RELAP5 SIMULATION OF REACTOR WATER BACK FLOW INTO THE HIGH PRESSURE CORE SPRAY (HPCS) SYSTEM PIPING

J. L. Thompson
Gulf States Utilities Co.
P. O. Box 220
St. Francisville, LA 70775
(504) 381-4193

J. S. Miller
Gulf States Utilities Co.
P. O. Box 220
St. Francisville, LA 70775
(504) 381-4862

J. R. White
Gulf States Utilities Co.
P. O. Box 220
St. Francisville, LA 70775
(504) 381-4862

ABSTRACT

A thermal hydraulic evaluation of River Bend Station's high pressure core spray (HPCS) system injection piping was performed following a flow reversal event which allowed hot reactor water to enter the system. Hand calculations were used to estimate the maximum temperatures along the HPCS pipe using measurements taken after the event. The hand-calculated temperature profile was used by others to show that the thermal stress levels in the pipe were acceptable. A RELAP5 simulation provided a best-estimate temperature profile along the pipe for comparison with the hand calculated profile. The results of the RELAP5 simulation verified that the hand-calculated temperatures and the thermal stress evaluation were conservative. In addition, the R5FORCE program was used in conjunction with RELAP5 to calculate the dynamic loads on the HPCS piping as a result of the flow reversal event. The piping loads for this event were less than 20 percent of the design basis loads. The RELAP5 simulations along with computer recorded data demonstrate that the low pressure portions of the HPCS system piping were not overpressurized.

INTRODUCTION

On August 25, 1988, a loss of electric load occurred at the River Bend Station (RBS) BWR/6. With the unit at 100 percent power, the reactor automatically scrammed due to a turbine control valve fast closure caused by automatic main generator and turbine trips.

Immediately following the scram, reactor pressure spiked to a peak between 1100 and 1117 psig causing five safety relief valves to open. The high pressure core spray (HPCS) and reactor core isolation cooling (RCIC) systems injected as a result of a spurious low reactor water level 2 signal caused by a hydraulic perturbation in the reactor water level instrument reference lines. As a result of the feedwater flow continuing (due to the "A" feedwater control valve being in the manual mode at 50 percent open) in conjunction with the HPCS and RCIC injections, reactor water level rapidly increased to level 8 causing the HPCS injection valve and the RCIC injection and steam supply valves to close and the reactor feedwater pumps to trip.

A sequence of events for Scram 88-04 is given in Table 1. It was postulated that inadvertent actuation of the HPCS injection valve (F004) at approximately 13:24 allowed reactor water to enter the HPCS piping system after the HPCS pump was tripped. This was confirmed by chemistry samples of the water subsequent to the event.

This situation is significant for the following reasons.

1. The HPCS piping is designed for cold water (100°F) and the water from the reactor vessel is extremely hot (530°F). This hot water condition may exceed the original design basis thermal stress analysis.
2. The HPCS piping between the HPCS pump and the reactor vessel is high pressure piping. The piping at the HPCS pump suction and upstream is low pressure piping. Therefore, if a pressure wave from reactor vessel moves into the HPCS pump suction piping, there's a chance for

an overpressurization event to occur, i.e., high pressure/high temperature water in a low pressure/low temperature piping system may rupture the pipe, which could lead to an interfacing loss of coolant accident (LOCA) if the valves between the postulated break and the reactor vessel failed to close. This is commonly referred to as the WASH 1400 V Event.

3. The thermal/hydraulic dynamic loads caused by the fluid flowing from the reactor vessel at high pressure into the HPCS system piping could exceed design basis loads. This is an unanalyzed event since the analyzed events are the HPCS pump trip and start transients.

   Several questions were asked concerning the safety consequences of this event.

1. What was the estimated temperature profile on the piping during transient? (Thermal Structural Effects)
2. Was there a stratification impact? (Thermal Structural Effects)
3. Was there an overpressure of the low pressure piping in the HPCS system? (WASH 1400 V Event)
4. Were the dynamic loadings previously evaluated exceeded by this unanalyzed event? (Dynamic Structural Effects)

Calculations which made use of RELAP5/MOD2 and other support programs were used to answer these questions. The calculations and results are discussed in the remaining sections of this paper.

DESCRIPTION OF PROGRAMS

The RELAP5/MOD2[1] computer program was used to model the HPCS injection pipe heatup event. The RELAP5/MOD2 code uses a one-dimensional, transient, two fluid nonequilibrium, nonhomogeneous hydrodynamic model. Seven equations are used to simulate flow of steam-water-noncondensible mixtures. The equation set consists of two phasic continuity equations, two phasic momentum equations, two phasic energy equations, and one mass conservation equation for noncondensibles if present. The steam-water mixture capability of RELAP5/MOD2 make it ideal for modelling the HPCS injection pipe heatup event since steam-water mixtures are expected to occur in the pipe.

The R5FORCE[3] subroutine of the BLAZER[2] computer program was used to calculate hydrodynamic forces on the HPCS injection piping. The R5FORCE subroutine was developed at INEL to support the USNRC Safety/Relief Valve Program. GSU initiated computer program modifications to R5FORCE which were required to provide correct results. In addition, GSU merged the R5FORCE program with RELAP5 so the large data files generated could be easily manipulated. The R5FORCE subroutine uses the hydrodynamic output from RELAP5/MOD2 at each time step to calculate forces using the following equation.

$$F = -(P_{I1} + \rho_I u_I) A_{I1} + (P_{I2} + \rho_I u_I) A_{I2} \quad (1)$$

$$+ P_{E1} A_{EI} - P_{E2} A_{E2} + \tau_s A_s$$

where F = force on pipe segment

A = volume surface area,

P = fluid pressure,

u = fluid velocity,

ρ = fluid density, and

τ = shear force per unit area.

The subscripts I and E represent interior and exterior conditions. Subscripts 1 and 2 represent the volume inlet and outlet respectively, and the subscripts represent the interior surface parallel to the flow. The first and second terms in Equation 1 represent the forces due to change in momentum inside the pipe at the inlet and outlet respectively. The third and fourth terms represents the pressure force acting on the outside of the volume at the inlet and outlet respectively. The fifth term represents the wall shear force. Equation 1 was derived from a surface integral representation of the forces on a pipe segment[3] and will be referred to as the integral method.

An alternate form of the force equation, which is used in the FORCE1[5] subroutine of BLAZER, can be derived using the law of conservation of momentum. This equation is:

$$F = \frac{(L_i dm_i)}{dt} + (P_{I1} + \rho_{I1} u_{I1}) A_{I1} \quad (2)$$

$$+ (P_{I2} + \rho_{I2} u_{I2}) A_{I2}$$

where F = force on pipe segment,

L = length of volume,

m = mass flow rate,

P = fluid pressure,

ρ = fluid density, and

u = fluid velocity.

The subscript i represents the volume number and all other subscripts are as defined previously. Equation 2 contains the mass flow rate time derivative in the first term and will be referred to as the differential method.

The integral form of the equation has advantages over the differential form of the equation since calculation of the time derivative of the mass flow rate is not required. The derivative form of the equation frequently produces erroneous force spikes caused by the numerical differentiation technique.

For analysis of the HPCS injection pipe heatup event it is important that the calculated forces not have erroneous spikes in the results which may exceed the design basis loads. For this reason the R5FORCE subroutine was chosen for calculating the piping loads.

VALIDATION OF METHODS

To solve a complicated problem such as the HPCS backflow event, two important aspects must be met: 1) an adequate analytical tool, i.e., computer program, must be available to perform the calculation and 2) the analytical tool must be validated with respect to known results that are applicable to the application being simulated.

For the results presented in this paper, the RELAP5/MOD2 Cycle 36.05 computer program was used for the temperature and pressure determination. Validation of the application was made by comparing the RELAP5 calculated results with test results from Edward's blowdown test[6].

For the dynamic load determination, RELAP5/MOD2 was also used along with the R5FORCE computer program[3] as the analytical tools. Validation of the application was made by comparing RELAP5/R5FORCE calculated results to published information from Lahey/Moody[7] and to EPRI test results[4] from the Combustion Engineering Test Facility for safety valve testing. The test data used was from test CE908.

MODELS USED TO SIMULATE THE EVENT

Data Taken During The Event

Transient data for this event was recorded by the in-plant monitoring computers (process computer and emergency response information system (ERIS) computer). This data was valuable in determining the sequence of events following the scram and the range of values for critical parameters. The boundary conditions, such as reactor pressure and level in the condensate storage tank, for the RELAP5 model of the HPCS system were taken from the recorded data.

The ERIS data revealed that the HPCS injection valve was off of its full closed position for nine seconds just after the HPCS pump was secured. Approximately thirty minutes after the HPCS pump was secured, valve 1E22*MOVF004 was again recorded as being off of its full closed position for a period of 24 seconds. This data is the basis for the nine and 24 second valve strokes used in the RELAP5 model.

In addition to the computer recorded data, manual temperature measurements of the surface of the HPCS injection piping were taken at several times and positions along the pipe. These measurements were the basis for hand calculations which extrapolated the data backward in time to estimate the maximum pipe temperatures which could have occurred at the time the hot water entered the injection piping.

Calculated Estimate of Temperature Profile

The manual temperature measurements along the length of the injection pipe as a function of time were used to estimate the temperature profile just after the hot water entered the pipe. Temperature measurements were not taken until several hours after the pipe was first heated. Therefore, it was necessary to calculate the maximum temperature which occurred just after the hot water entered the pipe by extrapolating the data using the method of least squares. The temperature at each point on the pipe was assumed to decrease exponentially with time and was fit using an equation of the following form:

$$T = ae^{bt},$$

where T = pipe temperature in degrees above ambient,

a = constant determined from least squares fit,

b = constant determined from least squares fit, and

t = time in hours.

RELAP5 Model To Determine Temperature Profile

To confirm the data extrapolation method, a RELAP5 model with heat transfer was developed to predict the transient temperature heat up during the HPCS backflow event. A RELAP5/MOD2 model of the HPCS system injection piping was developed from as-built piping drawings and other design drawings. The RELAP5 nodalization diagram is shown in Figure 1. A description of each of the components in the nodalization diagram is provided in Table 2.

It should be noted that the model was developed with positive flow from the reactor vessel toward the HPCS pump. However the terms "upstream" and "downstream" refer to the normal flow direction from the HPCS pump toward the reactor vessel.

The HPCS model consists of a time dependent volume which represents the system upstream of the HPCS pump discharge, a time dependent volume which represents the reactor pressure vessel, and pipe components representing the injection piping. Valve components were used to model the injection valve F004 and the check valves F005 and F024. The HPCS injection piping located inside the reactor vessel was also modelled. Heat structures were used to model the pipe walls for all piping.

The initial condition for the reactor vessel was saturated liquid at 906 psia. This information was obtained from ERIS computer data. The fluid in volumes representing the HPCS piping downstream of check valve F005 were also set to saturated liquid at 906 psia. These volumes represent the HPCS piping inside the reactor vessel and insulated piping outside the vessel. The piping between check valve F005 and injection valve F004 was set to a pressure of 906 psia and a temperature of 135 degrees F. The initial fluid conditions upstream of valve F004 were 50 psia and 100 degrees F. The ambient temperature in the auxiliary building was assumed to be 100 degrees F. Convective heat transfer was assumed to take place between the pipe surface and the surrounding air.

The transient was started at time zero which is near the time at which the nine second opening of injection valve F004 occurred. The transient was allowed to run for 10 seconds of problem time so that the hydrodynamic solution could reach a steady state. Valve F004 was opened at 10.0 seconds with its position changing linearly at a rate corresponding to the 10 second stroke time of the valve. Also at 10 seconds, check valve F005 was opened to 0.25 times its full open area. Check valve F024 was also assumed partially stuck open at 10 seconds to 0.008 times the full open area of the valve. The check valves were left open to simulate sticking valve discs which would allow reverse flow to occur. At 14.5 seconds into the transient, the injection valve F004 began to close at the same rate at which it opened. Valve F004 was full closed at 19.0 seconds. During this stroke, the injection valve was off of its full closed position for about nine seconds. The hot fluid which moved upstream from the reactor vessel while the injection valve was open was allowed to heat the structures until 1950.8 seconds when the injection valve began to open again. This represented the time between the 9 second stroke and the 24 second stroke. Valve F004 continued to open until 1960.8 seconds when it was full open. The valve remained full open until 1964.5 seconds at which time it began to close and reached the full closed position at 1974.5 seconds. The injection valve was off of its full closed position for about 24 seconds during the second stroke.

RELAP5 Model To Determine Thermal/Hydraulic Forces

The RELAP5 model of the HPCS system used for the dynamic load analysis was developed from the existing HPCS model used for piping temperature estimation. The nodalization and other modelling techniques were based on recommendations given in Reference 4. Figure 2. shows an isometric of the HPCS piping as well as the nodalization diagram for the RELAP5 model. Dynamic force segments 1-17 are defined to coincide with segments defined in previous design basis dynamic force calculations.

The control volumes were renodalized to lengths of approximately one foot each for the dynamic load model. The finer nodalization results in better capability to track pressure wave propagation through the system. Heat structure modifications were also required to accommodate the finer nodalization. Additional pipe components were added to model the piping between the HPCS pump discharge and check valve F024. These pipe segments were added to the model so that their hydrodynamic forces could be compared to the design basis HPCS pump trip event. Heat structures were not used on these additional pipe components because the hot water did not reach this portion of the piping. The relief valve F035 and it's associated piping and heat structures were deleted since it was determined that this was not the primary flow-path.

ANALYSIS AND RESULTS OF THE TRANSIENT

Temperature Prediction Based On Measured Data

The results of the curve fits performed to predict the temperature profile along the injection pipe are shown in Figure 4.1. The results envelope both the data from the best fit curve and the extrapolated data at each measured location. The predicted maximum temperature distribution as a function of length appears reasonable for the following reasons:

1) The paint on the piping should blister at about 220 degrees F. The estimated temperature profile has a temperature of 220 degrees at a point which corresponds to where the paint was observed to be discolored. This indicates that the estimate is higher than the temperature indicated by the condition of the paint.

2) The range of the values lie under the 438 degree F estimate based on an adiabatic calculation of the pipe temperature. This indicates that the curve is not unrealistically high.

3) By extrapolating the data downstream of the injection valve F004, the temperature reaches 545 degrees F at approximately 50 feet downstream. This point is consistent with the point at which the pipe is insulated.

The predicted temperature distribution was used by the RBS Engineering Department's Civil/Structural Group to evaluate the stresses on the pipe during the event. The results of the stress evaluation showed that the pipe was not overstressed.

RELAP5 Calculation Of The Temperature Profile

The RELAP5/MOD2 calculated temperature profile for the HPCS flow reversal event is shown in Figure 3 along with the profile predicted by curve fits from the measured data. The RELAP5 calculated profile follows the general trend of the predicted profile but has a lower temperature at all locations along the pipe. The RELAP5 profile is consistent with field observations. Specifically, paint on the pipe was discolored upstream of valve F004 but not blistered. Paint blistering is expected to occur around 220 degrees F whereas the RELAP5 results show that the maximum temperature of the pipe just upstream of valve F004 was about 217 degrees F.

The sharp drop in pipe temperature at the location of valve F004, which corresponds to zero feet upstream of F004, is due to the fluid downstream being subcooled liquid at a pressure of 900 psia and a temperature of 317 degrees F while the conditions downstream are saturated steam at a temperature of 209 degrees F with a void fraction near 1.0.

Thermal/Hydraulic Forces Evaluation

During the periods while valve F004 was closed, the mass flow rate through the system and the pipe segment forces were zero. The only nonzero forces occurred during the first two seconds of the injection valve opening and during the last two seconds of the valve closing. This behavior is due to choked flow at check valve F024. While F004 is opening, the flow through the system is limited by the area reduction at F004. As the piping system upstream of F004 pressurizes and flow is established, then the flow rate is limited by critical flow through the F024 check valve and a steady flow exists which results in zero forces on the piping. The reverse happens during closing of the injection valve. When the F004 area is small enough to begin limiting flow, then the flow rate decreases and the fluid deceleration results in nonzero piping forces. The maximum peak-to-peak forces occur on pipe segments 4, 11, and 13 and range from about 1600 lbf on segments 4 and 13 to about 1800 lbf on segment 11. The design basis event which results in the worst case loads for the HPCS system is a HPCS pump trip with subsequent check valve slams due to reactor back pressure. The design basis forces for each pipe segment were reviewed and compared against the calculated dynamic loads for the HPCS flow reversal event. The largest forces for the HPCS flow reversal event occurred on segments 4, 11, and 13. The forces on segment 13 are compared with the design basis pump trip forces in Figure 4. It can be seen that the pipe heatup event resulted in much smaller loads than those calculated for a pump trip. The peak loads for the heatup event were less than 20 percent of the peak loads calculated for the pump trip event.

Based on this comparison, the dynamic forces caused by the HPCS reverse flow event is bounded by the design basis event and is within the analyzed basis of RBS.

Other Characteristics Of The Transient Event

The potential for thermal stratification existed in some portions of the HPCS injection piping. Thermal stratification occurs when cold fluid and hot fluid exist in the same portion of piping. Buoyancy forces caused by density differences will cause the hot fluid to seek the top of the pipe while the cold fluid remains at the bottom of the pipe. One of the adverse effects of thermal stratification is pipe bowing due to unequal thermal expansion of the upper and lower surfaces of a pipe caused by the temperature difference. Due to the geometry, the bowing effect due to thermal stratification will only be seen in horizontal pipes. This bowing effect can be large enough to damage pipe supports.

The flow path of the hot water in the HPCS flow reversal event was from the reactor vessel to portions of piping at a lower elevation. Following the nine second stroke of the injection valve, the hot/cold liquid temperature gradient came to rest in a horizontal section of pipe located inside containment. Thermal stratification is generally associated with cold liquid injection at low velocity near the bottom of a pipe containing hot liquid such that adequate mixing between the liquids does not occur. The HPCS flow reversal event resulted in stagnant fluids which would only stratify under buoyant forces. Since the temperature gradient occurred over a distance of about 25 feet, the buoyancy forces are not believed to be great enough to cause significant thermal stratification. Field walkdowns and inspections of the HPCS injection piping showed no signs of excessive expansion or pipe support damage. The hot/cold liquid temperature gradient was located in a vertical section of piping following the 24 second stroke of the injection valve. Thermal stratification in this vertical section of piping is of no concern since stratification could not result in pipe bowing.

Another concern for the HPCS flow reversal event was the possibility of overpressurizing the HPCS pump low pressure suction piping. Overpressurization of the suction piping by reactor pressure could rupture the piping resulting in an interfacing LOCA. The interfacing LOCA event is also known as the WASH 1400 V Event.

The results of the RELAP5 runs show that choked flow existed at the HPCS pump discharge check valve F024 which prevented the upstream piping from pressurizing significantly. These results are supported by ERIS computer data which shows that the HPCS pump discharge pressure, which is measured just upstream of check valve F024, did not increase above the elevation head of water in the condensate storage tank. Based on the RELAP5 results and the HPCS pump discharge pressure measurements, overpressurization of the low pressure HPCS pump suction piping did not occur.

CONCLUSIONS

Evaluations were performed to determine the following consequences from the HPCS flow reversal event that occurred subsequent to Scram 88-04.

1. What was the estimated temperature profile on the HPCS piping during the flow reversal transient? This evaluation was necessary to ultimately determine the thermal structural effects. Based on a temperature profile provided by temperature data taken after the scram and on a temperature profile calculated by RELAP5, it was determined that the thermal structural stresses were at an acceptable level.

2. Was there an addition stress factor due to possible stratification effects? Based on a HPCS piping walk down and on RELAP5 calculations, stratification did not appear to be a significant contribution to additional stresses.

3. Was there an overpressurization of the low pressure piping in the HPCS system? Based on the RELAP5 calculations, a rupture of the low pressure HPCS piping due to the HPCS flow reversal event was not possible due to the relatively low pressure and temperature calculated in the low pressure HPCS piping during the event.

4. Were the dynamic loadings previously evaluated as part of the design basis stress analysis exceeded by the unanalyzed event? Based on RELAP5/R5FORCE calculations, the dynamic loads generated during the HPCS flow reversal event were a fraction of the design basis loads, i.e., less than 20 percent of the HPCS pump trip loads.

The evaluation presented in this paper shows that the HPCS flow reversal event did not result in unacceptable thermal structural stresses or dynamic loadings.

REFERENCES

1. V. H. RANSOM et. al., "RELAP5/MOD2 Code Manual Volumes 1-3," NUREG/CR-4312, EGG-2396 Rev. 1 (March 1987).

2. J. R. OLSEN, "BLAZER: Release 3 Version 1 Code Manual," RE-A-82-045 (June 1982).

3. J. C. WATKINS, "R5FORCE: A Program to Compute Fluid Induced Forces Using Hydrodynamic Output From the RELAP5 Code," EGG-EA-5920 (October 1982).

4. R. K. HOUSE et al., "Applications of RELAP5/MOD1 for Calculation of Safety and Relief Valve Discharge Piping Hydrodynamic Loads," EPRI NP-2479, Project V102-28, Final Report (December 1982).

5. R. L. WILLIAMSON, "FORCE1: A Program to Compute Fluid Induced Forces Using Hydrodynamic Output from the RELAP5 Code," EGG-EA-5631 (October 1981).

6. A. R. EDWARDS and T. P. O'BRIEN, "Studies of Phenomena Connected with the Depressurization of Water Reactors," Journal of the British Nuclear Energy Society, 9, pp. 125-135 (April 1970).

7. R. T. LAHEY, Jr. and F. J. MOODY, The Thermal-Hydraulics of a Boiling Water Nuclear Reactor (1977).

Table 1. SEQUENCE OF EVENTS - HPCS INJECTION, SCRAM 88-04

12:32:39.8 - Generator Turbine Trip

12:32:39.9 - Reactor Scram -TSV Fast Closure

12:32:40 - HPCS Level 2 Initiation

12:32:40.3 - HPCS Diesel Initiation

12:32:50 - HPCS Diesel Generator output breaker closes

12:32:52 - HPCS Min Flow valve (F012) off closed seat

12:32:53 - HPCS Injection valve (F004) off closed seat

12:32:58 - HPCS Min Flow valve (F012) closed

12:33:23.1 - HPCS Min Flow valve (F012) off closed seat

12:33:23.2 - HPCS Injection valve (F004) closed

12:51:35 - HPCS Pump Motor off

12:51:37 - HPCS Injection valve (F004) off closed seat

12:51:41 - HPCS Min Flow valve (F012) closed

12:51:47 - HPCS Injection valve (F004) closed

12:51:59 - HPCS Level 2 Initiation reset to normal

13:24:08 - HPCS Injection valve (F004) open

13:24:32 - HPCS Injection valve (F004) closed

13:24 - HPCS Diesel generator paralleled to offsite power

13:30 - Fire watch in Auxiliary Building reports HPCS pipe
Approx Elevation 114, Elevation 123 piping was also hot. Operator was sent to investigate. Accompanied by Operation Quality Assurance. Found smoke on 123 Auxiliary Building. HP placard melted. HPCS pipe hot. Suction pipe cold. Min flow warm. Verified seating of HPCS injection valve (F004) using handwheel.

13:32 to 13:48 - Engineer observes HPCS pipe hot at Elevation 123 Auxiliary Building.

17:30 - Engineering begins temperature measurements of pipe.

Table 2

Component Description for RELAP5 Model Used For Temperature Evaluations

Component 015:	The piping from the Reactor Vessel to the F005 check valve,
Component 005:	The F005 check valve,
Component 054:	The piping from the F005 check valve to the MOV F004 valve,
Component 004:	The MOV F004 valve,
Component 424:	The piping from the MOV F004 valve to the tee joining with piping CSH-003-15-2.
Component 014:	The tee off of piping CSH-014-04-2 to CSH-003-15-2.
Component 024:	The VF024 check valve,
Component 435:	The piping from the tee with CSH-014-4-2 downstream through the piping CSH-003-15 and CSH-001-46-2 to the F035 relief valve.
Component 035:	The F035 relief valve.
Component 001:	The boundary condition representing the reactor vessel upstream of core spray nozzles,
Component 002:	The boundary condition representing the HPCS pump discharge
Component 003:	The boundary condition representing the F035 relief valve discharge piping

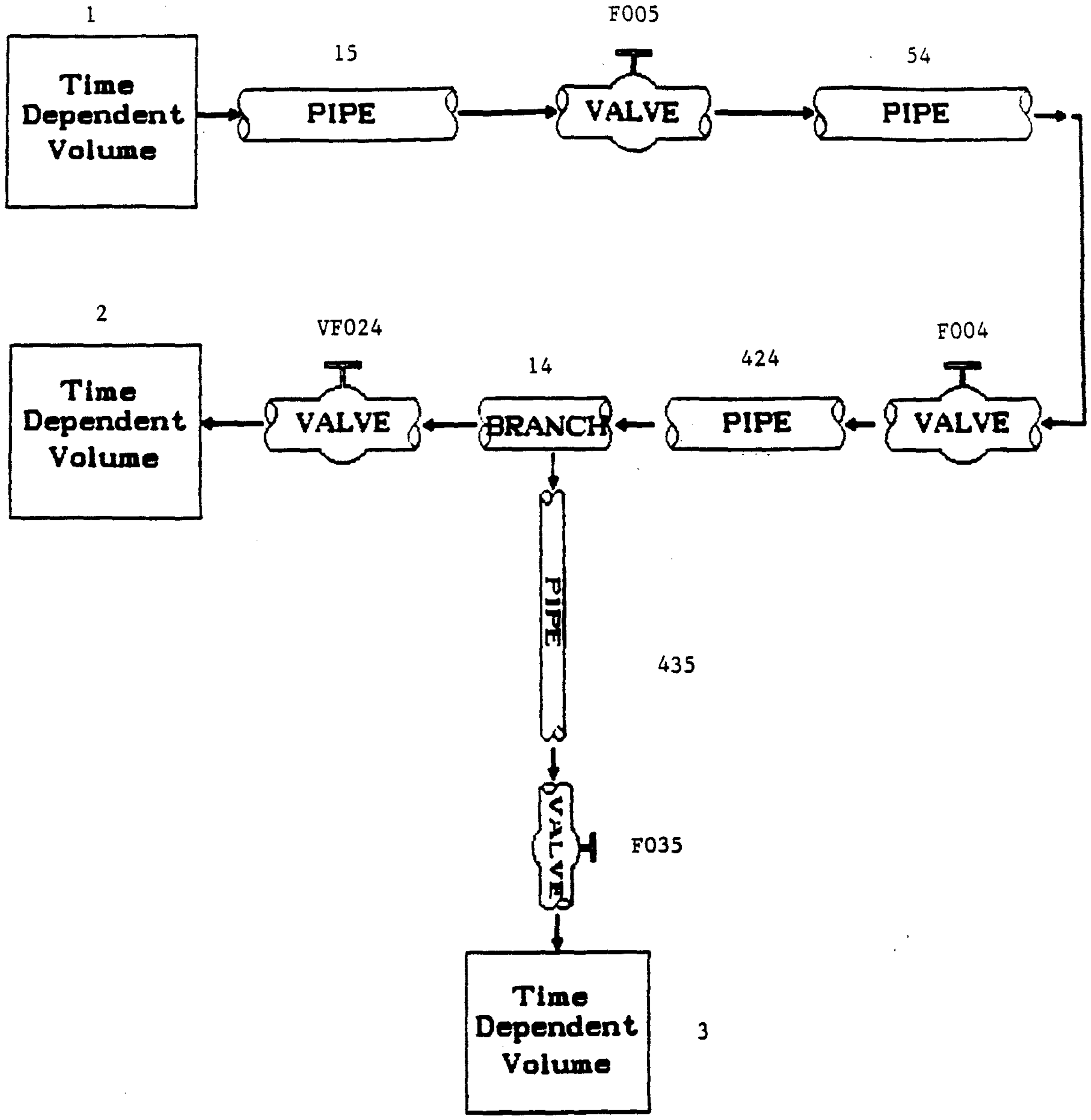

Figure 1. RELAP5 Nodalization for Temperature Determination

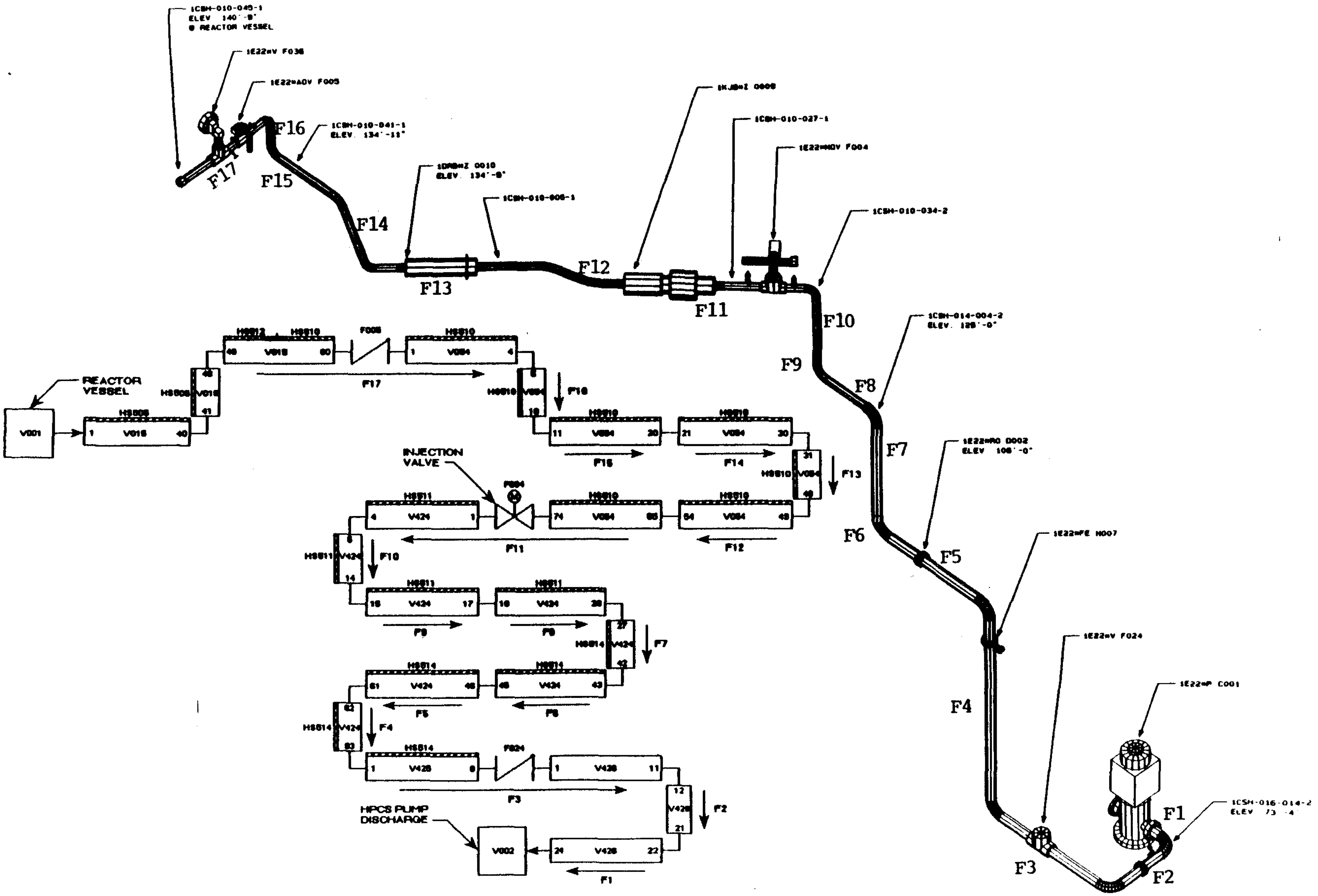

Figure 2. RELAP5 Nodalization for Thermal/Hydraulic Load Calculation and HPCS Piping Isometric

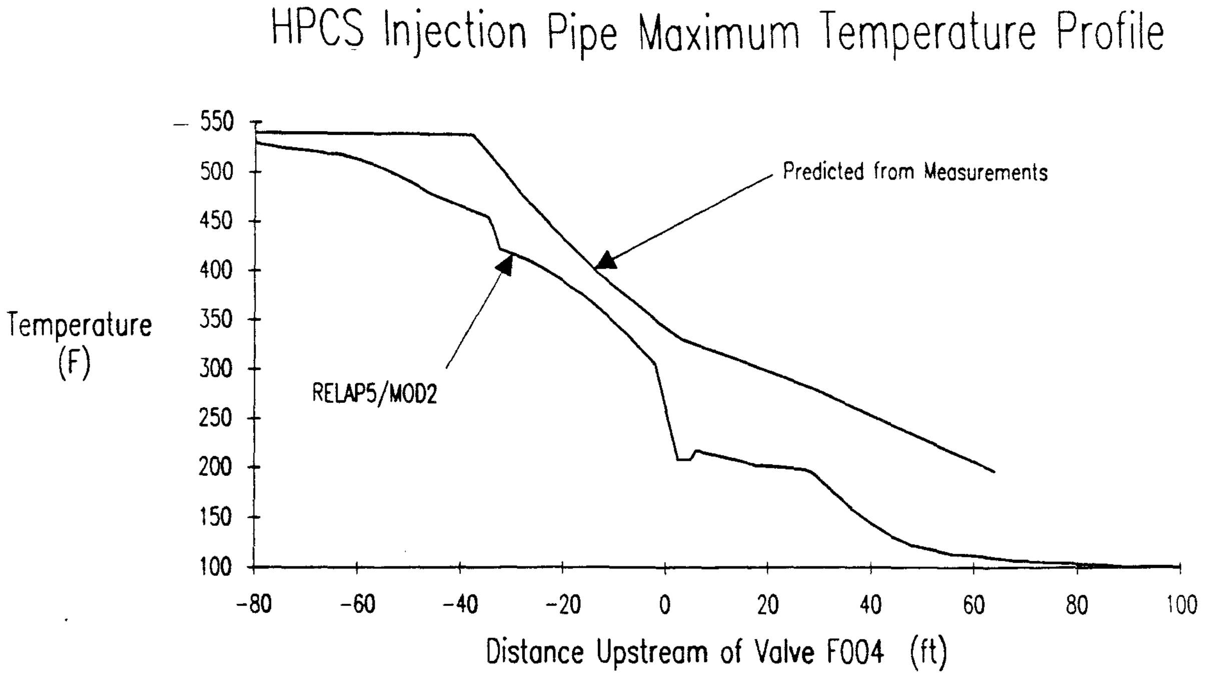

Figure 3. RELAP5 Calculation Temperature Versus Predicted Temperatures

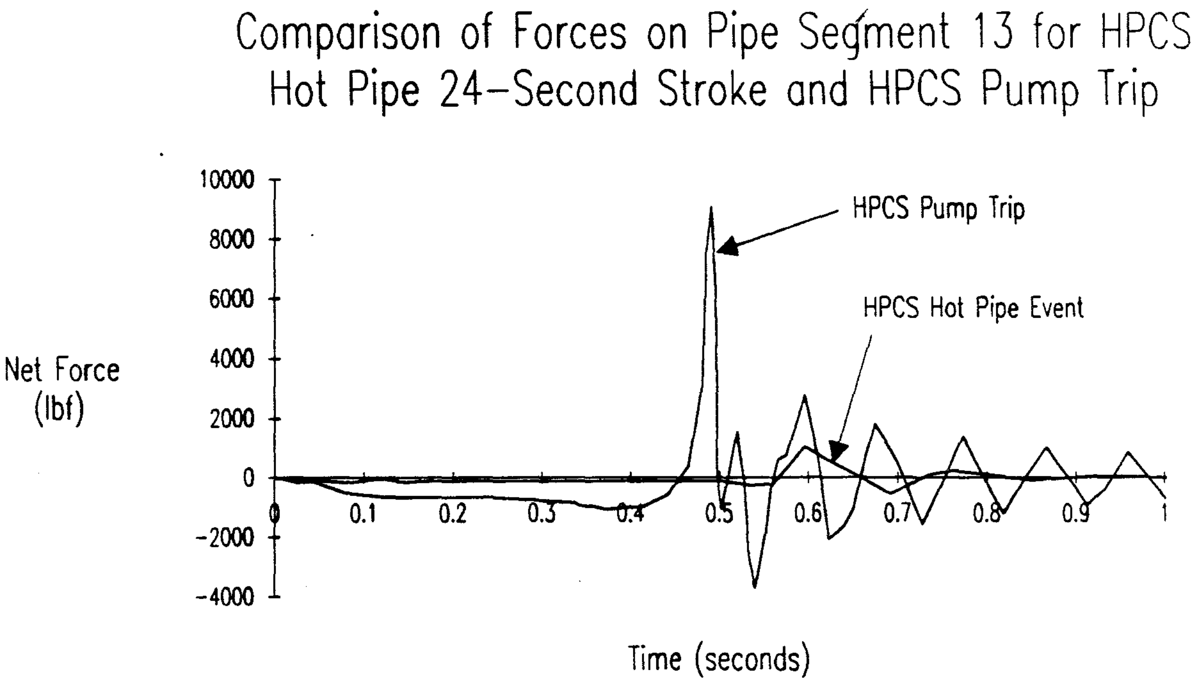

Figure 4. Forces for Backflow Event and Design Basis Pump Trip