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Braidwood Station, Units 1 and 2
Facility Operating License Nos. NPF-72 and NPF-77
NRC Docket Nos. STN 50-456 and STN 50-457

Byron Station, Units 1 and 2
Facility Operating License Nos. NPF-37 and NPF-66
NRC Docket Nos. STN 50-454 and STN 50-455

Subject: Response to Request for Additional Information Related to NRC Generic Letter 96-06, "Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions"

References:

(1) Letter from J. B. Hickman (USNRC) to O. D. Kingsley (Commonwealth Edison Company), "Request for Additional Information Related to the Generic Letter 96-06 Response for Braidwood Station, Units 1 and 2, and Byron Station, Units 1 and 2," dated April 13, 1998

(2) Letter from R. M. Krich (Commonwealth Edison Company) to USNRC, "Response to Request for Additional Information Related to Generic Letter 96-06, 'Assurance of Equipment Operability and Containment Integrity during Design-Basis Accident Conditions,'" dated September 30, 1998

(3) Letter from G. F. Dick (USNRC) to O. D. Kingsley (Commonwealth Edison Company), "Request for Additional Information Related to Generic Letter 96-06; Byron Station, Units 1 and 2, and Braidwood Station, Units 1 and 2," dated July 28, 2000

In Reference 1, the NRC requested that Commonwealth Edison (ComEd) Company provide additional information to supplement our initial response to Generic Letter (GL) 96-06, "Assurance of Equipment Operability and Containment Integrity during Design-Basis Accident Conditions." This additional information was provided in Reference 2. In reviewing the information provided in Reference 2 regarding waterhammer and two-phase flow analyses to assess the adequacy and conservatism of the analyses, the NRC determined that supplementary information was needed, particularly with respect to the use of the RELAP5 computer code. Attachment 1, "Request for Additional Information Summary Related to Generic

A072

Letter 96-06, 'Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions,'" provides a summary response to the requested additional information. Attachment 2, "Validation of RELAP5 Application to Calculations Addressing GL 96-06, 'Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions,'" provides comprehensive information confirming that application of the RELAP5 code is valid and conservative as it pertains to GL 96-06 related issues.

Should you have any questions regarding this matter, please contact Mr. J. A. Bauer at (630) 663-7287.

Respectfully,

R. M. Krich
Director, Licensing
Mid-West Regional Operating Group

Attachment 1: Request for Additional Information Summary Related to Generic Letter 96-06, "Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions"

Attachment 2: Validation of RELAP5 Application to Calculations Addressing Generic Letter 96-06, "Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions"

cc: Regional Administrator – NRC Region III
NRC Senior Resident Inspector – Braidwood Station
NRC Senior Resident Inspector – Byron Station

Attachment 1

Braidwood Station, Units 1 and 2
Byron Station, Units 1 and 2
Request for Additional Information Summary Related to Generic Letter 96-06, "Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions"

In a letter from G. F. Dick (USNRC) to O. D. Kingsley (Commonwealth Edison Company), "Request for Additional Information Related to Generic Letter 96-06; Byron Station, Units 1 and 2, and Braidwood Station, Units 1 and 2," dated July 28, 2000, the following additional information was requested.

"The hydrodynamic loading for the waterhammer and two-phase flow analysis was evaluated by the licensee using the RELAP5/MOD3.1.1 computer code. Although the code input and modeling assumptions, such as the use of homogeneous equilibrium model choking at the coil exits, were deliberately chosen to achieve conservative results, in the absence of any specific benchmark calculations, the validity of the RELAP5 results is questionable and may not be conservative. Additionally, the applicability of the one dimensional integrated thermal hydraulic models in addressing some important phenomena of concern to the waterhammer issue (e.g. water/steam stratification in horizontal lines) is questionable. Following are the staff's comments and observations regarding ComEd's September 30, 1998, response to the staff's [Request for Additional Information] RAI of April 13, 1998."

A. "The licensee's response to question 2.a states that there was no specific assessment or validation performed for this application of RELAP5. This brings into question the capability of the model to accurately model the water hammer and two phase flow for the containment air cooling water systems. RELAP5 relies heavily on empirical models that were developed for specific phenomena and accident conditions. The code must be assessed against data that are applicable and properly scaled to show that it adequately predicts the accident conditions. In this case both the details of the two-phase flow calculations and the load generation methodology need to be assessed against applicable test data. Please provide a discussion of the results obtained from the load generation methodology validation."

   Response to Question A

   The RELAP5 code has been applied to analyze test data from recently performed low pressure waterhammer tests. These include the Altran Corporation 2B test configuration, which is prototypical of condensation-induced waterhammer in Reactor Containment Fan Cooler (RCFC) installations, as well as Fauske and Associates Inc. (FAI) tests for steam condensation and vacuum-induced waterhammer. The Altran Corporation test included force time history data on piping supports, allowing a direct comparison to forces generated by RELAP5 postprocessing methods. This comparison is discussed in detail in Attachment 2, Section 2. First principles calculations are also included, providing additional validation of the RELAP5 code in this application.

B. "In the licensee's response to question 2.b, key features of the model are listed. While they are desirable features, their value is uncertain without code comparison to specific

assessment data that are applicable to the problem. The justification for introducing a non-condensable gas into the system is not stated except as a means to compensate for perceived code deficiencies and to make the code run without failing. This is an indication that use of RELAP5 is not appropriate for this calculation."

Response to Question B

The test data comparisons in Attachment 2 were performed utilizing the same code features as applied in the original Mod 3.1.1 plant calculation. These test comparisons included the use of limited amounts of non-condensables for numerical stability considerations. The results of the test data comparisons conservatively matched the test data, thus demonstrating that the modeling approach is valid. Additional detail is provided in Attachment 2.

C. "As a part of the response to question 2.c, the licensee is requested to provide justification for the use of pressure boundary conditions to simulate pump behavior. Further, the licensee's interpretation of the results is that the observed pressure spikes were water packing problems. The RELAP5 code can not distinguish between water packing and real waterhammer events. Therefore, the pressure spike that is described as an artifice of the computational method could be a waterhammer. The peak pressure which exceeded the design pressure was apparently deleted during the filtering out of other "numerical" noise. Use of the water packing model for these calculations can distort the physical phenomenon of interest. This description of the simulation supports the staff's concern that use of RELAP5 is not appropriate for this calculation."

Response to Question C

The boundary condition approach used to simulate Essential Service Water (i.e., designated "SX") pump behavior is discussed in detail in Section 3 of Attachment 2. Please note that the boundary condition pressure applied was deliberately selected to overpredict the void closure velocities and therefore maximize generated forces. The reverse situation is applied in Section 6 for the prediction of two phase instability phenomena. The boundary pressure is returned to the steady state value, with no allowance for the two phase friction effects causing higher pressure drops.

The pressure spike example cited was deliberately highlighted in the previous submittal (i.e., Reference 2) to demonstrate the numeric problems encountered in the application of version 3.1.1 to the RCFC analysis. The pressure spike occurred when a volume in the middle of a vertical pipe went from partial void to single phase only, while the adjacent control volume remained 2 phase. High pressure in this situation is clearly non-physical and was one reason why load filtering was necessary. It should be noted that the RELAP5 Mod 3.2 calculations did not display these pressure spikes, although there were enough discontinuities experienced to suggest filtering was still warranted.

D. "The licensee's response to question 2.e, regarding "engineering judgment" should include the technical rational for the decisions made with respect to "filtering." Discuss the method used to distinguish numerical oscillations from real phenomena. Also, high frequency waterhammer loads can amplify modes of vibration other than bending modes; therefore a

structural frequency cutoff significantly greatly than 33 hertz (typically used for seismic analysis) should be used in order to properly evaluate the structural response. Therefore, please provide assurance that the filtering methodology will not result in underestimating the structural response."

Response to Question D

A detailed discussion of the load generation methods and filtering is provided in Section 5 of Attachment 2. The filtering method selected was chosen after consultation with the structural analysts and was exercised in a manner that preserved the impulse loading to the structure to ensure that real response was not mitigated by artificial means.

E. "In the licensee's response to question 3, it is not possible to know if the analytical results are conservative without a detailed code assessment against applicable experiments. Also, the staff does not agree that the use of the HEM choking model will maximize the flow out of the coils."

Response to Question E

Attachment 2 documents the code comparisons to experimental data, as discussed above. Section 4 of Attachment 2 specifically provides a sensitivity case run with the choking models switched off throughout the model. The comparison of this case to the Homogeneous Equilibrium Model (HEM) choking model applied at limited locations, as recommended by the RELAP5 newsletter, shows that for this particular problem, there is very little impact.

F. "The staff questions the conclusions stated by the licensee in response to question 4 because there was is no validation of the forcing functions generated by RELAP5 (as discussed previously), and because part of the loading was arbitrarily filtered out."

Response to Question F

Based on the additional validation provided in Attachment 2, ComEd has concluded that the loads analyzed for the RCFC SX structures are conservatively derived and bound the postulated potential low pressure waterhammer conditions.

G. "With regard to the two-phase flow assessment, quantitative analysis and justification are needed in support of the conclusion that flow stall due to increased two-phase pressure drop is highly unlikely. For example, the difference in system refill time due to the presence of steam was not quantified."

Response to Question G

Section 6 of Attachment 2 provides a case that returns the boundary condition to steady state pressure only. This case shows that full recovery of the RCFC coils without two phase instabilities occurs. The reflood time is extended by 2-3 seconds relative to the high

pressure case, but this is not expected to result in any impact on containment pressure response.

Attachment 2

Braidwood Station, Units 1 and 2
Byron Station, Units 1 and 2
Validation of RELAP5 Application to Calculations Addressing
Generic Letter 96-06,"Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions"

Braidwood Station, Units 1 and 2
Byron Station, Units 1 and 2

Validation of RELAP5 Application to Calculations Addressing Generic Letter 96-06, "Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions"

Document Number ***GL96-06 Support***
Revision 0

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Prepared by: _____ Date: 11/6/2000

Approved by: _____ Date: 11/6/2000

Abstract

The purpose of this report is to compile the benchmark calculations, sensitivity studies, and additional material prepared in support of the Generic Letter (GL) 96-06, "Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions," calculations for the Byron Station and Braidwood Station Reactor Containment Fan Coolers (RCFC) Essential Service Water (SX) piping. These calculations were performed using the RELAP5 computer code, Version 3.1.1 and were completed in 1998.

This report contains the following sections:
Overview
Validation of RELAP with ALTRAN test data
Validation of RELAP with FAI test data.
Comparison of RELAP to first principles calculations.
Comparison of RCFC calculations using Mod 3.1.1 and Mod 3.2
Sensitivity studies of base model using RELAP5 Mod 3.2 including choking model and noncondensable content effects.
Structural analysis effects and filtering methodology application.
Calculation of RCFC two-phase hydraulic stability following SX pump restart.

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1. Overview

Commonwealth Edison (ComEd) Company, in response to the Generic Letter (GL) 96-06, "Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions," elected to perform a detailed thermal-hydraulic analysis of the Byron Station and Braidwood Station Reactor Containment Fan Coolers (RCFC) and related Essential Service Water (SX) piping. The transient condition of concern was the Loss of Coolant Accident (LOCA) coupled with Loss of Offsite Power (LOOP). This yields high temperature on the outside of the RCFC coils, and a coastdown of SX flow, rapid void generation, and the potential for dynamic loads due to void collapse and acceleration following restart of the SX pump. Because of the need to quantify heat transfer, steam generation, void propagation, and subsequent transport and collapse of the voids, the RELAP5 computer code was selected for use in simulating this condition.

A detailed model of the SX piping and RCFC coil was prepared and exercised. In the course of performing this work, ComEd followed developments in the industry with respect to the Electric Power Research Institute (EPRI) program to address this issue, as well as developments in the RELAP5 computer code. The ComEd analysis was completed prior to the completion of additional testing performed as part of the EPRI program. The version of the RELAP5 code employed was version 3.1.1, which showed considerable numerical instability, particularly at the low pressures that would occur in this event. Based on observation of the developmental work and guidelines for use of version 3.2, the model features recommended with respect to low pressure choked flow situations were employed, along with the addition of small amounts of non-condensable gas to facilitate stability.

The model with these modifications was then found to successfully execute, and a calculation was completed. A methodology was developed to generate piping segment force time history information from the RELAP5 output data.

The NRC staff, in reviewing the ComEd response to their initial Request for Additional Information (RAI), had a number of questions regarding the applicability of the RELAP5 code to GL96-06 analysis, particularly with respect to the validation and benchmarking of the code to low pressure waterhammer situations. There were additional concerns regarding the need and methods used to filter the RELAP5 data for use in structural evaluation models, and a further question regarding the potential for two phase instability to occur in the RCFC coils following SX pump restart. This report has been prepared to address these questions, by documenting validation studies performed to recent low pressure waterhammer test data, and by performing the additional sensitivity cases necessary to respond to questions regarding specific methodology issues. Since this work has largely been performed using version 3.2 of the code, an additional section has been included to demonstrate the applicability of this work to the calculations performed using version 3.1.1. The intent of this document is to provide a single reference to the detailed information prepared to address the NRC questions.

2. RELAP5 Validation for Low Pressure Waterhammer Applications

The EPRI program to address GL 96-06 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, as documented in the Technical Basis Report (TBR), Reference 1. Reference 1 was submitted to the NRC in a letter from V. Wagoner, (Chairman, EPRI Waterhammer Project Utility Advisory Group), "Resolution of Generic Letter 96-06 Waterhammer Issues," dated September 23, 1999. This testing was performed by ALTRAN Corporation and Fauske and Associates, Inc. (FAI), and the data generated provides the opportunity to perform direct assessment of RELAP5 capabilities.

Comparison to ALTRAN TEST DATA

The ALTRAN testing program performed a number of tests, covering simple column closure to more complicated geometries. A particularly desirable aspect of the ALTRAN testing was that support reaction loads were measured, which allows not only the RELAP5 pressure response to be validated, but also the force time history generation methodology employed to generate piping segment loads. ALTRAN test 240-2-75-2-E was selected for a validation case. 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 (discussion with ALTRAN personnel indicated that the test data labeled as 240-2-75-2-E was in fact run at 70 psig, with the tank isolation valve V3 open throughout).

This test is the most representative of the RCFC application, due to the geometry as well as the driving pressure being comparable to the SX pump discharge pressure.

The test configuration is shown in the Figures 1 and 2. A RELAP5 model was prepared and the model diagram is shown in Figure 3. The RELAP5 model was configured to employ the same key modeling features as those utilized in the RCFC analysis. Specifically, a small amount of non-condensable gas 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). A listing of the model is provided in Appendix C.

The model was run on version 3.2 of the code.

Hydraulic Response

The model as described above was executed to completion. The code predicted waterhammer pressures of approximately 800 psig. Comparisons of the predicted to measured pressures are provided in Figures 5 through 8. For the purposes of comparison, the test data was plotted on the same figure as the calculated values, and a time shift was applied to the test data to place it at the proper location. The figures show that the RELAP5 model as configured generated pressure responses that were consistent and conservative with respect to the test data. The same time shift was employed for all the figures, which demonstrates that the overall timing predicted by the model is consistent, and that the model also effectively predicts the propagative behavior.

The TBR 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 738.13 psig, with a median of 751.7 psig and a standard deviation of 59.81 psig. The RELAP model as configured predicts the peak reported pressures within approximately a 1-sigma variation, and on the conservative side.

Structural Response

The same methodology applied to the generation of RCFC piping segment loads 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 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 ringout 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 9 provides the force time history calculated for support F1. The forces

generated by postprocessing of the RELAP calculation are compared to the test data in the following table.

Table 1
ALTRAN Test Configuration 2B Loads in Horizontal Support F1

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

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

The force time history was then transferred to a MATHCAD input file and the FFT filtering routines were applied, consistent with the approach used in developing load information for the RCFC SX piping. The worksheets are enclosed. Filtering at two different frequencies was performed. The minimum frequency that would allow convergence within the two percent criteria ended up being 241.2 Hz. Inspection of the Fourier coefficients as a function of frequency as well as the power spectral density (PSD) plot indicated that significant power existed up through 350 Hz. Therefore, a second filtering case was performed at a filter frequency of 400 Hz. Two things can be gleaned from this exercise:

1) It is important to review the PSDs to ensure that significant frequencies are not inadvertently filtered.
2) The 2% convergence criterion offers protection as well, with the total impulse (as calculated by the integrals between 0.42 and 0.44 seconds in the worksheets) for the main load being preserved within 0.25%.

Comparison to FAI Waterhammer Test Data

The FAI test program focussed on the effects of thermal layers and air present during the closing of a water column. The FAI test apparatus is shown in Figure 10. It consists of a vertical column above a quick opening valve. The area above the valve can be evacuated with a vacuum pump, or filled with steam. The driving force for the transient is supplied by the reservoir and its air pressure setting. Two tests were modeled with the RELAP5 Mod 3.2 code, both of which encountered strong waterhammer effects:

1) Test V-024, which employs a 10 psig pressure in the reservoir and a vacuum of 0.7 psia in the upper column.
2) Test 394, which employs a reservoir pressure of 30 psig, and a steam pressure of about 8 psig in the upper column.

A RELAP5 model was prepared that used the same key features as employed in the RCFC analysis. The model diagram is shown in Figure 11. The listings of the models for both cases are provided.

Case 1 results

The model was initialized with the same non-condensable quality values as were employed in the RCFC analyses, (i.e., q=0.00001). The model executed to completion. Very small time steps were experienced immediately upon valve motion, which was expected since fluid flashing at the interface between the fluid and the vacuum would occur, since the vapor pressure was lower than the saturation pressure for the fluid. Figure 12 shows the pressure at the piezoelectric sensor. Figure 13 shows the fluid velocity at the flowmeter location. Figure 14 shows the vapor generation rate in the first volume above the quick opening valve. Table 3 below provides a comparison between RELAP calculated values, test data, and an analytical solution. As can be seen, the RELAP peak pressure is conservative relative to the test data. The RELAP flow rate is more consistent with the analytically calculated value, and is higher than the test data. The close agreement on void closure time suggests that the test flow rate reported may be somewhat low.

Case 2 Results

The model was initialized with the slightly higher non-condensable quality values as were employed in the RCFC analyses, (i.e., q=0.000015 for Volume 100 and q=0.00002 for volume 200). The model executed to completion. After the valve opened, condensation occurs and the vapor pressure drops rapidly, accelerating the fluid column. Figure 15 shows the pressure at the piezoelectric sensor. Figure 16 shows the fluid velocity at the flowmeter location. Figure 17 shows the vapor generation rate in the first volume above the quick opening valve, which clearly

demonstrates the condensation effects. Table 4 below provides a comparison between RELAP calculated values, test data, and an analytical solution. Similar trends are noted as with the vacuum test. RELAP overpredicts the test data peak pressure and agrees very closely with the analytically derived peak flow rate and time of void closure.

Comparison with Analytical Solutions

A MATHCAD model capable of simulating the column acceleration and determining time of void closure and impact velocity was prepared as a further check of the RELAP5 predictions. The model is based on the integral form of the Bernoulli equations, and performs a numerical integration to solve the equation of motion for the column of water. Wall friction and form losses are included in the solution, along with inertial effects. The waterhammer pressures are predicted based on the Joukowski formula.

The ALTRAN 2B configuration test was simulated, along with the FAI tests V-024 and the steam condensation test 394. The worksheets are attached. The results of the calculations are provided in the following tables:

Table 2
ALTRAN Test 2b Configuration

Parameter	MATHCAD	Test Data	RELAP5
Driving Pressure	84.7 psia	84.7 psia	84.7 psia
Void Pressure	14 psia	14 psia	14 psia
Maximum fluid velocity	35.4 fps		34 fps
Maximum Pressure in void region	1095 psia (Joukowski)	325 psia	661 psia
Time of void closure	0.293 sec		.31 sec after start of valve motion

Table 3
FAI Test V-024

Parameter	MATHCAD	Test Data	RELAP5
Driving Pressure	24.7 psia	24.7	24.7 psia
Void Pressure	0.7 psia	0.7	0.7 psia
Maximum fluid velocity	18.5 fps	14.6 fps (153 gpm)	17.77 fps
Maximum Pressure in void region	1147 psia (Joukowski)	694.7psia	747.3 psia
Time of void closure	0.547 sec		0.57 sec after start of valve motion

Table 4
FAI Steam Test 394

Parameter	MATHCAD	Test Data	RELAP5
Driving Pressure	24.7 psia	24.7 psia	24.7 psia
Void Pressure	2.9 psia (Psat for 140F fluid)		4.5 psia at minimum point
Maximum fluid velocity	26.24 fps	13.67fps (143 gpm)	23 fps
Maximum Pressure in void region	1147 psia (Joukowski)	674.7psia	697.4 psia
Time of void closure	0.386 sec		0.395 sec after start of valve motion

These comparisons provide additional demonstration that RELAP5 is generating physically meaningful characterization of the waterhammer tests. The slight differences in event timing and peak flow rates are expected since the mathematical model is predicated on instantaneous valve opening, while the RELAP5 analysis employs the valve stroke time explicitly.

3. Comparison of RELAP5 Mod 3.2 and RELAP5 Mod 3.1.1

The 3.1.1 version of the RELAP5 computer code was employed in the characterization of the RCFC SX system. This was the version that was available on the ComEd system for design use at that time. This version has since been replaced with the 3.2 version. The benchmark calculations have all been performed with the 3.2 version. Therefore, in order to provide a meaningful comparison, the RCFC SX analysis has also been run in version 3.2. Then the adequacy of the loads generated with the previous version can be assessed. Model diagrams for the overall RCFC SX model and coil nodalization are provided in Figures 18 and 19.

Description of Mod 3.1.1 Case

This case was run with limited non-condensables available throughout the system, (i.e. volume initialization option 4 selected with q=1E-5). The heat transfer coefficient on the exterior of the RCFC coil was set to 500 Btu/hr-ft2-F to maximize heat influx to the coil. Choking models were switched off, except at the major area changes, and the Homogeneous Equilibrium Model (HEM) single velocity momentum option was applied at the choke points, consistent with RELAP5 Newsletter guidance. A rapid coastdown of the SX pump was simulated by reducing the inlet boundary pressure over a 5 second interval. Pump restart was simulated by raising the inlet boundary pressure to maximum value in 1 second, and then allowing it to decay to nominal values over a 20 second interval. This yielded inrush flows to each fan cooler equivalent to the full rated flow of the SX pump, ensuring that a conservative void closure velocity would be simulated.

With these boundary conditions applied, the 3.1.1 model predicted rapid void generation and nearly complete voiding of the RCFC coils. The steam generation in the coils occurred early and fluid was rapidly pushed ahead of the steam. The flow regimes in the coils tended toward slug flow early in the event, changing to horizontal stratified conditions later on. The model predicted an overexpansion and some inrush/fallback loads prior to pump restart. Following pump restart, rapid closure and re-establishment of single phase flows was observed.

Description of Mod 3.2 Case

The Mod 3.1.1 basedeck was exercised in version 3.2. The same boundary conditions for fluid flow and heat transfer were utilized. The same options for volume initial conditions and choke flow modeling were applied. The Mod 3.2 basedeck employed a boundary pressure at the exhaust side of the model that was reduced by 1 psi to reflect a recent modification to the Braidwood Station SX piping discharge to the lake (i.e., raising the discharge above the lake surface, which has the potential effect of reducing the available pressure on the exhaust following the void expansion). The transient was run to completion. The most significant difference noted was that the void generation was less 'explosive' in the 3.2 version when compared to the 3.1.1. Review of the heat transfer and fluid behavior in the coils provided the observation that in the steam generation period of the transient, the coils stayed in the horizontal stratified flow regime and the vapor and liquid temperatures followed the saturation temperature very closely. In the 3.1.1 run, the vapor tended to superheat and remain superheated, and slug flow dominated the steam generation portion of the transient, rapidly ejecting fluid from the coils. The net result was somewhat reduced amounts of voiding in the system in the Mod 3.2 run. As a consequence, void closure occurred earlier in the Mod 3.2 run, compared to the Mod 3.1.1 case.

Comparison of results

The flow at the entrance Time Dependent Volume (TDV) is shown in Figure 20, and clearly shows the effects of the more rapid voiding that occurred in the Mod 3.1.1 calculation. Figure 21 shows the flow regime at a location near the entrance to the upper coil, and demonstrates the tendency of Mod 3.1.1 to leave the horizontal stratified flow (HST) regime early in the transient and drop to bubbly and slug flow, ejecting more fluid from the coil. Figure 22 shows the saturation and vapor temperatures discussed previously. Figure 23 shows the pressure in the upper coil, and it can be seen that there are relatively minor differences in the peak pressures achieved between the two cases. Figure 24 provides the pressures at the bottom of the inlet header, with the Mod 3.2 peak pressure being slightly higher. Figure 25 shows the pressure at the top of the inlet header which reflects the spiking that was observed at void boundary passage in Mod 3.1.1 that is absent in Mod 3.2.

The piping segment force time histories were calculated for this case, for comparison with the Mod 3.1.1 loads, for several key locations. Figure 26 shows the forces calculated for the upper coil (i.e., Volume 120) and shows that the base loading is similar with Mod 3.1.1 experiencing somewhat higher peaks (note that the Mod 3.1.1 data was shifted in time for comparison with the Mod 3.2 data. Figure 27 provides the forces on the inlet header, and the Mod 3.1.1 data shows more spiked behavior than the Mod 3.2 data. Figure 28 shows the forces on the exhaust header, with no time shift applied. Mod 3.1.1 clearly experiences more loading than predicted by Mod 3.2,

primarily because the overexpansion occurring in 3.1.1 led to fallback loads that were not experienced in the Mod 3.2 model.

From these examples, it is concluded that the hydraulic behavior between the models is relatively similar at the point at which reflooding occurs. The loads calculated from the Mod 3.1.1 version are generally larger and will bound those calculated with Mod 3.2.

4. Sensitivity Studies

The basedeck described in the previous section was run on 3 additional cases to quantify the effects of choking model selection, as well as reducing non-condensable fractions. RELAP5 Mod 3.2 was used for these sensitivity cases.

Choking Model Effects

The base model employed the RELAP5 Newsletter guidance with respect to low pressure choking applications. These were that choking be only applied to limited locations where choking would be anticipated, and that the HEM (i.e., h=2 junction control word to select single velocity momentum equation) be utilized at those locations. The intent of this guidance was to limit the tendency of the code to stay in choked flow longer than appropriate at low pressure conditions.

To assess the sensitivity of the model to this option, the base model was modified to eliminate the use of choking at any junction. The HEM option previously applied in conjunction with the choke flow option was also reset for this case. The results of this case are compared to the Mod 3.2 base case described above.

The general behavior of the non-choking case was to allow somewhat more voiding to occur in the model. This increased the reflood time slightly, approximately 1 second. The flow at the inlet TDV is shown in Figure 29, and reflects more void generation. The liquid void fraction in the upper coil is shown in Figure 30, and shows that voiding occurs somewhat more rapidly for the non choked case, although both cases reach approximately the same value at pump start (i.e., 43 seconds). Examination of the pressures at the bottom of the inlet header (Figure 31) and the upper coil (Figure 32) show little difference in the peak pressures between choked and non choked cases. The force time history generated for the upper coil (Figure 33) shows very little difference between the cases. The force time history for the inlet header (Figure 34) shows an increase in peak loads for this segment, to values comparable to those calculated for the Mod 3.1.1 case (Figure 27).

Based on the behavior observed, it is concluded that the choking model selection has limited impact on the pressures and subsequent loads generated by the model. The effects appear to be more than bounded by the Mod 3.1.1 results, which as previously discussed were subject to void generation beyond that observed in the Mod 3.2 model.

Effects of Reduced Non-condensables

Two additional cases were run with the base model in version 3.2, to quantify the impact of the non-condensable fractions input. These two cases did not include the 1 psi exit pressure change described above, but were in all other respects identical. The first case employed a factor of 10 less non-condensable (i.e., Q=0.000001), and

the second case reduced this by an additional factor of 2 (i.e., Q=0.0000005). Generally, there was very slight difference noted between the three cases. Figure 35 shows the pressure at the bottom of the inlet header, and is the most significant difference noted between the cases. Figure 36 provides the pressures in the upper RCFC coil, and shows little difference between the cases. Figure 37 shows the flow at the entrance TDV, again with relative minor differences. Figure 38 provides a comparison of the flow regimes selected in the upper coil near the entrance. It can be seen that the lower non-condensable fractions tend to depart from horizontal stratified flow regime significantly more than the base case, particularly in the early phases of void generation. This leads to slightly more void generation and larger overall voiding in the low non-condensable cases. This is most likely the reason for differences in the inlet header pressures. The force time histories for the upper coils are shown in Figure 39. There is little difference in the magnitudes predicted, but the timing reflects the additional voiding in the delay seen in the loads in the two low non-condensable cases. Based on the observations above, it can be concluded that the non-condensable fraction has a limited effect, but that limiting the amount to the minimum necessary to achieve numerical stability is desirable.

5. Structural Loading and Filtering Methodology

The development of force time history information for application to structural analysis models was based on the general force equations for a container. The methodologies utilized for extraction of forces from RELAP5 hydrodynamic calculations generally fall into two categories. These have been referred to as "old" methods and "new" methods, as documented in Idaho National Engineering Laboratory (INEL) Report, "R5FORCE/MOD3s: A Program to Compute Fluid Induced Forces Using Hydrodynamic Output From The RELAP5/Mod3 Code," J. C. Watkins, EGG-EAST-9232 Informal Report, September 1990. Both methods derive from the generalized force equation on a control volume, but differ in the execution of the solution. The generalized force equation in one dimensional form (see Figure 40) is:

$$F = -\frac{d}{dt}\iiint \frac{M_I}{A_I} dV_I - (P_{I1} + \rho_{I1} U^2{}_{I1}) A_{I1} + (P_{I2} + \rho_{I2} U_{I2}{}^2) A_{I2}$$

where the first term is recognizable as the time derivative of the momentum, sometimes referred to as the wave force. The second and third terms refer to control volume or boundary forces, which take slightly altered forms, dependent on the type of boundary condition that exists for a specific control volume. The difference between the "old" and "new" methods is that the "old" methods apply the above equation directly using edit information from the RELAP5 data. The "new" methods employ an altered characterization of the first term, based on the shear stress at the pipe wall. This offers an advantage over the old methods, primarily by eliminating the dependence on a potentially numerically "noisy" momentum time derivative. As described in the previously mentioned INEL report, page A-4, "...this technique (old method) has potential instabilities associated with computing the time derivative in the fluid acceleration term, often requiring various smoothing techniques to make the output useful." This requires that noise suppression techniques be applied to the calculated loads to produce valid data for input into structural models. Comparisons of the two methods demonstrates comparable response, but with the older methods generally producing higher peak loads due to the wave force calculation method.

A review of Section 11.2.3 of the EPRI Technical Basis Report provides a discussion of the use of trapezoidal models to simulate more complicated pressure time history behavior. The conclusion drawn is that truncating the pressure time history is acceptable provided the net impulse (i.e., pressure pulse area) is preserved. The preservation of net impulse is a key feature of the filtering approach applied in the RCFC analysis.

The approach selected was to perform the complex Fast Fourier transform (FFT) of each segment load, evaluate the power spectral density, and filter the load above a selected frequency. No frequency below 33 Hz was filtered. Typically, 75 Hz was applied in the coil loads. A fine mesh recursive integration subroutine was written to

integrate the "before" and "after" loads, and a criteria was applied that the difference of these integrations must be less than 2%, or the filter frequency adjusted. The loads provided to the structural analysts were increased by 2% to ensure that impulse loads were conserved. For vertical segments, the limits of integration were adjusted to ensure that only the dynamic portion of the event was compared, precluding deadweight loads from dominating the before/after comparisons. The frequencies used to filter each load are provided in the enclosed flow chart, (i.e., Figure 41).

The preceding paragraphs describe the mechanics of the filtering, and demonstrate that care was taken in the application of this filtering. However, the ultimate validity of any filtering that is applied rests primarily in the response of the structure. Filtering is valid, and appropriate, provided the structure is not sensitive to dynamic loading in the frequency ranges being filtered out. This check was also performed, iteratively with the structural analyst.

Filtering is valid, and appropriate, provided the structure is not sensitive to dynamic loading in the frequency ranges being filtered out. For piping systems, the dominant frequencies are bending mode frequencies, and the major bending frequencies are typically below 33hz. Amplification of the lower frequency piping modes by the frequencies which have been filtered out does not occur; in fact, the higher driving frequencies have little impact on the dominant lower frequency piping modes, since the dynamic load factor drops off quickly for low damped (i.e., 2%) single degree of freedom systems when the driving frequency divided by the system frequency is above 1.4. As noted above, the dominant frequencies of the input were preserved (i.e., via comparison of the PSDs), and the total impulse (force times time) input to the system was preserved.

6. Two phase flow assessment

The derivation of loads on SX structures employed models that were deliberately driven to maximize the potential for rapid void closure and yield conservative loads. An additional concern is the potential for a stable two phase situation to exist in the RCFC coils following SX pump restart. An additional analytical case has been run to investigate this situation. The base deck was modified to eliminate the high pressure point in the inlet TDV history, effectively causing pump restart to be simply a return to the steady state inlet pressure. This case has been run using the Mod 3.2 version of the code, and employs the same configuration as described above.

The inlet TDV pressure vs. time is shown in Figure 42, with the base case also plotted for comparison. Figure 43 provides the flows between the inlet TDV and the system for the base case and the low head case. As can be seen, the inrush flow on pump start is much higher in the base case, while the low head is much more gradual. Figure 44 shows the void fraction in the uppermost RCFC coil, and demonstrates that the high pressure (HP) case refloods the coil faster than the low head case. Figure 45 shows the void fractions in the uppermost coil for the low pressure (LP) case only, and demonstrates that complete reflood and return to single phase flow occurs. Figure 46 shows the force time histories for the upper coil for the two cases, and demonstrates that the only significant difference between the cases is the timing of the loading.

Based on the results of this case, it can be concluded that the formation of stable two phase regions within the coils following restart of the SX pump is unlikely. The applied pressure in this case on restart was no greater than that needed to support design flow rates in the model. It should be noted that high heat transfer values on the coil external surfaces were applied throughout to ensure maximum heat flow into the coil.

7. Conclusions/Discussion

A series of cases have been run to demonstrate that RELAP5 Mod 3.2 can effectively simulate low pressure waterhammer behavior and generate pressures and forces comparable to those achieved in experiments. These cases employed the same modeling assumptions applied in the actual RCFC analysis. These have been further validated by performing analytical solutions of the test response and comparing key aspects of these solutions to RELAP5 results. A comparison of the RCFC calculation using RELAP5 Mod 3.1.1 and RELAP5 Mod 3.2 has also been completed and it has been concluded that forces generated with RELAP5 Mod 3.1.1 will bound those produced by the more numerically stable RELAP5 Mod 3.2. Sensitivity cases performed with the RELAP5 Mod 3.2 demonstrate the effects of choking models and the initial non-condensable fraction assumed in the SX piping. The basis, need for, and application of numerical methods to filter the loads has been discussed and demonstrated to preserve the impulsive loading to the structure. The potential for two-phase instability on SX pump restart has been evaluated using a low pressure boundary condition that minimizes refill/reflood potential and demonstrates that timely return to single phase flow regimes in the SX system are expected following pump restart.

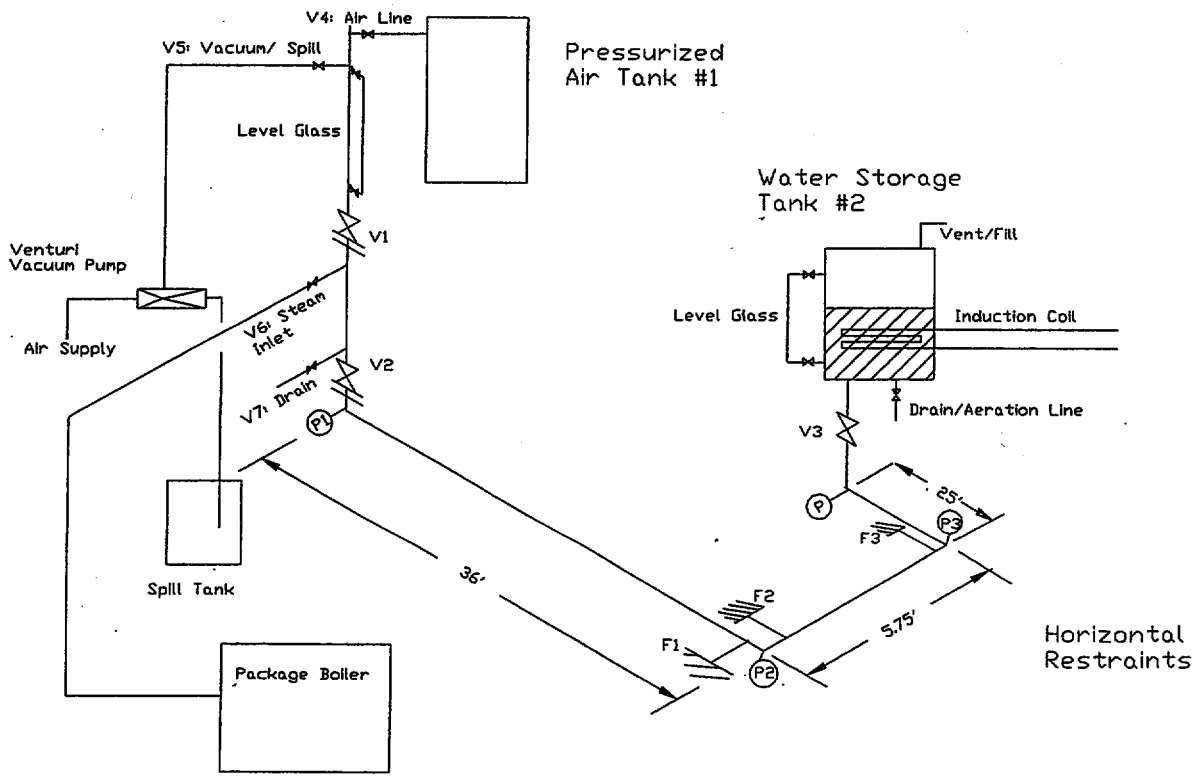
8. References

1. "Resolution of Generic Letter 96-06 Waterhammer Issues," Volume 1: Technical Basis Report, TR-112594-V1, Interim Report, September 1999.

Appendix A - Figures

Figure 1 ALTRAN Test Configuration 2B

Test Loop



Waterhammer Test Loop
with Configuration 1 Shown

Figure 2 ALTRAN Test Configuration 2B Detail

Configuration 2b

- Modified for Longer (6') Heated Jacket
- Additional Sight Glasses for Known Steam Volume
- Water Inlet to Control Steam Volume
- Longer Driving Column

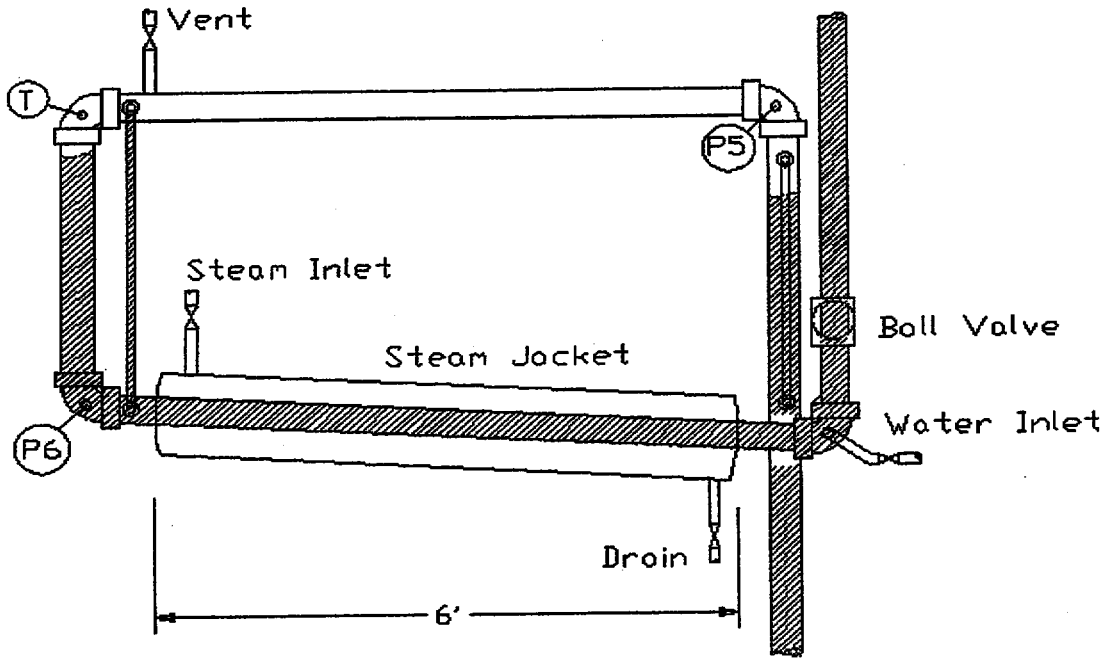


Figure 3 RELAP 5 Model of ALTRAN Test Configuration 2B

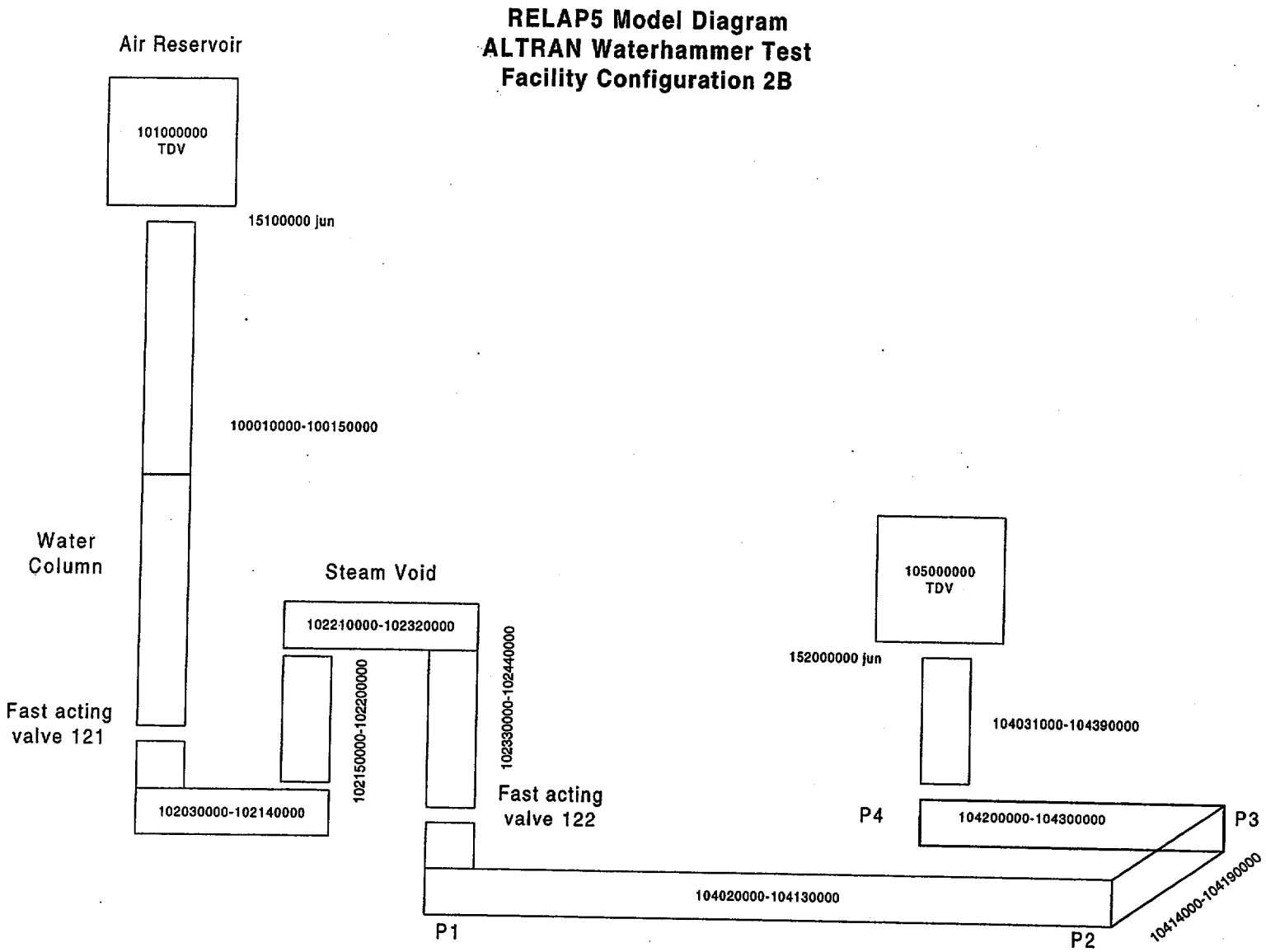
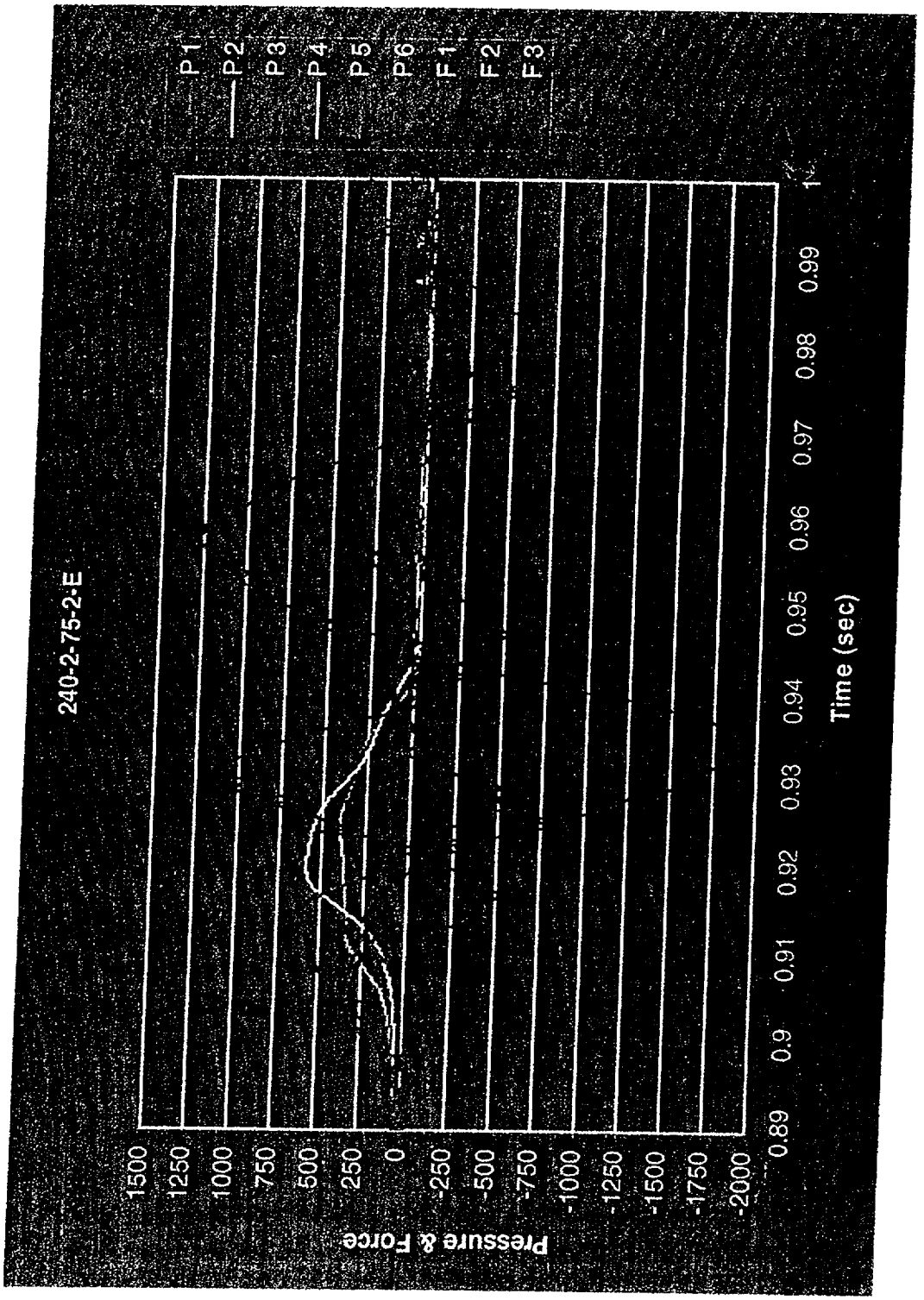


Figure 4 Altran Test 240-2-75-2-E Raw Data



CCWH Test Program

Figure 5 RELAP/Altran Test 2B Comparison for Pressure P1

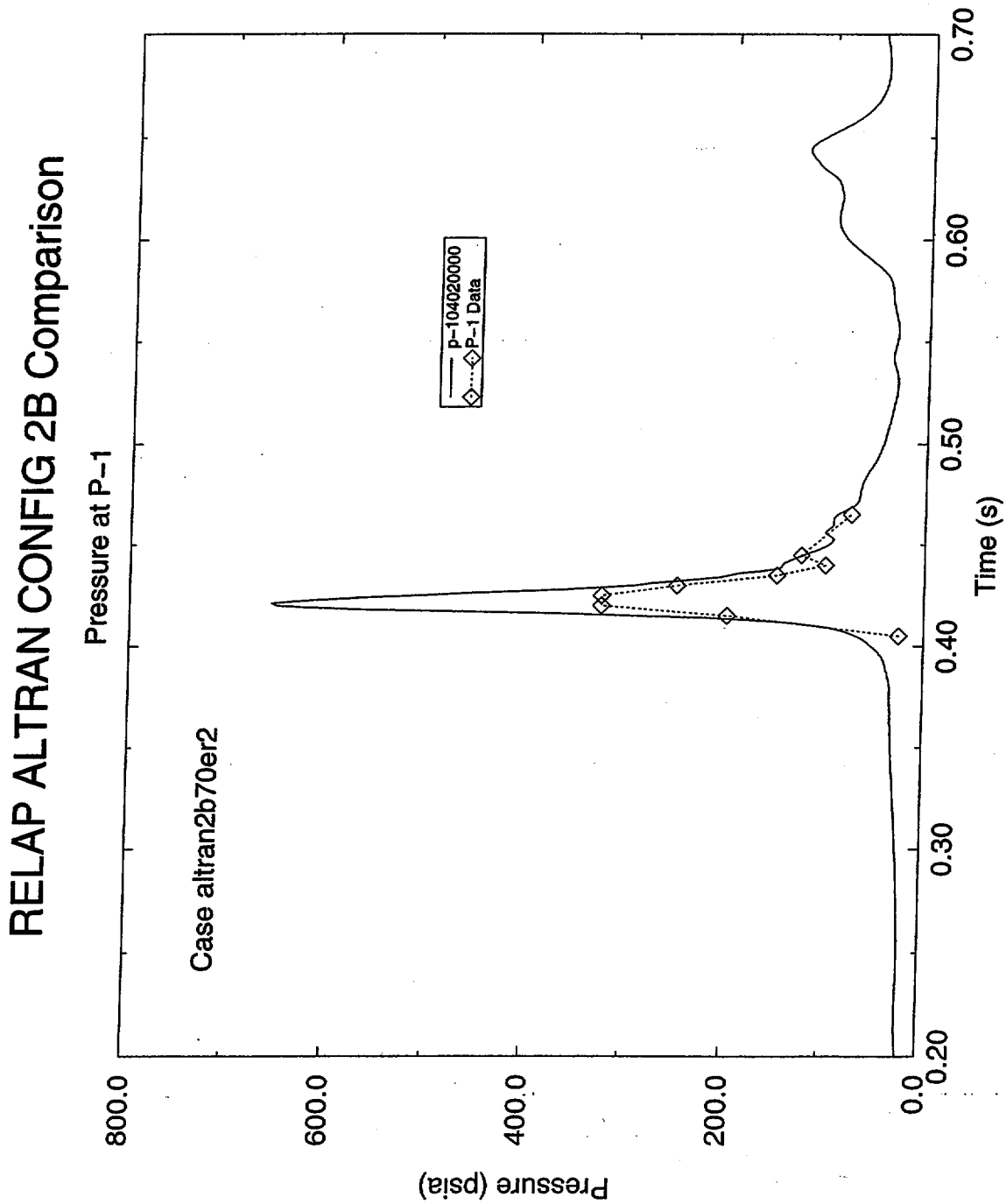


Figure 6 RELAP/Altran Test 2B Comparison for Pressure P2

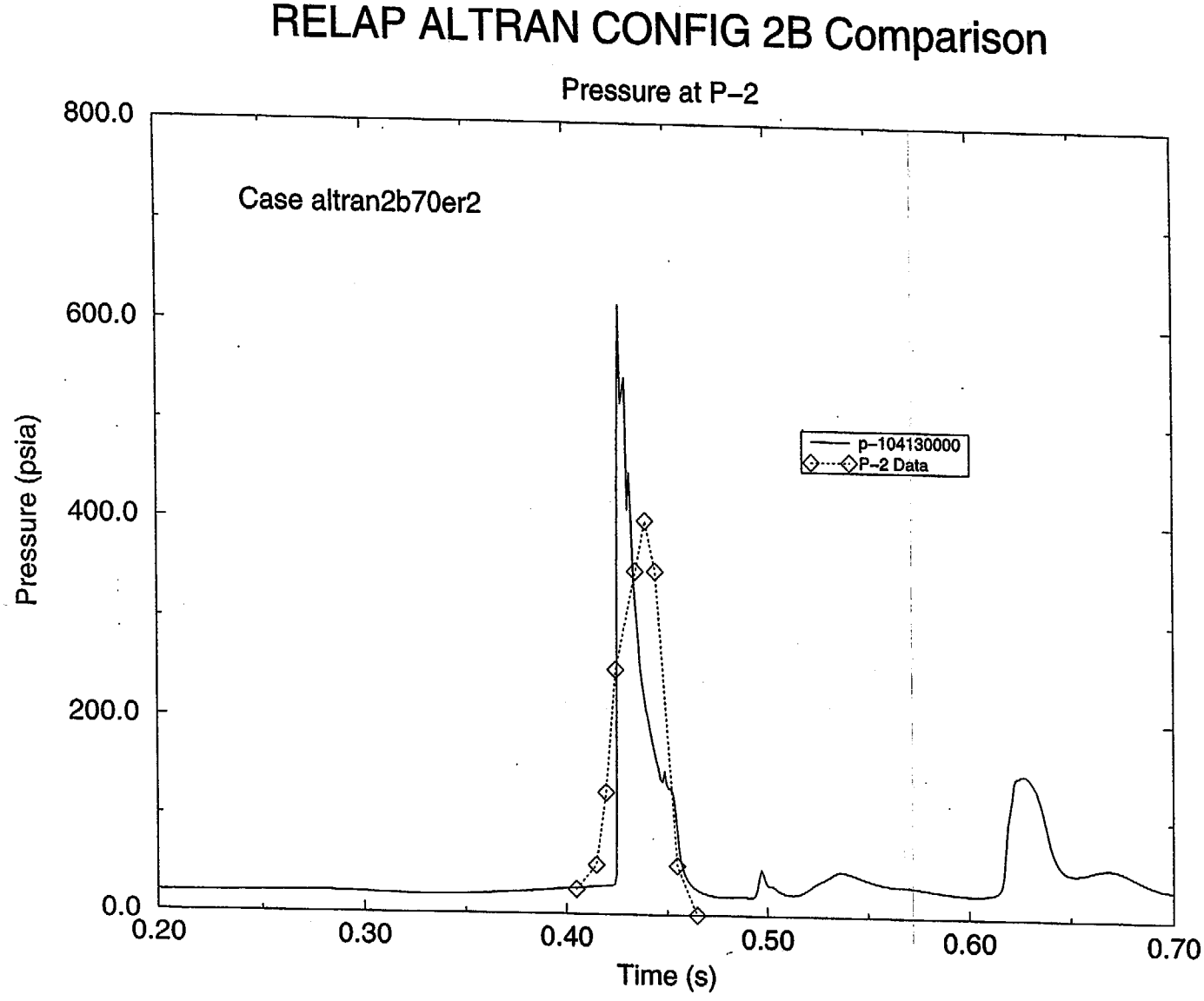


Figure 7 RELAP/Altran Test 2B Comparison for Pressure P3

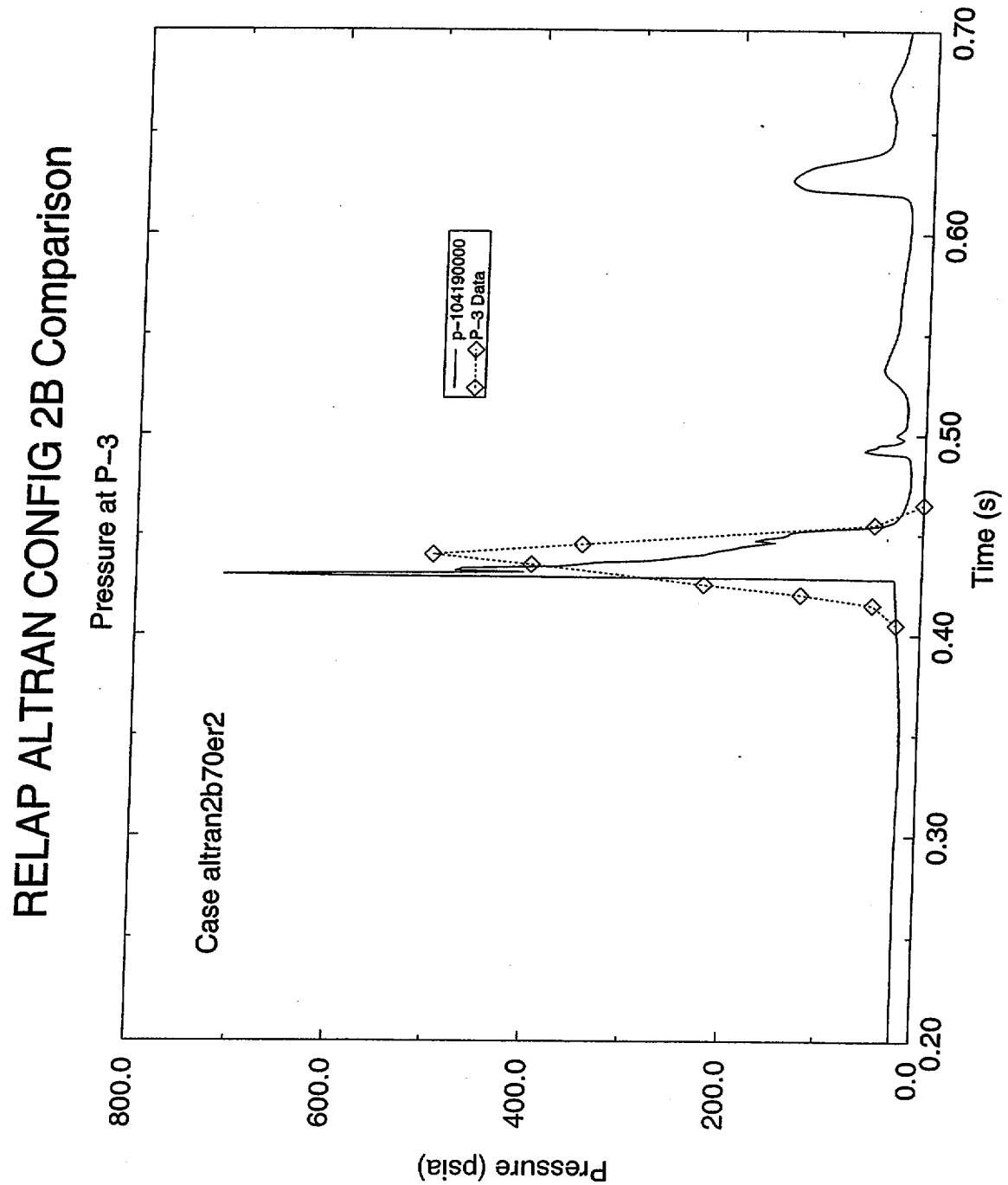


Figure 8 RELAP/Altran Test 2B Comparison for Pressure P4

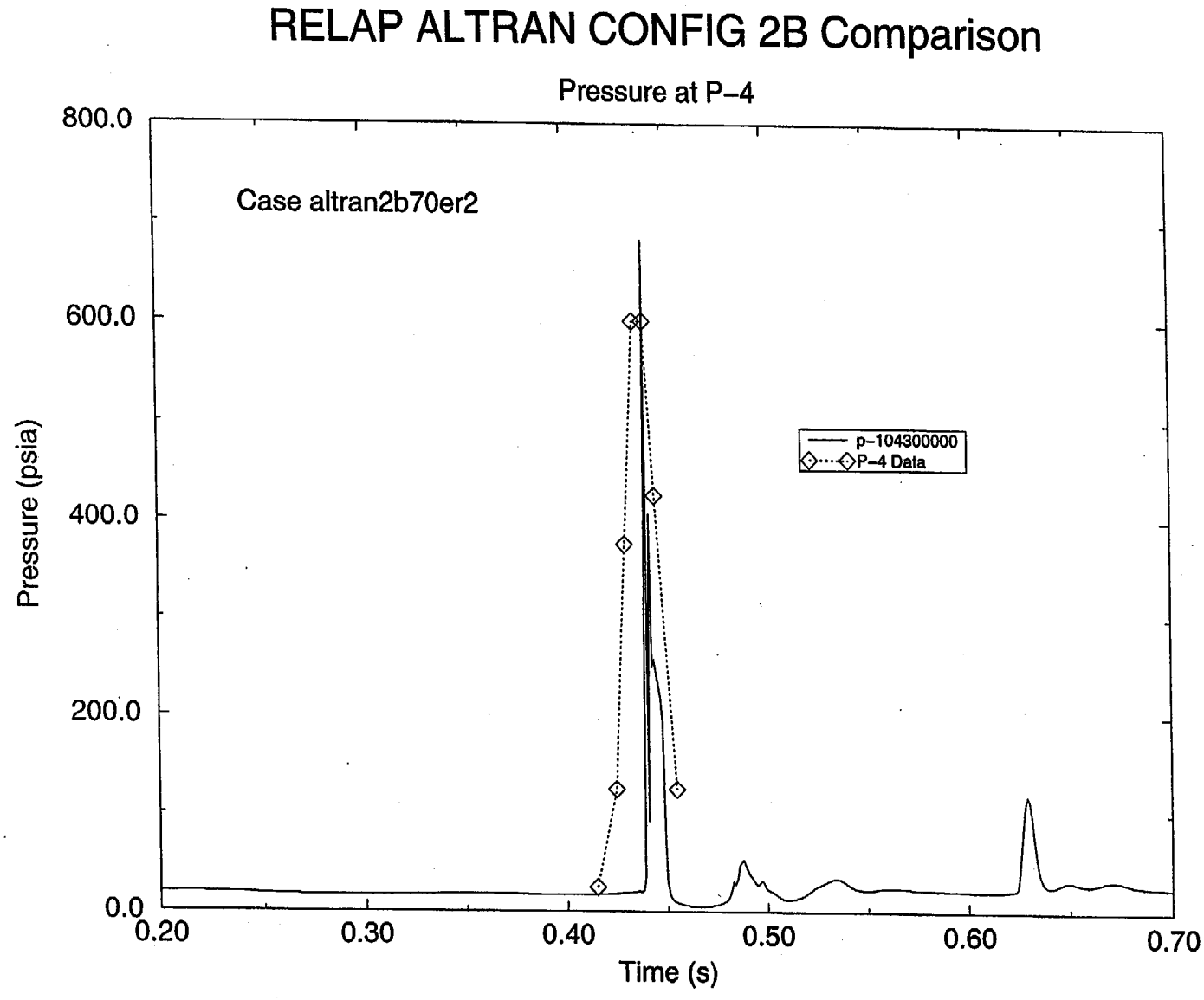


Figure 9 RELAP/Altran Test 2B Force Time History for Support F1

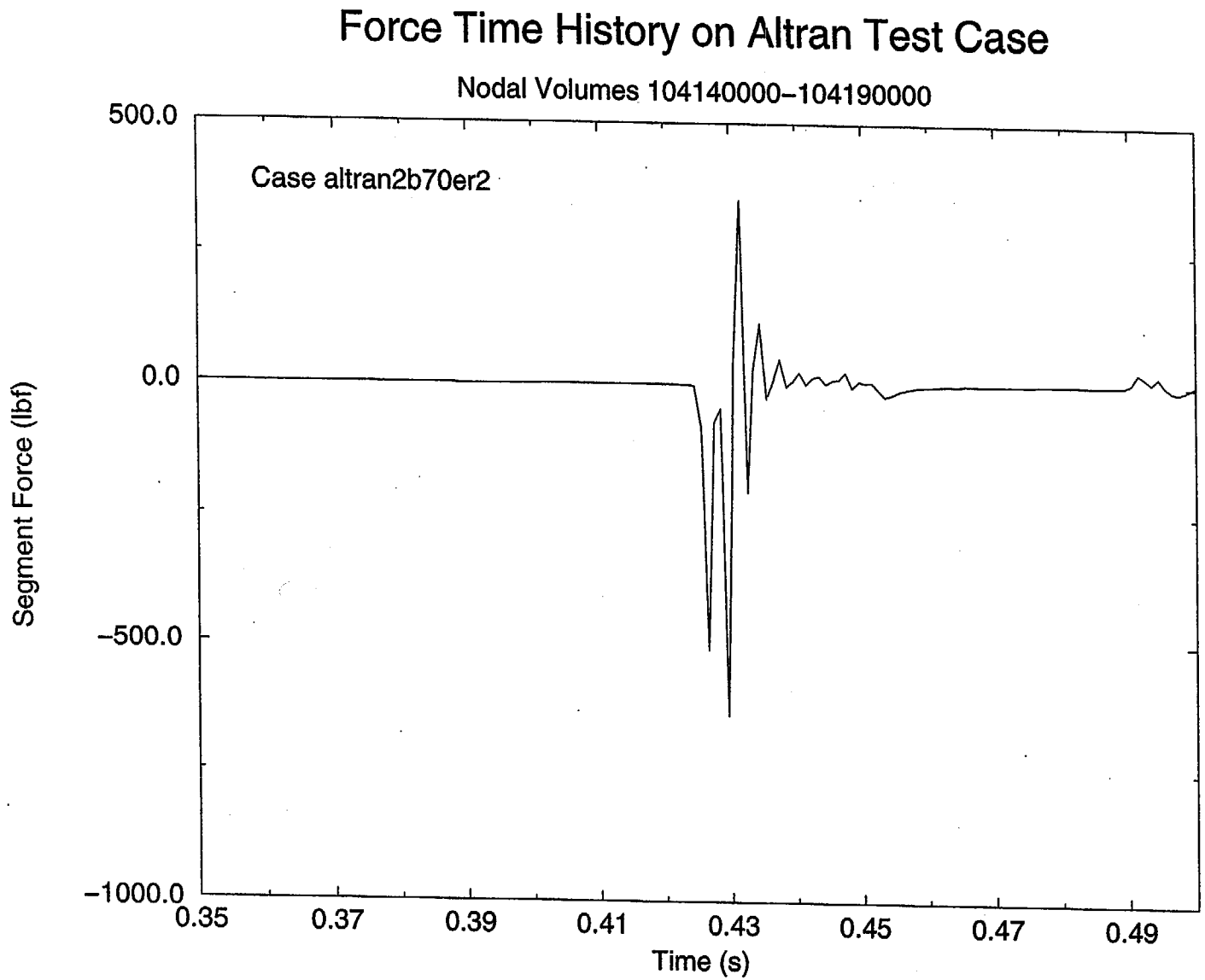


Figure 10 FAI Waterhammer Test Facility Diagram

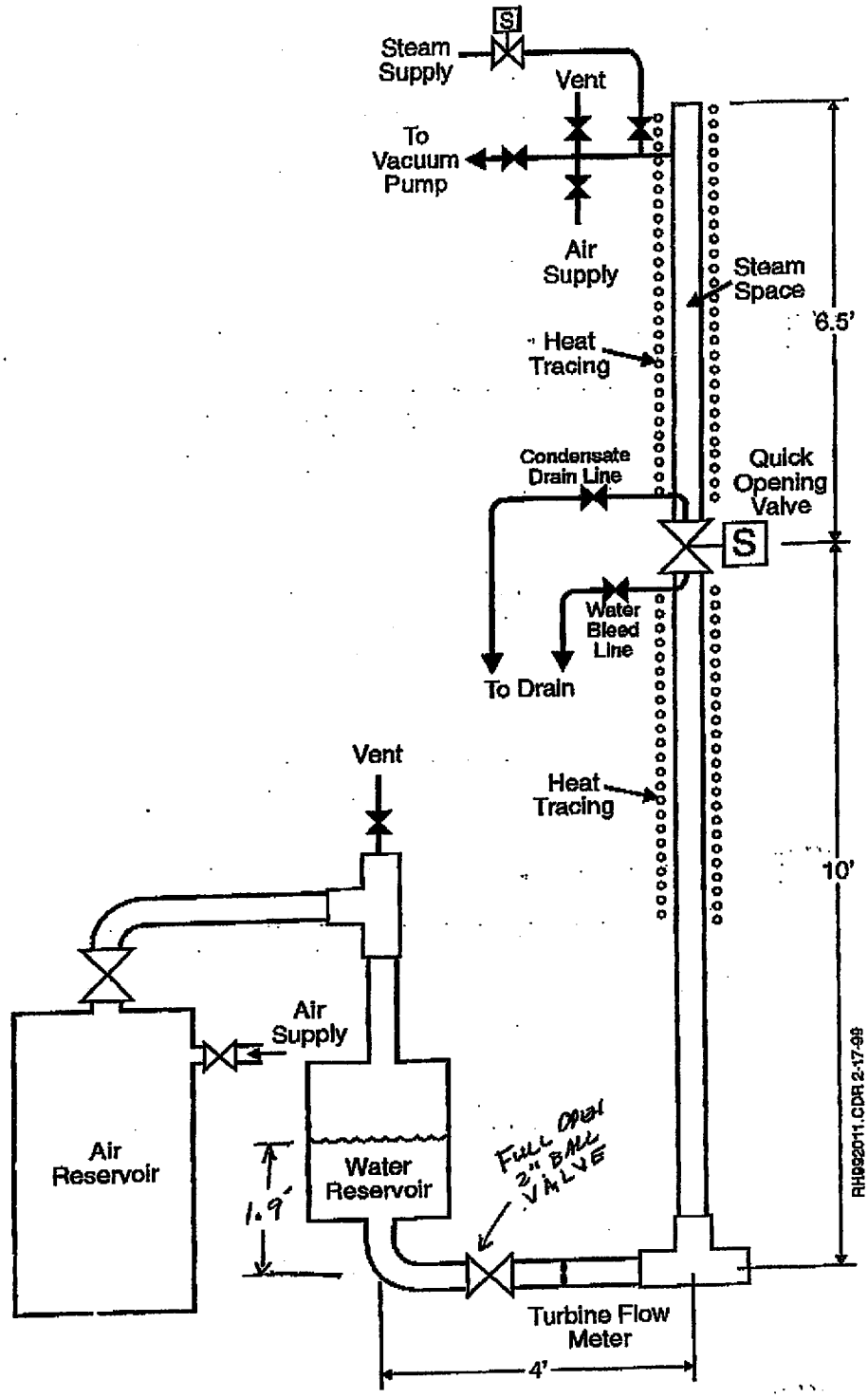


Figure 11 RELAP5 Model of FAI Test Facility

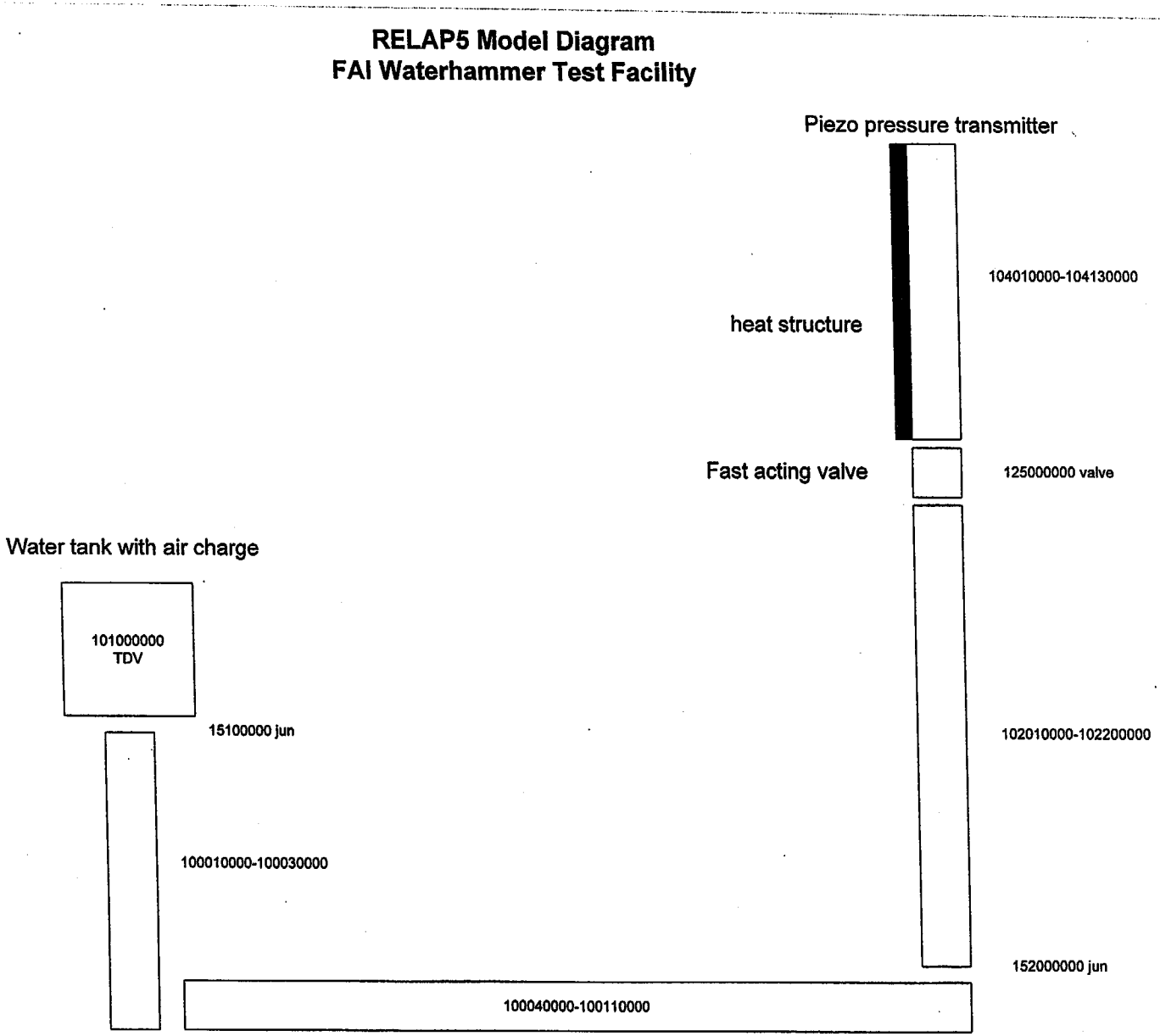


Figure 12 RELAP5 Pressure Response for FAI Test V024

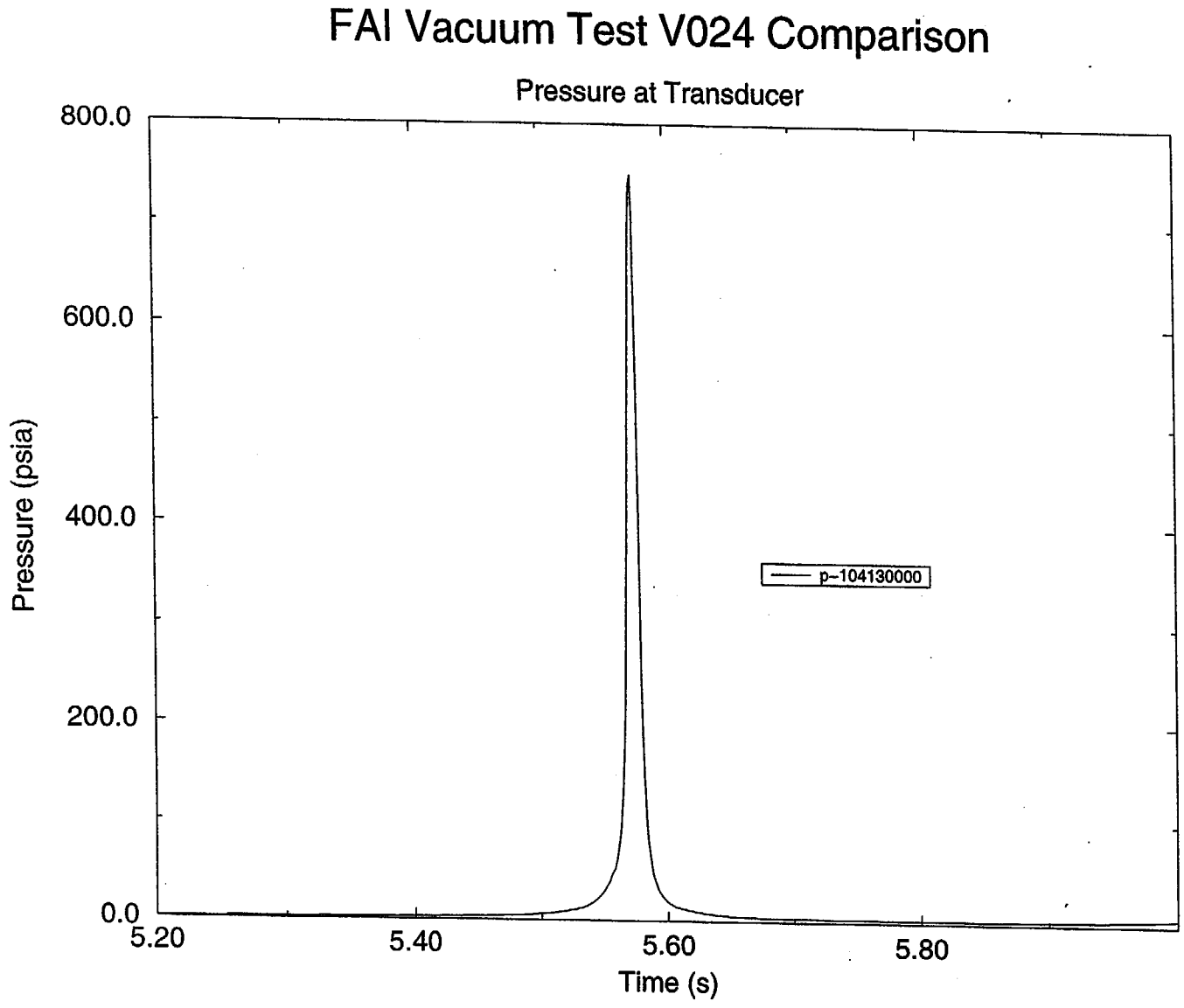


Figure 13 RELAP5 Fluid Velocity Response for FAI Test V024

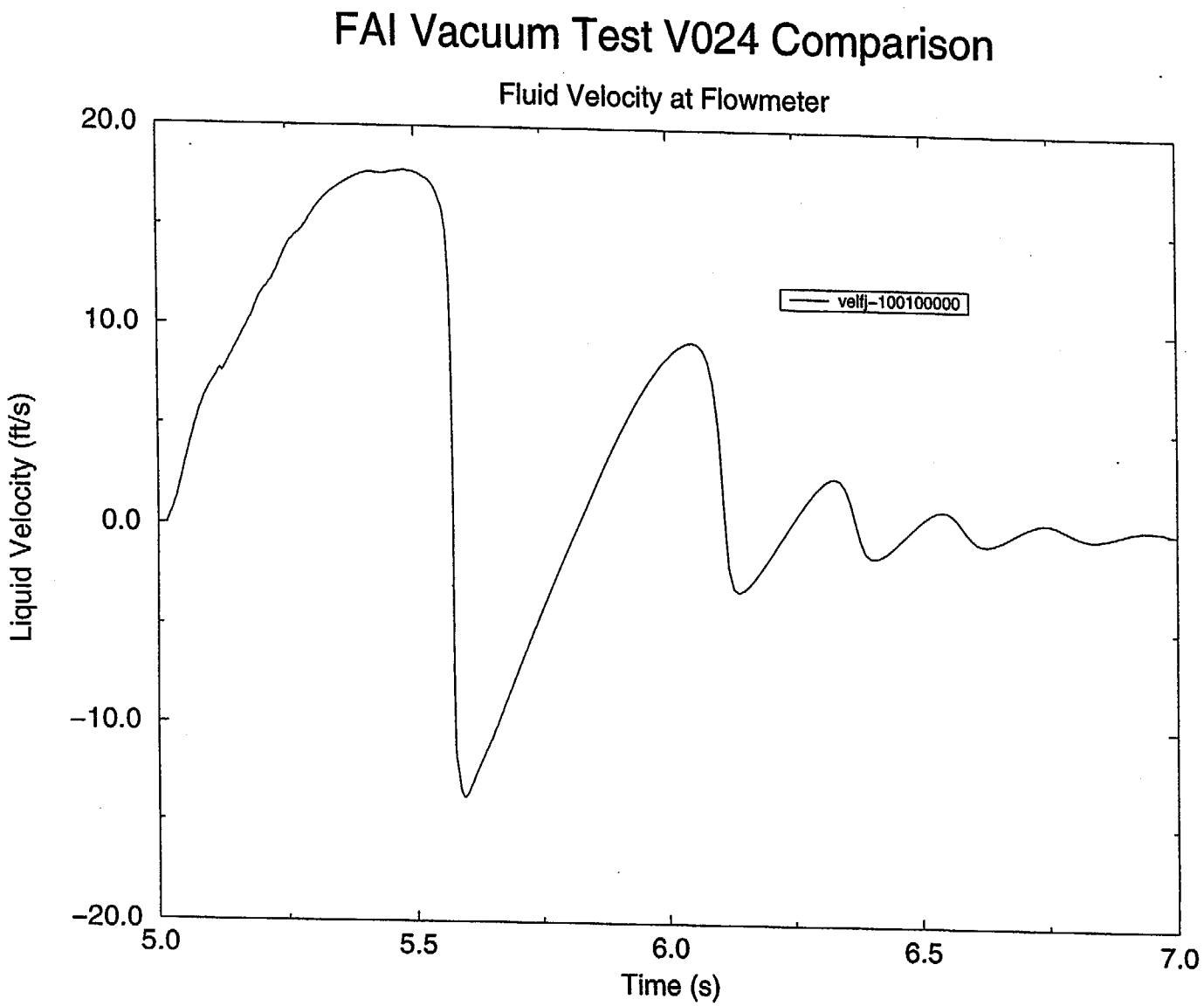


Figure 14 RELAP5 Vapor Generation Behavior for FAI Test V024

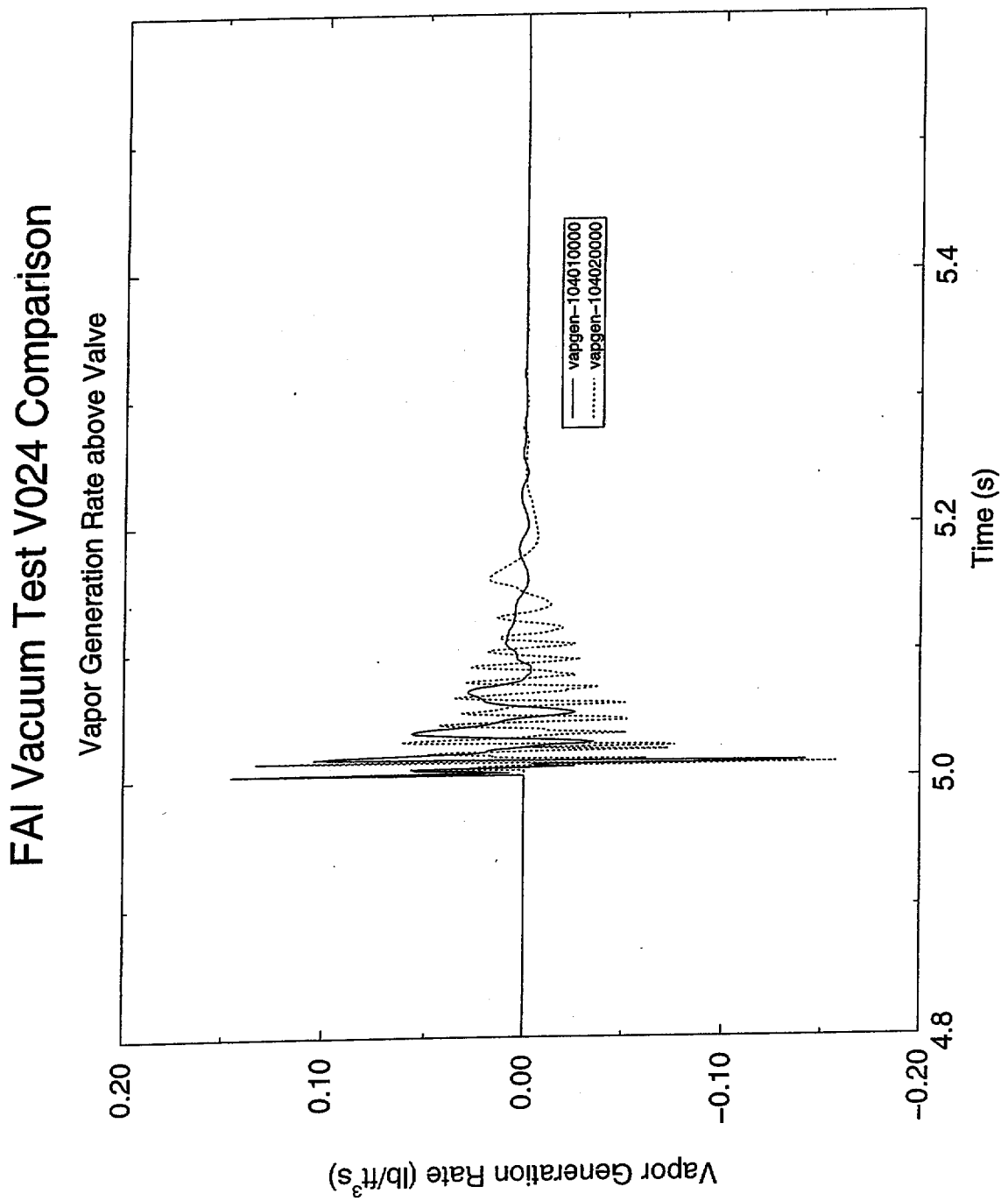


Figure 15 RELAP5 Pressure Response for FAI Test 394

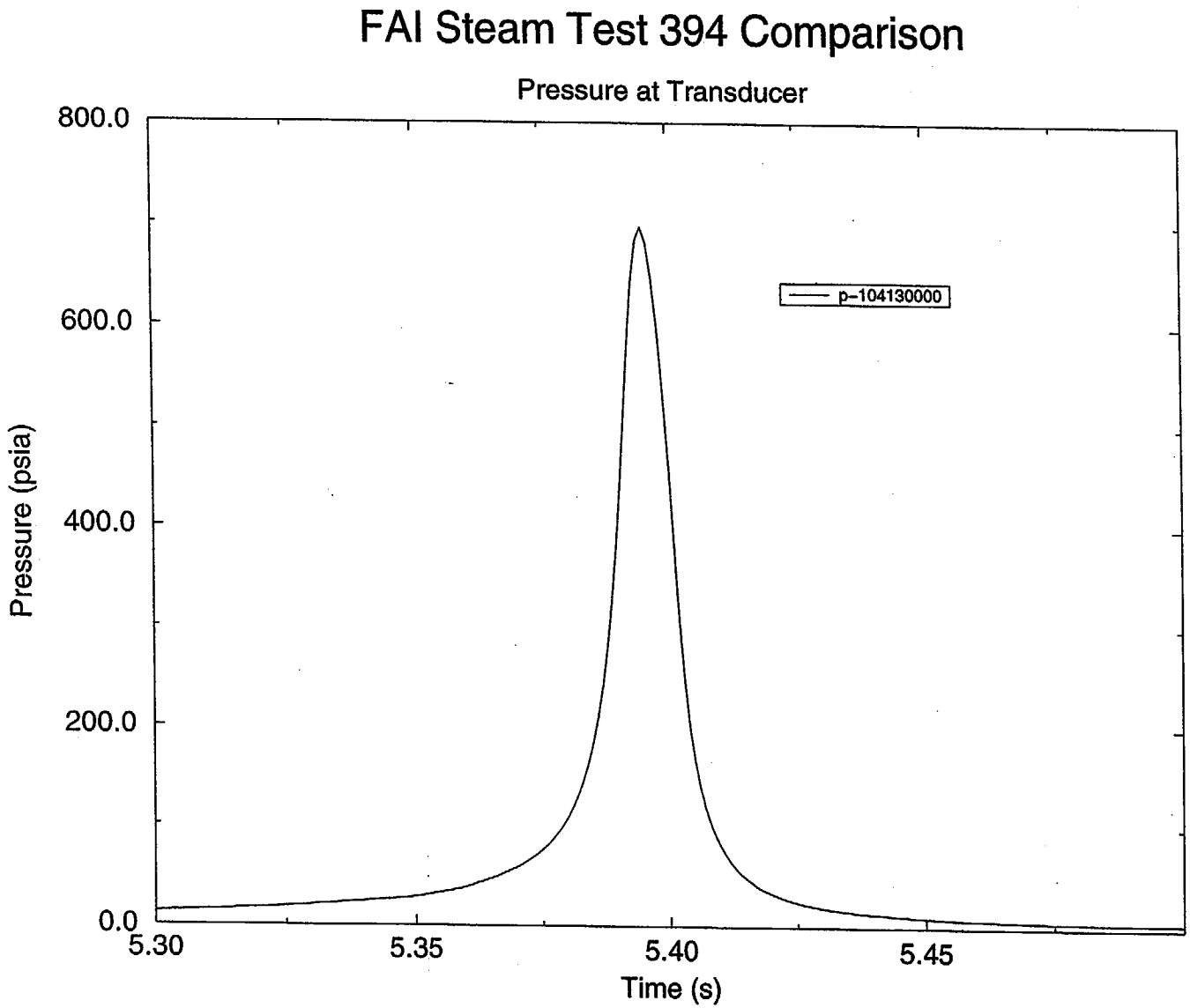


Figure 16 RELAP5 Fluid Velocity Response for FAI Test 394

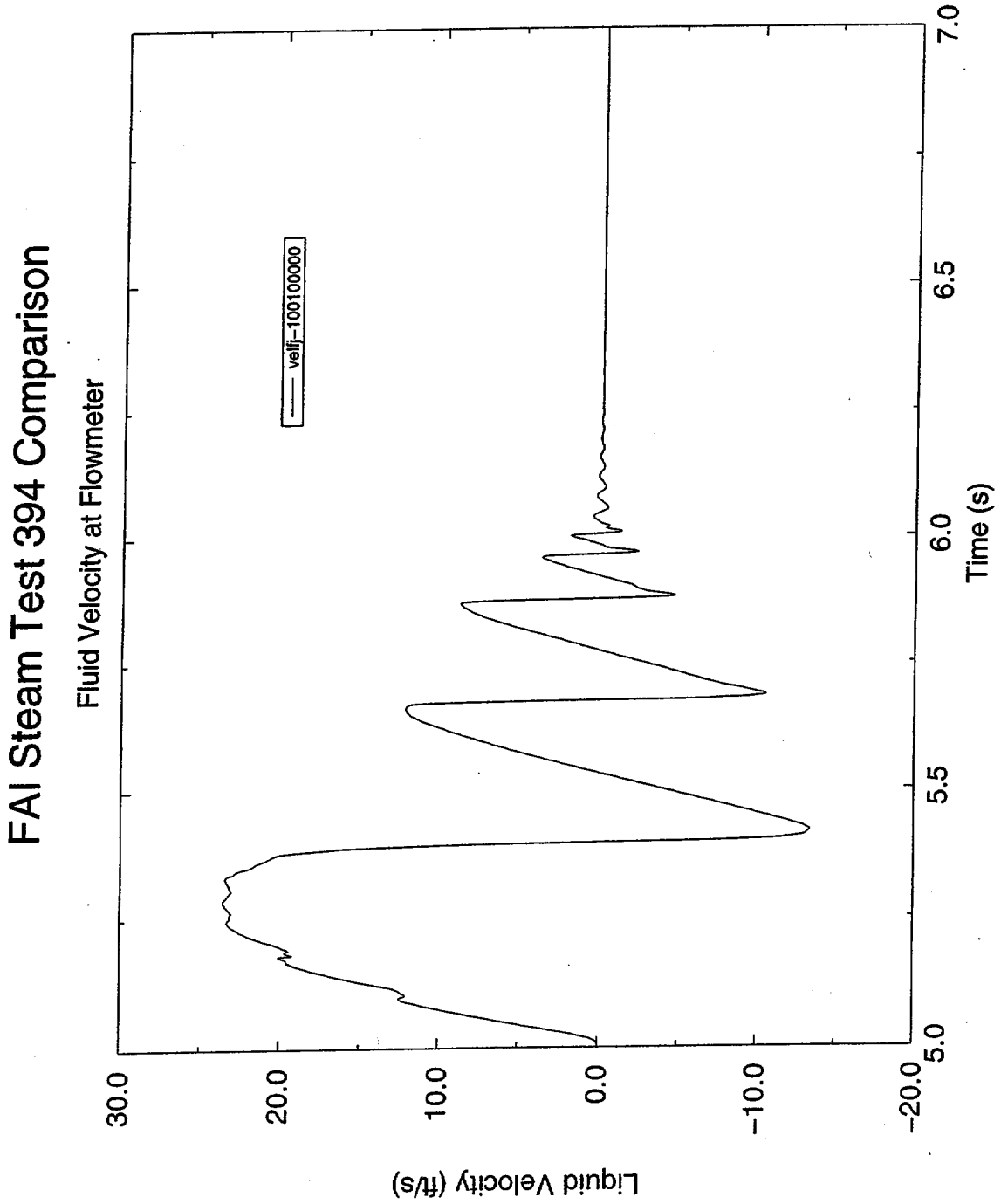


Figure 17 RELAP5 Vapor Generation for FAI Test 394

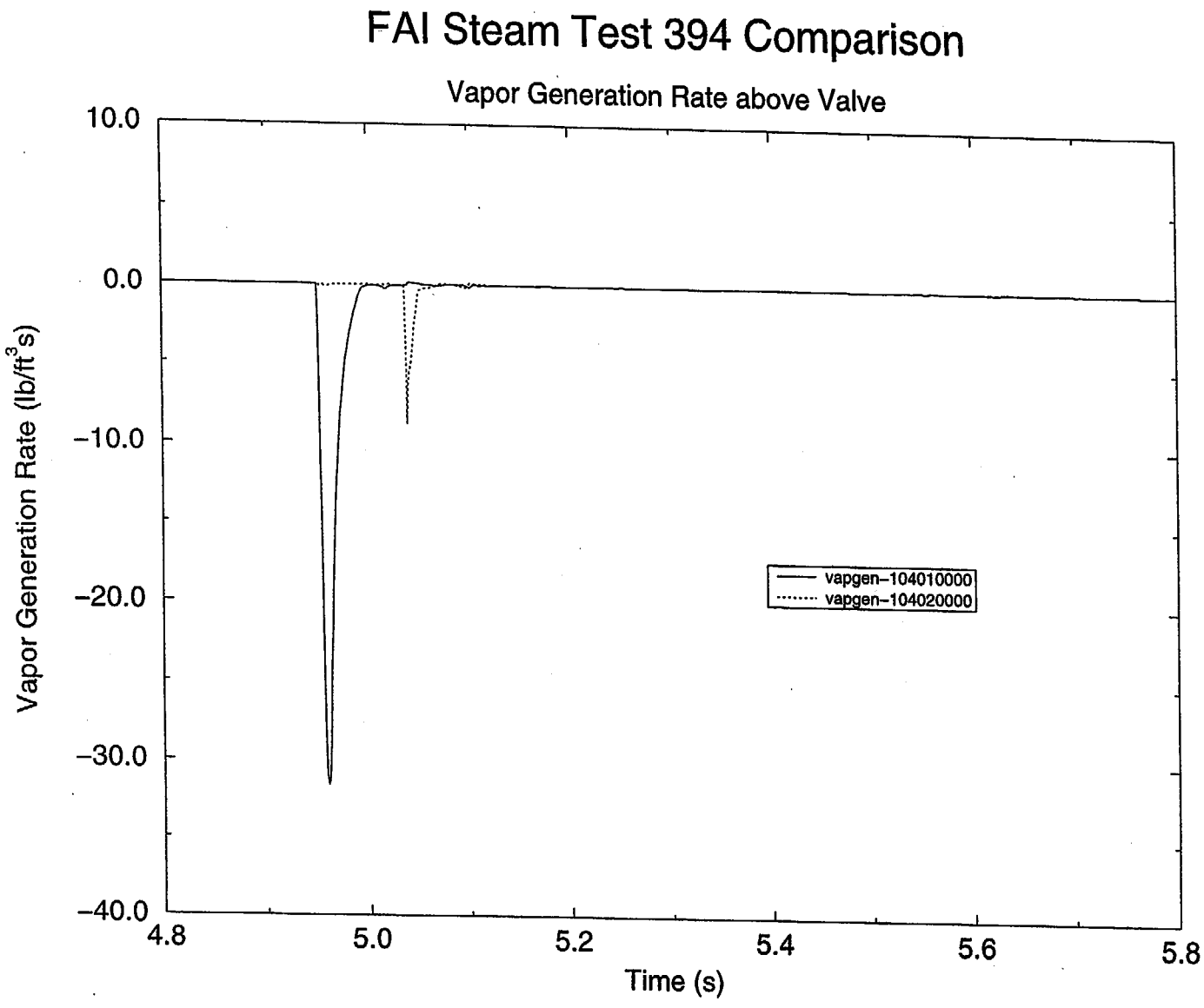


Figure 18 Byron/Braidwood RCFC SX Piping Base Model

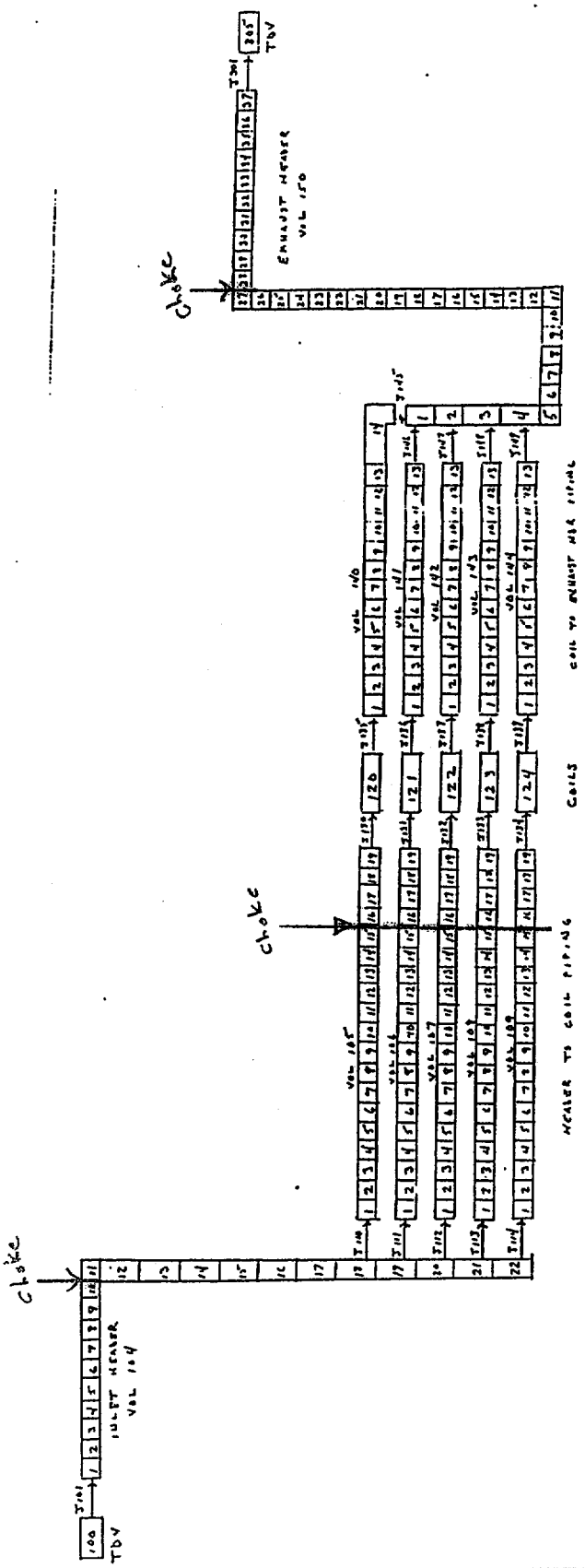


Figure 19 Byron/Braidwood RCFC Base Model Coil Detail

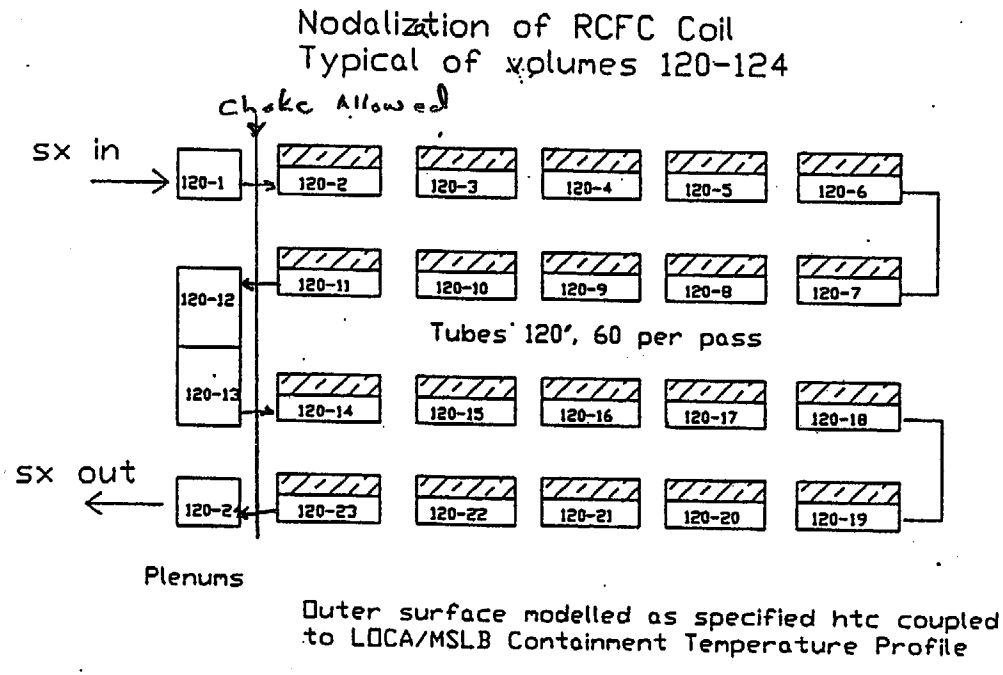


Figure 20 RELAP5 Mod3.1.1 to Mod3.2 Comparison, Flow at TDV

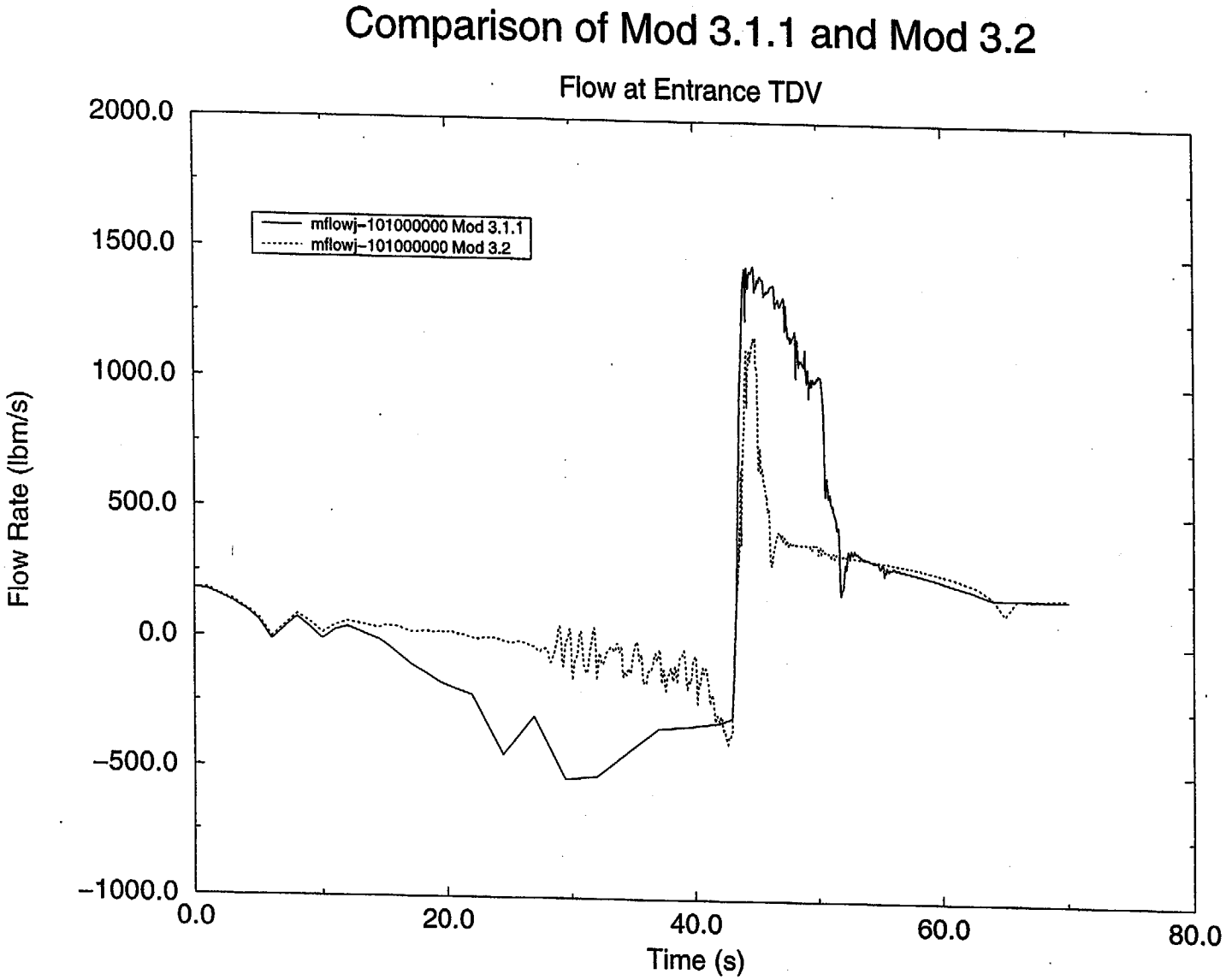


Figure 21 RELAP5 Mod3.1.1 to Mod3.2 Comparison, Flow Regime at Coil

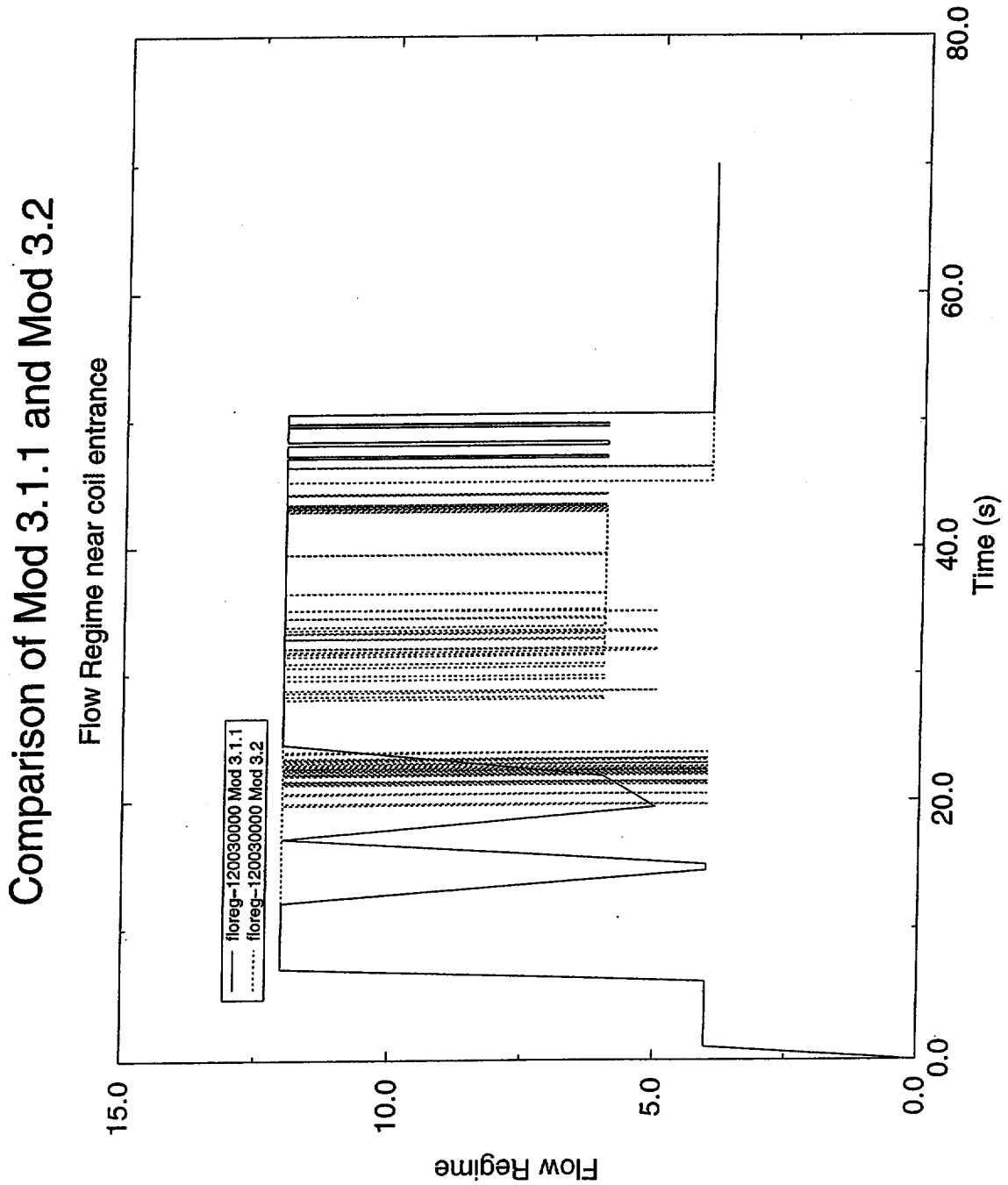


Figure 22 RELAP5 Mod3.1.1 to Mod3.2 Comparison, Tsat and Tvap in Coil

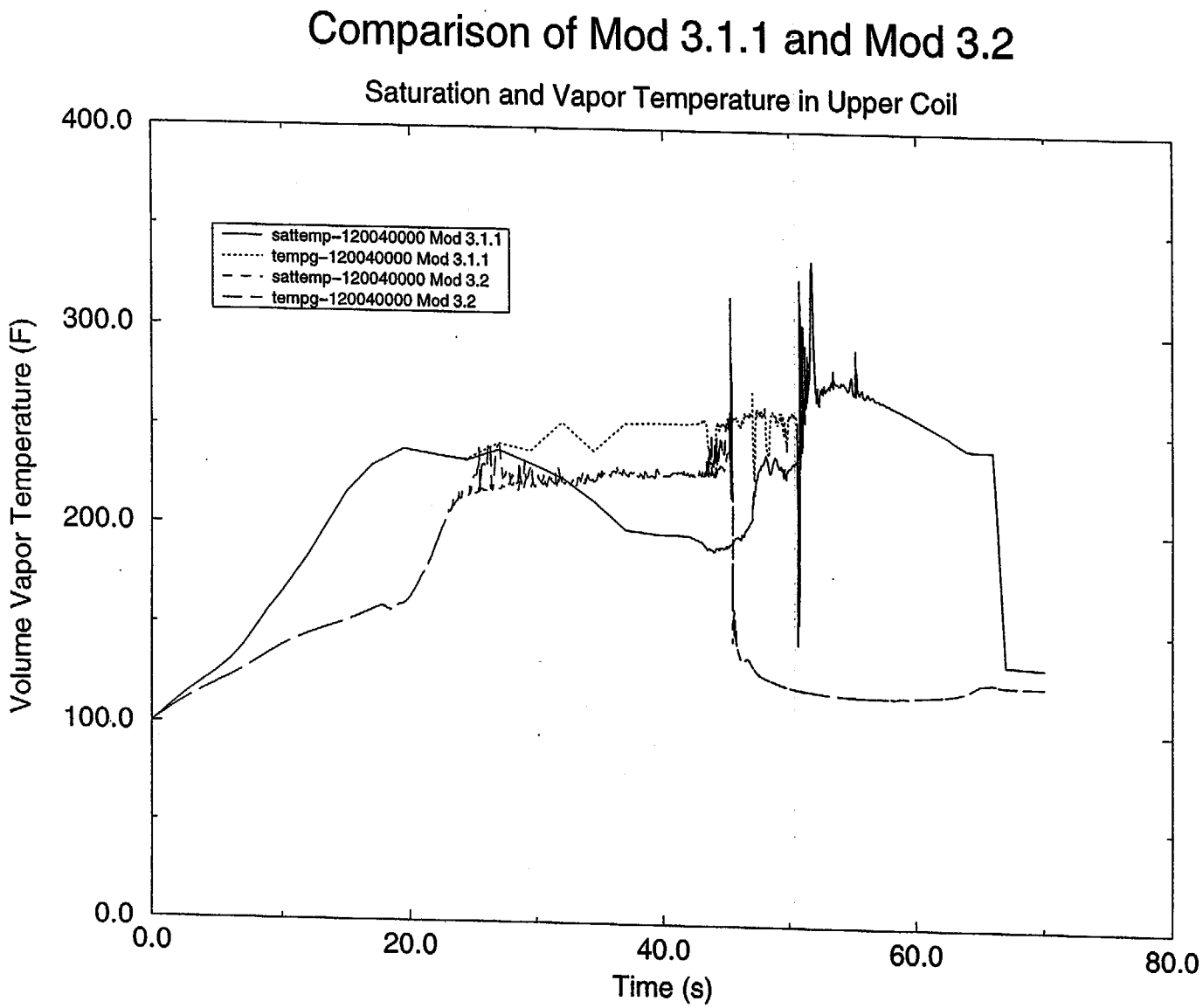


Figure 23 RELAP5 Mod3.1.1 to Mod3.2 Comparison, Pressure in Upper Coil

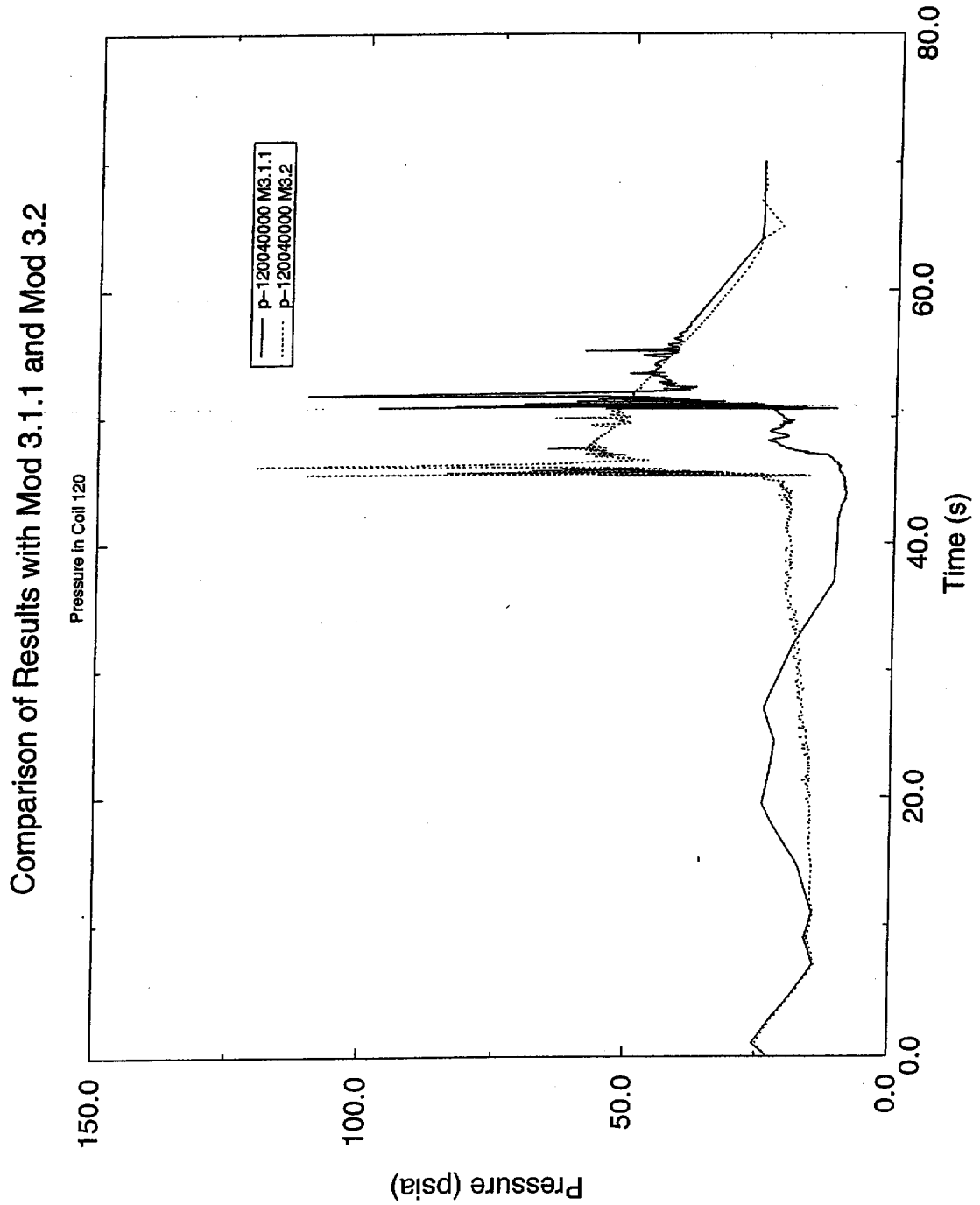


Figure 24 RELAP5 Mod3.1.1 to Mod3.2 Comparison, Pressure at Inlet Hdr Bottom

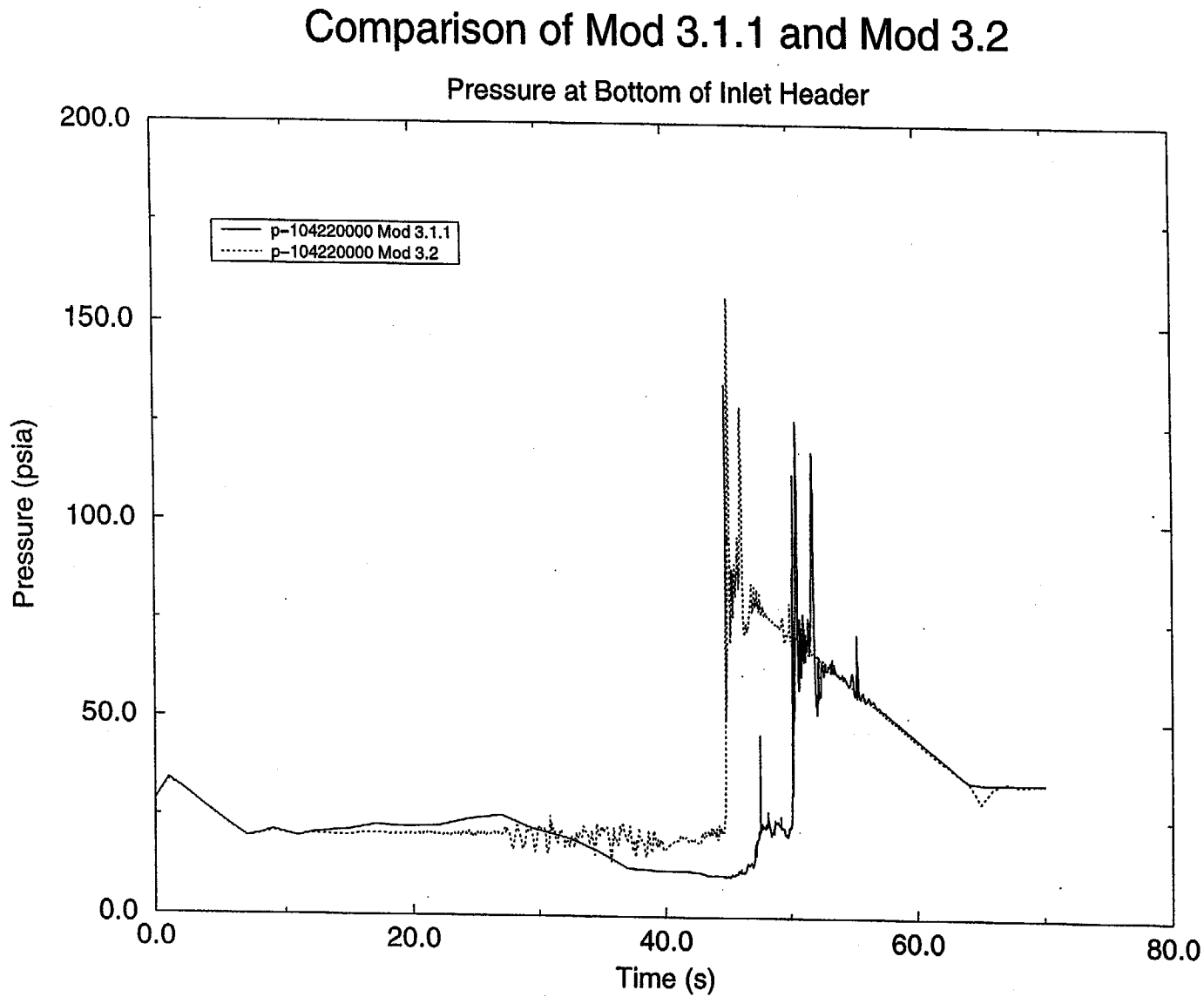


Figure 25 RELAP5 Mod3.1.1 to Mod3.2 Comparison, Pressure at Inlet Hdr Top

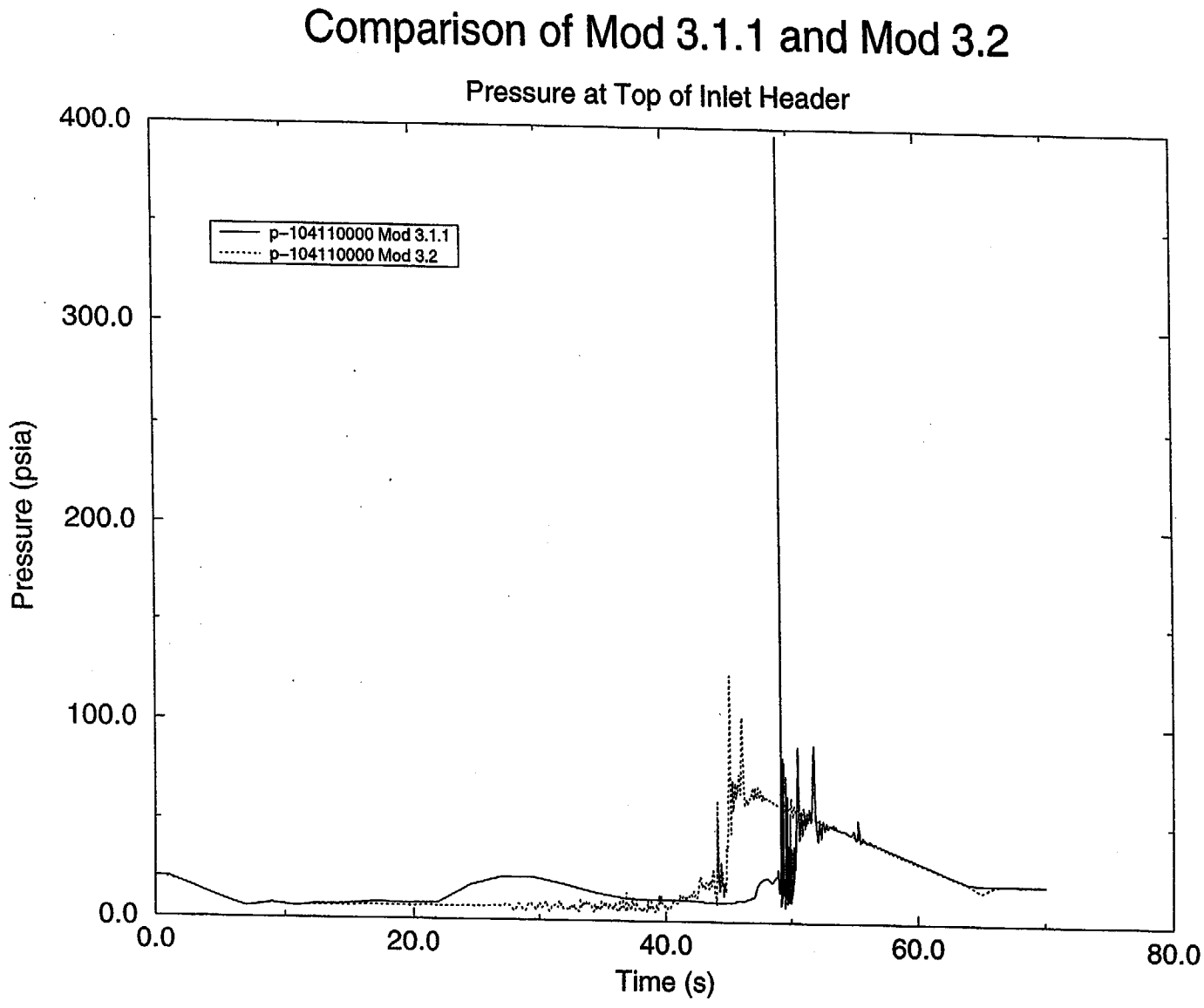


Figure 26 RELAP5 Mod3.1.1 to Mod3.2 Comparison, Forces on Upper Coil

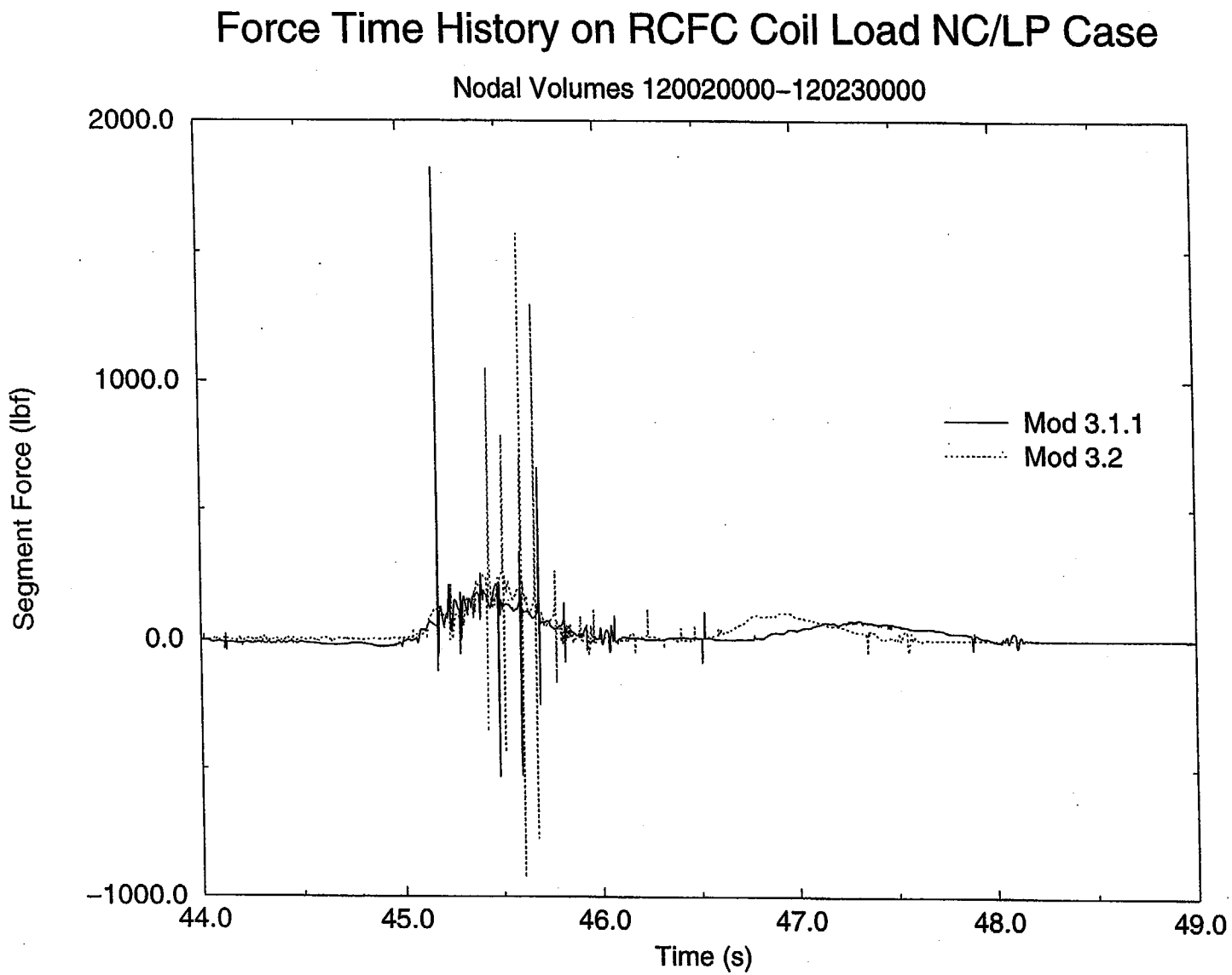


Figure 27 RELAP5 Mod3.1.1 to Mod3.2 Comparison, Forces on Inlet Hdr

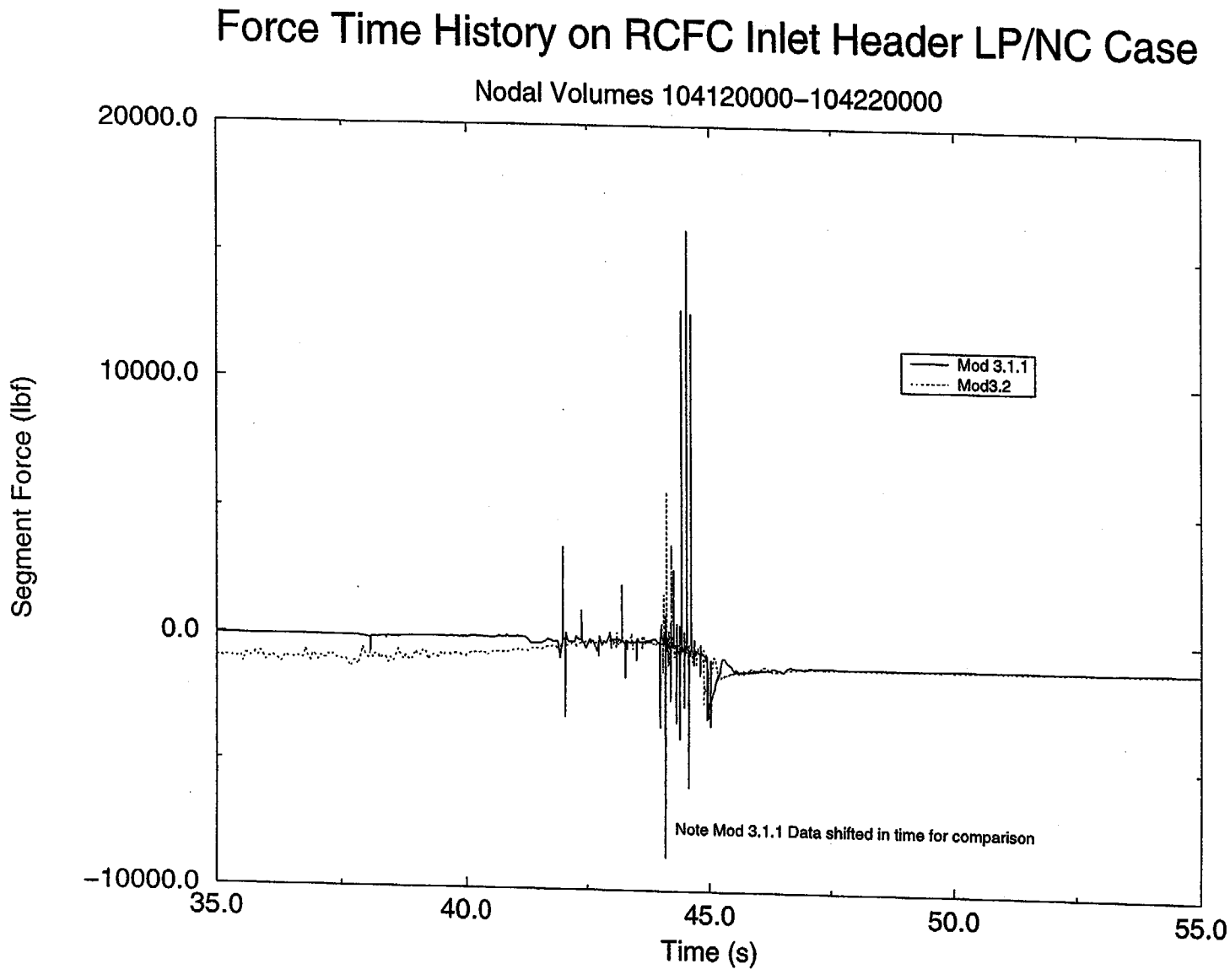


Figure 28 RELAP5 Mod3.1.1 to Mod3.2 Comparison, Forces on Exhaust Hdr

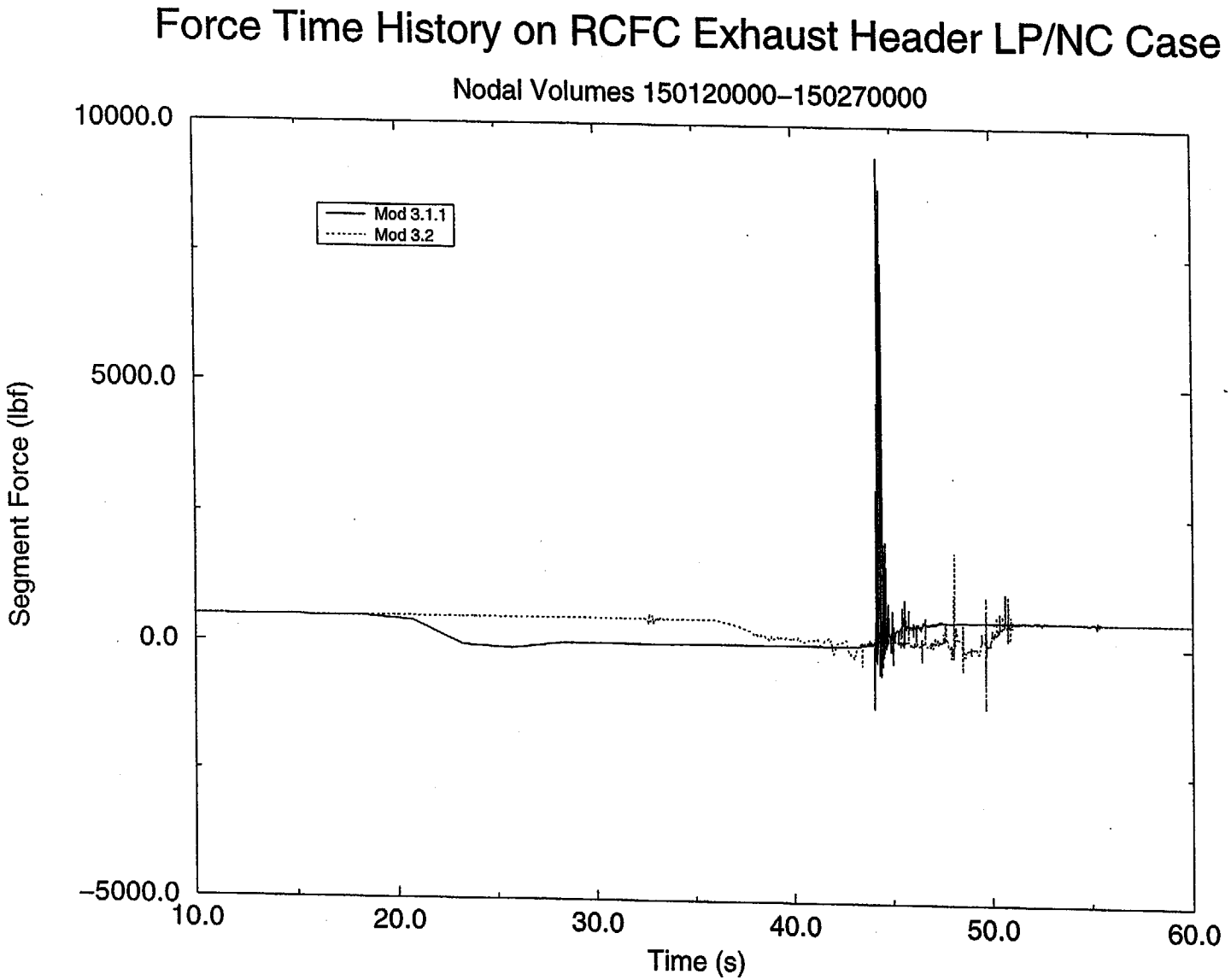


Figure 29 Choking Sensitivity Case, Flow at TDV

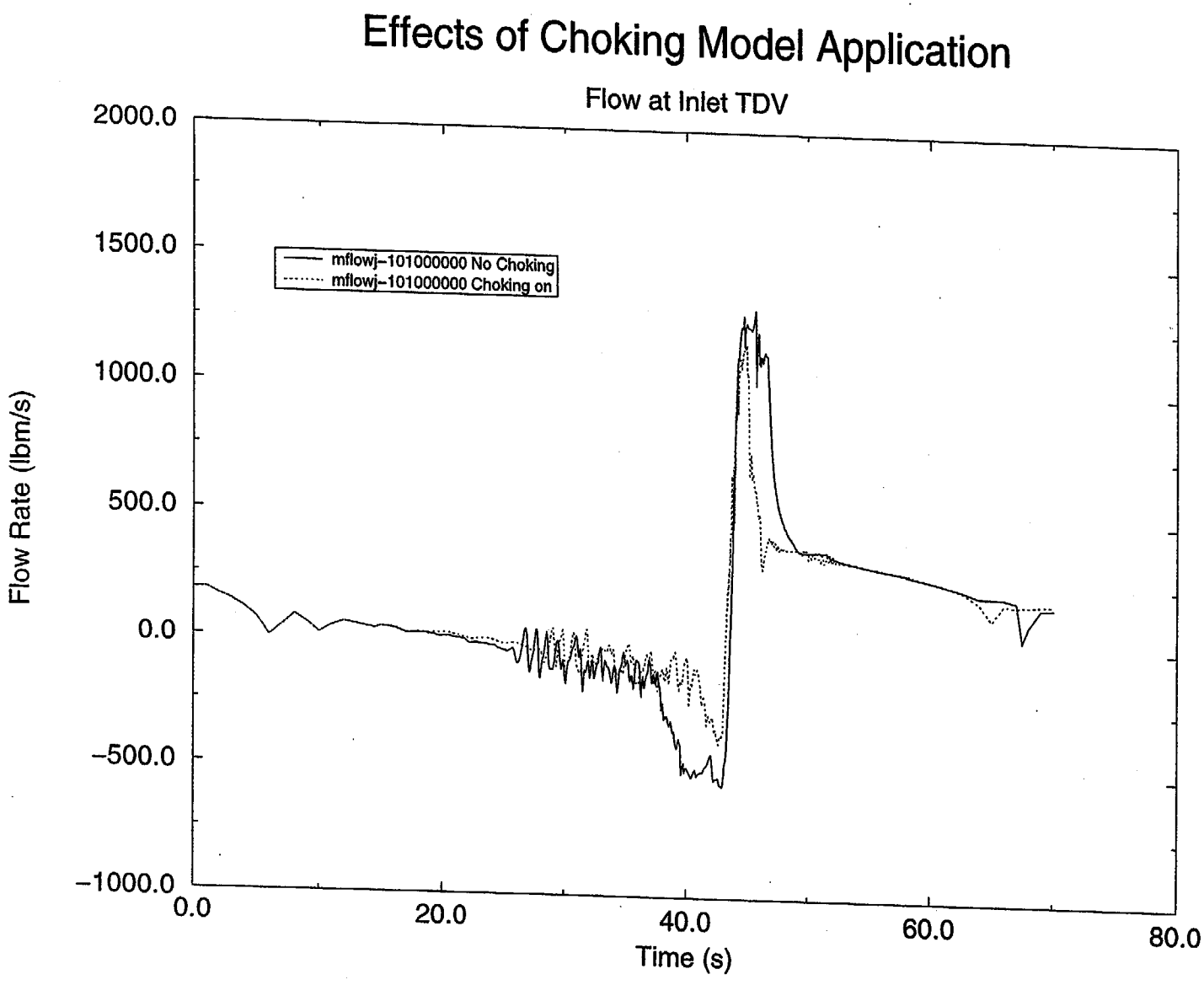


Figure 30 Choking Sensitivity Case, Void Fraction in Upper Coil

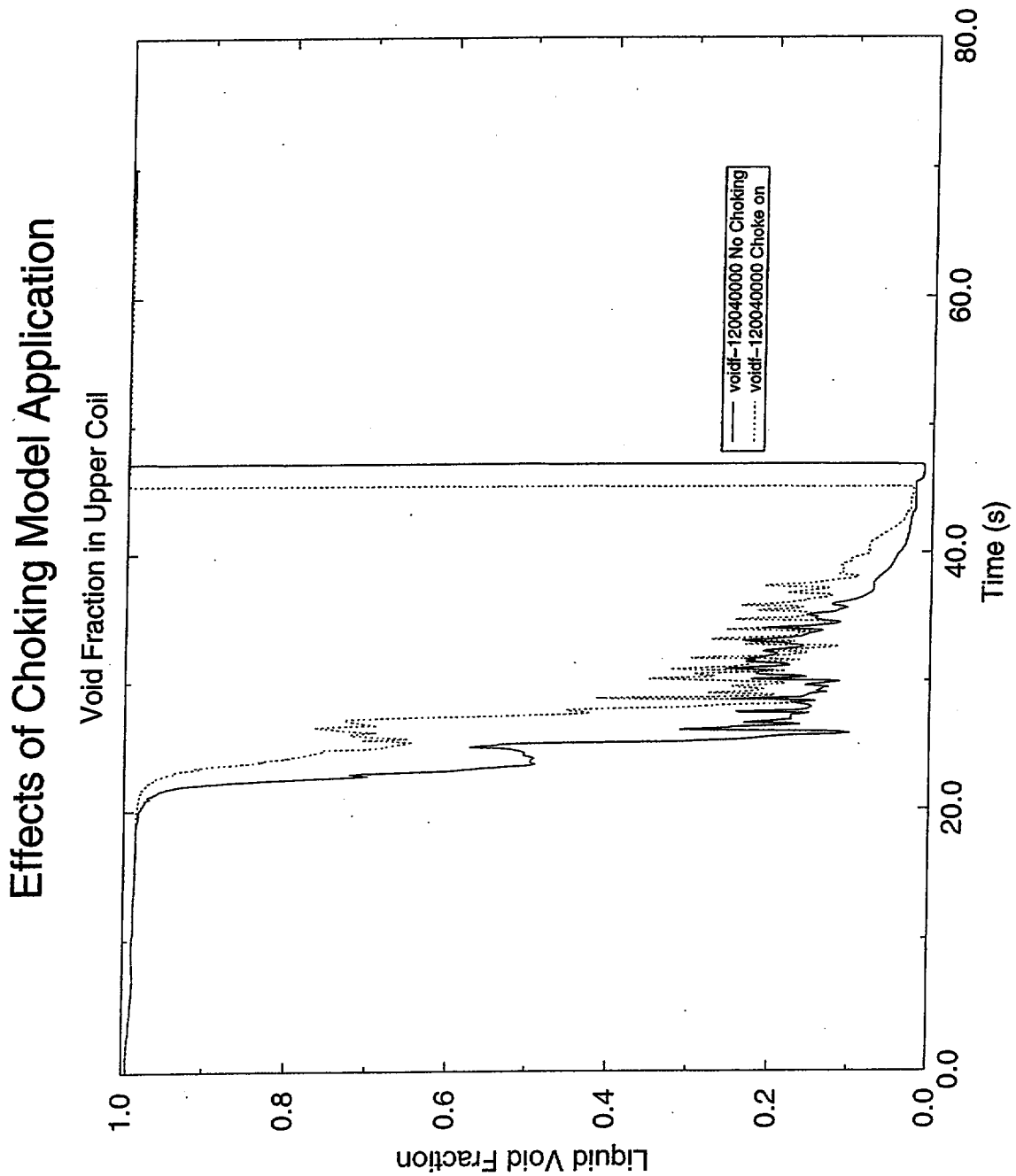


Figure 31 Choking Sensitivity Case, Pressure at Inlet Hdr Bottom

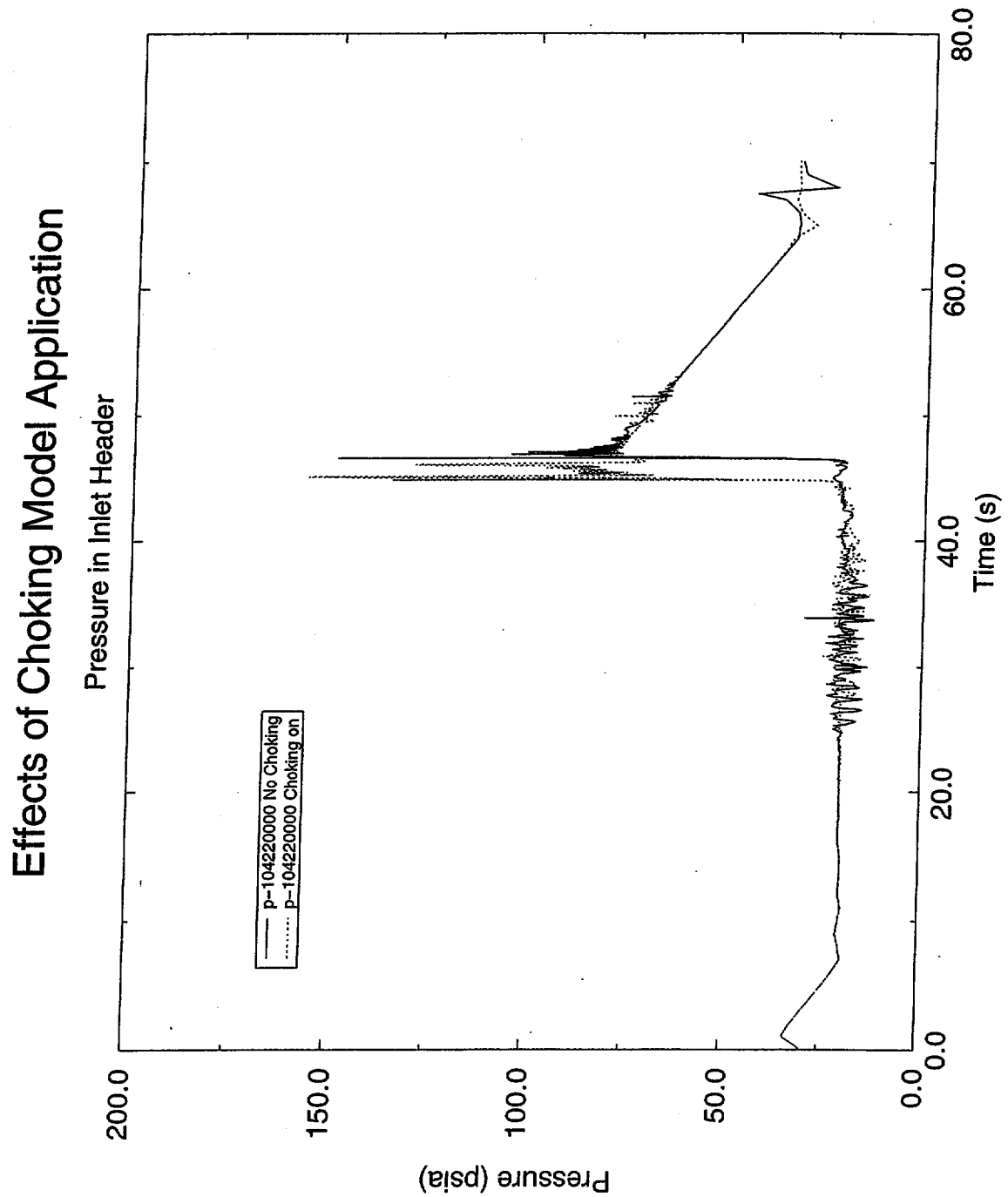


Figure 32 Choking Sensitivity Case, Pressure in Upper Coil

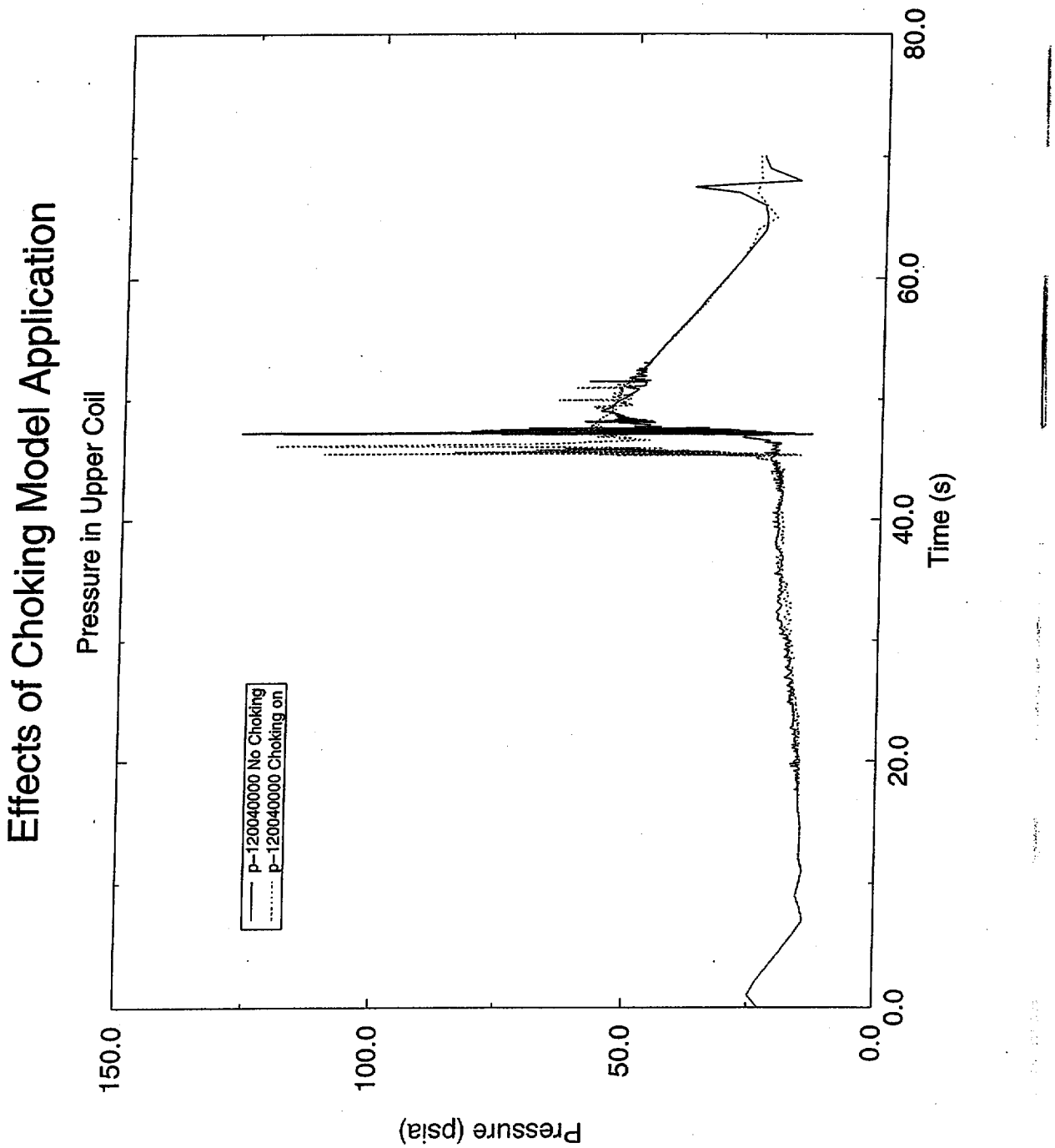
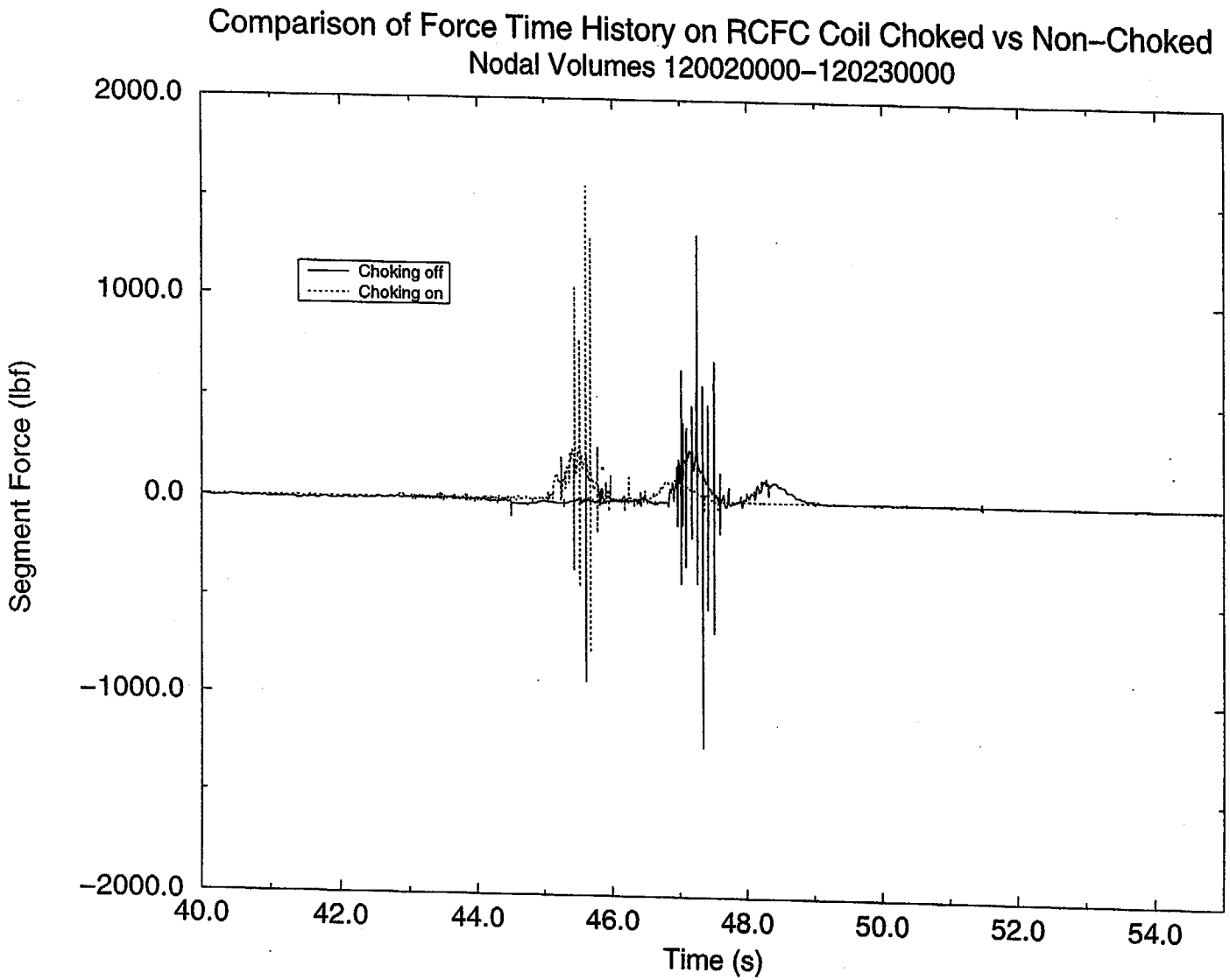


Figure 33 Choking Sensitivity Case, Forces on Upper Coil



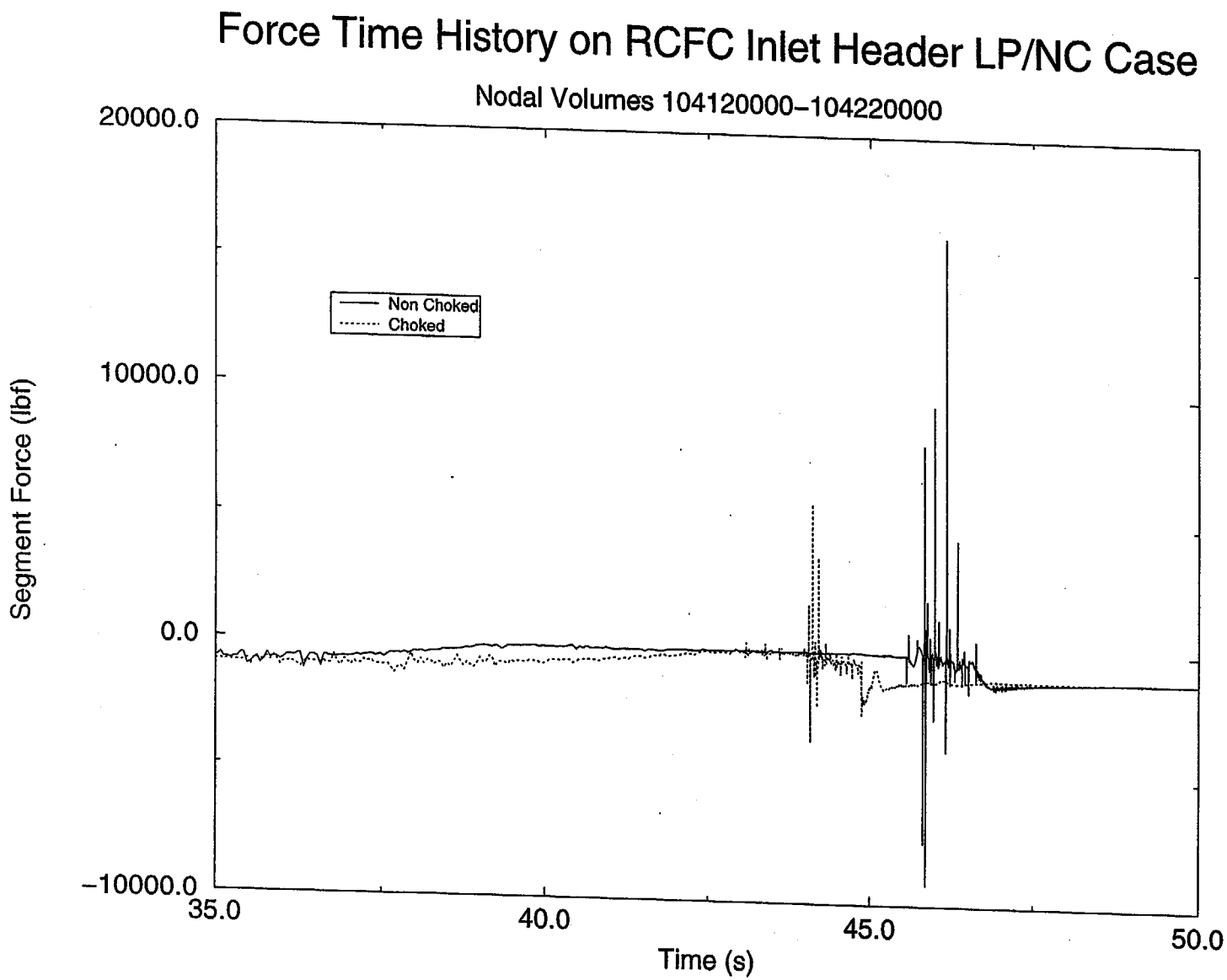


Figure 34 Choking Sensitivity Case, Forces on Inlet Hdr

Figure 35 Non-Condensable Sensitivity, Pressure at Inlet Hdr Bottom

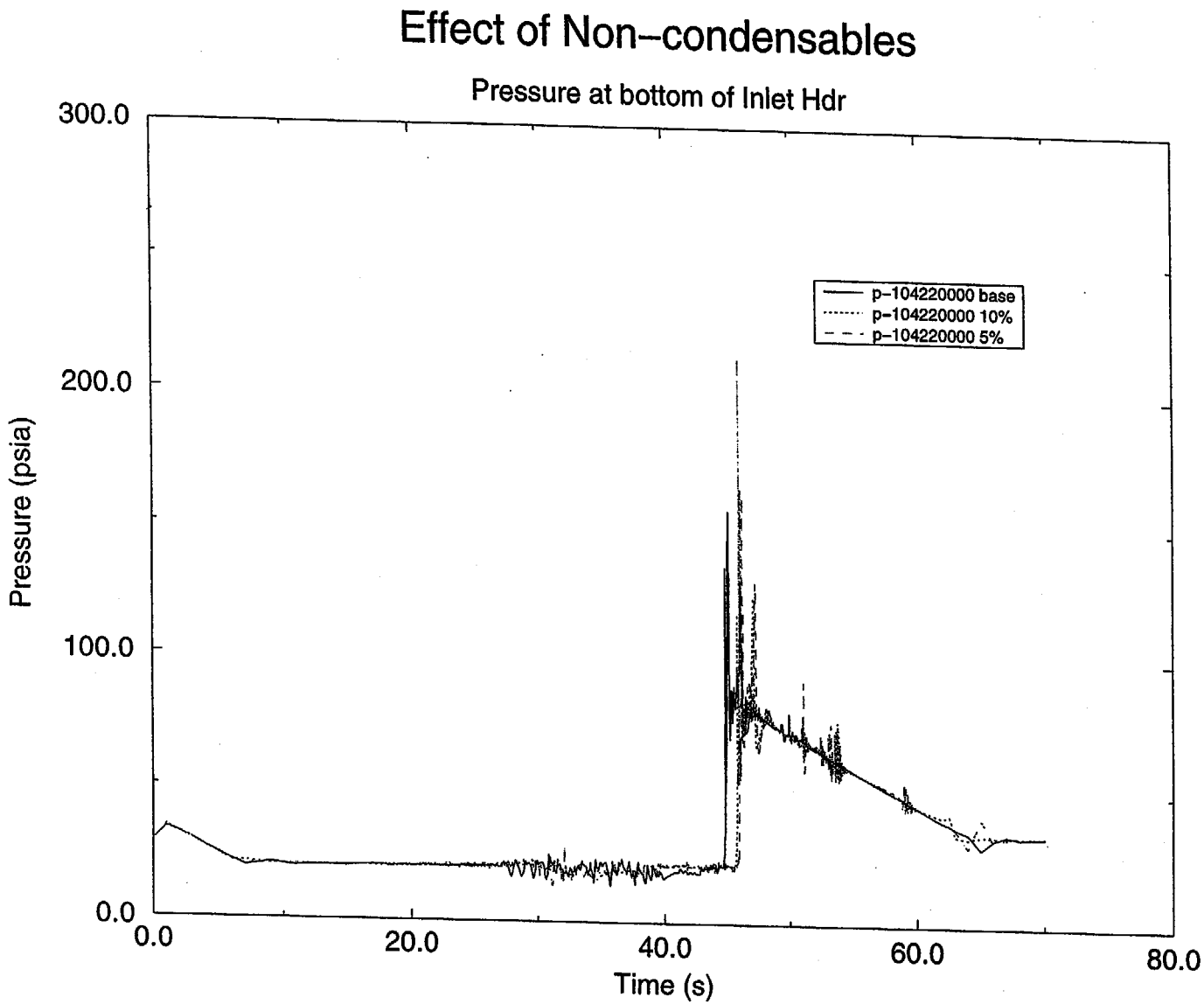


Figure 36 Non-Condensable Sensitivity, Pressure in Upper Coil

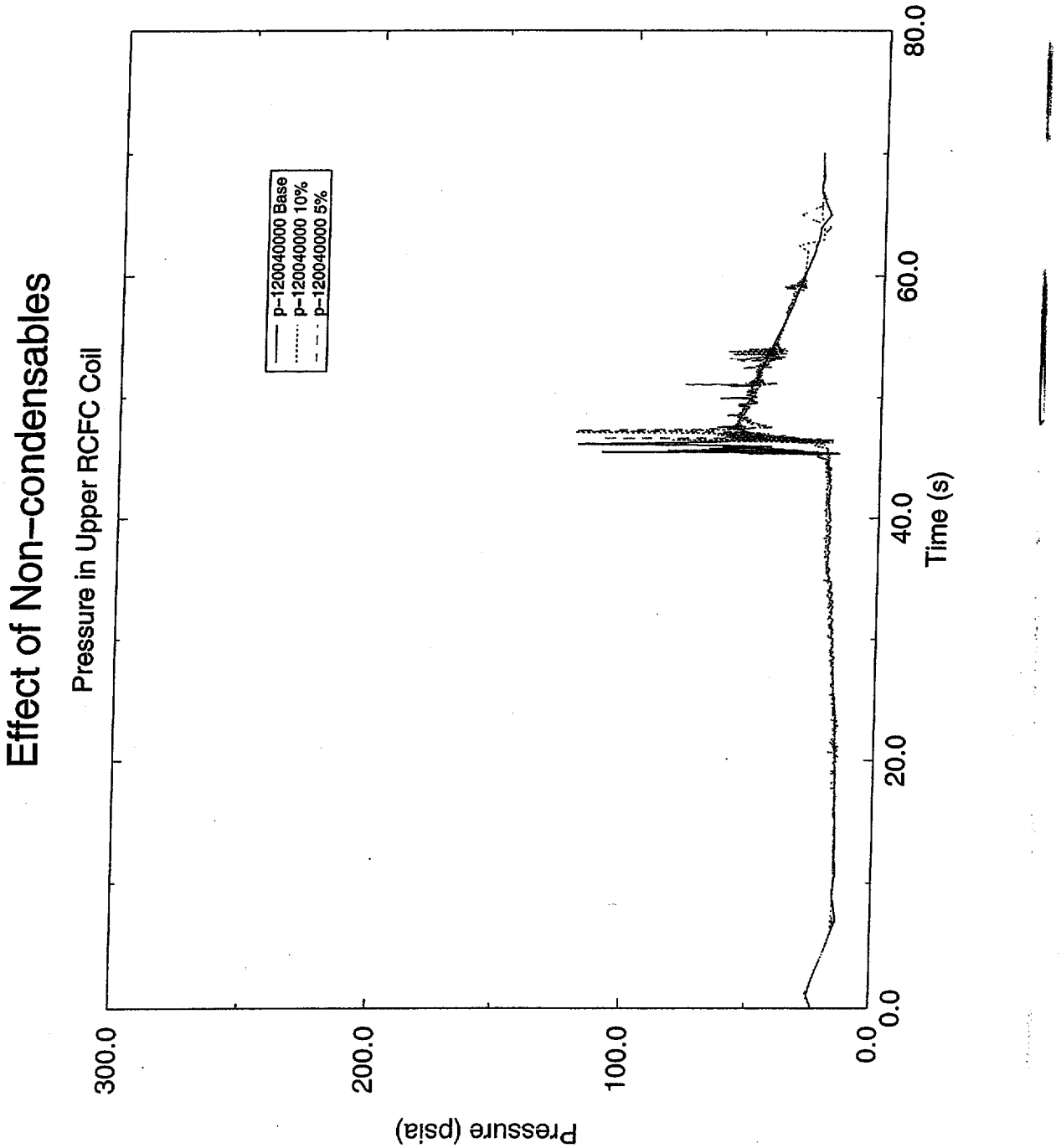


Figure 37 Non-Condensable Sensitivity, Flow at TDV

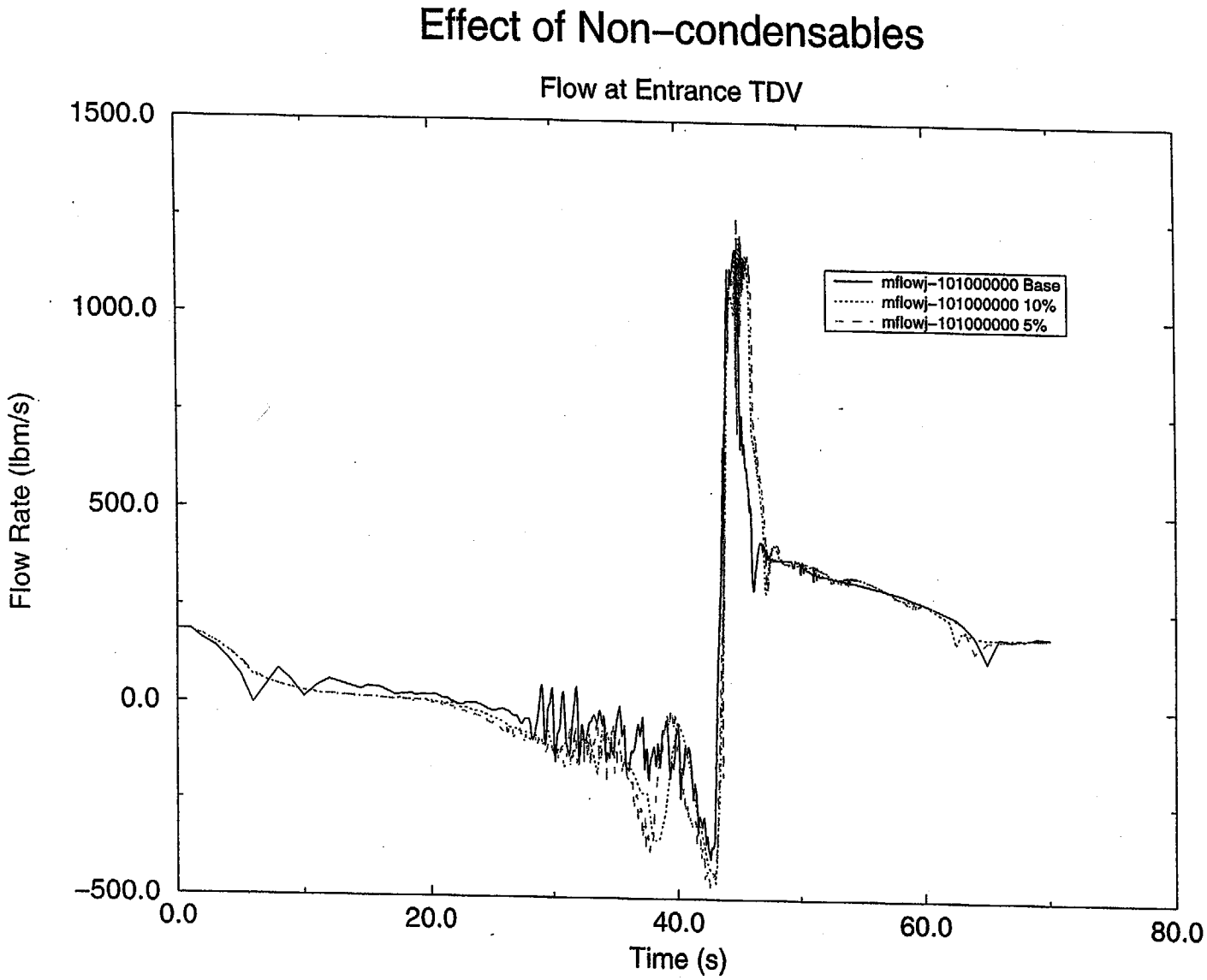


Figure 38 Non-Condensable Sensitivity, Flow Regimes in Upper Coil

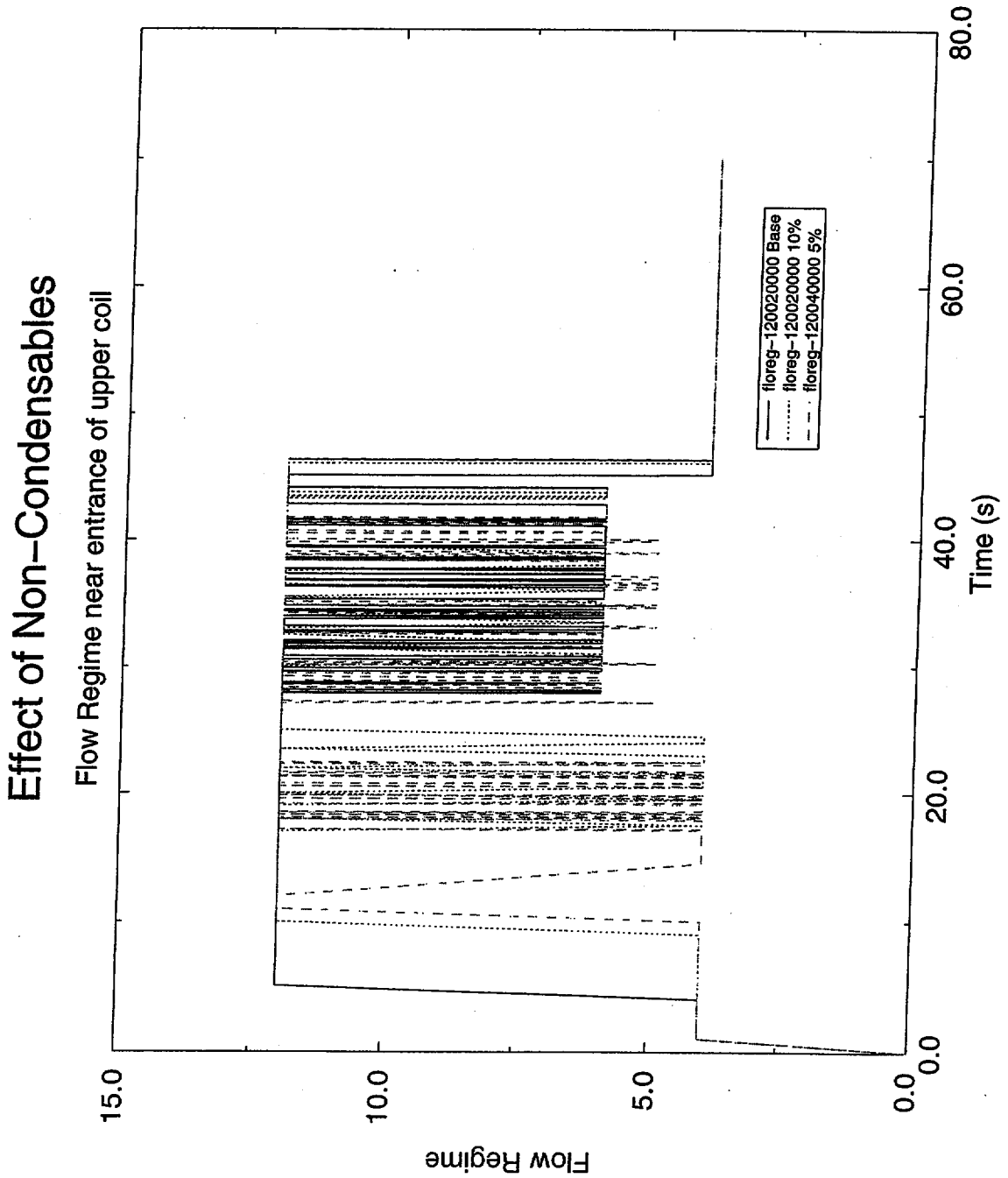


Figure 39 Non-Condensable Sensitivity, Forces on Upper Coil

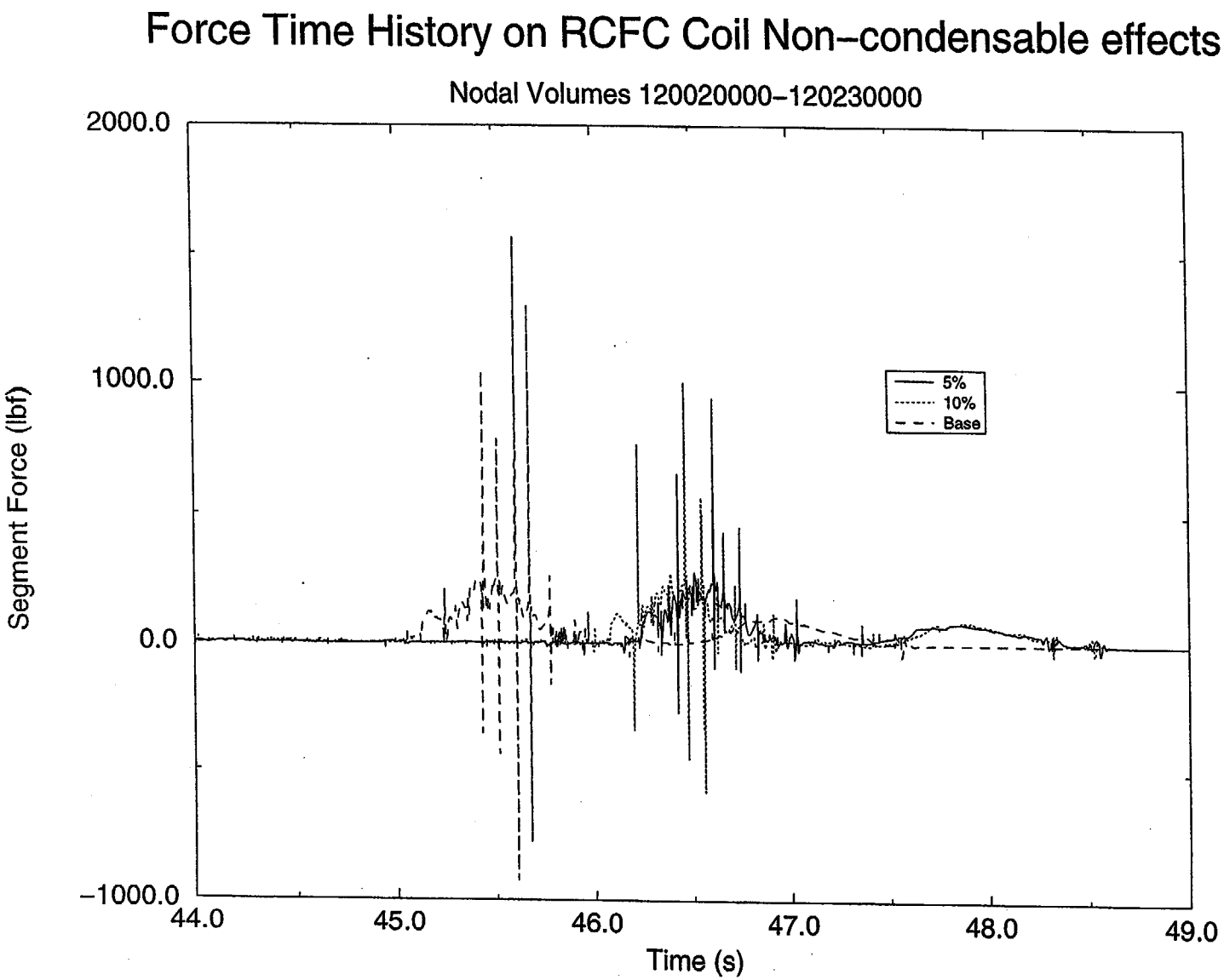


Figure 40 Control Volume Force Balance

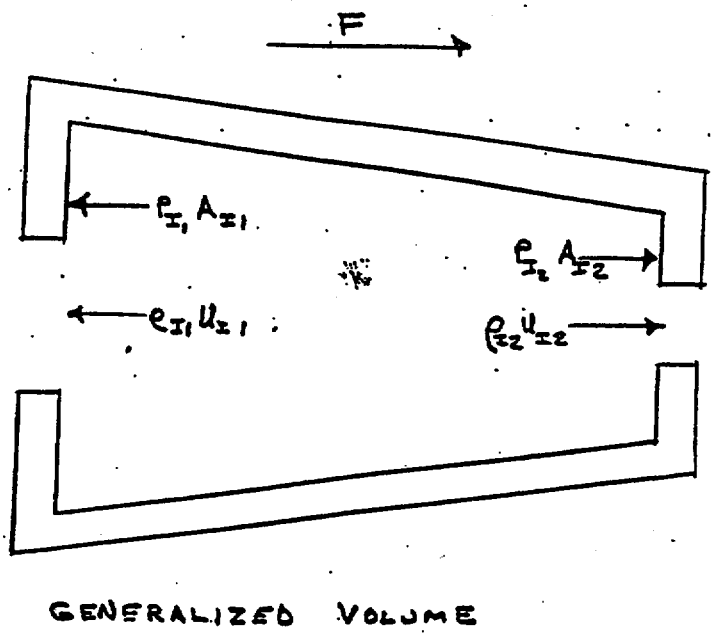


Figure 41 Filter Frequencies Applied in RELAP5 Mod 3.1.1 Loads Calculation

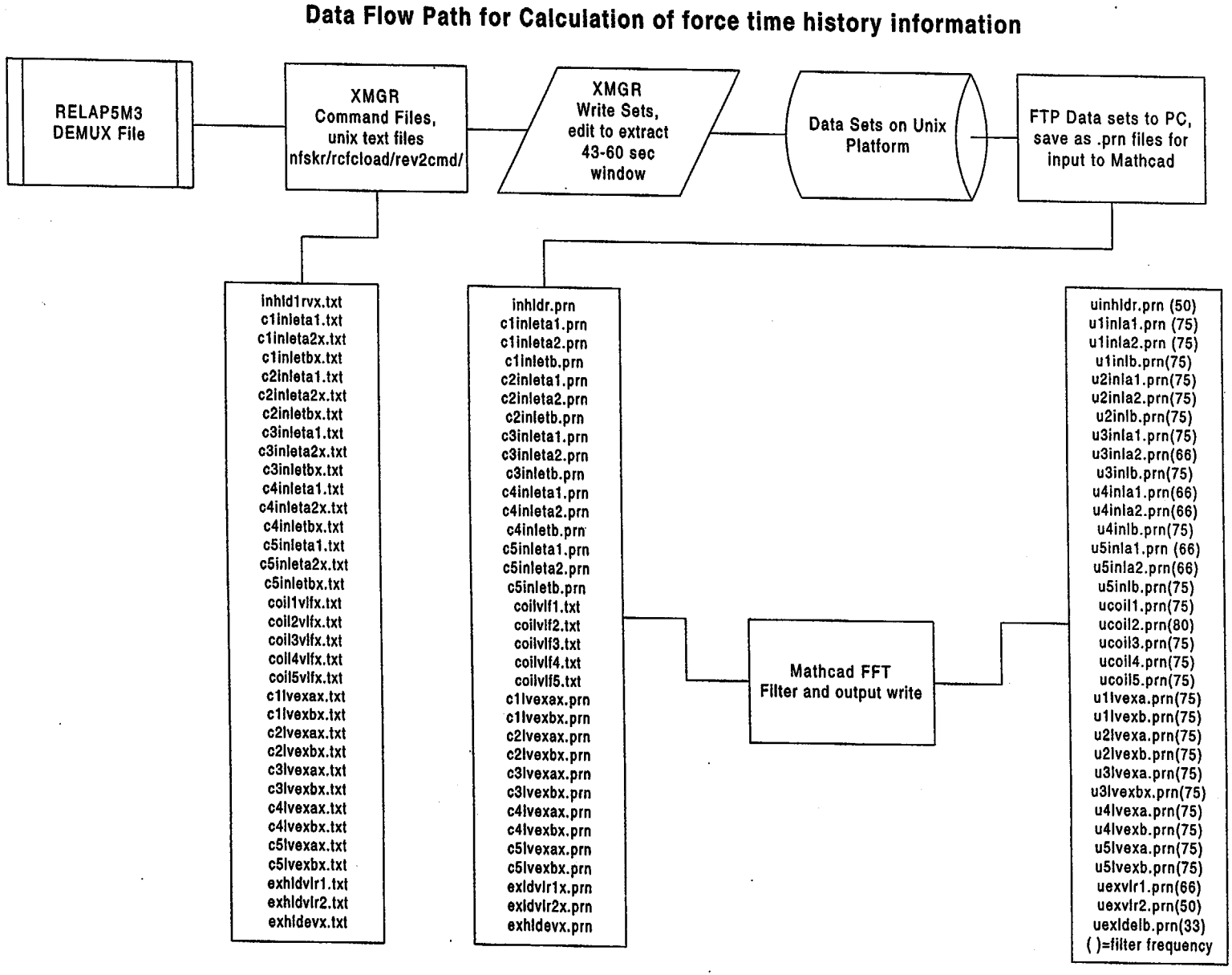


Figure 42 Two Phase Assessment, Boundary Pressure Applied

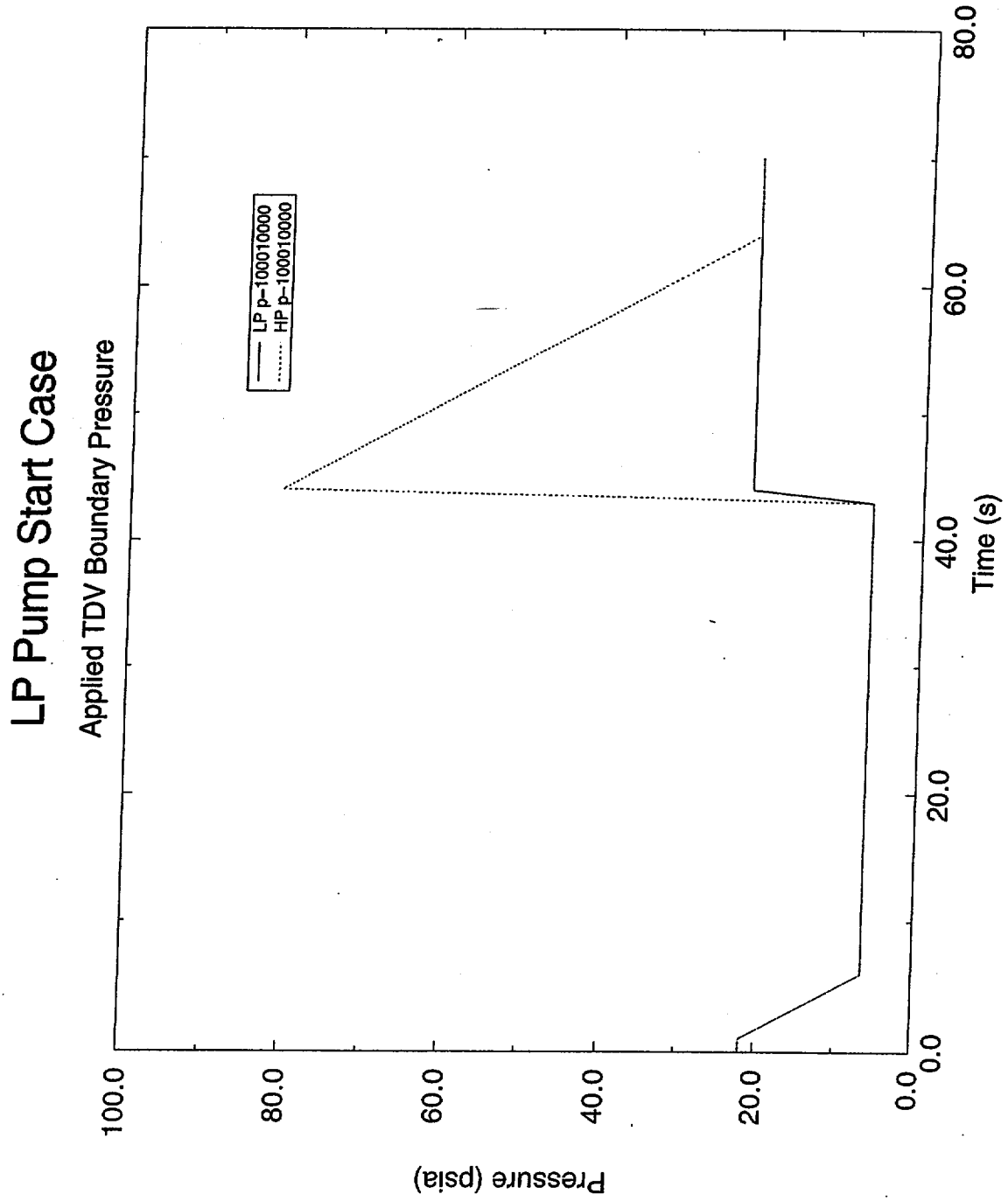


Figure 43 Two Phase Flow Assessment, Flow at TDV

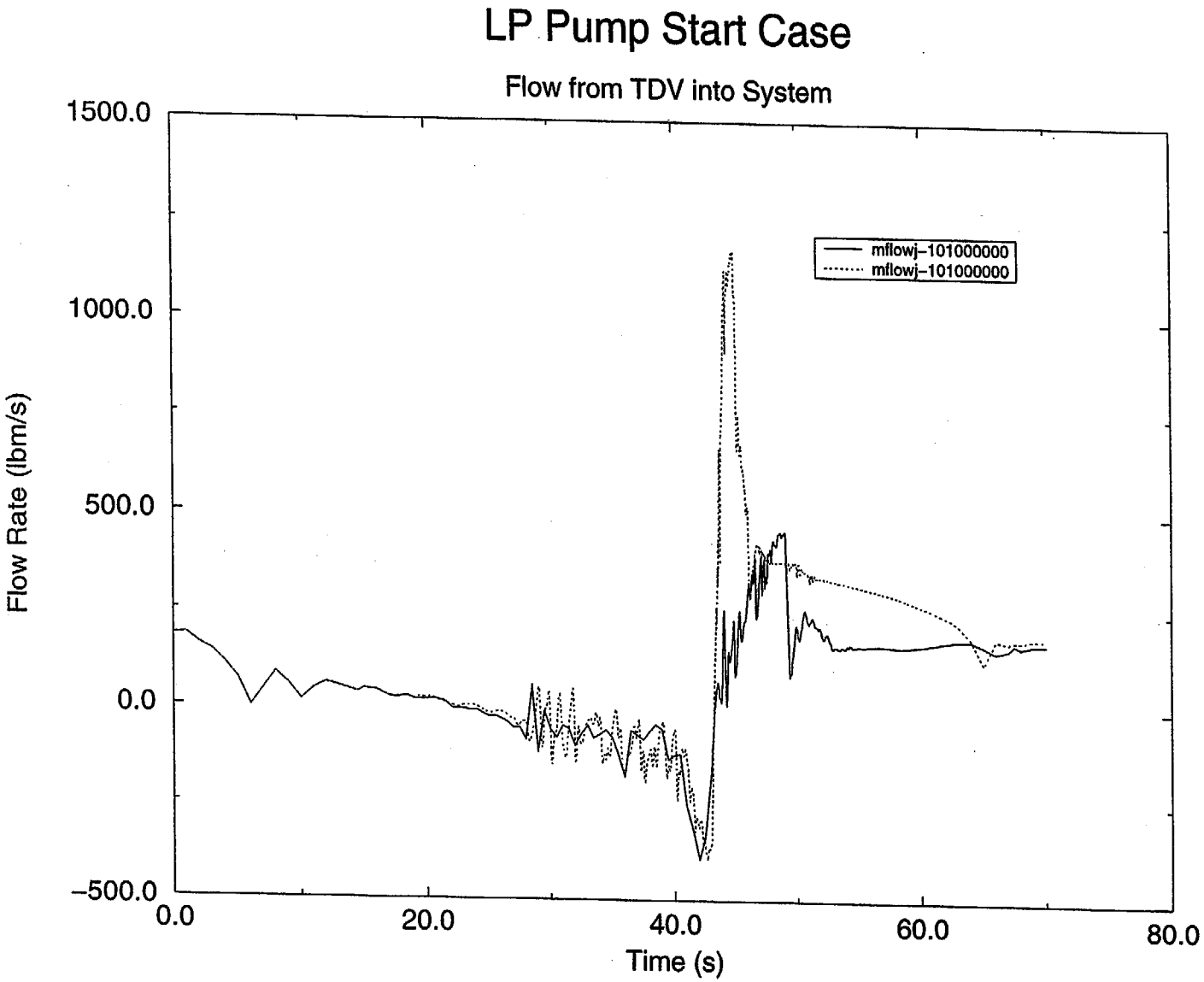


Figure 44 Two Phase Flow Assessment, Void Fraction in Upper Coil

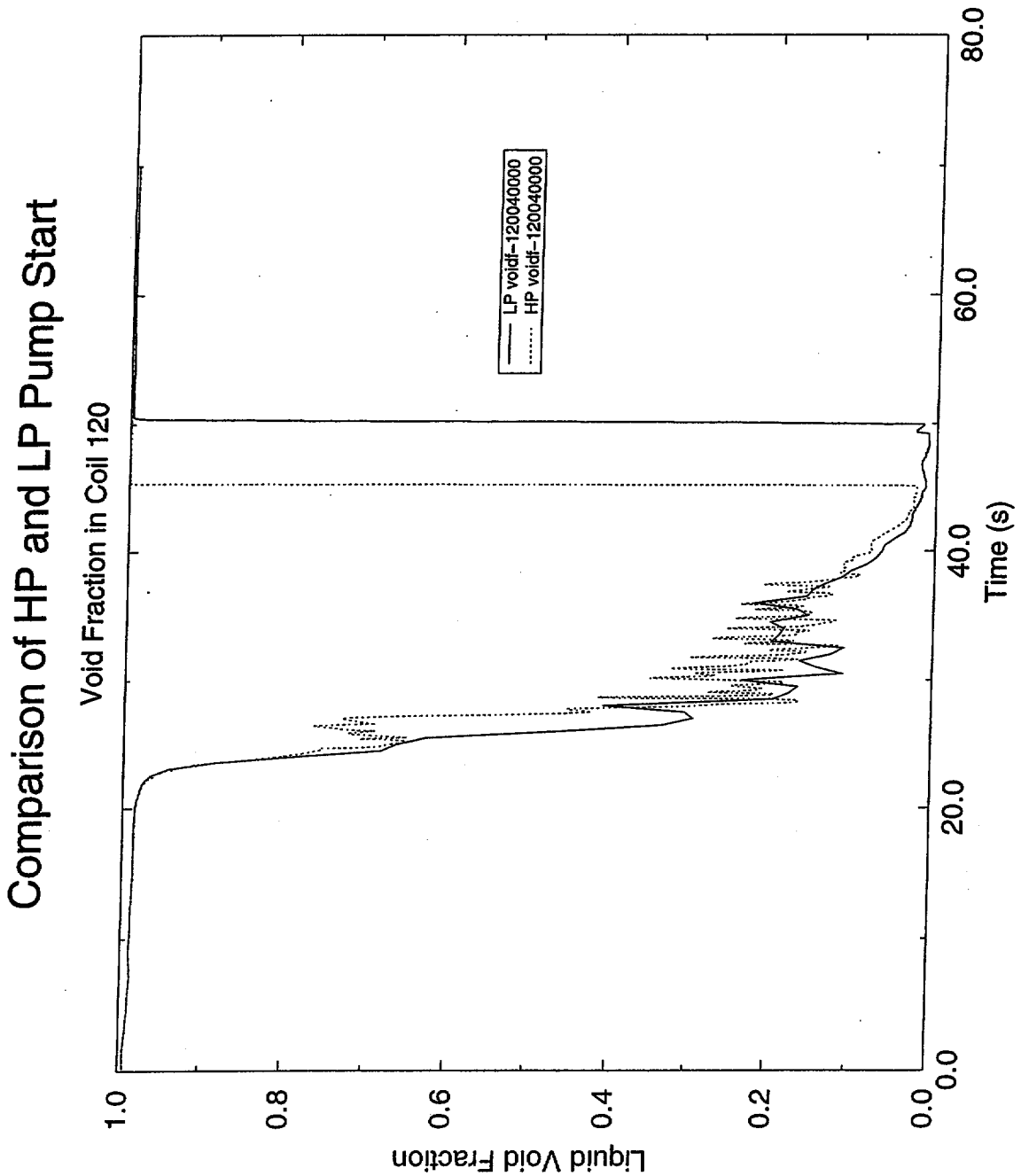


Figure 45 Two Phase Flow Assessment, LP case Upper Coil Void Fractions

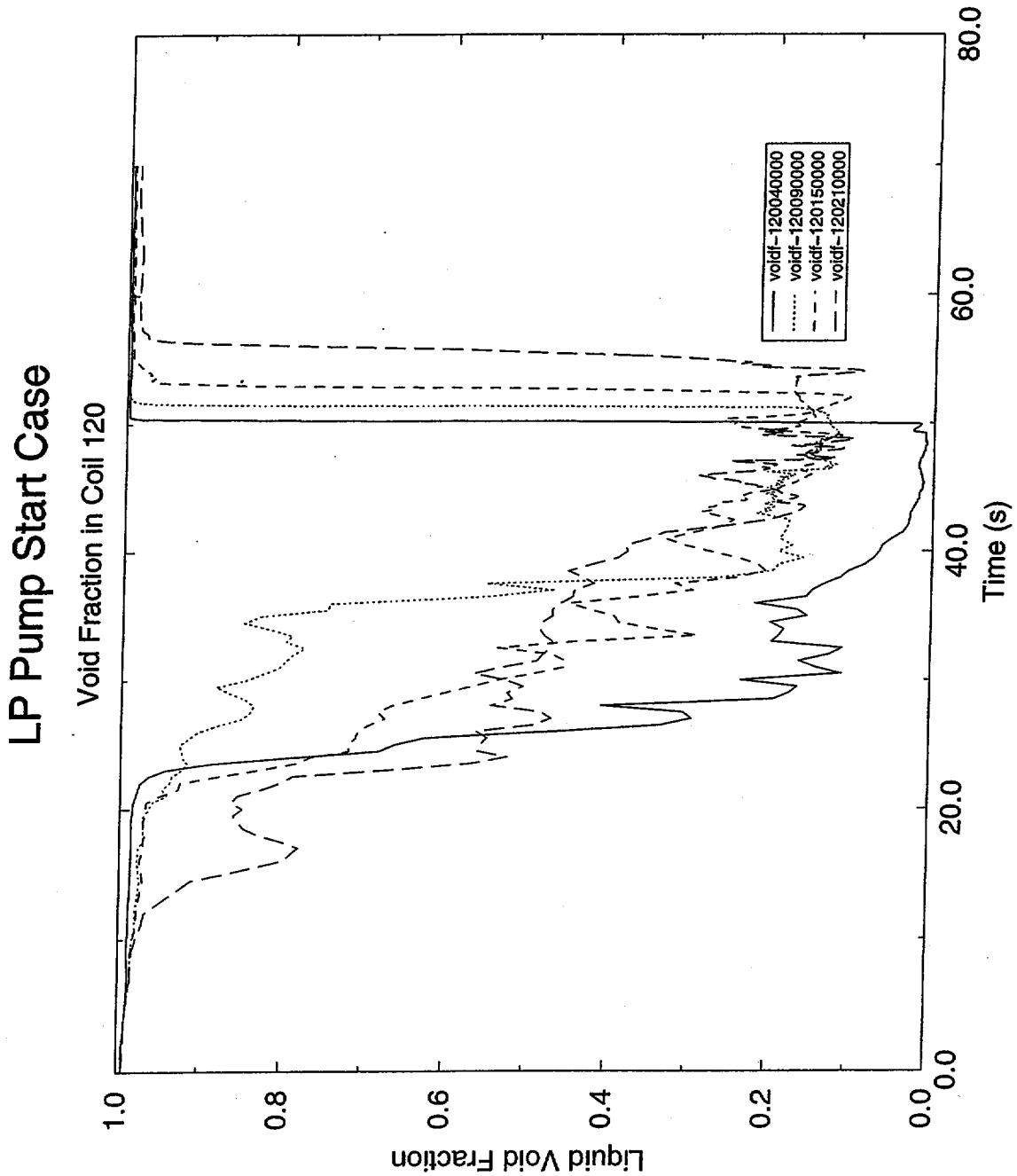
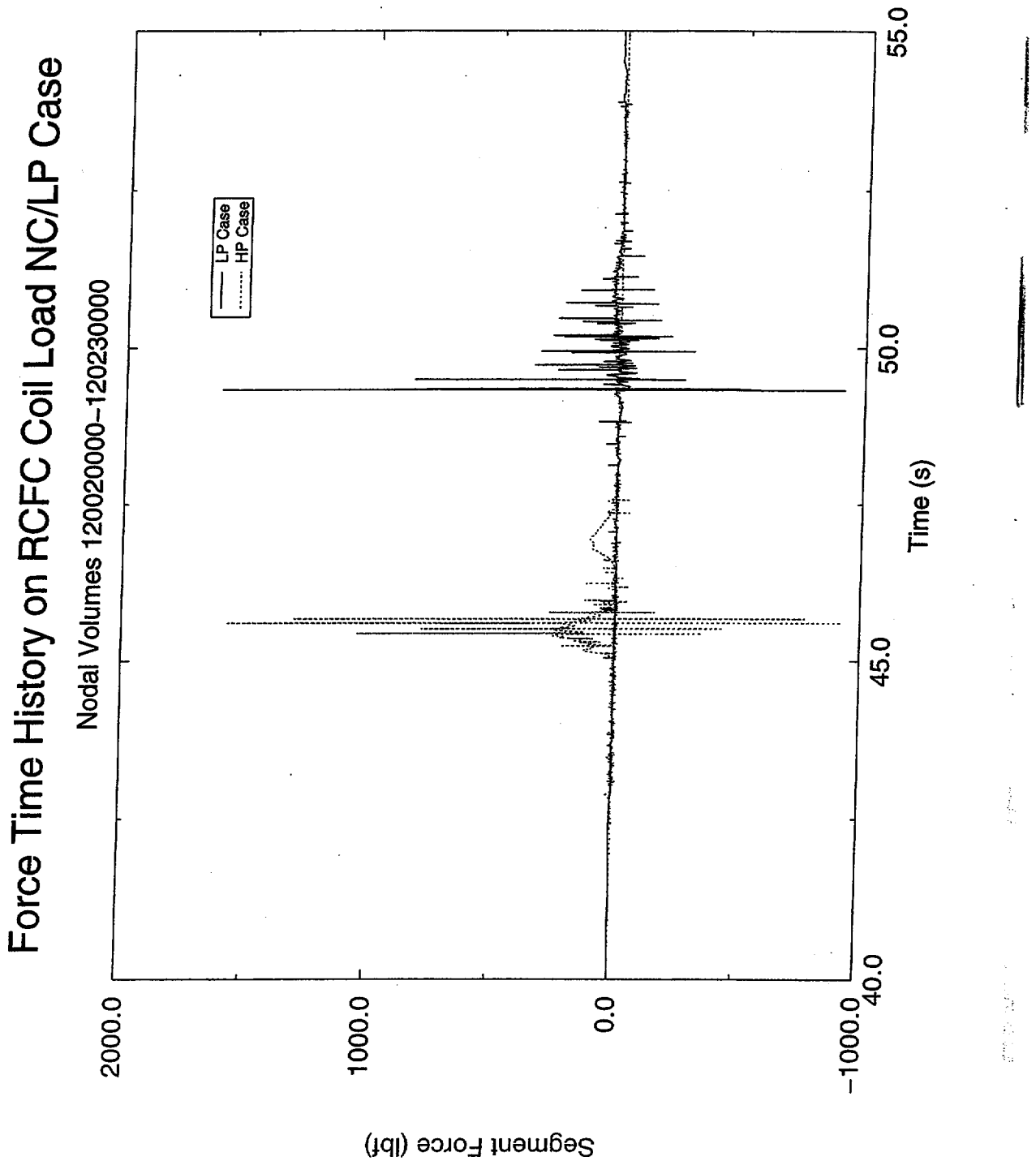


Figure 46 Two Phase Flow Assessment, Forces on Upper Coil



Appendix B – Mathcad Worksheets

This Appendix contains the following worksheets:

1) Analytical Solution to FAI V-024 Test
2) Analytical Solution to FAI 394 Test
3) Analytical Solution to Altran 2B Test
4) FFT Filtering of Altran 2B Test Force on F1 (241 Hz)
5) FFT Filtering of Altran 2B Test Force on F1 (399 Hz)

A Simplified Approach to Assessing Slug Waterhammer Pressures, Applied to FAI Waterhammer Test V024

Introduction

A simple physical model to describe the fluid behavior of the fluid slug being accelerated can be developed based on the Bernoulli integral equation, as described in Kazimi's "Nuclear Systems I" text. The differential pressure across the slug, geometry of the pipe and void are inputs to this solution. The acceleration of the fluid slug is calculated, allowing the calculation of the time to close the void. The velocity at void closure then allows prediction of the pressure using the Joukousky equation. This solution is appropriate for the case of a pressurized source of water being suddenly introduced to a steam void via a valve opening.

Geometrical Input

The pipe must be characterized with respect to numbers of fittings, area, length, and wall friction factors to allow an appropriate solution to be performed. The Crane manual is a good source for selection of the input for this type of problem.

Pipe areas

$A_i := 0.0233$ Flow Area at inlet(typically use pipe area)

$A_o := 0.0233$ Flow Area at outlet

$A_p := .0233$ Area of pipe

length of pipe from pressure source(ie vessel/pump/plenum), including voided section

$L_{total} := (5.9 + 10 + 6.5)$

length of voided section

$L_{void} := 6.5$

Diameter of pipe

$D := \frac{2.067}{12}$

inertia of system

$I := \frac{L_{total}}{A_p}$

losses, based on Crane

$f_t := .019$ input friction factor for appropriate pipe size, Crane, p. A26

$K_{wall} := f_t \cdot \frac{L_{total}}{D}$

$K_{wall} = 2.471$

$K_{fittings} := 4.022$ total losses as input into RELAP5

$K_p := K_{wall} + K_{fittings}$

$K_p = 6.493$

Pressure differentials

$p_u := 24.7$ source pressure psia

$p_d := 0.7$ sink/void pressure psia

$dp_1 := (p_u - p_d) \cdot 32.2 \cdot 144$ Differential Pressure

$\rho := 62.4$ Fluid Density

$g := 32.2$

$P_{grav} := \rho \cdot 32.2 \cdot (10 - 1.9 + 6.5)$ where these are the initial heights of water and include the distance that the column will rise

$dp := dp_1 - P_{grav}$ effective dp driving the slug

$dp = 8.195 \cdot 10^4$

General Solution

Kazimi derives a solution with a constant C^2 of the form indicated below:

$$C_0 := \frac{1}{2 \cdot \rho \cdot dp} \cdot \left[\left(\frac{1}{A_i^2} - \frac{1}{A_o^2} \right) + \frac{K_p}{A_p^2} \right]$$

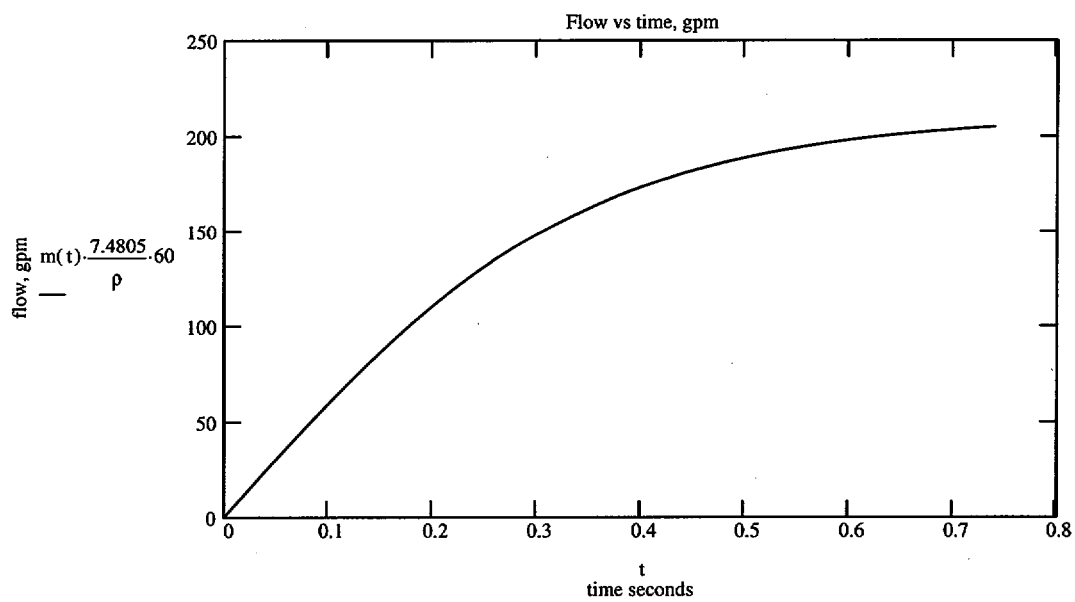
$$C := \sqrt{C_0}$$

$$t := 0, .02 .. 0.75$$

The time dependent solution is of the form

$$m(t) := \frac{1}{C} \cdot \left[\frac{e^{\left(\frac{2 \cdot C \cdot dp}{I} \cdot t \right)} - 1}{e^{\frac{2 \cdot C \cdot dp}{I} \cdot t} + 1} \right]$$

The results are shown graphically below



now calculate the instantaneous waterhammer pressure vs time for the velocity calculated above. The time of impact can be determined by integrating the velocity and observing the time at which the column has moved sufficiently to close the 6.5 foot gap available.

$V(t) := \frac{m(t)}{\rho \cdot A_p}$ velocity of slug fps

$x(t) := \int_0^t V(t)\,dt$ displacement of slug, ft

exact integral of velocity, with a boundary condition applied of zero initial displacement

$$x1(t) := \frac{\frac{1}{(c^2 \cdot dp)} \cdot I \cdot \ln\left(\exp\left(2 \cdot c \cdot \frac{dp}{I} \cdot t\right) + 1\right) - \frac{1}{[2 \cdot (c^2 \cdot dp)]} \cdot I \cdot \ln\left(\exp\left(2 \cdot c \cdot \frac{dp}{I} \cdot t\right)\right) - \frac{1}{(c^2 \cdot dp)} \cdot I \cdot \ln(\exp(0) + 1)}{\rho \cdot A_p}$$

now use root finder to determine time of gap closure

$tc := 1$ initial guess for closure time

$$a := \mathrm{root}\left[\frac{\frac{1}{(c^2 \cdot dp)} \cdot I \cdot \ln\left(\exp\left(2 \cdot c \cdot \frac{dp}{I} \cdot tc\right) + 1\right) - \frac{1}{[2 \cdot (c^2 \cdot dp)]} \cdot I \cdot \ln\left(\exp\left(2 \cdot c \cdot \frac{dp}{I} \cdot tc\right)\right) - \frac{1}{(c^2 \cdot dp)} \cdot I \cdot \ln(\exp(0) + 1)}{\rho \cdot A_p} - L_{void}, tc\right]$$

$a = 0.547$ closure time, seconds

$V(a) = 18.522$ closure velocity, fps

$flowm := V(a) \cdot A_p \cdot 60 \cdot 7.4805$

$flowm = 193.695$ gpm

now, can use Joukowsy eqn to determine the peak pressure in psia

$c := 4600$ sound velocity fps

$P(a) := \frac{\rho}{g} \cdot c \cdot V(a) \cdot \frac{1}{144}$ Joukowsky eqn, in units of pressure, psi

$P(a) = 1.147 \cdot 10^3$ psia

A Simplified Approach to Assessing Slug Waterhammer Pressures, Applied to FAI Waterhammer Test 394

Introduction

A simple physical model to describe the fluid behavior of the fluid slug being accelerated can be developed based on the Bernoulli integral equation, as described in Kazimi's "Nuclear Systems I" text. The differential pressure across the slug, geometry of the pipe and void are inputs to this solution. The acceleration of the fluid slug is calculated, allowing the calculation of the time to close the void. The velocity at void closure then allows prediction of the pressure using the Joukousky equation. This solution is appropriate for the case of a pressurized source of water being suddenly introduced to a steam void via a valve opening.

Geometrical Input

The pipe must be characterized with respect to numbers of fittings, area, length, and wall friction factors to allow an appropriate solution to be performed. The Crane manual is a good source for selection of the input for this type of problem.

Pipe areas

$A_i := 0.0233$ Flow Area at inlet(typically use pipe area)

$A_o := 0.0233$ Flow Area at outlet

$A_p := .0233$ Area of pipe

length of pipe from pressure source(ie vessel/pump/plenum), including voided section

$L_{total} := (5.9 + 10 + 6.5)$

length of voided section

$L_{void} := 6.5$

Diameter of pipe

$D := \frac{2.067}{12}$

inertia of system

$I := \frac{L_{total}}{A_p}$

losses, based on Crane

$f_t := .019$ input friction factor for appropriate pipe size, Crane, p. A26

$K_{wall} := f_t \cdot \frac{L_{total}}{D}$

$K_{wall} = 2.471$

$K_{fittings} := 4.022$ total losses as input into RELAP5

$K_p := K_{wall} + K_{fittings}$

$K_p = 6.493$

Pressure differentials

$p_u := 44.7$ source pressure psia

$p_d := 2.9$ sink/void pressure psia (based on Psat for 140F water column)

$dp_1 := (p_u - p_d) \cdot 32.2 \cdot 144$ Differential Pressure

$\rho := 62.4$ Fluid Density

$g := 32.2$

$P_{grav} := \rho \cdot 32.2 \cdot (10 - 1.9 + 6.5)$ where these are the initial heights of water and include the distance that the column will rise

$dp := dp_1 - P_{grav}$ effective dp driving the slug

$dp = 1.645 \cdot 10^5$

General Solution

Kazimi derives a solution with a constant C^2 of the form indicated below:

$$C_0 := \frac{1}{2 \cdot \rho \cdot dp} \cdot \left[\left(\frac{1}{A_i^2} - \frac{1}{A_o^2} \right) + \frac{K_p}{A_p^2} \right]$$

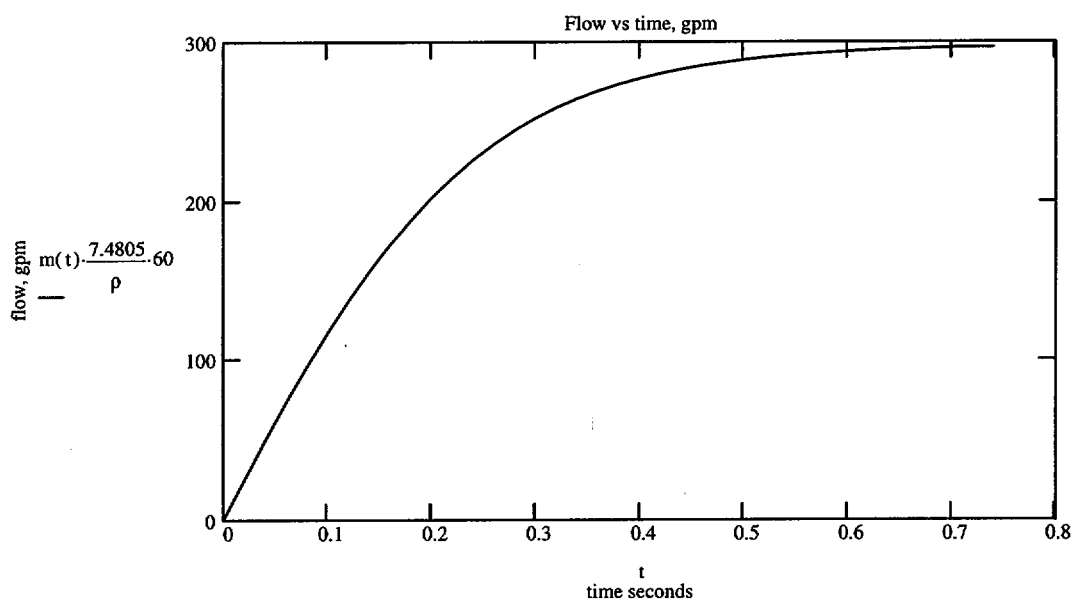
$$C := \sqrt{C_0}$$

$$t := 0, .02 .. 0.75$$

The time dependent solution is of the form

$$m(t) := \frac{1}{C} \cdot \left[\frac{e^{\left(\frac{2 \cdot C \cdot dp}{I} \cdot t \right)} - 1}{e^{\frac{2 \cdot C \cdot dp}{I} \cdot t} + 1} \right]$$

The results are shown graphically below



now calculate the instantaneous waterhammer pressure vs time for the velocity calculated above. The time of impact can be determined by integrating the velocity and observing the time at which the column has moved sufficiently to close the 6.5 foot gap available.

$V(t) := \frac{m(t)}{\rho \cdot A_p}$ velocity of slug fps

$x(t) := \int_0^t V(t)\,dt$ displacement of slug, ft

exact integral of velocity, with a boundary condition applied of zero initial displacement

$$x1(t) := \frac{\frac{1}{(c^2 \cdot dp)} \cdot I \cdot \ln\left(\exp\left(2 \cdot C \cdot \frac{dp}{I} \cdot t\right) + 1\right) - \frac{1}{\left[2 \cdot (c^2 \cdot dp)\right]} \cdot I \cdot \ln\left(\exp\left(2 \cdot C \cdot \frac{dp}{I} \cdot t\right)\right) - \frac{1}{(c^2 \cdot dp)} \cdot I \cdot \ln(\exp(0) + 1)}{\rho \cdot A_p}$$

now use root finder to determine time of gap closure

$tc := 1$ initial guess for closure time

$$a := \mathrm{root}\left[\frac{\frac{1}{(c^2 \cdot dp)} \cdot I \cdot \ln\left(\exp\left(2 \cdot C \cdot \frac{dp}{I} \cdot tc\right) + 1\right) - \frac{1}{\left[2 \cdot (c^2 \cdot dp)\right]} \cdot I \cdot \ln\left(\exp\left(2 \cdot C \cdot \frac{dp}{I} \cdot tc\right)\right) - \frac{1}{(c^2 \cdot dp)} \cdot I \cdot \ln(\exp(0) + 1)}{\rho \cdot A_p} - L_{void}, tc\right]$$

$a = 0.386$ closure time, seconds

$V(a) = 26.241$ closure velocity, fps

$flowm := V(a) \cdot A_p \cdot 60 \cdot 7.4805$

$flowm = 274.416$ gpm

now, can use Joukowsy eqn to determine the peak pressure in psia

$c := 4600$ sound velocity fps

$P(a) := \frac{\rho}{g} \cdot c \cdot V(a) \cdot \frac{1}{144}$ Joukowsky eqn, in units of pressure, psi

$P(a) = 1.624 \cdot 10^3$ psia

A Simplified Approach to Assessing Slug Waterhammer Pressures, Applied to ALTRAN Waterhammer Test Configuration 2B

Introduction

A simple physical model to describe the fluid behavior of the fluid slug being accelerated can be developed based on the Bernoulli integral equation, as described in Kazimi's "Nuclear Systems I" text. The differential pressure across the slug, geometry of the pipe and void are inputs to this solution. The acceleration of the fluid slug is calculated, allowing the calculation of the time to close the void. The velocity at void closure then allows prediction of the pressure using the Joukousky equation. This solution is appropriate for the case of a pressurized source of water being suddenly introduced to a steam void via a valve opening.

Geometrical Input

The pipe must be characterized with respect to numbers of fittings, area, length, and wall friction factors to allow an appropriate solution to be performed. The Crane manual is a good source for selection of the input for this type of problem.

Pipe areas

$A_i := 0.0205$ Flow Area at inlet(typically use pipe area)

$A_o := 0.0205$ Flow Area at outlet

$A_p := .0205$ Area of pipe

length of pipe from pressure source(ie vessel/pump/plenum), including voided section

$L_{total} := (3+14+3+.5+6+3+6)$

length of voided section

$L_{void} := 6.0$

Diameter of pipe

$D := \frac{2.0}{12}$

inertia of system

$I := \frac{L_{total}}{A_p}$

losses, based on Crane

$f_t := .019$ input friction factor for appropriate pipe size, Crane, p. A26

$K_{wall} := f_t \cdot \frac{L_{total}}{D}$

$K_{wall} = 4.047$

$K_{fittings} := 1.767$ total losses as input into RELAP5

$K_p := K_{wall} + K_{fittings}$

$K_p = 5.814$

Pressure differentials

$p_u := 84.7$ source pressure psia

$p_d := 14.$ sink/void pressure psia (based on initial pressure of steam)

$dp_1 := (p_u - p_d) \cdot 32.2 \cdot 144$ Differential Pressure

$\rho := 62.4$ Fluid Density

$g := 32.2$

$P_{grav} := \rho \cdot 32.2 \cdot (-3 + -14 + -3 + -.5 + 3)$ where these are the initial heights of water and include the distance that the column will rise

$dp := dp_1 - P_{grav}$ effective dp driving the slug

$dp = 3.63 \cdot 10^5$

General Solution

Kazimi derives a solution with a constant C^2 of the form indicated below:

$$C_0 := \frac{1}{2\cdot\rho\cdot dp}\cdot\left[\left(\frac{1}{A_i^{\,2}} - \frac{1}{A_o^{\,2}}\right) + \frac{K_p}{A_p^{\,2}}\right]$$

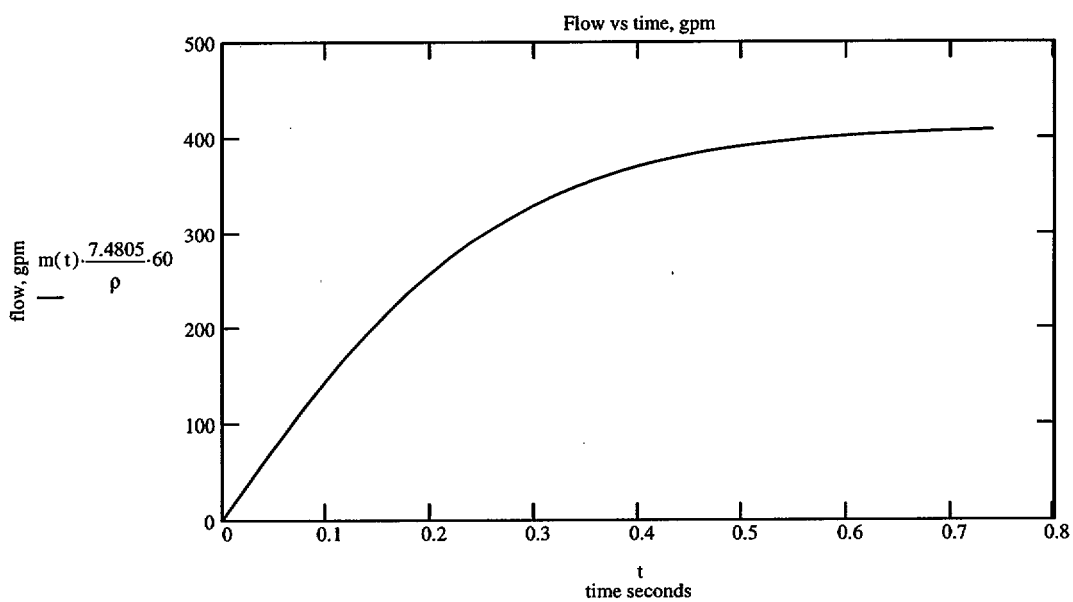
$$C := \sqrt{C_0}$$

$t := 0, .02 .. 0.75$

The time dependent solution is of the form

$$m(t) := \frac{1}{C}\cdot\left[\frac{e^{\left(\frac{2\cdot C\cdot dp}{I}\cdot t\right)} - 1}{e^{\frac{2\cdot C\cdot dp}{I}\cdot t} + 1}\right]$$

The results are shown graphically below



now calculate the instantaneous waterhammer pressure vs time for the velocity calculated above. The time of impact can be determined by integrating the velocity and observing the time at which the column has moved sufficiently to close the 6.5 foot gap available.

$V(t) := \frac{m(t)}{\rho \cdot A_p}$ velocity of slug fps

$x(t) := \int_0^t V(t)\,dt$ displacement of slug, ft

exact integral of velocity, with a boundary condition applied of zero initial displacement

$$x1(t) := \frac{\frac{1}{(c^2 \cdot dp)} \cdot I \cdot \ln\left(\exp\left(2 \cdot c \cdot \frac{dp}{I} \cdot t\right) + 1\right) - \frac{1}{\left[2 \cdot (c^2 \cdot dp)\right]} \cdot I \cdot \ln\left(\exp\left(2 \cdot c \cdot \frac{dp}{I} \cdot t\right)\right) - \frac{1}{(c^2 \cdot dp)} \cdot I \cdot \ln(\exp(0) + 1)}{\rho \cdot A_p}$$

now use root finder to determine time of gap closure

$tc := 1$ initial guess for closure time

$$a := \mathrm{root}\left[\frac{\frac{1}{(c^2 \cdot dp)} \cdot I \cdot \ln\left(\exp\left(2 \cdot c \cdot \frac{dp}{I} \cdot tc\right) + 1\right) - \frac{1}{\left[2 \cdot (c^2 \cdot dp)\right]} \cdot I \cdot \ln\left(\exp\left(2 \cdot c \cdot \frac{dp}{I} \cdot tc\right)\right) - \frac{1}{(c^2 \cdot dp)} \cdot I \cdot \ln(\exp(0) + 1)}{\rho \cdot A_p} - L_{void}, tc\right]$$

$a = 0.293$ closure time, seconds

$V(a) = 35.384$ closure velocity, fps

$flowm := V(a) \cdot A_p \cdot 60 \cdot 7.4805$

$flowm = 325.568$ gpm

now, can use Joukowsy eqn to determine the peak pressure in psia

$c := 4600$ sound velocity fps

$P(a) := \frac{\rho}{2 \cdot g} \cdot c \cdot V(a) \cdot \frac{1}{144}$ Joukowsky eqn, in units of pressure, psi, water water impact

$P(a) = 1.095 \cdot 10^3$ psia

FFT Filtering of ALTRAN Force Time History Data - Horizontal support

This calculation takes the post pump startup segment force time history and performs a transformation using a complex fast fourier transform algorithms. The data period of interest is from 43 seconds in a post-LOCA transient, when the SX pumps are assumed to start, and continues until 60 seconds when the two phase load conditions are over in the system. The data is generated via a RELAP5 model, with post-processing being applied to determine the force time history. The methodology applied in the post-processor has the drawback of being inherently numerically noisy, since it relies on the determination of the derivative of momentum, which due to waterpacking phenomena calculated in the RELAP model, results in very short duration, high magnitude spikes. The elimination of these spikes is the purpose of this calculation. A filter is applied to fourier coefficients to eliminate frequency response above a selected point. The inverse transformation then restores the data to the time domain for input into structural analysis models.

Get Data from Edited Relap file 43-60 seconds

$M := \mathrm{READPRN}(\mathrm{alt2b70erf1})$

$t := M^{<0>}$ 1st column is time variable

$f := M^{<1>}$ 2nd column is force

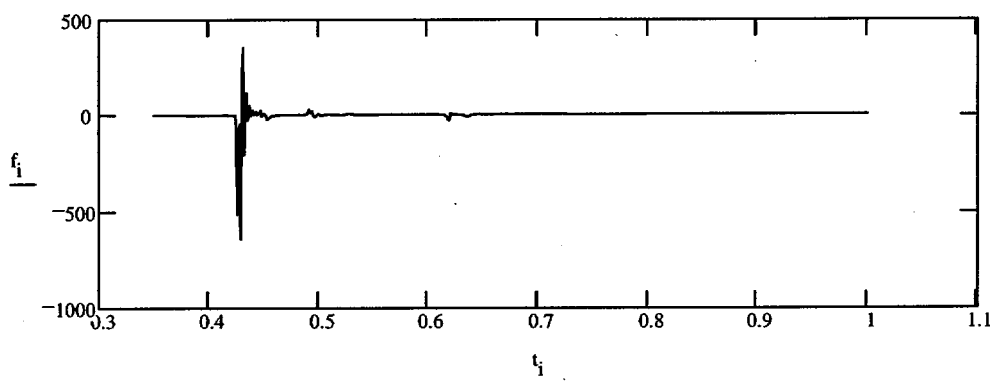
$N := \mathrm{length}(f)$ $N = 651$ number of data points

$i := 0..N-1$

$DT := t_2 - t_1$ $DT = 1 \cdot 10^{-3}$ time step

$\mathrm{freq}(i) := \frac{i}{N \cdot DT}$ frequency

plot of original data



Perform the Transform of f

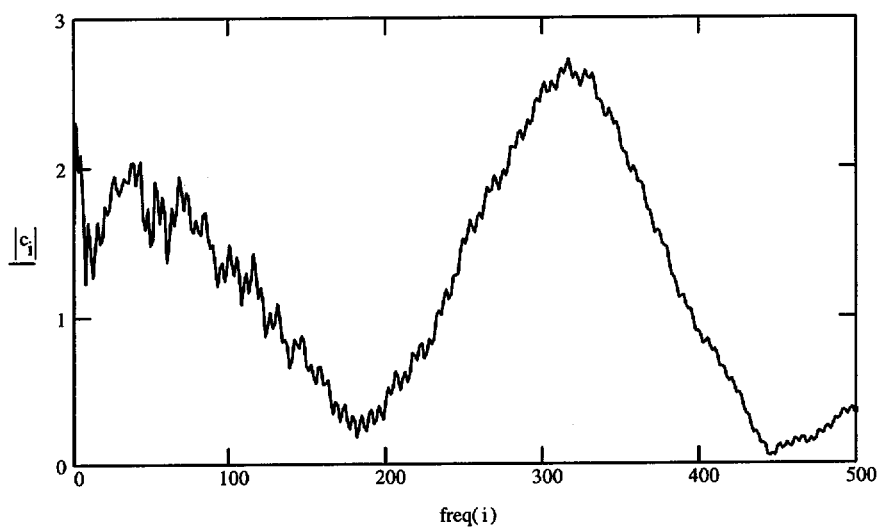
$c := CFFT(f)$

$fNyquist := \frac{1}{2} \cdot \frac{1}{DT}$

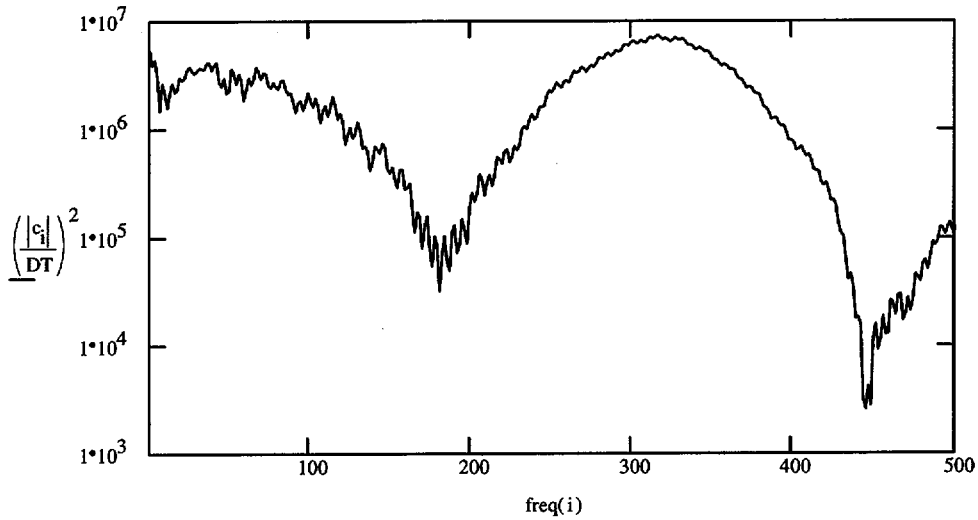
$fNyquist = 500$

This is the practical upper limit of the frequency predictions in this transform, based on the sample rate

plot of the magnitude of the fourier coefficients as a function of frequency



Plot the power spectral density



Now need to apply filter to coefficients

$ftp := 157$

$freq(ftp) = 241.167$ shows filter frequency in hertz

The following filter creates a window, setting the coefficients of all frequencies above the selected frequency to zero:

$Wf(i) := if(i \le ftp, 1, if(i \ge N - ftp, 1, 0))$

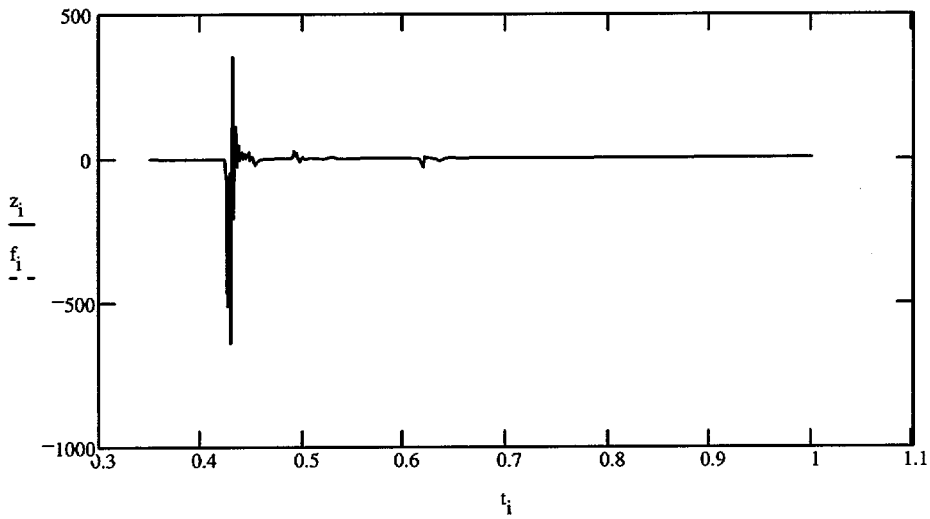
Operate on coefficients using filter

$cf_i := Wf(i) \cdot c_i$

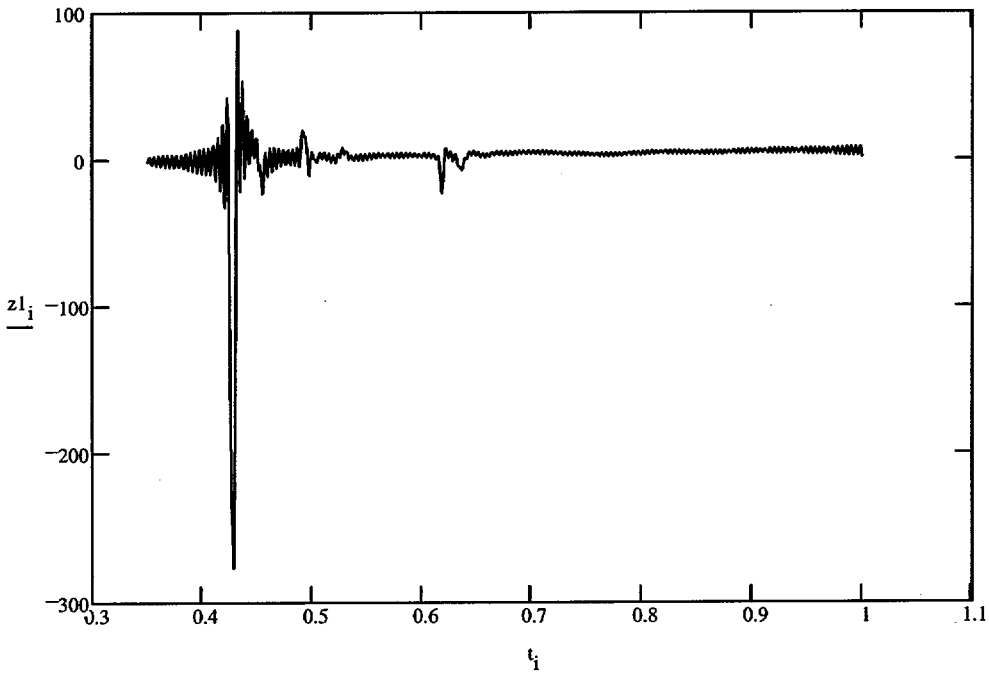
Next step is to perform inversion, invert both original plus filtered version for comparison

$z := ICFFT(c)$ $z1 := ICFFT(cf)$

plot original data and unfiltered transform to demonstrate fidelity of transformations



Plot of the transformed filtered data vs time



write an output file

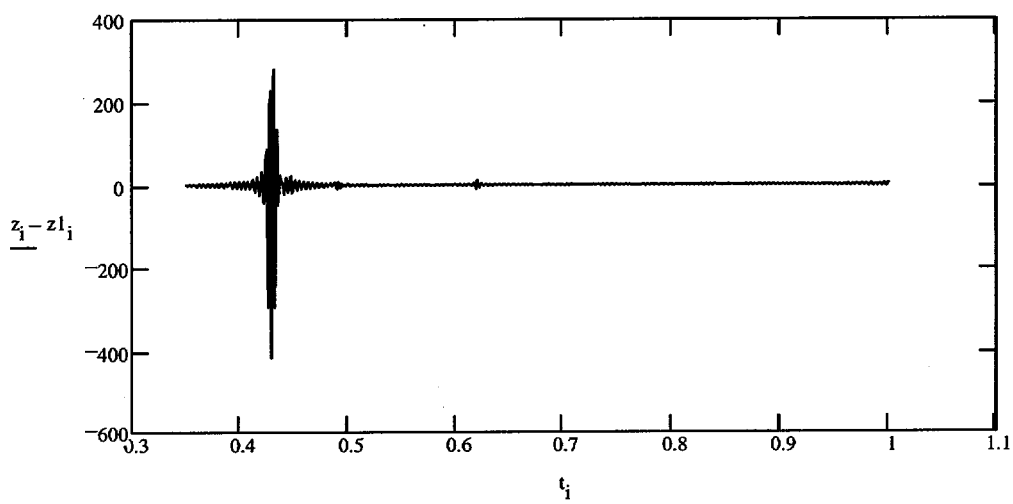
$Fout_{i,0} := t_i$

$Fout_{i,1} := Re(z1_i) \cdot 1.02$

note that Real component is selected to eliminate the residual imaginary components, typically of magnitudes 1E-15 or smaller
Also 2% factor to adjust for effects of filtering

WRITEPRN(falt2b70f1) := Fout

plot difference of filtered and unfiltered to compare effect of filtering



Validation of Loads

The forcing functions, unfiltered and filtered are fit to functions using a linear interpolation routine. These functions are then integrated with respect to time to yield a total impulse loading on the structure. The percentage of filtered versus unfiltered load is then determined. A criteria of 2% is utilized in this analysis and the filtered loads are multiplied by this factor to ensure that total impulse to the structure is conserved.

Notes: 1) The integrals are divided into .1 second intervals to obtain better numerical performance, since the forcing functions are oscillatory at high frequency.

2) The integration interval is shortened on the vertical pipe segments to include only the dynamic portion of the event. This prevents the deadweight load present after reflood from dominating the evaluation of dynamic filtering being performed.

$Q(x) := \mathrm{linterp}(t, z, x)$

$Q1(x) := \mathrm{linterp}(t, z1, x)$

$$UF := \left| \begin{array}{l} s \leftarrow 0 \\ \text{for } n \in 0..29 \\ \quad s \leftarrow s + \displaystyle\int_{.35+\frac{n}{200}}^{.35+\frac{n+1}{200}} |Q(x)|\, dx \end{array} \right.$$

$$FF := \left| \begin{array}{l} s \leftarrow 0 \\ \text{for } n \in 0..29 \\ \quad s \leftarrow s + \displaystyle\int_{.35+\frac{n}{200}}^{.35+\frac{n+1}{200}} |Q1(x)|\, dx \end{array} \right.$$

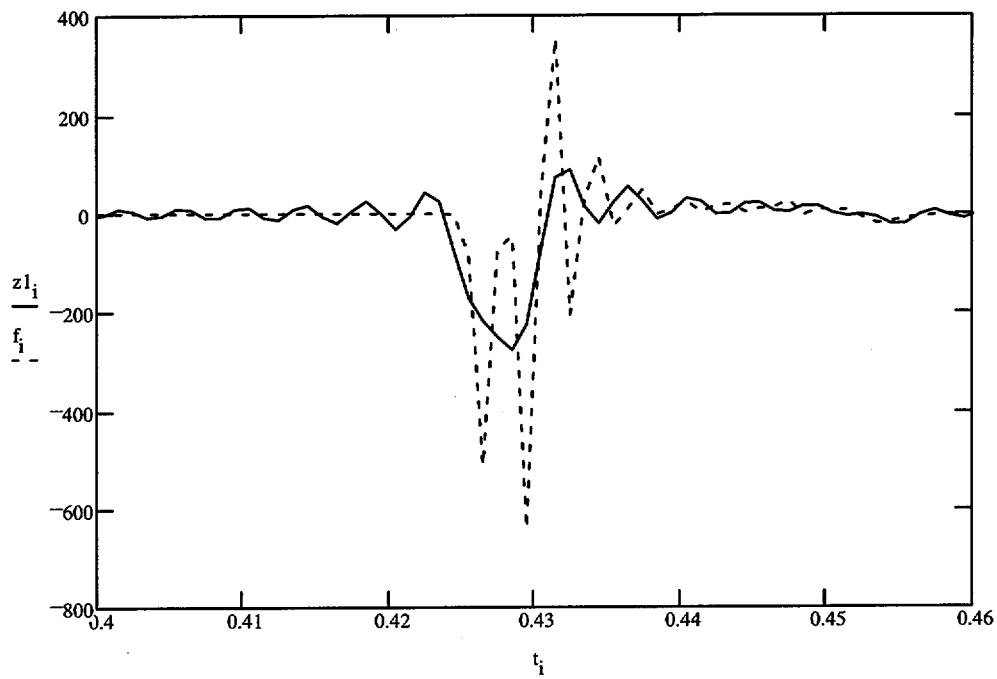
$FF = 2.325$

$UF = 2.373$

$\frac{UF - FF}{UF} = 0.02$ this number should be less than .02

$freq(ftp) = 241.167$ filter frequency

Plot of the transformed filtered data and unfiltered data vs time



$$\int_{0.42}^{0.43} |Q1(x)|\, dx = 1.275$$

$$\int_{0.43}^{0.44} |Q1(x)|\, dx = 0.337$$

$$\int_{0.42}^{0.43} |Q(x)|\, dx = 1.278$$

$$\int_{0.43}^{0.44} |Q(x)|\, dx = 0.696$$

FFT Filtering of ALTRAN Force Time History Data - Horizontal support

This calculation takes the post pump startup segment force time history and performs a transformation using a complex fast fourier transform algorithms. The data period of interest is from 43 seconds in a post-LOCA transient, when the SX pumps are assumed to start, and continues until 60 seconds when the two phase load conditions are over in the system. The data is generated via a RELAP5 model, with post-processing being applied to determine the force time history. The methodology applied in the post-processor has the drawback of being inherently numerically noisy, since it relies on the determination of the derivative of momentum, which due to waterpacking phenomena calculated in the RELAP model, results in very short duration, high magnitude spikes. The elimination of these spikes is the purpose of this calculation. A filter is applied to fourier coefficients to eliminate frequency response above a selected point. The inverse transformation then restores the data to the time domain for input into structural analysis models.

Get Data from Edited Relap file 43-60 seconds

$M := \mathrm{READPRN}(\mathrm{alt2b70erf1})$

$t := M^{<0>}$ 1st column is time variable

$f := M^{<1>}$ 2nd column is force

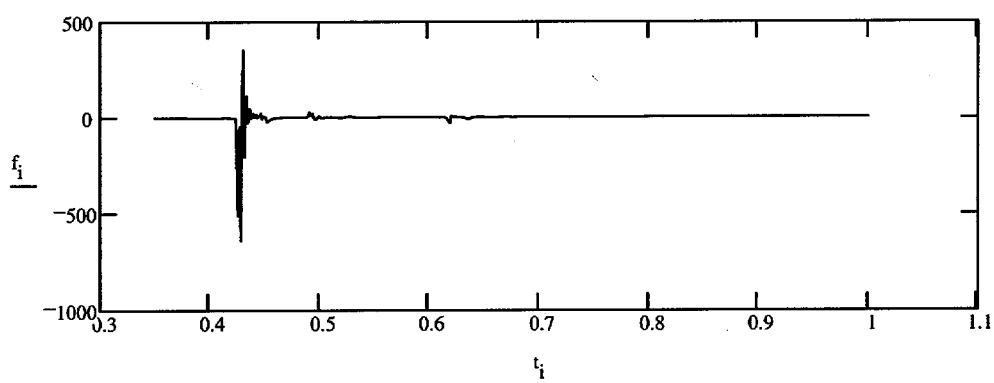
$N := \mathrm{length}(f)$ $N = 651$ number of data points

$i := 0..N-1$

$DT := t_2 - t_1$ $DT = 1 \cdot 10^{-3}$ time step

$\mathrm{freq}(i) := \frac{i}{N \cdot DT}$ frequency

plot of original data



Perform the Transform of f

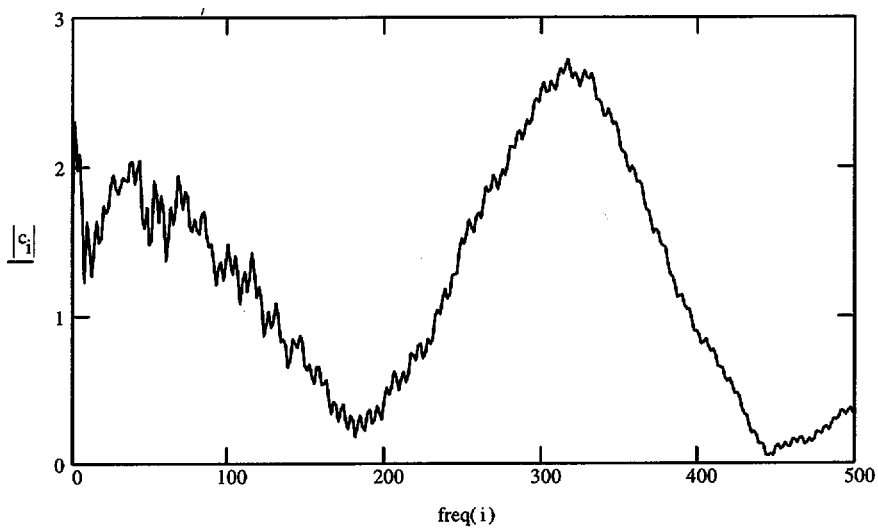
$c := CFFT(f)$

$fNyquist := \frac{1}{2} \cdot \frac{1}{DT}$

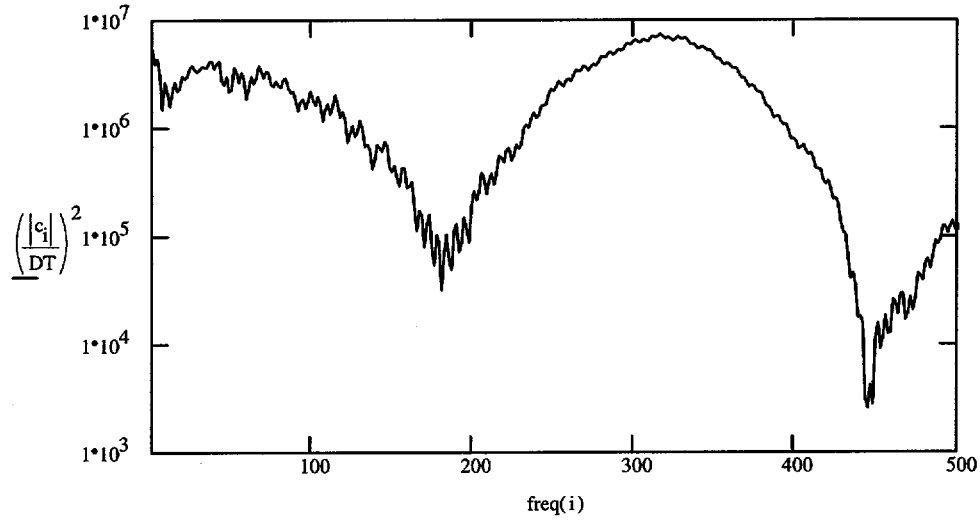
$fNyquist = 500$

This is the practical upper limit of the frequency predictions in this transform, based on the sample rate

plot of the magnitude of the fourier coefficients as a function of frequency



Plot the power spectral density



Now need to apply filter to coefficients

$ftp := 260$

$freq(ftp) = 399.386$ shows filter frequency in hertz

The following filter creates a window, setting the coefficients of all frequencies above the selected frequency to zero:

$Wf(i) := if(i \le ftp, 1, if(i \ge N - ftp, 1, 0))$

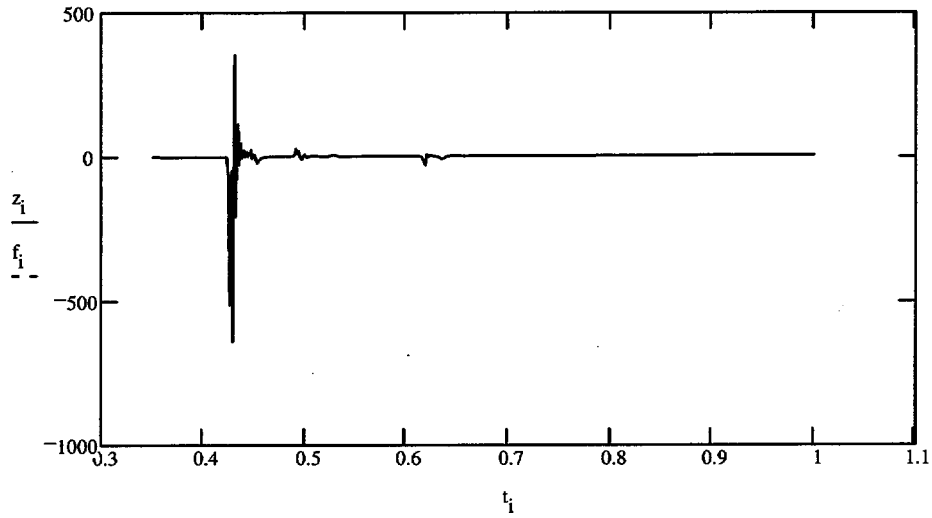
Operate on coefficients using filter

$cf_i := Wf(i) \cdot c_i$

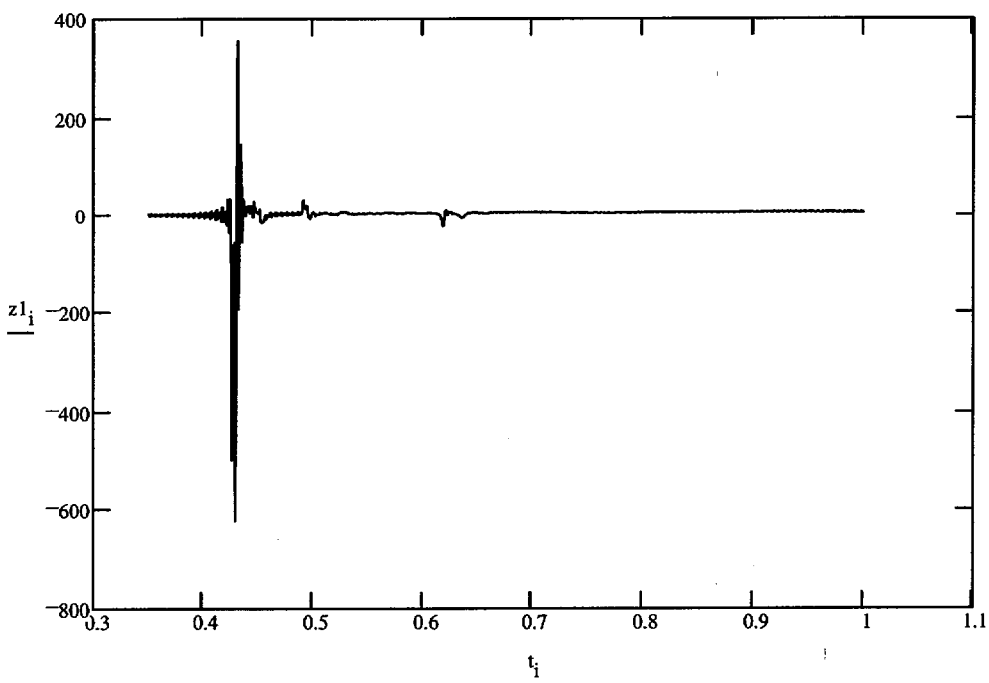
Next step is to perform inversion, invert both original plus filtered version for comparison

$z := ICFFT(c)$ $z1 := ICFFT(cf)$

plot original data and unfiltered transform to demonstrate fidelity of transformations



Plot of the transformed filtered data vs time



write an output file

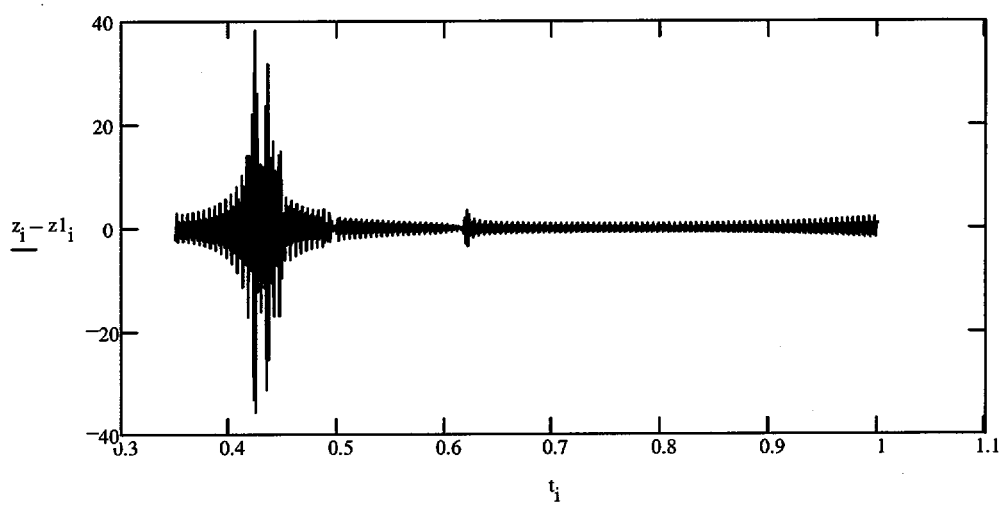
$Fout_{i,0} := t_i$

$Fout_{i,1} := Re(z1_i) \cdot 1.02$

note that Real component is selected to eliminate the residual imaginary components, typically of magnitudes 1E-15 or smaller
Also 2% factor to adjust for effects of filtering

WRITEPRN(falt2b70f1) := Fout

plot difference of filtered and unfiltered to compare effect of filtering



Validation of Loads

The forcing functions, unfiltered and filtered are fit to functions using a linear interpolation routine. These functions are then integrated with respect to time to yield a total impulse loading on the structure. The percentage of filtered versus unfiltered load is then determined. A criteria of 2% is utilized in this analysis and the filtered loads are multiplied by this factor to ensure that total impulse to the structure is conserved.

Notes: 1) The integrals are divided into .1 second intervals to obtain better numerical performance, since the forcing functions are oscillatory at high frequency.

2) The integration interval is shortened on the vertical pipe segments to include only the dynamic portion of the event. This prevents the deadweight load present after reflood from dominating the evaluation of dynamic filtering being performed.

$Q(x) := \mathrm{linterp}(t, z, x)$

$Q1(x) := \mathrm{linterp}(t, z1, x)$

$$UF := \left| \begin{array}{l} s \leftarrow 0 \\ \text{for } n \in 0..29 \\ \quad s \leftarrow s + \displaystyle\int_{.35+\frac{n}{200}}^{.35+\frac{n+1}{200}} |Q(x)|\, dx \end{array} \right.$$

$$FF := \left| \begin{array}{l} s \leftarrow 0 \\ \text{for } n \in 0..29 \\ \quad s \leftarrow s + \displaystyle\int_{.35+\frac{n}{200}}^{.35+\frac{n+1}{200}} |Q1(x)|\, dx \end{array} \right.$$

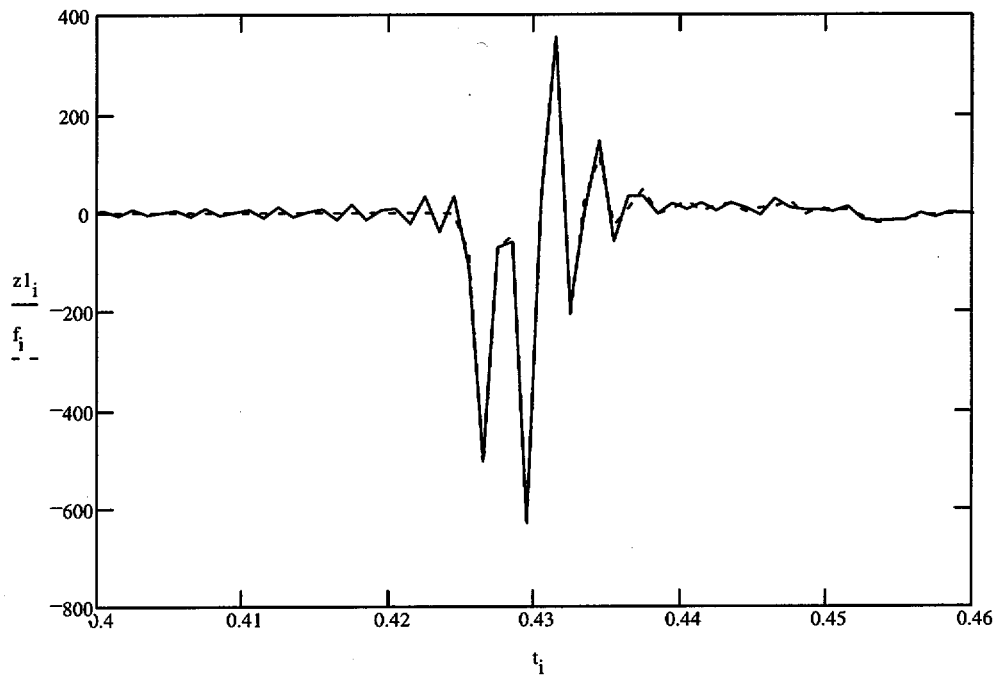
$FF = 2.593$

$UF = 2.373$

$\frac{UF - FF}{UF} = -0.093$ this number should be less than .02

$freq(ftp) = 399.386$ filter frequency

Plot of the transformed filtered data and unfiltered data vs time



$$\int_{0.42}^{0.43} |Q1(x)|\, dx = 1.338$$

$$\int_{0.43}^{0.44} |Q1(x)|\, dx = 0.729$$

$$\int_{0.42}^{0.43} |Q(x)|\, dx = 1.278$$

$$\int_{0.43}^{0.44} |Q(x)|\, dx = 0.696$$

Appendix C – RELAP5 Basedecks

This Appendix contains the following basedecks:

1) RELAP5 Model of Altran 2B Configuration
2) RELAP5 Model of FAI Test V024
3) RELAP5 Model of FAI Test 394

```
=Model of Altran waterhammer test rig
* this deck is set up to model the config 2b
100 new transnt
*
*
102  british   british
105  90.  100.
105    0.  0.
110 air
*******************************************************
*                                                     *
*               time step cards                       *
*                                                     *
*******************************************************
*     end   dtmin    dtmax  opt min  maj rstrt
201     0.35  1.d-7    0.001   3   2   1000 4000
202     5.0  1.d-7    0.01   3   2   1000 2000
202     0.5  1.d-7    .001   3   1   5000 20000
203     2.5  1.d-7    0.001   3  1   1000 20000
204     20.  1.d-7    0.001   3   1   1000 2000
*
*******************************************************
*                                                     *
*              minor edit variables                   *
*                                                     *
*******************************************************
*
301  p   104130000
302  mflowj   151000000
*303  tmass    0
*304  tmassv  104170000
*305  tmassv  104180000
*306  tmassv  104190000
*307  tmassv  104200000
*308  tmassv  104210000
*07  voidf  200010000
*05  mflowj 224010000
*04  voidg  345010000
*05  voidg  335060000
*06  voidg  212010000
*51  mflowj 505000000
*
*****************************************************************
*                      trip cards                               *
*                                                               *
*                    trip identifier                            *
*                                                               *
*     501   scram signal,rc pump trip,steam generator main      *
*           feed and main steam outlet trip                     *
*     502   initiate power decay curve                          *
*     503   pressure trip for si and charging initiation        *
*     504   si and charging initiation with 5.0 sec delay       *
*     505   aux feed flow initiation with 14.0 sec delay        *
*     506   break initiation                                    *
*     507   time zero trip                                      *
*     508   <*****************>                                 *
*     509   < porv trip logic >                                 *
*     601   <                 >                                 *
*     602   <*****************>                                 *
*     603   porv trip                                           *
```

```
*     510   dummy trip for main steam isolation valves          *
*     511   <********************>                              *
*     512   <                    >                              *
*     604   < aux feed trip logic >                             *
*     605   <                    >                              *
*     606   <                    >                              *
*     607   <********************>                              *
*     608   aux feed trip                                       *
*                                                               *
*     550  <problem stop                                        *
*     600  < cards                                              *
*                                                               *
*****************************************************************
550  time   0            ge   null    0      1.0       1
600   550
*
510  time   0            ge   null    0      .11       1
511  time   0            ge   null    0      10000.       1
512  time   0            ge   null    0      0.1       1
*******************************************************
*                                                     *
*              hydrodynamic components                *
*                                                     *
*******************************************************
*
*
****
 1010000   source      tmdpvol
*         flowa  1    vol   azi   incl  dz   rough hyd    fe
 1010101     1.e2 1.0  0.0   0.0   0.0   0.0   0.0   0.0   10
*        ebt
 1010200  4
*         time  press   temp     qual
1010201   0.0    84.7    68.0    0.0000
1010202   50.0   84.7     68.0  0.0000
****
*
1510000   connect  sngljun
1510101   101000000 100000000    .00163   0.5  1.       01000
1510101   101000000 100000000    .005   0.5  1.       01000
*         flag lflow    vflow  interface flow
1510201   1    0.0       0.0      0.0
**
*==================
***
*
1000000   slug pipe
*         nv
1000001   17
*         flowa    nv
1000101   .0205   17
*         length   nv
1000301   1.0    4
1000302   2.0    11
1000303   0.5    17
*       incline angle  nv
1000601  -90.0          17
*         rough  hyd dia  nv
1000801   0.00015 0.0     17
*
```

```
*   901   fjunf   fjunr    nj
1000901    0.0     0.0      16
*         fe   nv
1001001   00   17
*         cahs nj
1001101   1000  16
*        flag   p        t        x   dummy nv
1001201   4     84.7   68.0     0.0000   0 0  1
1001202   4     84.7   68.0     0.00001   0 0 17
*         flag 1=lbm/sec
1001300   1
*         lflow    vflow  interface flow nj
1001301   0.0        0.0         0.0     16
*
1210000   valve1 valve
1210101   100010000 102000000    .0205   0.057      0.057       001100
1210201   1  0.0  0.0
1210300   mtrvlv
*         opentrp  cltrp  rate   ip   vtn
1210301   510     511     16.7   0.0
1210301   510     511     7.4   0.0
1210301   510     511     4.9   0.0
*
*
1020000   steam pipe
*         nv
1020001   44
*         flowa    nv
1020101   .0205   44
*         length   nv
1020301   0.25      2
1020301   0.5       44
*       incline angle  nv
1020601  -90.0          2
1020602    0.0          14
1020603  90.0           20
1020604    0.0          32
1020605  -90.0          44
*         rough  hyd dia  nv
1020801   0.00015 0.0     44
*
*   901   fjunf   fjunr    nj
1020901    0.0     0.0      1
1020902    0.57    0.57     2
1020903    0.0     0.0     13
1020904    0.57    0.57    14
1020905    0.0     0.0     19
1020906    0.57    0.57    20
1020907    0.0     0.0     31
1020908    0.57    0.57    32
1020909    0.0     0.0     43
*         fe   nv
1021001   00   44
*         cahs nj
1021101   1000  43
*        flag   p        t        x   dummy nv
1021201   3     14.7   210.     0.0000   0 0 20
*1021201   3     14.7   211.5     0.0000   0 0 20
1021202   2     14.7   1.0     0.0   0 0 32
1021203   3     14.7   210.     0.0000   0 0 33
```

```
1021204   4     14.7   68.0     0.000001   0 0 44
1021203   3     14.4   210.     0.0000   0 0 33
1021204   4     14.4   68.0     0.00001   0 0 44
*         flag 1=lbm/sec
1021300   1
*         lflow    vflow  interface flow nj
1021301   0.0        0.0         0.0     43
*
1220000   valve2 valve
1220101   102010000 104000000    .0205   0.057      0.057       001100
1220201   1  0.0  0.0
1220300   mtrvlv
*         opentrp  cltrp  rate   ip   vtn
1220301   510     511     16.7   0.0
1220301   512     511     7.4   1.0
*
1040000   upper pipe
*         nv
1040001   39
*         flowa    nv
1040101   .0205   39
*         length   nv
1040301   0.5      1
1040302   3.0      13
1040303   0.9583   19
1040304   4.1667   25
1040304   2.08335  31
1040305    1.0     39
*       incline angle  nv
1040601  -90.0          1
1040602    0.0          39
*         rough  hyd dia  nv
1040801   0.00015 0.0     39
*
*   901   fjunf   fjunr    nj
1040901    0.57     0.57    1
1040902    0.0     0.0    12
1040903    0.57     0.57    13
1040904    0.0     0.0    18
1040905    0.57     0.57    19
1040906    0.0     0.0    30
1040907    0.57     0.57    31
1040908    0.0     0.0      34
1040909    0.57     0.57    35
1040910    0.0     0.0      37
1040910    0.57     0.57    38
*         fe   nv
1041001   00   39
*         cahs nj
1041101   1000  38
*        flag   p        t        x   dummy nv
1041201   4     19.7    210.   0.000001   0 0 1
1041201   4     14.7    68.   0.000001   0 0 33
1041201   4     14.7    68.   0.00001   0 0 39
*         flag 1=lbm/sec
1041300   1
*         lflow    vflow  interface flow nj
1041301   0.0        0.0         0.0     38
*
*
```

```
1230000   valve3 valve
1230101   104010000 105000000    .0205   0.00      0.00       001100
1230201   1  0.0  0.0
1230300   mtrvlv
*         opentrp  cltrp  rate   ip   vtn
1230301   511      512     20.   0.0
*
*1520000   connect  sngljun
*1520101   104010000 105000000    .0205   1.0  0.5       01000 *
*         flag lflow    vflow  interface flow
*1520201   1    0.0       0.0      0.0
**
*
*
****
 1050000   sink      tmdpvol
*         flowa  l    vol   azi   incl  dz   rough hyd    fe
 1050101     1.e2 1.0  0.0   0.0   0.0   0.0   0.0   0.0   10
*        ebt
 1050200  4
*         time  press   temp     qual
1050201   0.0    14.7    68.0    .000001
1050202   50.0   14.7    68.0     .000001
1050201   0.0    17.3    68.0    .000001
1050202   50.0   17.3    68.0     .000001
*
****
************************************************
*                                              *
* end of input deck - problem end              *
*                                              *
************************************************
.
```

```
=Model of FAI waterhammer test rig detailed with ht
* this deck is set up to model the vacuum test (no air/no ht)
100 new transnt
*
*
102  british   british
105  90.  100.
105    0.  0.
110 air
*******************************************************
*                                                     *
*               time step cards                       *
*                                                     *
*******************************************************
*     end   dtmin    dtmax  opt min  maj rstrt
201     1.  1.d-7    0.001   3   2   1000 4000
202     5.0  1.d-7    0.01   3   2   1000 2000
203     5.1  1.d-7    .001   3   1   500 20000
204     5.75  1.d-7    0.0001   3   10   1000 20000
205     20.  1.d-7    0.005   3   2   1000 2000
*
*******************************************************
*                                                     *
*              minor edit variables                   *
*                                                     *
*******************************************************
*
301  p   104130000
302  mflowj   151000000
*303  tmass    0
*304  tmassv  104170000
*305  tmassv  104180000
*306  tmassv  104190000
*307  tmassv  104200000
*308  tmassv  104210000
*07  voidf  200010000
*05  mflowj 224010000
*04  voidg  345010000
*05  voidg  335060000
*06  voidg  212010000
*51  mflowj 505000000
*
*****************************************************************
*                      trip cards                               *
*                                                               *
*                    trip identifier                            *
*                                                               *
*     501   scram signal,rc pump trip,steam generator main      *
*           feed and main steam outlet trip                     *
*     502   initiate power decay curve                          *
*     503   pressure trip for si and charging initiation        *
*     504   si and charging initiation with 5.0 sec delay       *
*     505   aux feed flow initiation with 14.0 sec delay        *
*     506   break initiation                                    *
*     507   time zero trip                                      *
*     508   <*****************>                                 *
*     509   < porv trip logic >                                 *
*     601   <                 >                                 *
*     602   <*****************>                                 *
*     603   porv trip                                           *
```

```
*     510   dummy trip for main steam isolation valves          *
*     511   <********************>                              *
*     512   <                    >                              *
*     604   < aux feed trip logic >                             *
*     605   <                    >                              *
*     606   <                    >                              *
*     607   <********************>                              *
*     608   aux feed trip                                       *
*                                                               *
*     550  <problem stop                                        *
*     600  < cards                                              *
*                                                               *
*****************************************************************
550  time   0            ge   null    0      7.0       1
600   550
*
510  time   0            ge   null    0      5.0       1
511  time   0            ge   null    0      10000.       1
*****************************************************
*                                                   *
*              hydrodynamic components              *
*                                                   *
*****************************************************
*
*
****
 1010000   source      tmdpvol
*         flowa  1    vol   azi   incl  dz   rough hyd    fe
 1010101     1.e2 1.0  0.0   0.0   0.0   0.0   0.0   0.0   10
*        ebt
 1010200  4
*         time  press   temp     qual
1010201   0.0    24.7    68.0    0.00001
1010202   50.0    24.7     68.0  0.00001
*
*        ebt
 1010200  3
*         time  press   temp     qual
1010201   0.0    24.7    68.0
1010202   50.0    24.7     68.0
*
****
*
1510000   connect  sngljun
1510101   101000000 100000000    .0233   0.5  1.       01000
*         flag lflow    vflow  interface flow
1510201   1    0.0       0.0      0.0
**
*==================
***
*
1000000   horiz pipe
*         nv
1000001   11
*         flowa    nv
1000101   .0233   11
*         length   nv
1000301   .9    1
1000302   .5    11
*       incline angle  nv
```

```
1000601  -90.0          3
1000602   0.0          11
*         rough  hyd dia  nv
1000801   0.00015 0.0     11
*
*   901   fjunf   fjunr    nj
1000901    0.0     0.0      2
1000902    0.57     0.57      3
1000903    0.0     0.0      4
1000904    0.152     0.152   5
1000905    0.0     0.0      9
1000906    0.5     0.5      10
*         fe   nv
1001001   00   11
*         cahs nj
1001101   1000  10
*        flag   p        t        x   dummy nv
1001201   4     24.7   68.0     0.00001   0 0 11
*1001201   3     24.7   68.0     0.0   0 0 11
*         flag 1=lbm/sec
1001300   1
*         lflow    vflow  interface flow nj
1001301   0.0        0.0         0.0     10
*
*
1520000   connect  sngljun
1520101   100010000 102000000    .0233   1.14  1.14        01000 *crane
1520101   100010000 102000000    .0233   2.3   2.3         01000 *idelchik
*         flag lflow    vflow  interface flow
1520201   1    0.0       0.0      0.0
**
*
1020000   linea pipe
*         nv
1020001   20
*         flowa    nv
1020101   .0233   20
*         length   nv
1020301   .5    20
*       incline angle  nv
1020601  90.0          20
*         rough  hyd dia  nv
1020801   0.00015 0.0     20
*
*   901   fjunf   fjunr    nj
1020901    0.0     0.0    19
*         fe   nv
1021001   00   20
*         cahs nj
1021101   1000  19
*        flag   p        t        x   dummy nv
1021201   4     37.7   140.0     0.00001   0 0 20
1021201   4     24.7   68.0     0.00001   0 0 12
1021202   4     24.7   68.0     0.00001   0 0 20
*1021201   3     24.7   68.0     0.0   0 0 12
*1021202   3     24.7   68.0     0.0   0 0 20
*         flag 1=lbm/sec
1021300   1
*         lflow    vflow  interface flow nj
1021301   0.0        0.0         0.0     19
```

```
*
**
1250000   line106 valve
1250101   102010000 104000000    .0233   0.057      0.057       001100
1250201   1  0.0  0.0
1250300   mtrvlv
*         opentrp  cltrp  rate   ip   vtn
1250301   510      511     16.7   0.0
1250301   510      511     10.    0.0
*
1040000   upper pipe
*         nv
1040001   13
*         flowa    nv
1040101   .0233   13
*         length   nv
1040301   0.5      13
*       incline angle  nv
1040601  90.0          13
*         rough  hyd dia  nv
1040801   0.00015 0.0     13
*
*   901   fjunf   fjunr    nj
1040901    0.0     0.0    12
*         fe   nv
1041001   00   13
*         cahs nj
1041101   1000  12
*        flag   p       t       x   dummy nv
1041201   4     0.7    75.2   0.0   0 0 13
1041201   4     0.7    68.    0.0   0 0 13
*1041201   5     215.6   0.999    .48   0 0 13
*1041201   5     75.2   0.999    .05   0 0 13
*         flag 1=lbm/sec
1041300   1
*         lflow    vflow  interface flow nj
1041301   0.0        0.0         0.0     12
*
****
*Heat Structures for upper pipe
*general data
*         nh  np   geo  ss    left coord.
*11041000  13  11    2    1     0.086125
*========================================
*mesh flags
*        location flg       format flag
*11041100     0                    2
*========================================
*mesh data
*        mesh interval   int #
*11041101 .0012833          10
*========================================
*composition data
*          comp. #     int #
*11041201      1          10
*========================================
*heat distribution data
*        source   int #
*11041301   0.0      10
*========================================
```

```
*initial temperature data
*          temp.      int #
*11041401    215.0       11
*11041401    75.2       11
*11041401    90.       11
*==========================================================
*left bc cards
*          bvl     inc  type  surf     cyl ht     struct #
*11041501  104010000 10000 1      1       0.5          13
*==========================================================
*right bc cards
*          bvr inc  type  surf     cyl ht     struct #
*11041601  -1 0000 3002      1       0.5          13
*11041601  0 0000   0      1       0.5          13
*==========================================================
*==========================================================
*source data
*         source  mult     ldh     rdh   struct #
*11041701    0     0.0      0.0     0.0     13
*==========================================================
*left boundary cards
*          hdiam  hlf     hlr    gridf   gridr   grdlssf grdlssr lbf struct #
*11041801    0.    10.0      10.0    1.5  1.5     0.0        0.0   1.   13
*==========================================================
*right boundary cards
*          hdiam  hlf     hlr    gridf   gridr   grdlssf grdlssr lbf struct #
*11041901    0.    10.0      10.0    1.5  1.5     0.0        0.0   1.   13
************************************************************
**
*----- heat structure thermal property data
*
*composition type and data format
*          material type    flag    flag
*20100100       c-steel
*=====================================================
*===================================
*tables
*****************************************************************************
*20200100  temp
*20200101  0.  70.
*20200102  1.e6  70.
*
*20200200  htc-t
*20200201  0.   2.777e-4
*20200202  1.e6 2.777e-4
*20200201  0.   2.777e-7
*20200202  1.e6 2.777e-7
***********************************************
*                                             *
* end of input deck - problem end             *
*                                             *
***********************************************
.
```

```
=Model of FAI waterhammer test rig detailed with ht
* this deck is set up to model the steam test
100 new transnt
*
*
102  british   british
105  90.  100.
105
110 air
*******************************************************
*                                                     *
*               time step cards                       *
*                                                     *
*******************************************************
*     end   dtmin    dtmax  opt min  maj rstrt
*201     1.  1.d-7    0.001   3   2   1000 4000
*202     5.0  1.d-7    0.01   3   2   1000 2000
*203     5.5  1.d-7    .0001   3   10   500 20000
*204     7.5  1.d-7    0.005   3   2   1000 20000
*205     20.  1.d-7    0.005   3   2   1000 2000
*
*     end   dtmin    dtmax  opt min  maj rstrt
201     1.  1.d-7    0.001   3   2   1000 4000
202     5.0  1.d-7    0.01   3   2   1000 2000
203     5.1  1.d-7    .001   3   1   500 20000
204     5.75  1.d-7    0.0001   3   10   1000 20000
205     20.  1.d-7    0.001   3   1   1000 2000
*******************************************************
*                                                     *
*             minor edit variables                    *
*                                                     *
*******************************************************
*
301  p   104130000
302  mflowj   151000000
*303  tmass    0
*304  tmassv  104170000
*305  tmassv  104180000
*306  tmassv  104190000
*307  tmassv  104200000
*308  tmassv  104210000
*07  voidf  200010000
*05  mflowj 224010000
*04  voidg  345010000
*05  voidg  335060000
*06  voidg  212010000
*51  mflowj 505000000
*
*****************************************************************
*                      trip cards                               *
*                                                               *
*                    trip identifier                            *
*                                                               *
*     501   scram signal,rc pump trip,steam generator main      *
*           feed and main steam outlet trip                     *
*     502   initiate power decay curve                          *
*     503   pressure trip for si and charging initiation        *
*     504   si and charging initiation with 5.0 sec delay       *
*     505   aux feed flow initiation with 14.0 sec delay        *
*     506   break initiation                                    *
```

```
*     507   time zero trip                                        *
*     508   <*****************>                                   *
*     509   < porv trip logic >                                   *
*     601   <                 >                                   *
*     602   <*****************>                                   *
*     603   porv trip                                             *
*     510   dummy trip for main steam isolation valves            *
*     511   <*********************>                               *
*     512   <                     >                               *
*     604   < aux feed trip logic >                               *
*     605   <                     >                               *
*     606   <                     >                               *
*     607   <*********************>                               *
*     608   aux feed trip                                         *
*                                                                 *
*     550  <problem stop                                          *
*     600  < cards                                                *
*                                                                 *
*******************************************************************
550  time   0            ge   null    0      7.0       1
600   550
*
510  time   0            ge   null    0      5.0       1
511  time   0            ge   null    0      10000.       1
*****************************************************
*                                                   *
*              hydrodynamic components              *
*                                                   *
*****************************************************
*
*
****
 1010000   source      tmdpvol
*         flowa  1    vol   azi   incl  dz   rough hyd    fe
 1010101     1.e2 1.0  0.0   0.0   0.0   0.0   0.0   0.0   10
*        ebt
 1010200  4
*         time  press   temp     qual
1010201   0.0    44.7    68.0    0.00001
1010202   50.0    44.7     68.0  0.00001
*
****
*
1510000   connect  sngljun
1510101   101000000 100000000    .0233   0.5  1.       01000
*         flag lflow    vflow  interface flow
1510201   1    0.0       0.0      0.0
**
*==================
***
*
1000000   horiz pipe
*         nv
1000001   11
*         flowa    nv
1000101   .0233   11
*         length   nv
1000301   .9    1
1000302   .5    11
*        incline angle  nv
```

```
1000601  -90.0          3
1000602   0.0          11
*         rough  hyd dia  nv
1000801   0.00015 0.0     11
*
*   901   fjunf   fjunr    nj
1000901    0.0     0.0      2
1000902    0.57     0.57      3
1000903    0.0     0.0      10
*modified losses to account for flow meter and valve
1000901    0.0     0.0      2
1000902    0.57     0.57      3
1000903    0.0     0.0      4
1000904    0.152     0.152   5
1000905    0.0     0.0      9
1000906    0.5     0.5      10
*         fe   nv
1001001   00   11
*         cahs nj
1001101   1000  10
*        flag   p       t       x   dummy nv
1001201   4     44.7   68.0    .000015  0 0 11
*         flag 1=lbm/sec
1001300   1
*         lflow    vflow  interface flow nj
1001301   0.0        0.0         0.0     10
*
*
1520000   connect  sngljun
1520101   100010000 102000000    .0233   1.14  1.14       01000
*increase resistance at tee to idlchik
1520101   100010000 102000000    .0233   2.3  2.3       01000
*         flag lflow    vflow  interface flow
1520201   1    0.0       0.0      0.0
**
*
1020000   linea pipe
*         nv
1020001   20
*         flowa    nv
1020101   .0233   20
*         length   nv
1020301   .5    20
*       incline angle  nv
1020601  90.0          20
*         rough  hyd dia  nv
1020801   0.00015 0.0     20
*
*   901   fjunf   fjunr    nj
1020901    0.0     0.0    19
*         fe   nv
1021001   00   20
*         cahs nj
1021101   1000  19
*        flag   p       t       x   dummy nv
1021201   4     37.7   140.0    .000015  0 0 20
1021201   4     44.7   68.0    .00002  0 0 12
1021202   4     44.7   140.0    .00002  0 0 20
*         flag 1=lbm/sec
1021300   1
```

```
*         lflow    vflow  interface flow nj
1021301   0.0        0.0         0.0     19
*
**
1250000   line106 valve
1250101   102010000 104000000    .0233   0.057      0.057      000100
1250201   1  0.0  0.0
1250300   mtrvlv
*         opentrp  cltrp  rate   ip   vtn
1250301   510     511     16.7   0.0
*
1040000   upper pipe
*         nv
1040001   13
*         flowa    nv
1040101   .0233   13
*         length   nv
1040301   0.5      13
*       incline angle  nv
1040601  90.0          13
*         rough  hyd dia  nv
1040801   0.00015 0.0     13
*
*   901   fjunf   fjunr    nj
1040901    0.0     0.0    12
*         fe   nv
1041001   00   13
*         cahs nj
1041101   1000  12
*        flag   p        t        x   dummy nv
1041201   4     1.0    75.2   0.0   0 0 13
1041201   5     233.6   0.999    .001   0 0 13
*1041201   5     215.6   0.52    .48   0 0 13
*         flag 1=lbm/sec
1041300   1
*         lflow    vflow  interface flow nj
1041301   0.0        0.0         0.0     12
*
****
*Heat Structures for upper pipe
*general data
*         nh  np   geo  ss    left coord.
11041000  13  11    2    1     0.086125
*=========================================
*mesh flags
*        location flg       format flag
11041100     0                   2
*=========================================
*mesh data
*        mesh interval   int #
11041101 .0012833          10
*=========================================
*composition data
*          comp. #     int #
11041201      1          10
*=========================================
*heat distribution data
*        source   int #
11041301   0.0      10
*=========================================
```

```
*initial temperature data
*           temp.       int #
11041401    215.0        11
11041401    233.6        11
*==========================================================
*left bc cards
*           bvl      inc  type  surf     cyl ht     struct #
11041501  104010000 10000 1      1       0.5          13
*==========================================================
*right bc cards
*          bvr inc  type  surf     cyl ht     struct #
*11041601  -1 0000 3002      1       0.5          13
11041601  0 0000   0      1       0.5          13
*=========================================================
*==========================================================
*source data
*          source  mult     ldh     rdh   struct #
11041701    0      0.0      0.0     0.0     13
*==========================================================
*left boundary cards
*          hdiam  hlf     hlr    gridf   gridr   grdlssf grdlssr lbf struct #
11041801    0.    10.0      10.0    1.5  1.5     0.0        0.0   1.   13
*==========================================================
*right boundary cards
*          hdiam  hlf     hlr    gridf   gridr   grdlssf grdlssr lbf struct #
11041901    0.    10.0      10.0    1.5  1.5     0.0        0.0   1.   13
************************************************************
**
*----- heat structure thermal property data
*
*composition type and data format
*          material type    flag    flag
20100100       c-steel
*=====================================================
*===================================
*tables
*****************************************************************************
*20200100  temp
*20200101  0.  70.
*20200102  1.e6  70.
*
*20200200  htc-t
*20200201  0.   2.777e-4
*20200202  1.e6 2.777e-4
*20200201  0.   2.777e-7
*20200202  1.e6 2.777e-7
***********************************************
*                                             *
* end of input deck - problem end             *
*                                             *
***********************************************
.
```