ANALYSIS OF A TWO INCH SURGE LINE BREAK RESULTING IN A POSTULATED PRESSURIZED THERMAL SHOCK VESSEL FAILURE IN THE CALVERT CLIFFS POWER PLANT

SUMMARY - A 2" surge line break in Calvert Cliffs was postulated to result in a PTS vessel failure after nominal PTS conditions were achieved. The principle purpose of this analysis was to provide mass and energy release information to be used in pressurized thermal shock (PTS) containment failure analyses. Two subsidiary purposes were:

1. To provide RCS pressure information that might be helpful in assessing the potential for RCS internal damage

2. To provide information about the timing of possible core damage after the vessel failure

A two inch surge line break was analyzed using RELAP5/MOD3.2.2 (version "Relapon") starting with a large break input deck that was developed for IPE success criteria analyses and improved for Appendix K rule change studies. After the annulus water temperature reached 300°F, the vessel was assumed to fail. The problem was then restarted at the closest restart time assuming a vertical split in the vessel.

PROBLEM DEFINITION AND DEVELOPMENT - The particular LBLOCA input deck (calsb33.i) was chosen as the starting point because it had a multi-region downcomer (12 axial regions, 6 azimuthal regions and 1 radial region). Six of the axial regions spanned the same elevation as a 20 axial region core. The core also had a hot channel equivalent to one fuel assembly which also included the heat structure for an additional hot pin. Figure 1 shows the vessel noding used for this problem. In order to perform a suitable PTS calculation, certain trips were modified to assure full pumped ECCS and aux. feed operation. The large cold leg break was replaced by a surge line break near the bottom of the surge line. After the 300°F vessel failure criterion was reached, the problem was restarted at the next subsequent restart time with a 12 square foot break extending from the top to bottom of the active core (See Figure 1). The vessel break consisted of 12 one square foot junctions discharging from each azimuthal face of the volumes shown in Figure 1.

Six vessel cavity volumes at the break junction elevations served as break repositories. A 10 volume vessel cavity (including the 6 break repositories) was developed based on information received from the utility (BG&E) for a previous direct containment heating (DCH) study. Other containment components included a tunnel to the sump (lower containment) and a large volume upper containment. A large containment wall heat structure was in place from the original deck, but no containment mitigation systems were used or available. The containment volume was arbitrarily increased to 4 million cubic feet to limit the containment pressure rise.

SYSTEM RESPONSE PRIOR TO VESSEL BREAK - The surge line break was initiated at time zero. The RCPs were manually tripped at 150 and 200 seconds according to small break procedures. Natural circulation was lost at about 1000 seconds (See Figure 2). Vessel pressure in the annulus is shown in Figure 3. Figure 4 shows the collapsed core and annulus water levels. As is expected in a hot leg side break, more than sufficient water level is available to maintain core cooling, especially with full ECCS.

In earlier versions of this calculation, numerically driven flows were observed. This phenomenon was discussed by Dave Bessette (Note to Farouk Eltawila, et al., 1/25/01) as part of the review of NRC PTS calculations for Oconee. The imposition of high reverse flow pump resistance was used for Calvert Cliffs as was done for Oconee. Figure 5 shows average loop flows from the termination of natural circulation until just before the vessel break after the loop flow "fix" was invoked. As can be seen no "numerically driven flows" are present. Figure 6 shows the water level in the containment components. The BG&E information says that at least one foot of water is required in the sump before sufficient NPSH is available for recirculation. This calculation indicates that this level is not present until after vessel failure. However, without containment mitigation systems, that important contribution to sump inventory is not considered. Figure 7 shows that the average of 24 annulus water temperatures closest to the core midplane reach 300°F by 3400 seconds after the surge line break. At that time the vessel break was initiated. Use of the pressures in Figure 3 and temperatures in Figure 4 should provide information to determine if the 300°F criterion used in this analysis is appropriate.

SYSTEM RESPONSE AFTER VESSEL BREAK - The next 8 figures are presented to provide boundary condition information for the PTS containment failure analysis. As shown in Figure 8, the vessel break blowdown is over within 10 seconds. Figure 9 shows that the vessel break flow increases somewhat after the blowdown when excess ECCS water spills out of the break. The high flow between 3420 and 3460 seconds is due to SIT injection. Figure 10 shows a break mass flow of ~1350 lbs/sec., due to pumped injection spilling out the vessel break. Figure 11 is the vessel break enthalpy flow rate during the vessel failure blowdown. Figure 12 is the vessel break enthalpy flow rate for the entire post-vessel failure period of the transient. Figures 13, 14 and 15 are presented in a form that may be useable for some containment codes. For these figures, the enthalpy flow rate was divided by the mass flow rate to provide a specific enthalpy of the break flow. When the net flow is near zero, countercurrent flow may be present or flows may be in different directions for each of the break junctions. Under these conditions of "mixed flow", a single specific enthalpy to be applied to a single break flow appears oscillatory and sometimes negative, which of course is impossible. Therefore in Figures 13 and 14, a "faired" line is drawn for the short time period between 3409 and 3422 seconds.

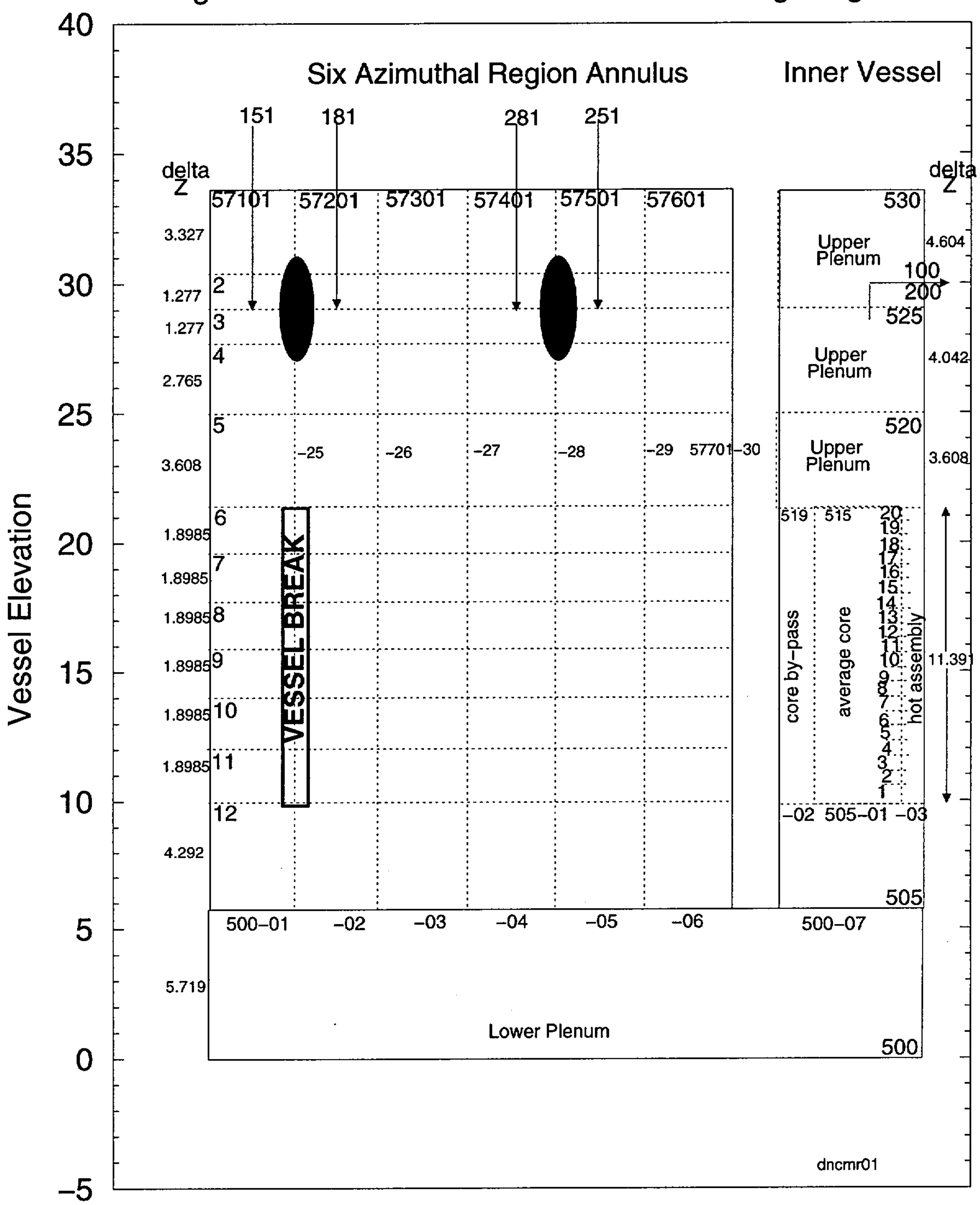
The next three plots are provided to assist in assessing the potential for vessel component and containment failure. Figures 16 and 17 show the pressure drop across the core barrel nearest the mid-point of the vessel split. Figure 17 shows that the maximum ΔP occurs within 30 milliseconds after the vessel split. Figure 18 shows that the lowest vessel cavity volume reaches a pressure of nearly 160 psia within 2 seconds of the vessel split.

The balance of the figures describe the onset of core damage that is calculated to occur within 800 seconds after the vessel split. Figure 19 shows the cladding temperature behavior of the three pins represented in this calculation. The single hot pin has a peak linear heat rate of 14.5 kw/ft at the 10 ft. elevation. The hot assembly is represented by a pin that has an average power of all the remaining pins in the hot assembly. The average core is represented by a pin that has an average power of all the remaining pins in the reactor. The calculation terminates in RELAP5 when the cladding temperature reaches melting, which is the limit of the conductivity property table. As shown in Figure 19, this is about 3500°F. For both the hot pin and the hot assembly the influence of the zirconium-steam reaction can be seen by the sharp upturn in cladding temperature. The average pin, however, has not yet reached a temperature where metal-water effects are significant. Extrapolating the average pin behavior would indicate that approximately 500 more seconds would be needed to approach clad melting for that pin. It should be noted that the solid body radiation model was not invoked in RELAP5 as it would normally be in SCDAP or MELCOR.

The cladding temperature heat up begins after termination of accumulator injection (@ 3456 seconds). The cladding temperature behavior is dependent on the water level in the core. Figure 20 is a plot of core and annulus collapsed liquid level relative to the bottom of the core. A dotted line is drawn to approximate the mixture level in the core. This line is based on individual void fractions in the average core channel. The collapsed level in the core is very dependent on the collapsed level in the annulus. For this problem, the annulus collapsed level is dependent on the vessel break characterization. The intent of developing 12 one square foot break junctions from the vessel to the cavity over the length of the core was to simulate a longitudinal 12 square foot vessel split. The results appear to be reasonable. After the system has depressurized, the break is a very low energy process in which water is spilled out of the bottom region of the break. Figure 21 shows the individual liquid flow rates from all 12 break junctions during this time period. Also shown is the total break flow from all 12 junctions. The four lowest junctions each contribute about 320 lbs/sec for a total of 1280 lbs/sec or about 95% of the break flow. Figure 21 also shows that the total vessel break flow is about 1340 lbs/sec., which is equal to the total pumped ECCS flow with all pumps operating. Thus most of the water being pumped into the RCS is being spilled out the break, which is to be expected in this large vessel break.

There is a concern however, that RELAP5 may not be calculating the annulus water level properly for this kind of spillage. Annulus water level is a strong determinant of core liquid level and the time available before core damage begins. Figure 20 shows that the annulus collapsed water level during this time period is about 2 feet. This height is relative to the bottom of the vessel split. If a rectangular split is assumed, the Francis formula for constrained weir flow can be applied and solved for the height of water above the crest of the weir. By assuming upstream velocities of zero and a maximum equal to the average spillage velocity, the water height is calculated to be between 3.5 and 4.3 ft.. Thus on this very simplified basis, RELAP5 does not appear to be "overestimating" the water height in the annulus. It should be noted that weir formulae do not account for upstream pressure effects or other complexities that would exist in the annulus, especially in the break region. A good deal more assessment of vessel splits is needed including the nature of the break flow over a very wide range of conditions. CFD calculations could be helpful in scoping some of the issues related to annulus water level behavior.

Figure 1. Calvert Cliffs PTS Annulus Noding Diagram



Calvert Cliffs 2" Surge Line Break PTS Event

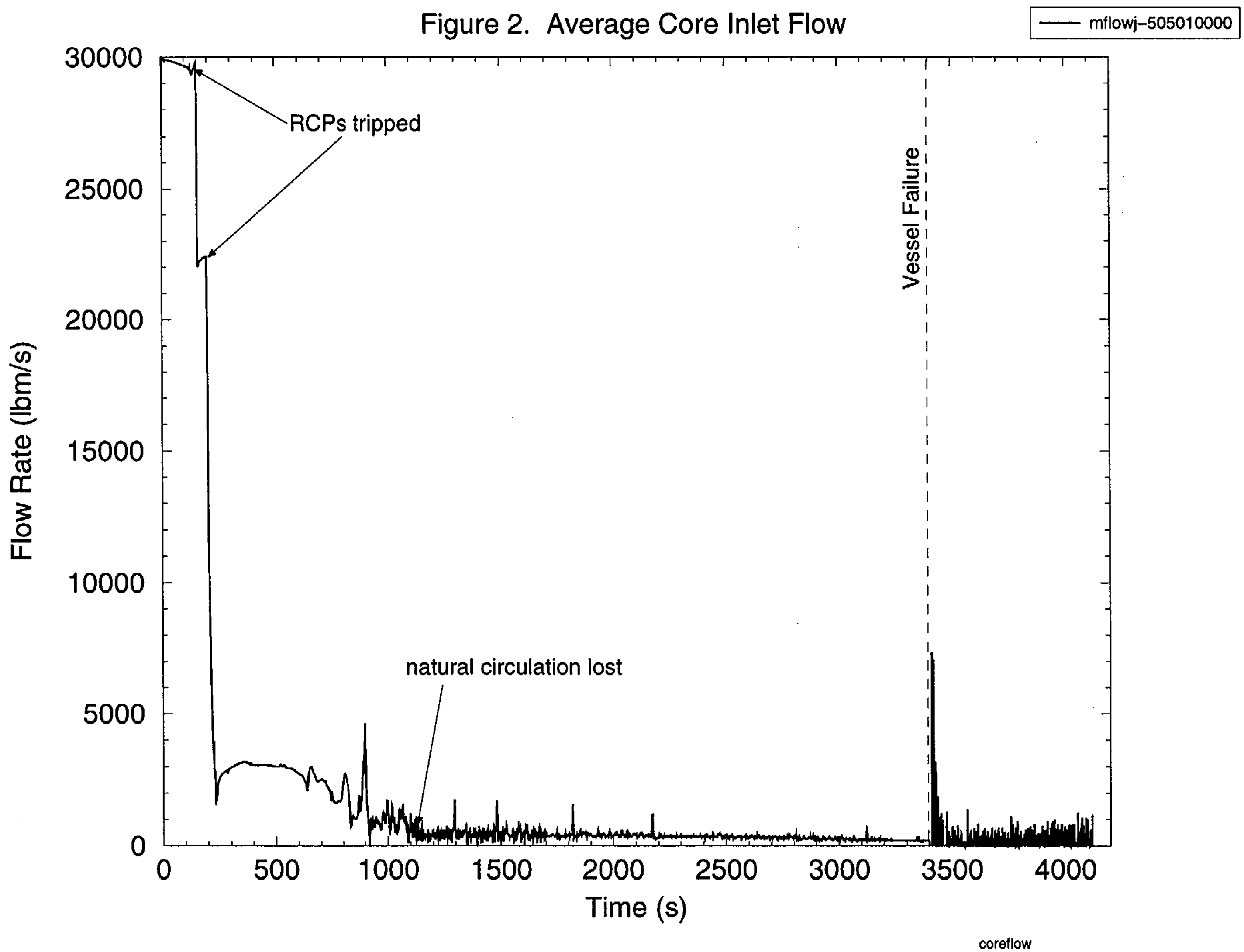
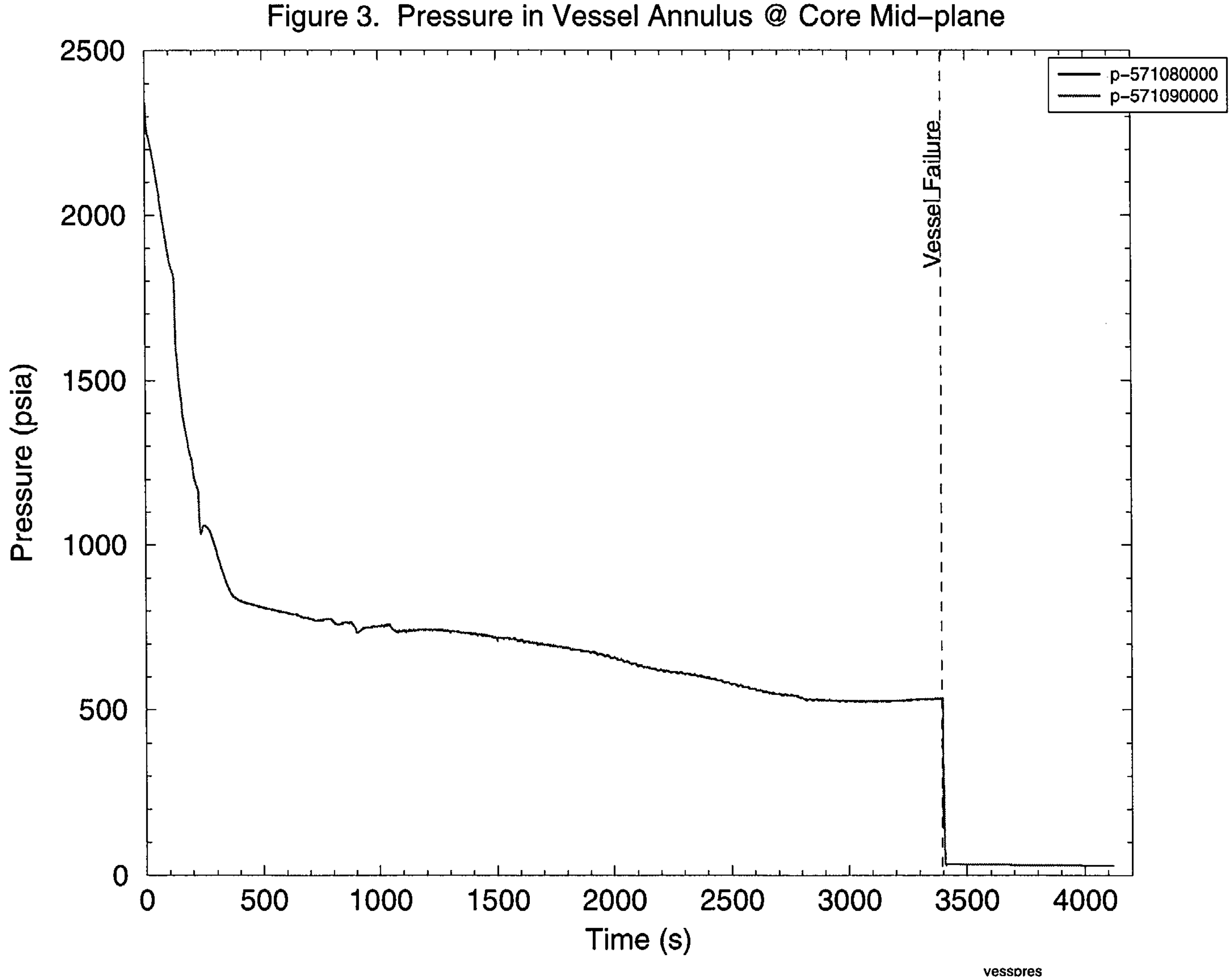


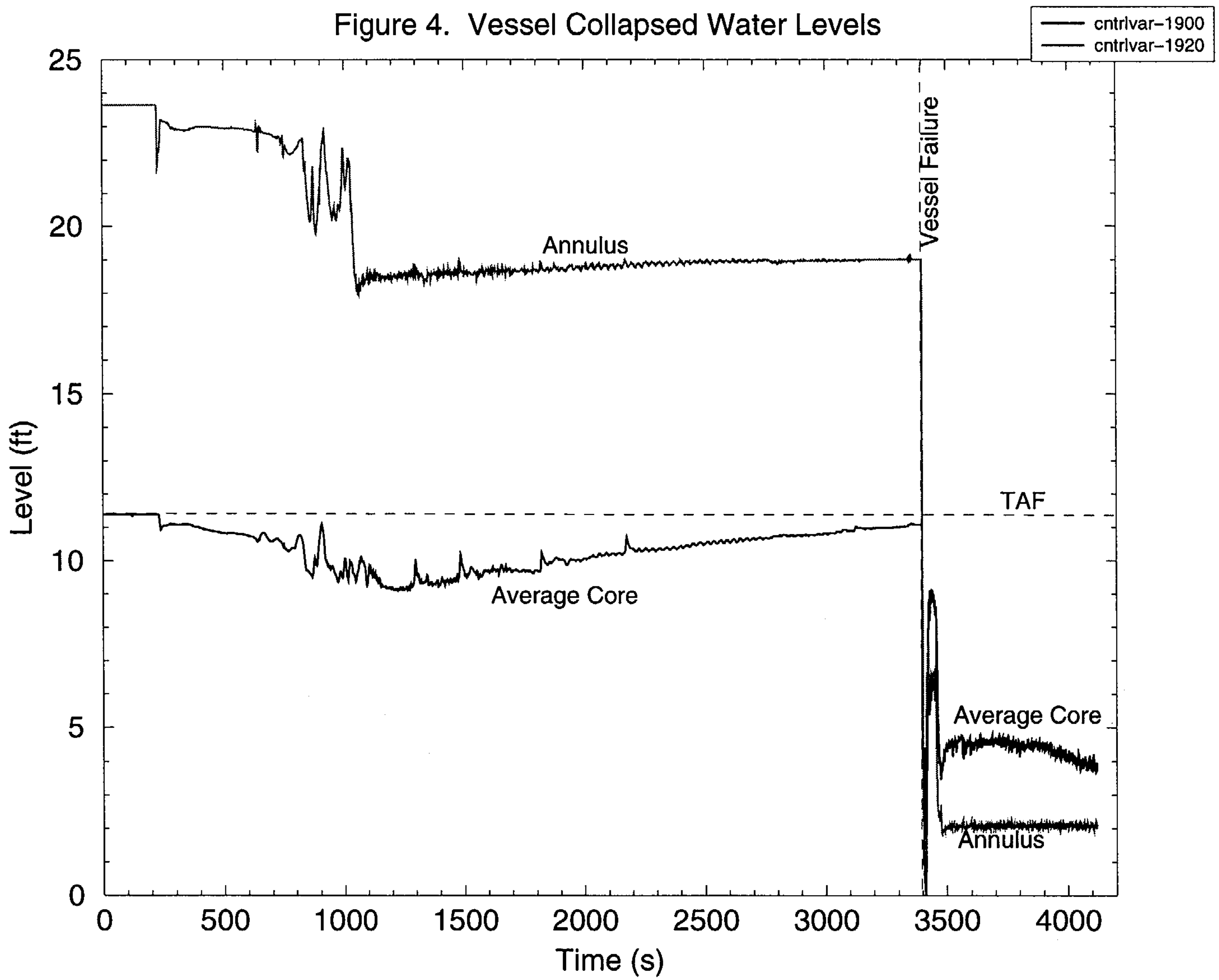
Figure 2. Average Core Inlet Flow

Calvert Cliffs 2" Surge Line Break PTS Event



Calvert Cliffs 2" Surge Line Break PTS Event

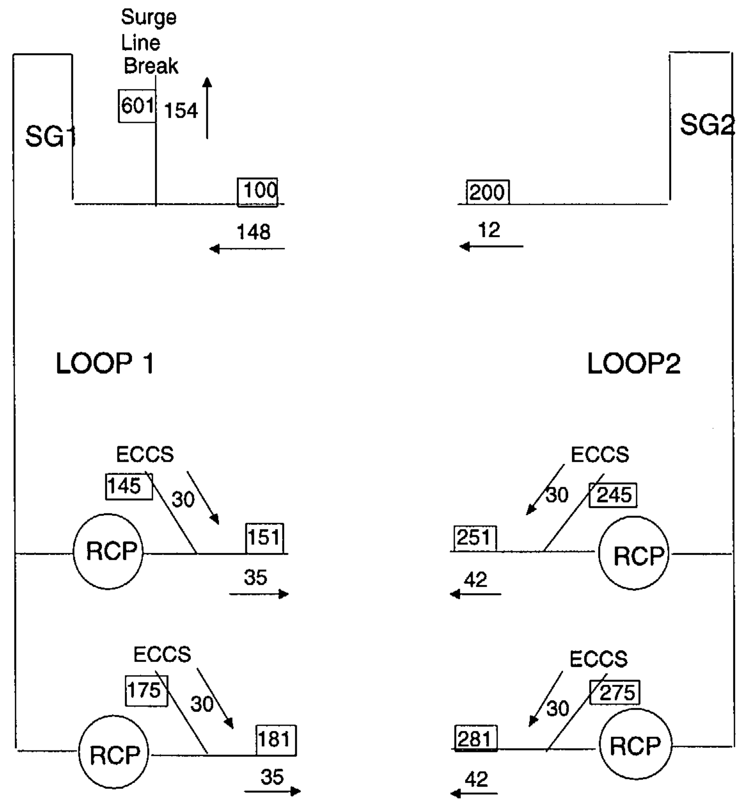
Figure 4. Vessel Collapsed Water Levels



veslevels02

Calvert Cliffs 2" Surge Line Break PTS Event

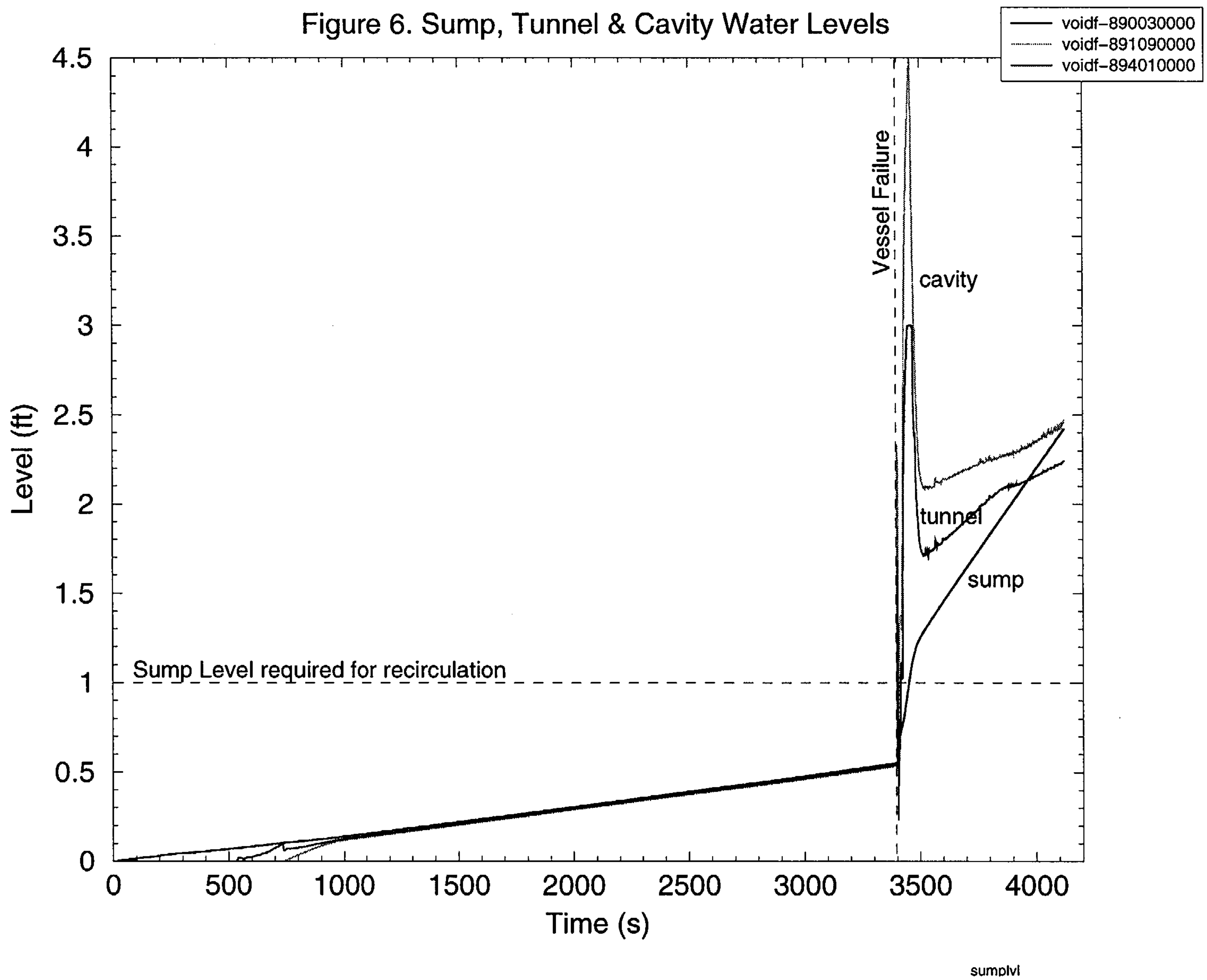
Figure 5. Loop Flows*

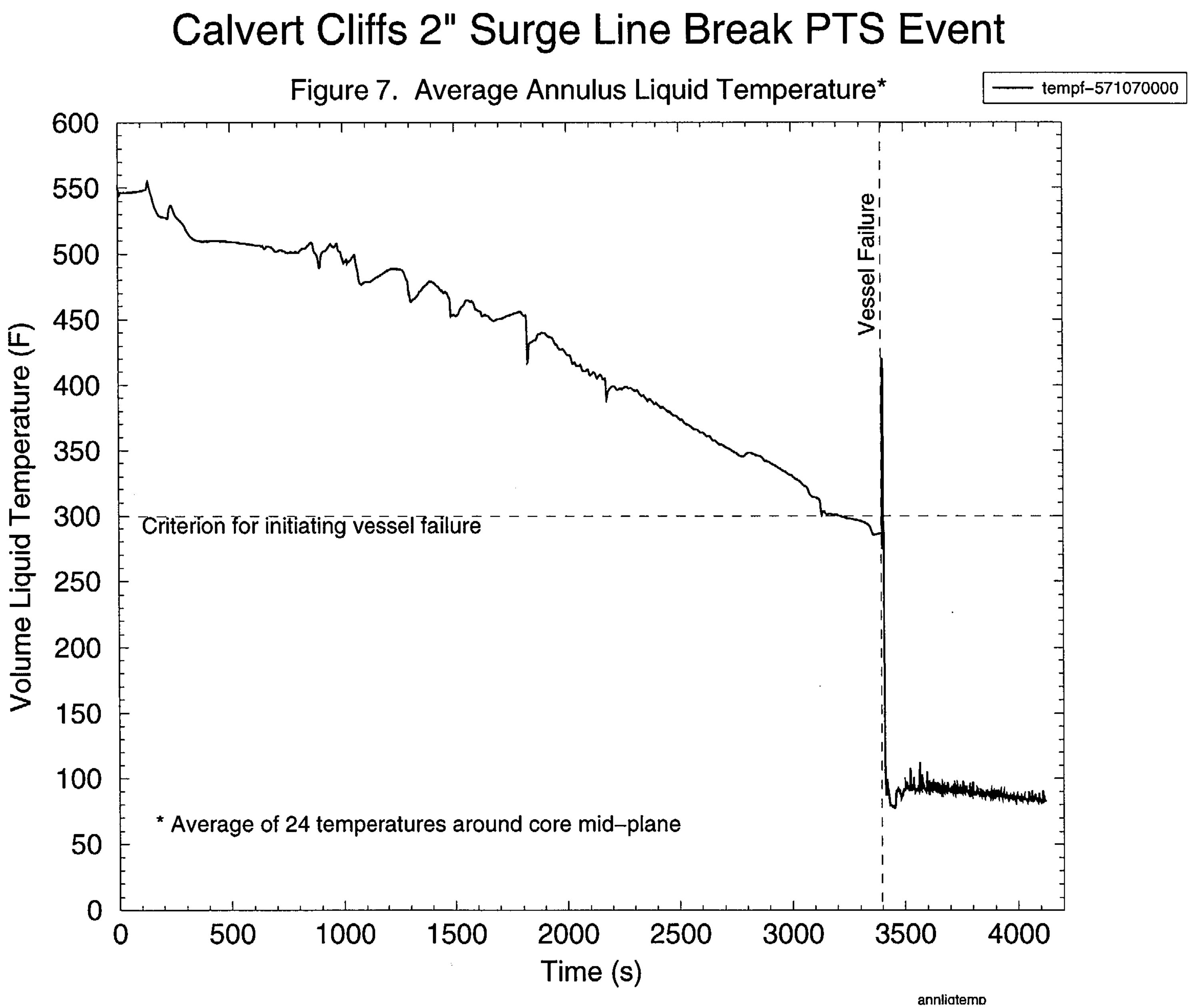


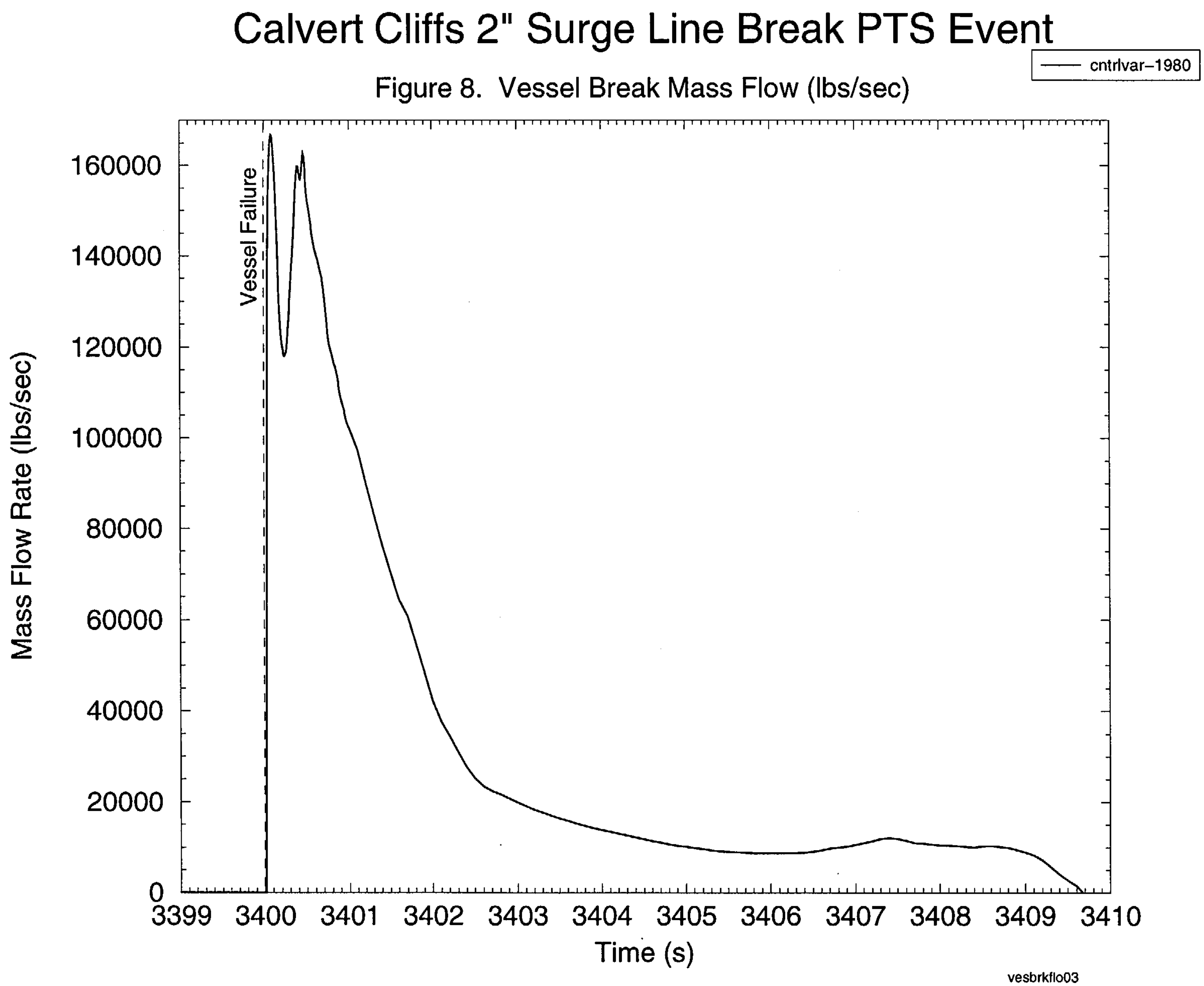
* Loop flows are average flows from 1100 to 3100 seconds.
XXX are junction numbers.
Arrows and adjacent numbers indicate direction and magnitude of flows.

loopflows

Calvert Cliffs 2" Surge Line Break PTS Event

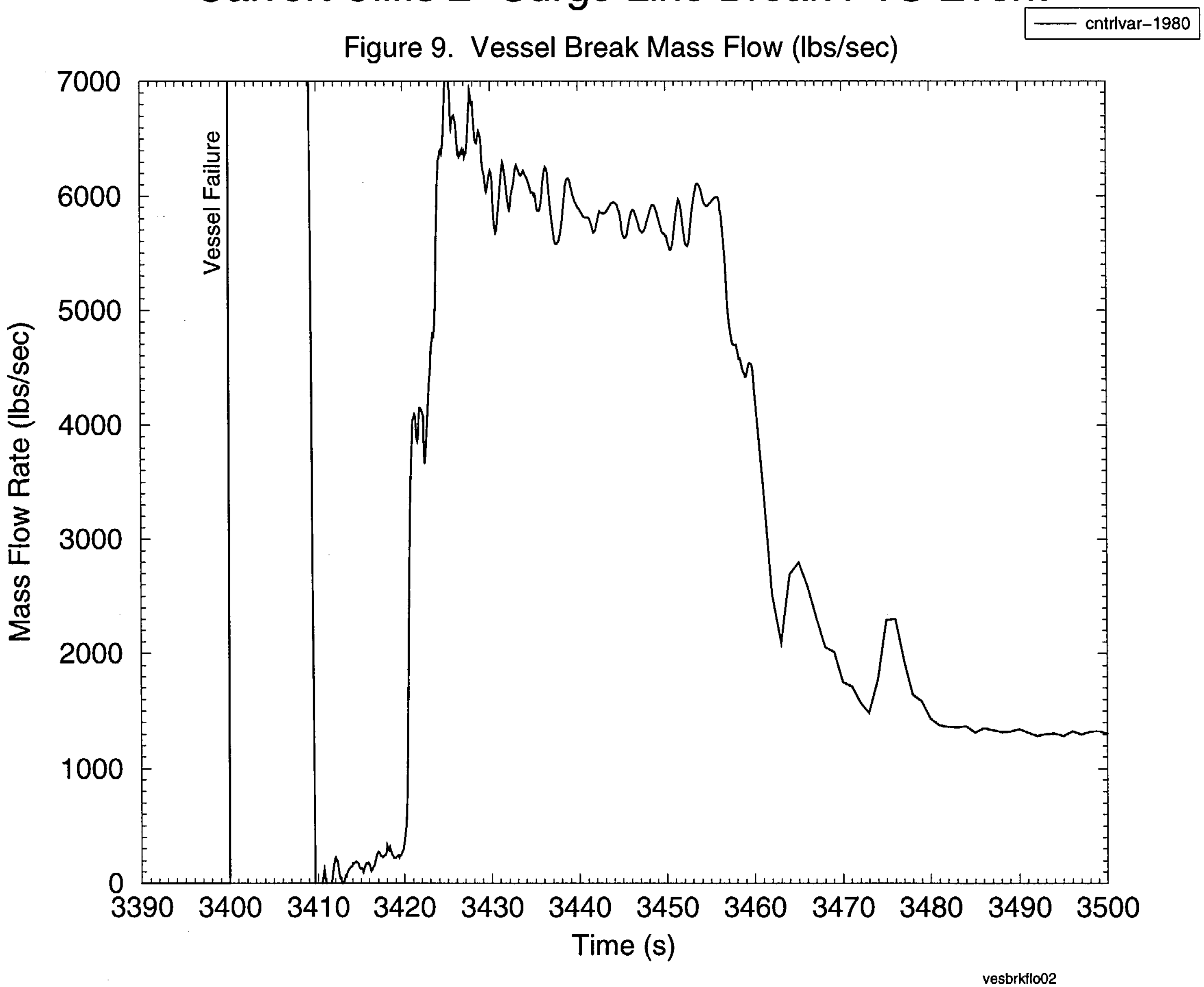



Calvert Cliffs 2" Surge Line Break PTS Event
Figure 7. Average Annulus Liquid Temperature*
tempf-571070000
Volume Liquid Temperature (F)
Time (s)
Vessel Failure
Criterion for initiating vessel failure
* Average of 24 temperatures around core mid-plane
600
550
500
450
400
350
300
250
200
150
100
50
0
500
1000
1500
2000
2500
3000
3500
4000
annliqtemp


Calvert Cliffs 2" Surge Line Break PTS Event
cntrlvar-1980
Figure 8. Vessel Break Mass Flow (lbs/sec)
Vessel Failure
Mass Flow Rate (lbs/sec)
160000
140000
120000
100000
80000
60000
40000
20000
0
3399
3400
3401
3402
3403
3404
3405
3406
3407
3408
3409
3410
Time (s)
vesbrkflo03

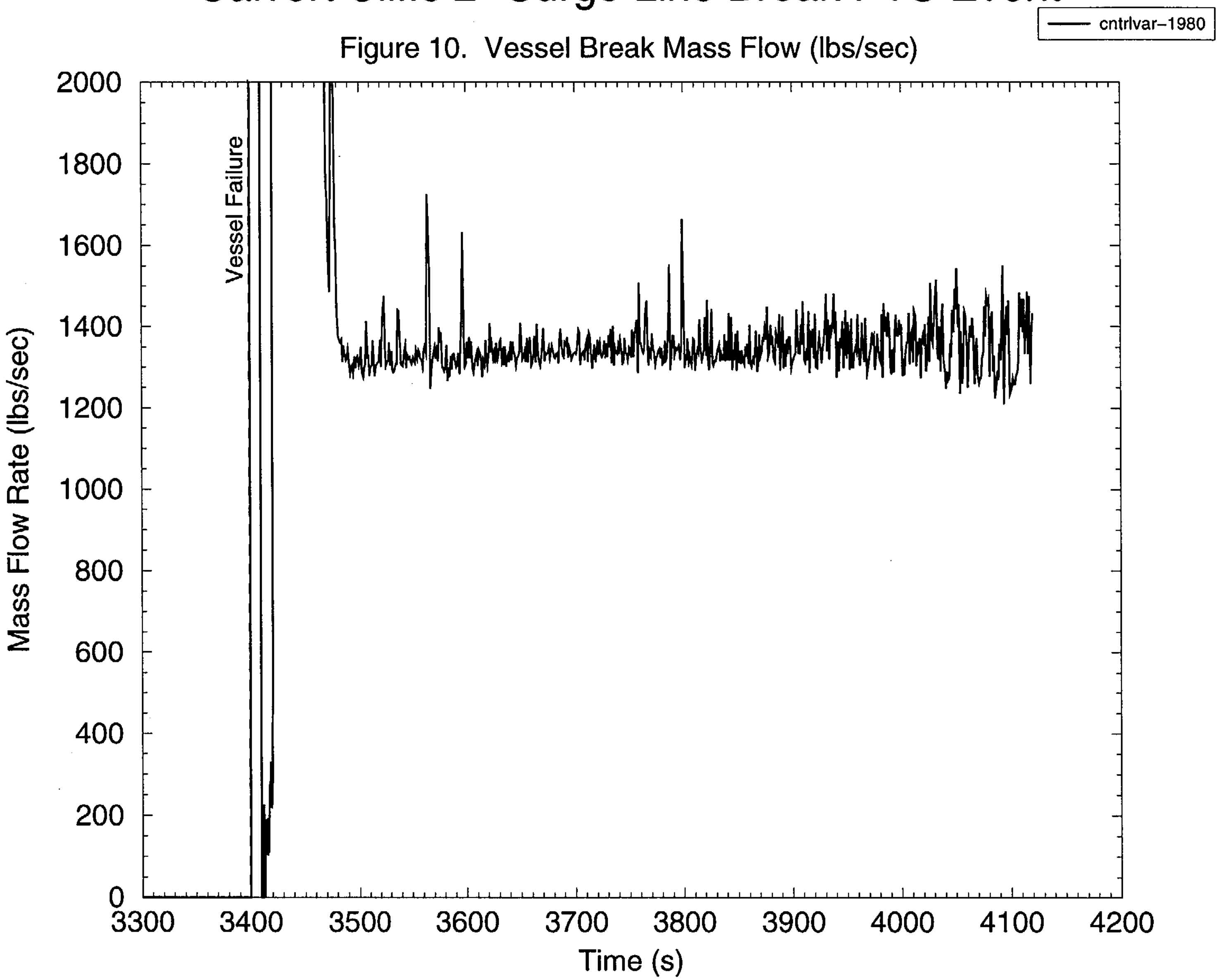
Calvert Cliffs 2" Surge Line Break PTS Event

Figure 9. Vessel Break Mass Flow (lbs/sec)



Calvert Cliffs 2" Surge Line Break PTS Event

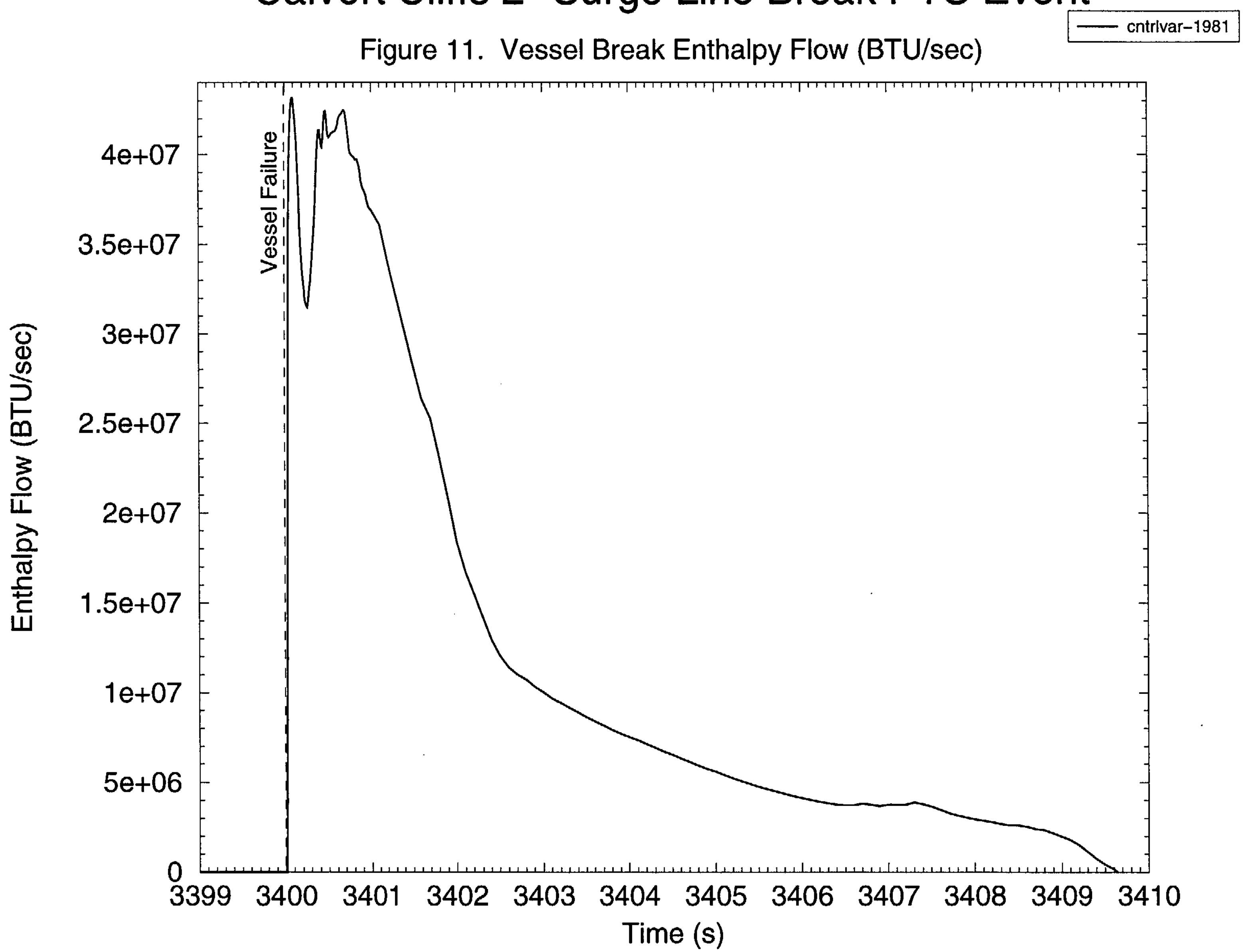
Figure 10. Vessel Break Mass Flow (lbs/sec)



vesbrkflo01

Calvert Cliffs 2" Surge Line Break PTS Event

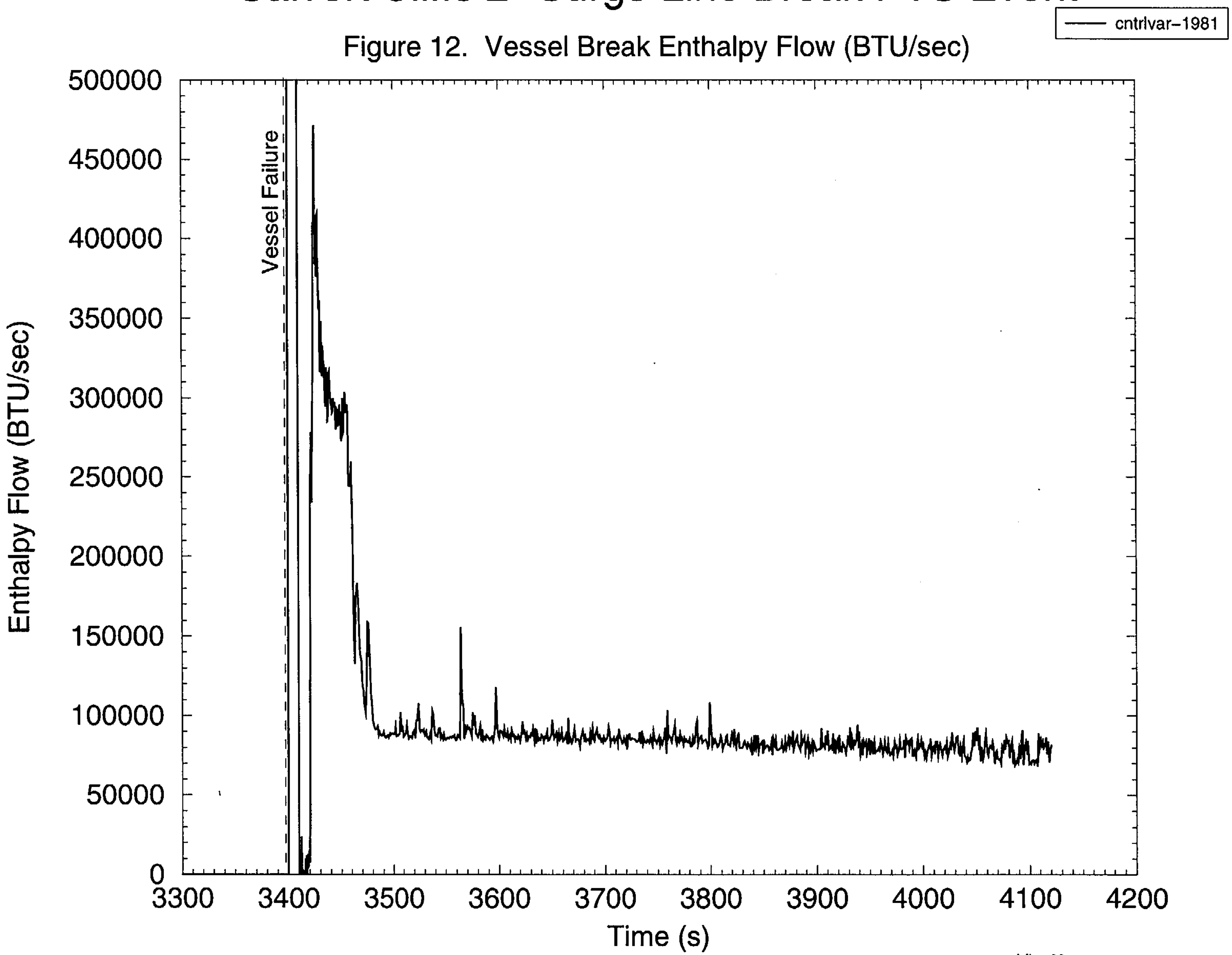
Figure 11. Vessel Break Enthalpy Flow (BTU/sec)



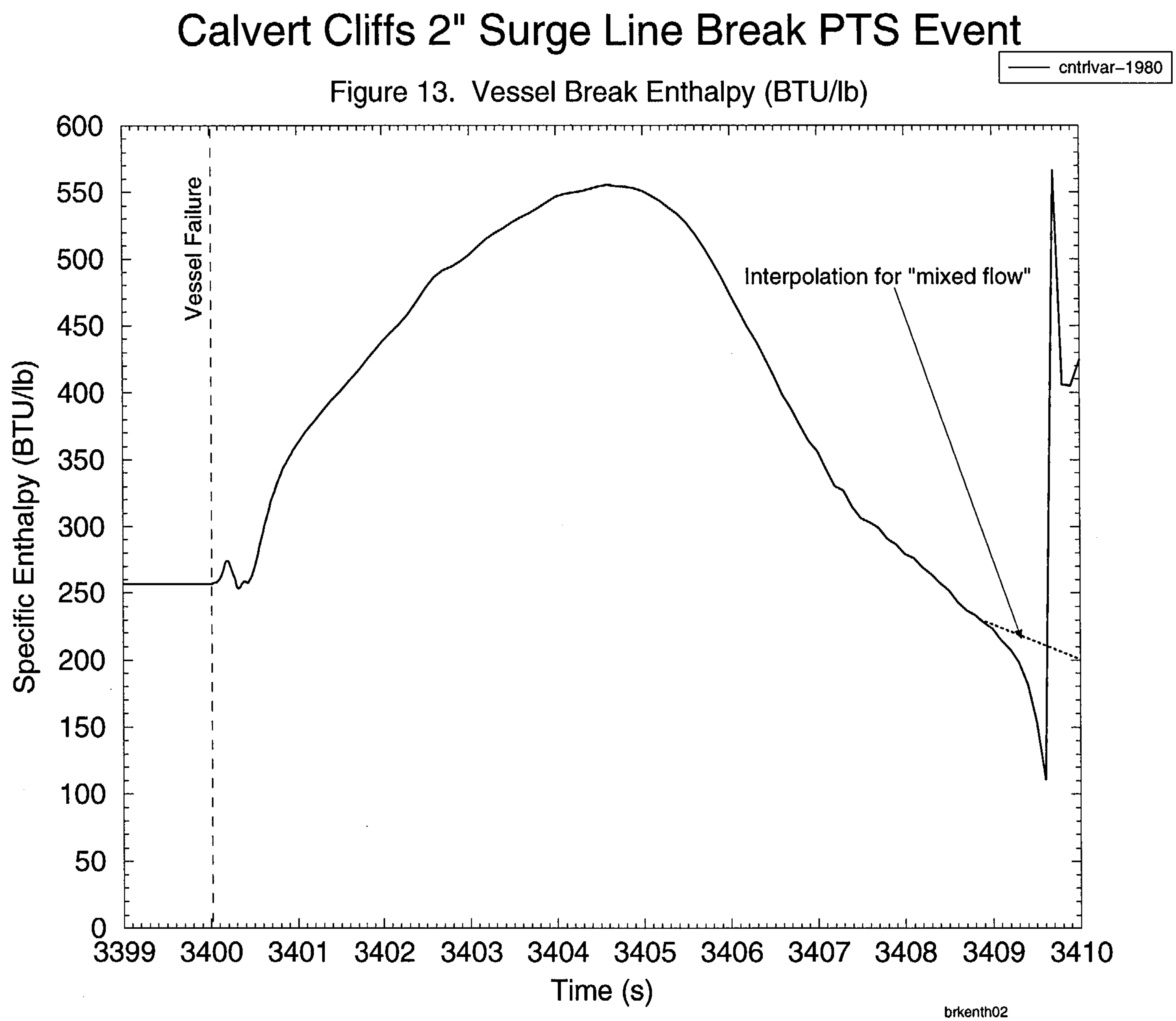
enthflow

Calvert Cliffs 2" Surge Line Break PTS Event

Figure 12. Vessel Break Enthalpy Flow (BTU/sec)



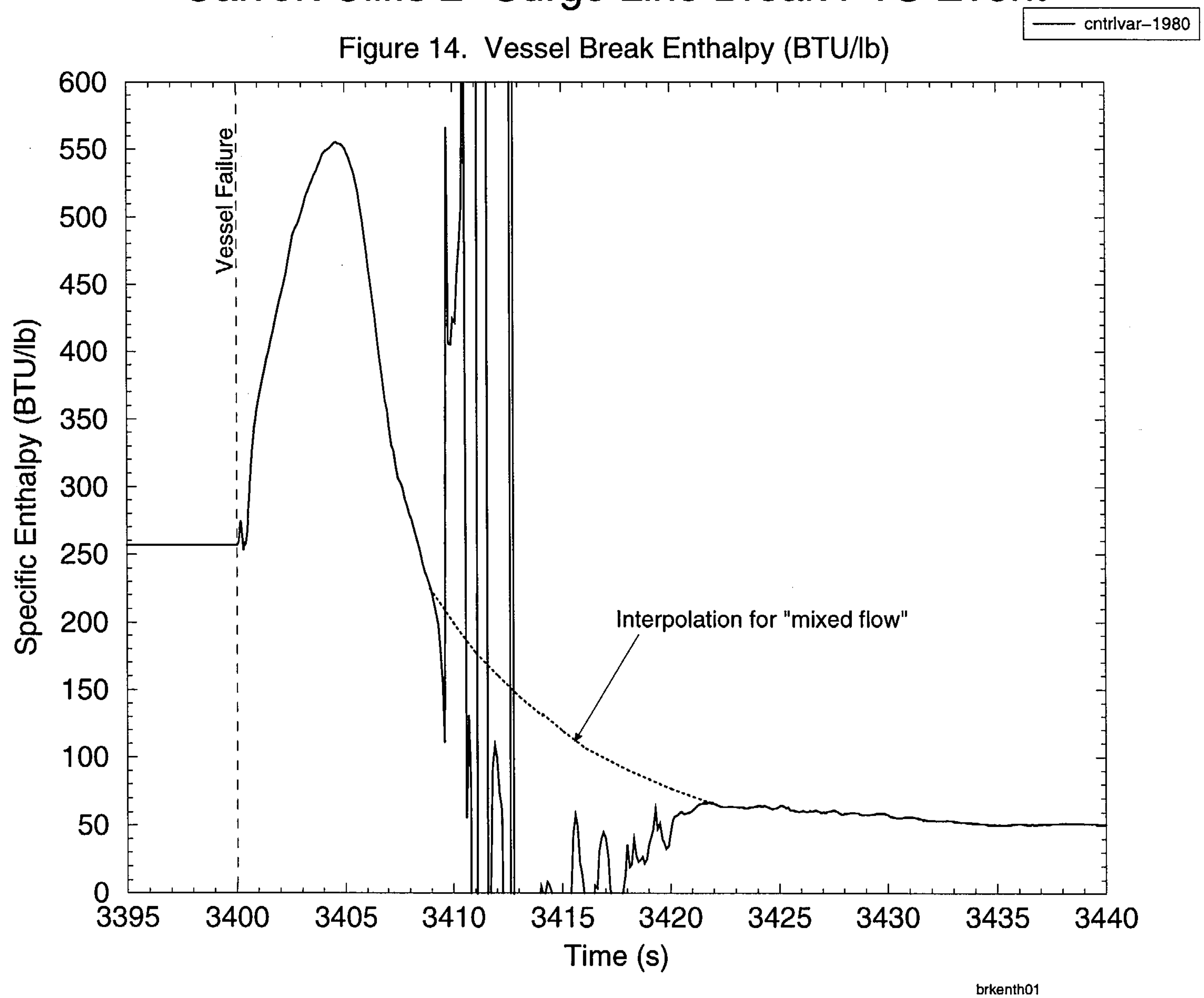
enthflow02



Calvert Cliffs 2" Surge Line Break PTS Event
cntrlvar-1980
Figure 13. Vessel Break Enthalpy (BTU/lb)
Specific Enthalpy (BTU/lb)
Time (s)
Vessel Failure
Interpolation for "mixed flow"
0
50
100
150
200
250
300
350
400
450
500
550
600
3399
3400
3401
3402
3403
3404
3405
3406
3407
3408
3409
3410
brkenth02

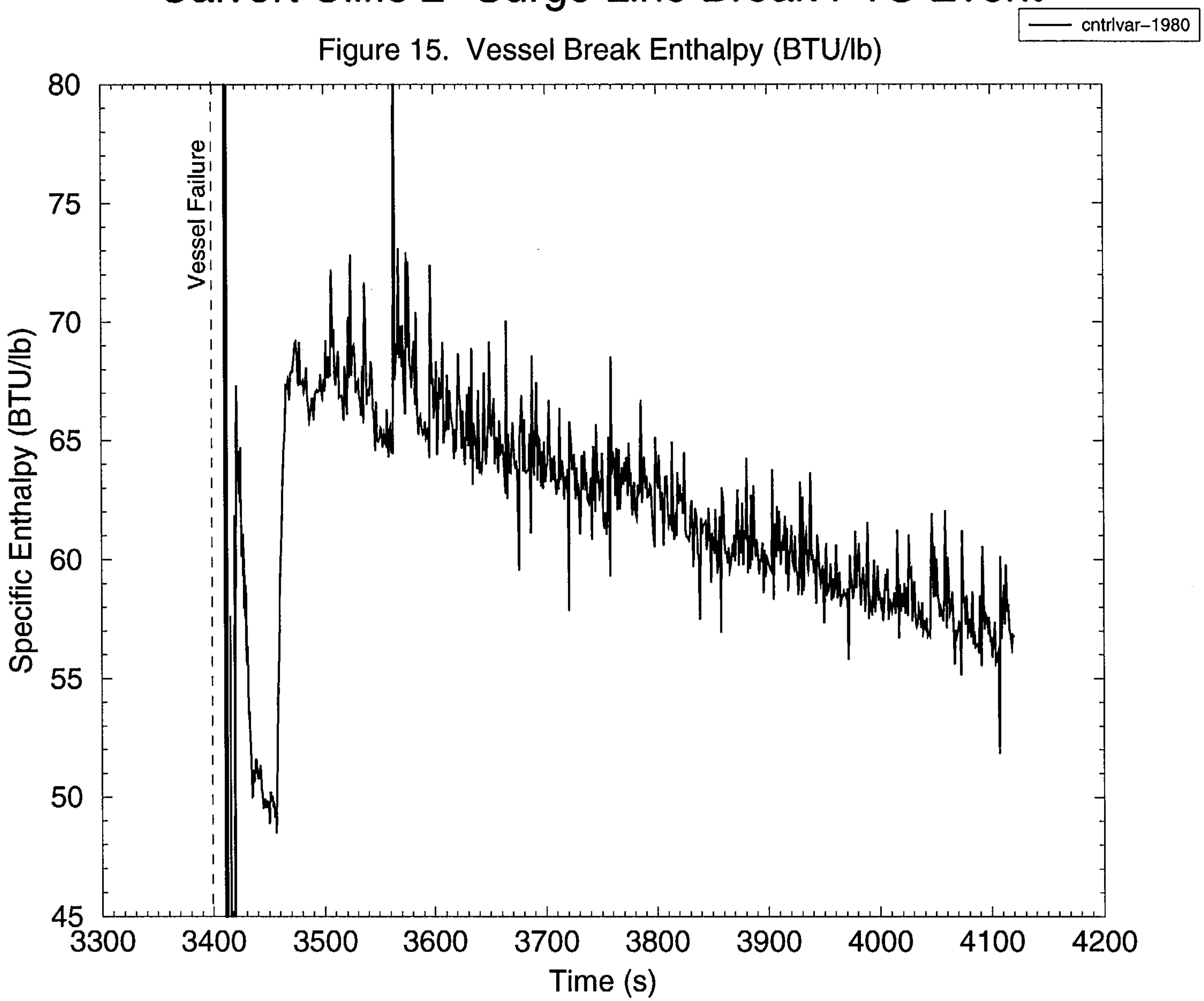
Calvert Cliffs 2" Surge Line Break PTS Event

Figure 14. Vessel Break Enthalpy (BTU/lb)



Calvert Cliffs 2" Surge Line Break PTS Event

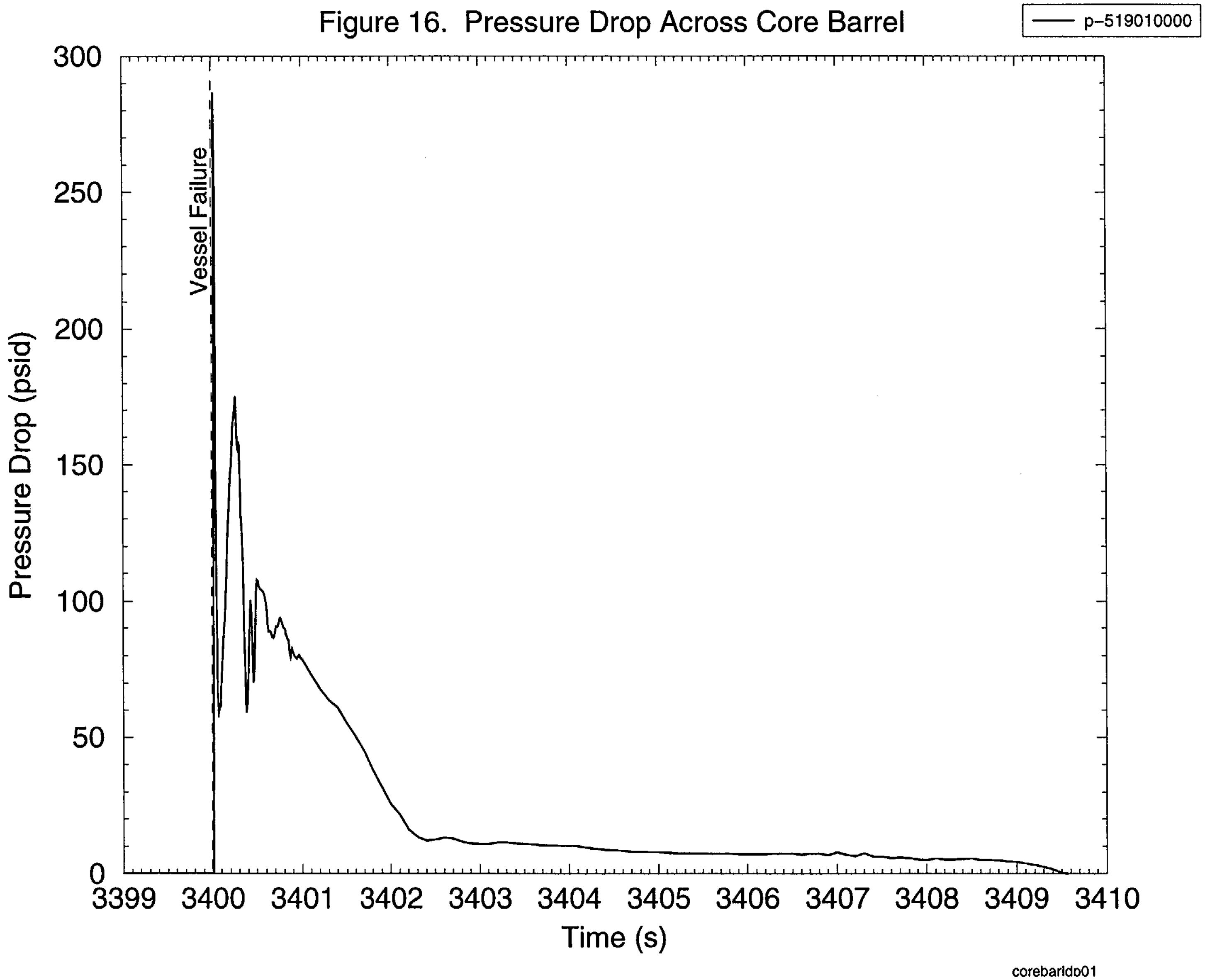
Figure 15. Vessel Break Enthalpy (BTU/lb)



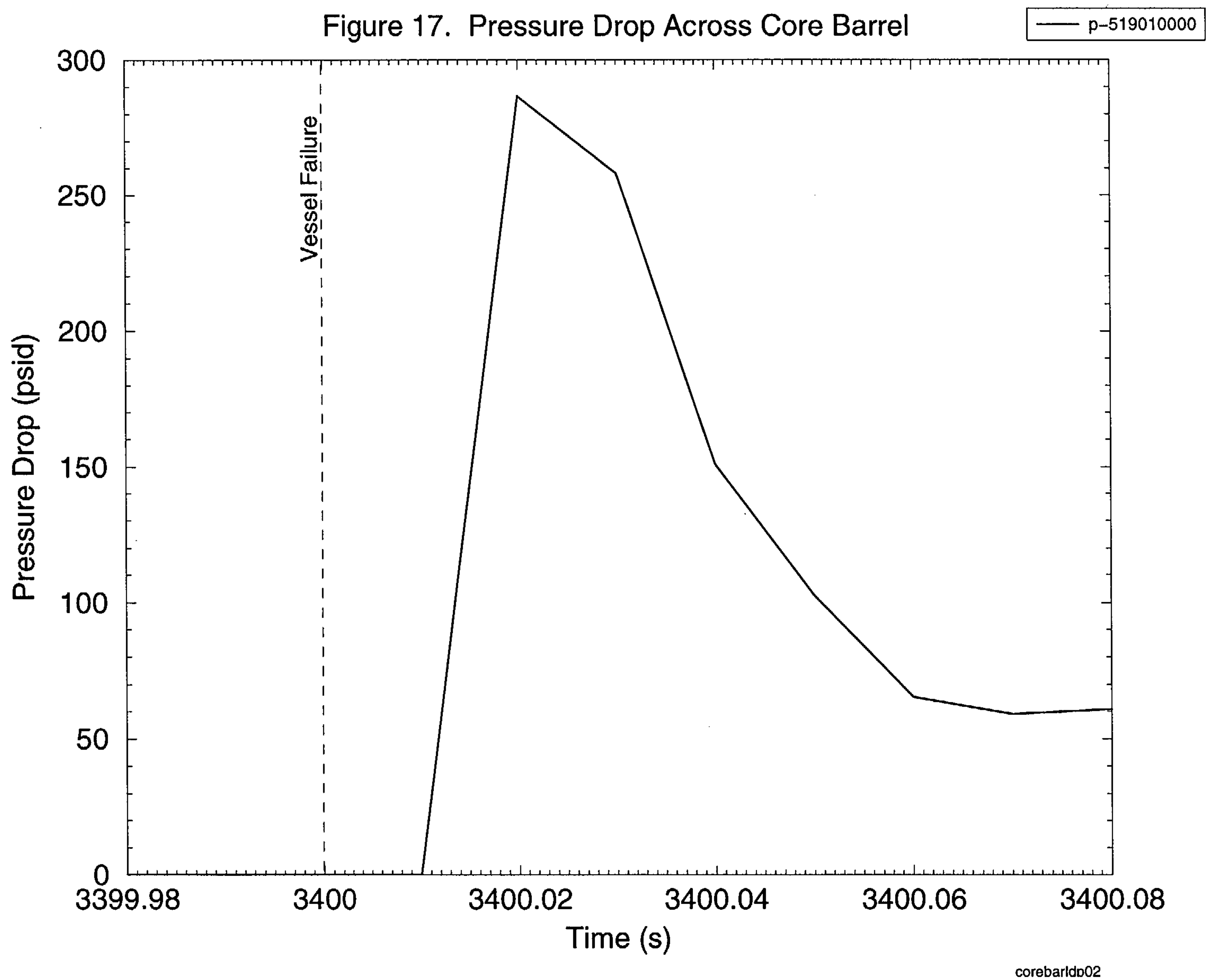
brkenth03

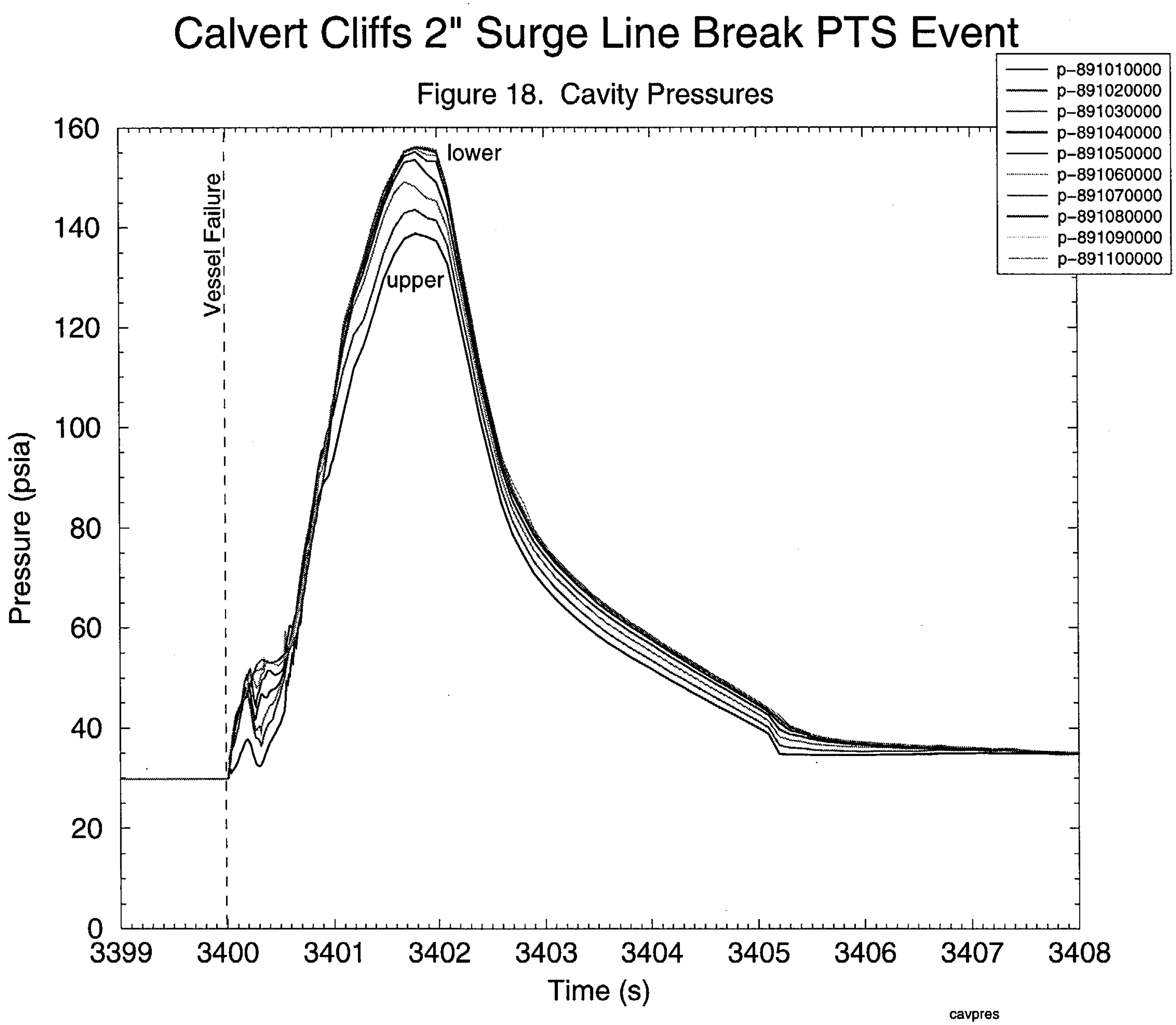
Calvert Cliffs 2" Surge Line Break PTS Event

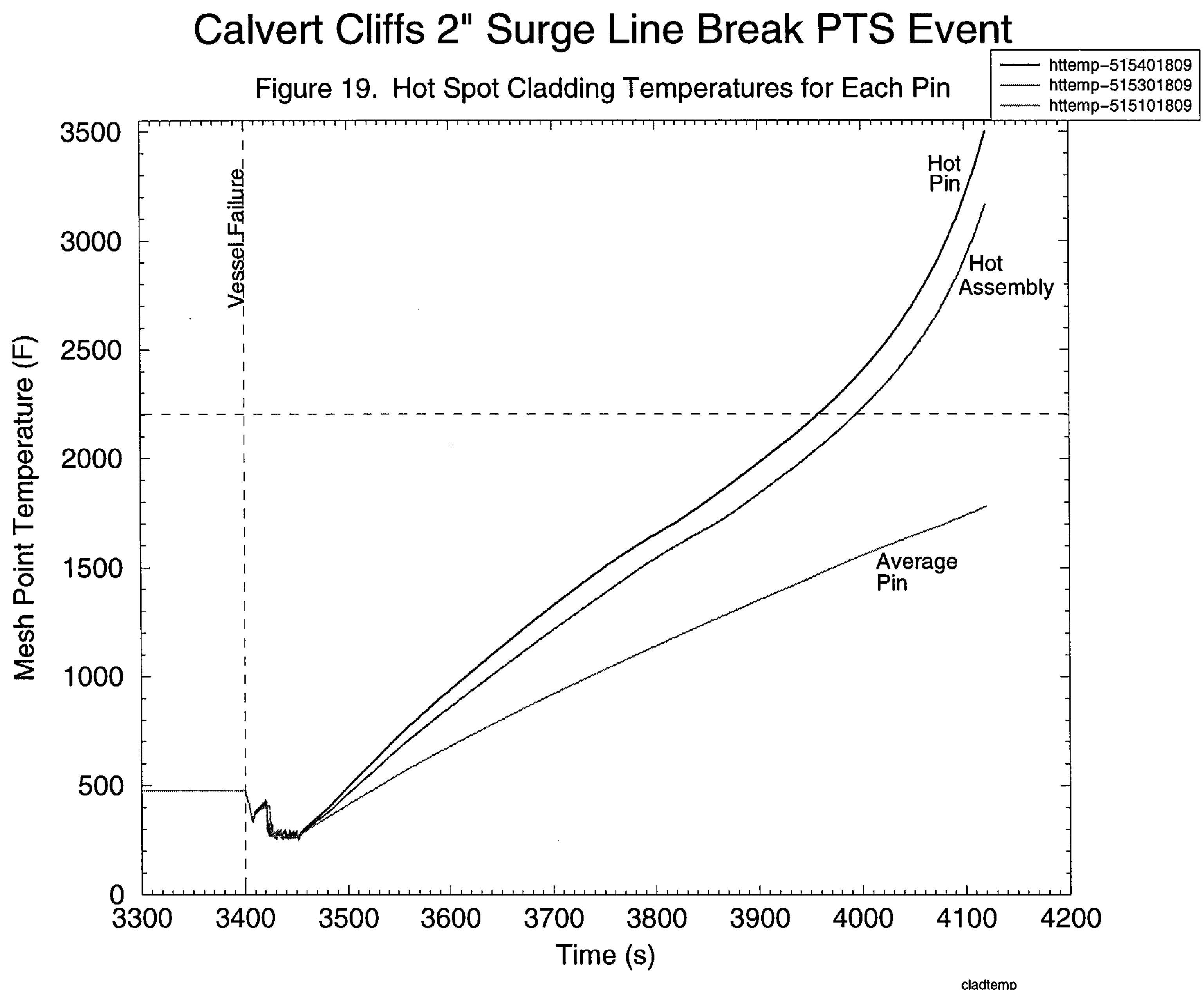
Figure 16. Pressure Drop Across Core Barrel



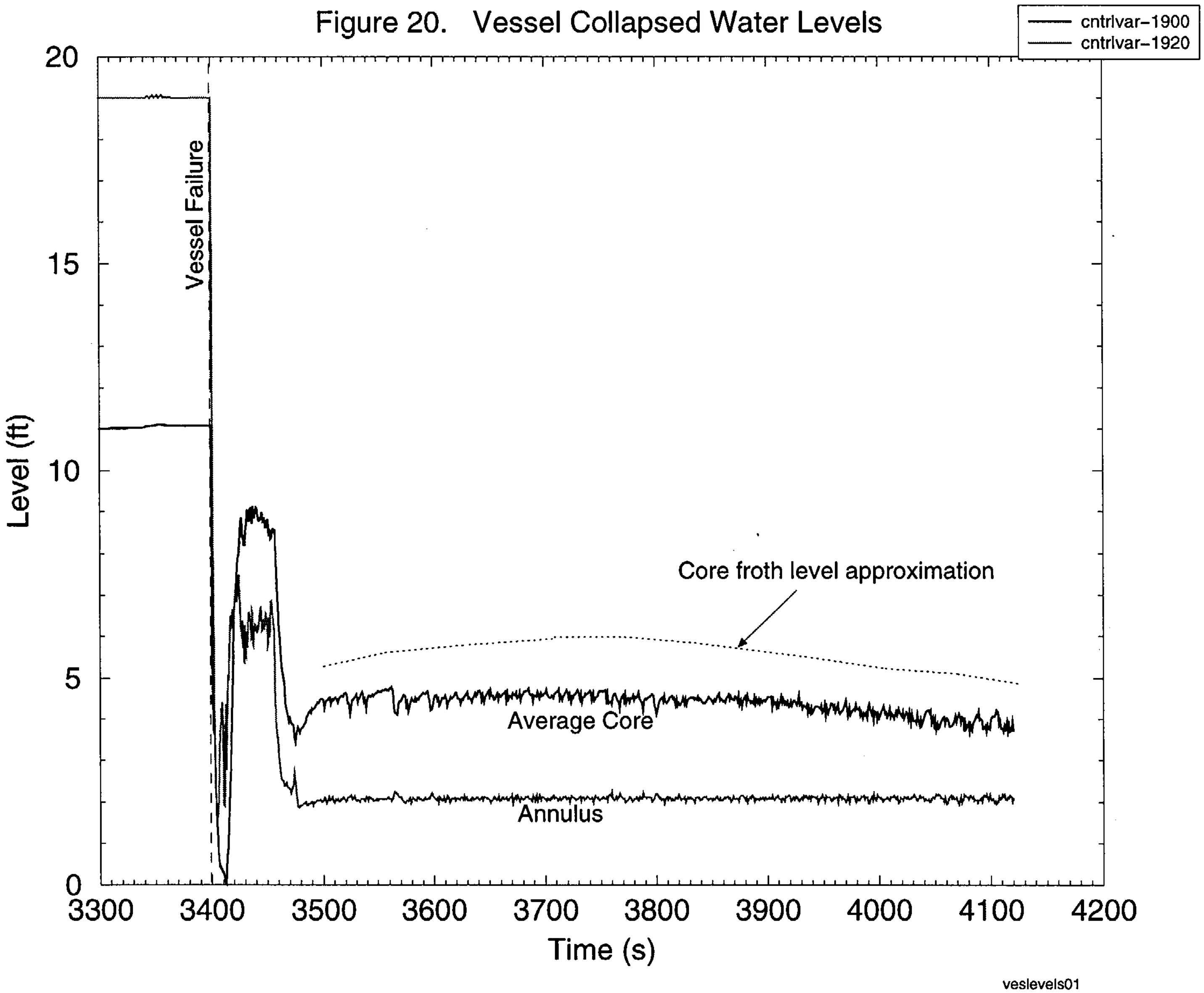
Calvert Cliffs 2" Surge Line Break PTS Event




Calvert Cliffs 2" Surge Line Break PTS Event
Figure 18. Cavity Pressures
p-891010000
p-891020000
p-891030000
p-891040000
p-891050000
p-891060000
p-891070000
p-891080000
p-891090000
p-891100000
Vessel Failure
lower
upper
Pressure (psia)
0
20
40
60
80
100
120
140
160
3399
3400
3401
3402
3403
3404
3405
3406
3407
3408
Time (s)
cavpres


Calvert Cliffs 2" Surge Line Break PTS Event
Figure 19. Hot Spot Cladding Temperatures for Each Pin
httemp-515401809
httemp-515301809
httemp-515101809
Mesh Point Temperature (F)
Time (s)
Vessel Failure
Hot
Pin
Hot
Assembly
Average
Pin
0
500
1000
1500
2000
2500
3000
3500
3300
3400
3500
3600
3700
3800
3900
4000
4100
4200
cladtemp

Calvert Cliffs 2" Surge Line Break PTS Event



Calvert Cliffs 2" Surge Line Break PTS Event