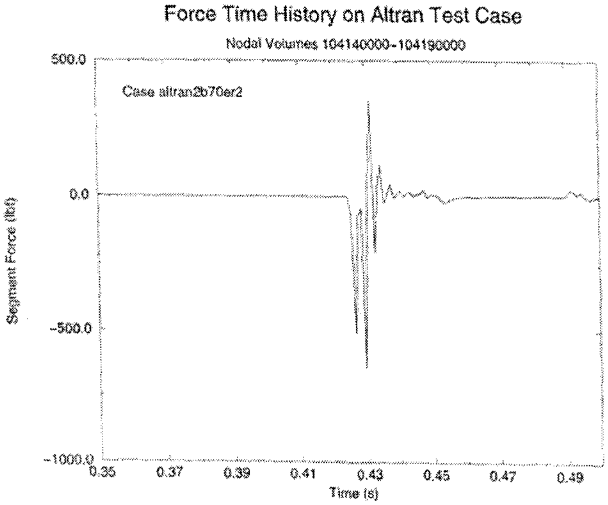

Figure 5 RELAP5/M3.3 Force Time History for ALTRAN CORPORATION

Table 1
Altran Corporation Test Configuration 2B Loads in Horizontal Support F1

Support	Measured Force in first loading cycle (lbf)	Maximum Force calculated by RELAP5/XMGR (lbf)
F1	-250	-640

As can be seen, the RELAP code and XMGR post-processing routine predicts forces that are conservative relative to the measured values.

Combustion Engineering Test Facility

The Combustion Engineering (CE) test facility was designed for full flow tests of selected safety valves under a wide range of inlet fluid conditions and inlet piping configurations. In this Section, a description of the test facility and valve used is provided.

It should be noted that the test data is EPRI proprietary therefore only approximate values of the data are presented here. The test loop is shown in Figure 6. The piping isometric for CE908 is shown in Figure 7.

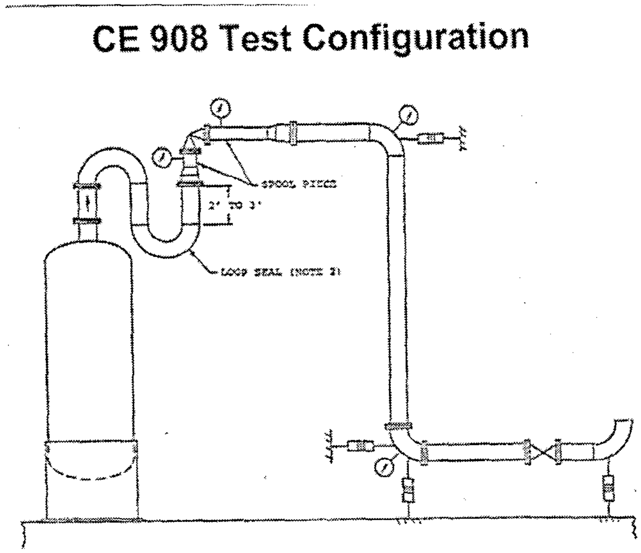

Figure 6 CE 980 Test Configuration

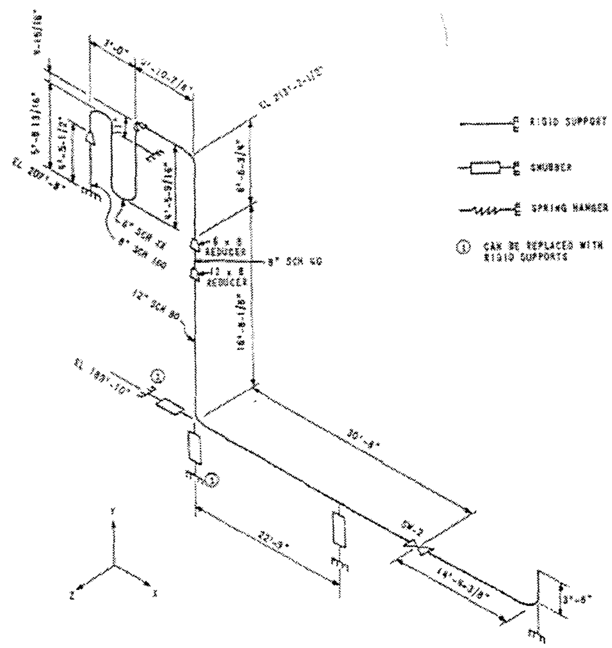

Figure 7 CE 980 Test Piping Isometric

The CE908 test used the Crosby 6M6 spring-loaded safety valve and a full-scale loop seal. More detailed information can be found in References 5 and 6.

CE908 Testing Facility Description

The major components of the facility were two large tanks with interconnected piping, a high pressure boiler, a test valve with associated inlet and outlet piping. The boiler is not shown in Figure 6. By varying the initial fluid conditions in the boiler tank, the opening rate of the valve between the boiler tank and the accumulator tank (shown in Figure 6), as well as the boiler flow are controlled and it was possible to simulate the appropriate condition for the prescribed test.

The CE908 Transient

There are several postulated reactor coolant system transients that may result in the actuation of the pressure relief system. These transients range from normal system transients to postulated accidents such as those analyzed in plant safety analysis reports. Typically, these plant transients result in a pressurization of the steam in the dome of the pressurizer that causes the safety and relief valves to open, thereby mitigating the overpressure transient. The pressurizer is a vessel that acts as a surge volume to control pressure in a pressurized water reactor (PWR).

To simulate the high-pressure transient that would actuate the safety valve, the high-pressure boiler provided the high-pressure source of steam to a 6-foot accumulator tank through a test initiation valve. The pressure rise in the accumulator was regulated by the opening speed of the test initiation valve. The test results showed that the safety valve began to simmer after the accumulator pressure exceeded the safety valve actuation set point of the safety valve at 2,580 psia. The water loop seal that was formed in front of the safety valve contained approximately 1.18 ft^3 of water. Although this water seal, during the normal operation of a power plant, was used to protect the inlet of the Crosby safety valve from steam erosion, it provided additional complexities to simulating the event and added significant piping loads to the facility. Simmering of the safety valve occurred during the passage of the water through the safety valve. Simmering is the rapid up and down motion of the safety valve. Once the water slug passes through the safety valve, the valve pops open to full steam flow at approximately 2700 psia. This causes the water slug that was relocated downstream of the safety valve during the simmering process to accelerate into the down stream piping. This produces significant piping loads on the down stream piping. Load cells are used to measure these forces during the event.

RELAP5/M3.3 Analysis Used to Simulate CE908

RELAP5/M3.3 was used to simulate the CE908 transient. To model the loop seal accurately, the temperature in the loop seal was modeled as shown in Figure 8. The node closest to the steam (Node 1) was the hottest (at approximately 652 °F) and the water node that was about 2.7 feet from the steam-water interface (Node 21) was at approximately 130 °F. Modeling the temperature distribution of the water that was driven into the down stream piping was critical in determining the correct piping loads.

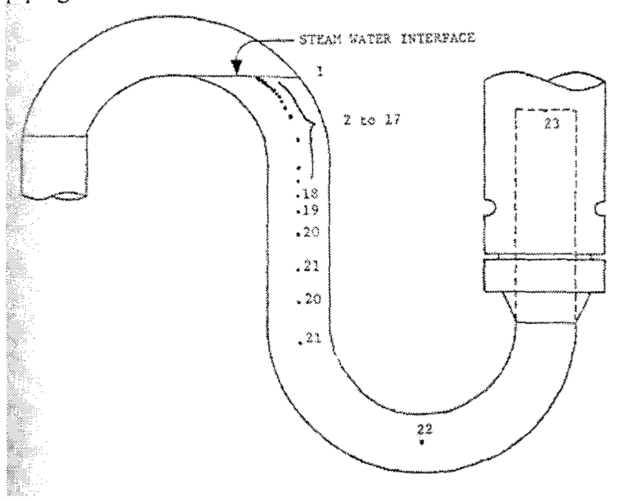

Figure 8 Temperature Distribution in Loop Seal

The RELAP5/M3.3 model was constructed to simulate the CE908 test facility. The RELAP5/M3.3 nodal diagram is shown in Figure 9.

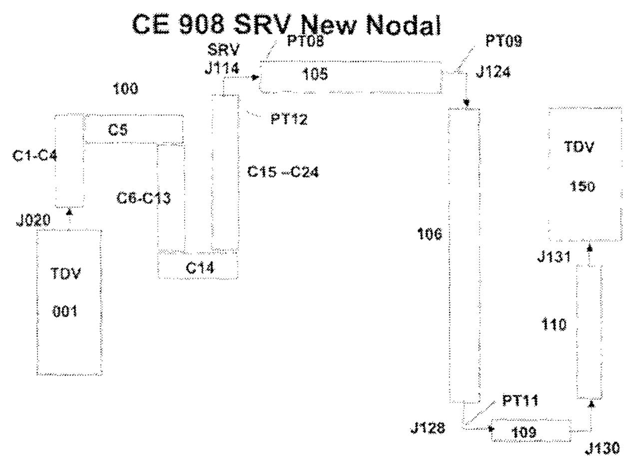

Figure 9 RELAP5/M3.3 Nodal Diagram of CE908

The pressures calculated by RELAP5/M3.3 are presented in Figure 10. As you can see, the pressures increase and subside in the pipe as the water slug moves downstream.

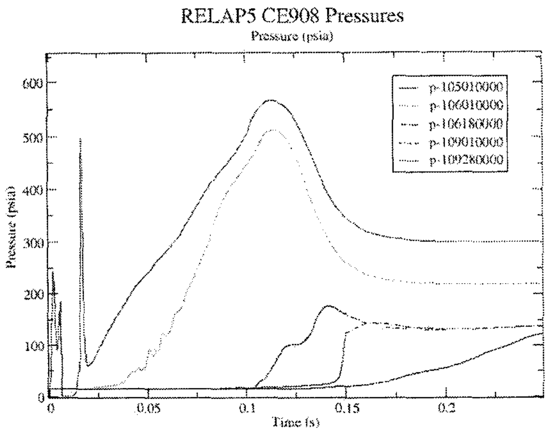

Figure 10 RELAP5/M3.3 Calculated Pressures for Test CE908

The pressure at PT11 was measure during the test and a comparison between the measured data and the calculated data is presented in Figure 11.

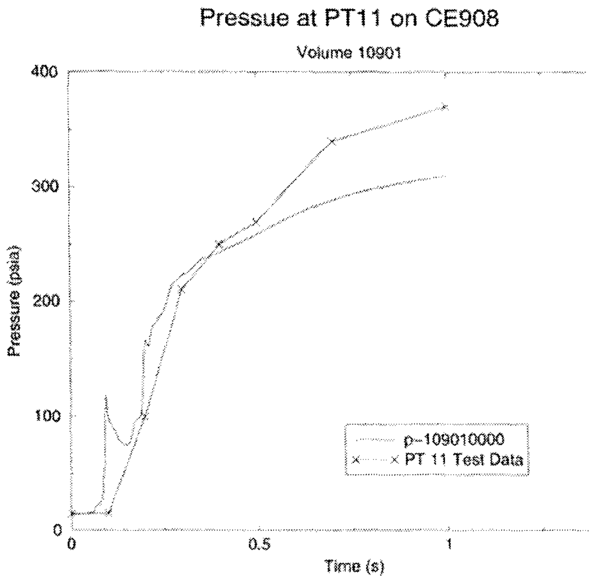

Figure 11 Comparison of Measured data and RELAP5 Calculated Pressure for Point PT11 for Test CE908

The forces were measured on the long vertical leg designated as RELAP5 volume 106 and shown in Figure 7. The RELAP5/M3.3 calculated force is compared to the measured force in Figure 12. The measured data load presented in Figure 12 was modified to account for structural magnification of the original data.

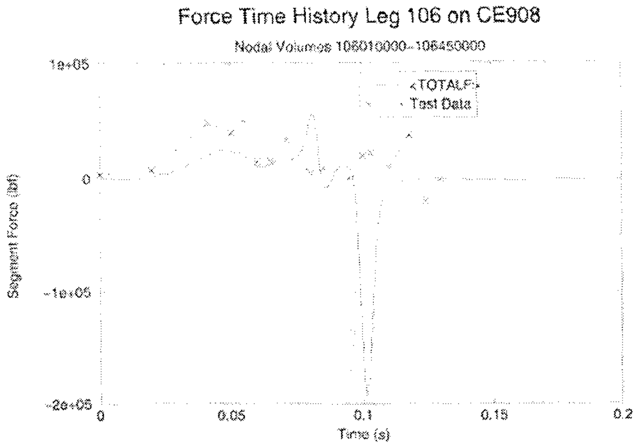

Figure 12 Comparison of Measured data and RELAP5 Calculated Forces on Leg 106 for Test CE908

Summary and Conclusions

Test data from Altran Corporation Test 2b and from CE 908 was compared to calculations performed by RELAP5/M3.3. These two test cases represented very complex flow phenomenon at a high pressure (CE 908) and at a low pressure (Altran Corporation Test 2b). In all cases, the RELAP5 predictions were conservative to the test data and it can be concluded that RELAP5 can be used to perform piping load calculations. These force comparisons also validated the force calculation mythology.

Acknowledgments

We would like to thank Jeff Drowley and Exelon Nuclear for supporting this work and Altran Corporation for reviewing and contributing to this paper.

References

1) "Generic Letter 96-06, Waterhammer Issues Resolution, Technical Basis Report 1003097", dated May 2002.

2) "Test Data and Comparison to Analysis for Column Closure Waterhammer", Thomas Esselman, Lenin Semprucci and Daniel VanDuyne , To be presented at the 11th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-11), Popes' Palace Conference Center, Avignon, France, October 2-6, 2005.

3) NUREG-0737, "Clarification of TMI Action Plan Requirements," Item II.D.1, November 1980.

4) NUREG/CR-5535/Rev1, RELAP5/MOD3.3 VOLUMES 1 through 8, Prepared by Information Systems Laboratories,

Inc., Idaho Falls, ID for Division of Systems Research, NRC, Washington, DC 20555. December 2001.

5) "EPRI/C-E PWR Safety and Relief Valve Test Program Summary Program Description," C-E Power Systems, Combustion Engineering Inc., 1982.

6) "Kewanee Nuclear Power Plant Safety and Relief Valves Piping Qualification Report," Wisconsin Public Service Corporation, June 28, 1982.