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GSI-191: Thermal-Hydraulic Response of PWR Reactor Coolant System and Containments to Selected Accident Sequences

Technical Letter Report

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Prepared by
K. W. Ross, D. V. Rao, and S. G. Ashbaugh

Los Alamos National Laboratory
Decision Applications Division
Probabilistic Risk Analysis Group (D-11)

M. L. Marshall, NRC Project Manager

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EXECUTIVE SUMMARY

The purpose of the Generic Safety Issue (GSI) 191 study is to determine if the transport and accumulation of debris in a containment following a loss-of-coolant accident (LOCA) will impede the operation of the emergency core cooling system (ECCS) in operating pressurized water reactors (PWRs). In the event of a LOCA within the containment of a PWR, thermal insulation and other materials (e.g., coatings and concrete) in the vicinity of the break will be damaged and dislodged. A fraction of this material will be transported to the recirculation (or emergency) sump and accumulate on the screen. The debris that accumulates on the sump screen forms a bed that acts as a filter. Excessive head loss across the debris bed may exceed the net positive suction head (NPSH) margin of the ECCS or containment spray (CS) pumps. For sump screens that are only partially submerged by water on the containment floor, excessive head loss across the debris bed may prevent water from entering the sump. Thus, excessive head loss can prevent or impede the flow of water into the core or containment. Also, excessive head loss across the debris bed may lead to ECCS or CS pump damage.

As part of the GSI-191 study, a parametric evaluation was performed to demonstrate whether sump failure is a plausible concern for operating PWRs. The results of the parametric evaluation form a credible technical basis for determining whether sump blockage is a generic concern for PWRs. In support of the parametric evaluation and the overall research objectives for GSI-191, US Nuclear Regulatory Commission (NRC) computer codes (RELAP5 and MELCOR) have been used to simulate reactor coolant system (RCS) and containment thermal-hydraulic response to a number of accidents that may potentially cause insulation debris to be collected on the sump screen. This technical letter report (TLR) documents these thermal-hydraulic calculations. The calculations were performed with three primary objectives.

1. Identify important RCS and containment thermal-hydraulic parameters that influence the generation and/or transport of debris in PWR containments.
2. Perform plant simulations using NRC computer codes to determine the value of each parameter as a function of time and, where applicable, as a function of the assumed system's response. Of particular interest are plant simulations of small and medium LOCAs for which information regarding accident progression is not readily available.
3. Use the calculated plant response information to construct accident progression sequences that form the basis for strainer blockage evaluations and probabilistic risk evaluations.

In considering the results presented here, it should be recognized that the RCS and containment models used, although representative of a class of PWRs, do not altogether reflect the uniqueness of any particular plant. RCS and containment responses to the accidents studied would likely differ sizably between plants dependent on numerous specific factors. Many of the noteworthy RCS and containment specifics included in the models used in the subject analyses are identified in this report. The reader should be mindful of the modeling specifics when considering the course of the accident simulations presented.

The research documented here was used directly in the generic assessment of vulnerability of the PWR population to the sump blockage safety concern as presented in Los Alamos National Laboratory report LA-UR-01-4083, "GSI-191: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance." Details regarding input data used, methods applied, and assumptions made in the parametric evaluation are based on this report.

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LIST OF ACRONYMS AND ABBREVIATIONS

ADV	Atmospheric Dump Valve
AFW	Auxiliary Feedwater
CCW	Component Cooling Water
CS	Containment Spray
DEGB	Double-Ended Guillotine Break
DER	Daily Event Report
ECCS	Emergency Core Cooling System
EOP	Emergency Operating Procedure
ESF	Engineered Safety Features
FSAR	Final Safety Analysis Report
GSI	Generic Safety Issue
HPSI	High-Pressure Safety Injection
LANL	Los Alamos National Laboratory
LLOCA	Large LOCA
LOCA	Loss-of-Coolant Accident
LOFW	Loss of Feedwater
LOSP	Loss of Offsite Power
LPSI	Low-Pressure Safety Injection
MLOCA	Medium LOCA
NEI	Nuclear Energy Institute
NPSH	Net Positive Suction Head
NRC	U.S. Nuclear Regulatory Commission
PDT	Pressurizer Drain Tank
PORV	Power-Operated Relief Valve
PRT	Pressurizer Relief Tank
PWR	Pressurized Water Reactor
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RHR	Residual Heat Removal
RWST	Refueling Water Storage Tank
SAT	Spray Additive Tank
SI	Safety Injection
SLOCA	Small LOCA
TLR	Technical Letter Report
ZOI	Zone of Influence

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1.0 INTRODUCTION

The purpose of the Generic Safety Issue (GSI) 191 study is to determine if the transport and accumulation of debris in a containment following a loss-of-coolant accident (LOCA) will impede the operation of the emergency core cooling system (ECCS) in operating pressurized water reactors (PWRs). In the event of a LOCA within the containment of a PWR, thermal insulation and other materials (e.g., coatings and concrete) in the vicinity of the break will be damaged and dislodged. A fraction of this material will be transported to the recirculation (or emergency) sump and accumulate on the screen. The debris that accumulates on the sump screen forms a bed that acts as a filter. Excessive head loss across the debris bed may exceed the net positive suction head (NPSH) margin of the ECCS or containment spray (CS) pumps. For sump screens that are only partially submerged by water on the containment floor, excessive head loss across the debris bed may prevent water from entering the sump. Thus, excessive head loss can prevent or impede the flow of water into the core or containment. Also, excessive head loss across the debris bed may lead to ECCS- or CS-pump damage.

As part of the GSI-191 study, a parametric evaluation (Ref. 1) was performed to determine whether sump failure is a plausible concern for operating PWRs. The results of the parametric evaluation form a credible technical basis for determining whether sump blockage is a generic concern for PWRs. In support of the parametric evaluation and the overall research objectives for GSI-191, seven plausible accidents were identified that may potentially cause insulation debris to be collected on the sump screen (Ref. 2). Computer codes (RELAP5 and MELCOR) developed for the U.S. Nuclear Regulatory Commission (NRC) were used to simulate the reactor coolant system (RCS) and containment thermal-hydraulic response to these accidents. The calculations were performed with three primary objectives.

1. Identify important RCS and containment thermal-hydraulic parameters that influence the generation and/or transport of debris in PWR containments.
2. Perform plant simulations using NRC computer codes to determine the value of each parameter as a function of time and, where applicable, as a function of the assumed system's response. Of particular interest are plant simulations of a small LOCA (SLOCA) and medium LOCA (MLOCA) for which information regarding accident progression is not readily available.
3. Use the calculated plant response information to construct accident progression sequences that form the basis for strainer blockage evaluations and probabilistic risk evaluations.

Figure 1 shows the major steps involved in the calculation effort. These include the following.

- RELAP5/MOD3.2 (Ref. 3) was used to simulate the RCS response to each of the postulated accident sequences. The plant type chosen for the simulations is a Westinghouse four-loop design.
- MELCOR Version 1.8.2 (Ref. 4) was used to simulate an ice-condenser containment and a large dry containment response to the release of steam/water into the containment as a result of each accident sequence.

This technical letter report (TLR) documents the RELAP5 and MELCOR thermal-hydraulic calculations described above. A description of the accident sequences analyzed, the scope of the analyses performed, and the parameters tracked are presented in Sec. 2. Section 3 provides a brief description of the input information used in the simulations, including nodalization drawings. Section 4 presents the results of simulations, with the supporting details provided in Appendices A through D. Finally, Sec. 5 lists the references cited in this report.

In considering the results presented here, it should be recognized that the RCS and containment models used, although representative of a class of PWRs, do not altogether reflect the uniqueness of any particular plant. RCS and containment responses to the accidents studied would likely differ sizably between plants dependent on numerous specific factors. Many of the noteworthy RCS and containment specifics included in the models used in the subject analyses are identified in this report. The reader should be mindful of the modeling specifics when considering the course of the accident simulations presented here.

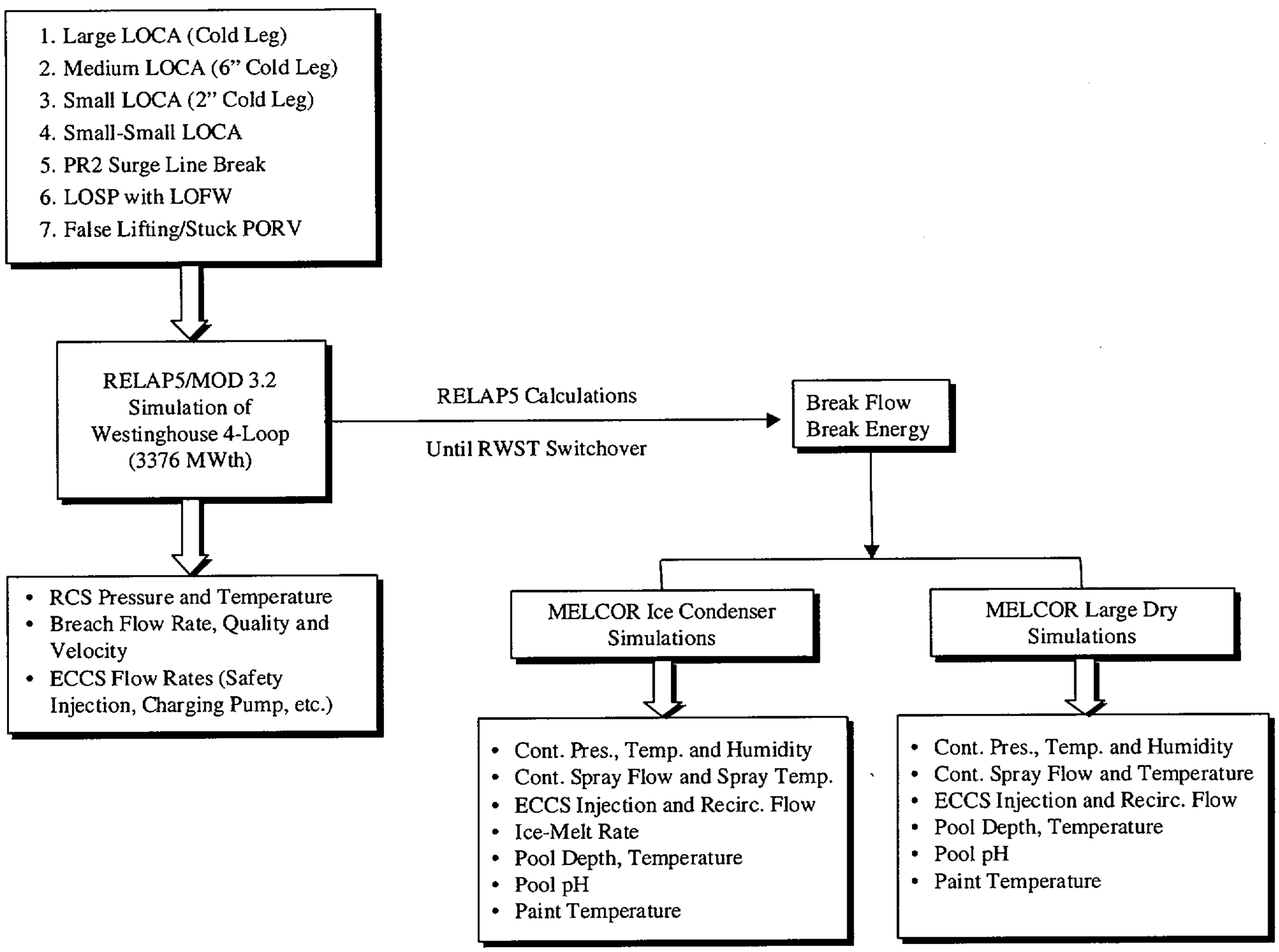


Fig. 1. Flow Chart of Analysis Process.

2.0 SCOPE

A primary breach[1] in a PWR (e.g., a LOCA) would expel the RCS inventory to the containment as an energetic two-phase jet that would have a destructive effect on structures and equipment. Thermal insulation in the proximity of the breach could be destroyed by direct jet impingement. Jet impingement could also create debris from concrete spallation, washdown of existing dirt and dust, or stripping of containment coatings from surfaces. The high-temperature/pressure containment environment that can be created by an accident could also potentially result in additional generation of debris in the long term. A valid concern is that these types of debris would be transported to the containment emergency sump, where they would restrict flow and either consume the available NPSH or starve the ECCS recirculation pumps.

The phenomena of debris generation associated with an energetic release of RCS inventory to containment would depend largely on the fluid properties and flow characteristics at the breach. The phenomena of the debris transport would depend strongly on the thermal-hydraulic conditions existing in containment. The intent of the simulations documented here was to characterize the breach flows and ensuing containment responses associated with several varied accident scenarios resulting in energetic releases of RCS inventory to containment. The scenarios addressed included LOCAs of varied sizes and transients where power-operated relief valve (PORV) venting to the pressurizer relief tank (PRT) eventually would lead to the rupturing of a PRT burst disk.

To predict the characteristics of a jet from an RCS breach and the subsequent response of a PWR containment, detailed computer simulations were performed with the RELAP5 and MELCOR computer codes. RELAP5 was used to predict the mass and energy additions to the containment that would result from various RCS breaches and to determine the originating properties of the associated jets. RELAP5 simulations incorporated realistic initial and boundary conditions and a full representation of a Westinghouse four-loop plant.

MELCOR was applied to predict the response of large dry and ice-condenser containments to the mass and energy additions predicted by RELAP5. The response of sub-atmospheric containments was inferred from the results of the large dry containment simulations (see Sec. 2.3). The MELCOR models used in the simulations accurately represented typical containment structures and systems.

The results of the accident simulations presented in Sec. 4 are limited to those parameters considered to influence debris generation and transport. A broader presentation of the results is included in Appendices A through D.

In considering the results presented here, it should be recognized that the RCS and containment models used are representative of a class of PWRs, but they do not altogether reflect the uniqueness of any particular plant. The RCS and containment responses to the accidents studied would likely differ sizably from plant to plant depending on numerous specific factors, for example, the containment high-high pressure set point (and associated CS activation logic). Many of the key factors included in the models used in the subject analyses are given in this report. The reader should be mindful of the modeling specifics when considering the course of the accident simulations presented here.

2.1 Initiating Events

Seven distinct initiating events and resulting accident scenarios were chosen for the thermal-hydraulic simulations. These were based on a comprehensive study performed by Los Alamos National Laboratory (LANL) that ranked the importance of postulated accidents to the sump blockage safety concern (Ref. 2). These rankings considered the potential for generation of debris using the preferred mitigation strategy and whether the preferred mitigation strategy requires the use of the ECCS sump for either core or containment cooling.

A pressurizer surge line break also was simulated because of issues related to piping qualified as leak-before-break. Also, in addition to the accidents recommended for consideration, an intermediatesized LOCA was included to more fully address the range of conceivable LOCAs. Therefore, integrated RELAP5 and MELCOR (both large dry and ice-condenser) simulations were performed for the following cases.

1. Large LOCA (LLOCA)
2. MLOCA
3. SLOCA
4. Small-small LOCA
5. Pressurizer surge line break
6. Loss-of-offsite-power (LOSP) event with subsequent loss of feedwater (LOFW)
   - Where the operators hold one PORV open when it first lifts
   - Where the operators aggressively cool the reactor beginning 30 min after the loss of offsite power
   - Where no action is taken by the operators for 2-1/2 h
7. False opening of a PORV and the valve sticking open

Descriptions of these events follow. Except where otherwise noted, all accident mitigation equipment and systems were assumed to function as designed.

LLOCA

The LLOCA simulated was a cold-leg, pump-discharge, double-ended-guillotine break (DEGB). The RCS pressure and average temperature before the break were 2250 psia and 570 °F, respectively. The cold-leg inside diameter was 27.5 in., corresponding to a cross-sectional area of 4.12 ft^2. The break was assumed to occur instantaneously, and a discharge coefficient of unity was applied.

MLOCA

The MLOCA simulated was a 6-in.-diam (0.1963-ft^2) circular hole in a cold leg downstream of the reactor coolant pump (RCP). The hole became full-sized instantaneously. It was situated on the side of the cold leg and centered halfway up. A unity discharge coefficient was applied. The cold-leg location of the hole was chosen arbitrarily and is not expected to be a determining factor in the simulation results.

SLOCA

The SLOCA studied was a 2-in.-diam (0.0218-ft^2) circular hole in a cold leg downstream of the RCP.[2] The hole became full-sized instantaneously. It was situated on the side of the cold leg and centered halfway up. A unity discharge coefficient was defined. The cold-leg location of the hole was chosen arbitrarily and is not expected to be a determining factor in the simulation results. The 2-in. specification of this hole was made with the expectation that the RCS pressure would stabilize above the accumulator pressure such that the accumulators would not inject. For SLOCA events, it is possible that automatic actuation of sprays may not be required, depending on the status of containment heat removal systems (e.g., fan coolers) and the spray actuation set point. Therefore, two sets of calculations were performed for SLOCA events in a large dry containment. The base MELCOR model assumes that the fan coolers are operational (see Sec. 3.2 for the MELCOR model description), and a sensitivity calculation was performed that assumed that the fan coolers did not operate. The results from these calculations can be compared to draw conclusions regarding whether spray actuation may be required for a particular plant (depending on whether fan coolers are qualified to operate under accident conditions and the CS set point).

SMALL-SMALL LOCA

The small-small LOCA considered was a 215-gpm leak with the reactor at power. The leak was placed in a cold leg downstream of the RCP. The cold-leg placement of the leak was chosen arbitrarily and is not expected to be a determining factor in the simulation results. The 215-gpm specification is insufficient to remove reactor core decay heat.

Pressurizer Surge Line Break

A DEGB of a pressurizer surge line was simulated. The break was placed at the mid-elevation between the top of the hot leg and the bottom of the pressurizer. The break was assumed to be complete instantaneously and to occur in the pressurizer compartment of the containment.

Loss of Offsite Power with Subsequent Loss of Feedwater

As a consequence of a LOSP (by definition),

- the condensate pumps lose power,
- the turbine-driven main feedwater pumps trip,
- the control rods drop,
- the turbine stop valve closes,
- the turbine bypass valve fails closed, and
- the RCPs lose power and begin coasting down.

The additional complication assumed here was that the auxiliary feedwater (AFW) system fails to deliver water to the steam generators indefinitely. This means that the steam generators become ineffective as a heat sink shortly into the transient and that reactor temperature must be managed with feed-and-bleed cooling. The steam generators become ineffective as heat sinks as they dry out, which occurs as their inventory boils off and vents through the atmospheric dump valves (ADVs). Feed-and-bleed operations have the potential to overwhelm the PRT, causing burst disk rupture, debris generation, and pool formation in containment. Extended feed-and-bleed operations have the potential to exhaust the refueling water storage tank (RWST) and require ECCS recirculation through the containment emergency sump.

Three variations on the LOSP event were undertaken. The variations were in the degree and timing of operator intervention. The variations were

- the operators hold one PORV open when it first lifts,
- the operators aggressively cool the reactor through managed feed-and-bleed operations beginning 30 min after the loss of offsite power, and
- the operators delay taking any manual action to cool the reactor until all core exit subcooling is lost approximately 2-1/2 h after the LOSP.

The first variation is consistent with expected operator actions for managing a desirable cooling rate for the reactor system with respect to thermal stress considerations (50°F/h to 100°F/h). The second variation explores the possibility of potential operator response if circumstances called for the reactor system to be cooled as quickly as possible. In this simulation, both PORVs and all four main steam ADVs were fixed open at 30 min. The third variation reflects considerable delay in operator intervention to cool the reactor system for any reason. In this simulation, the operator delay was assumed to persist up to the time when all core exit subcooling was lost. Upon that condition being reached, both PORVs were fixed open.

False Opening of a PORV and the PORV Sticking Open

As with the feed-and-bleed scenarios described above, a stuck-open PORV has the potential to overwhelm the PRT, causing burst disk rupture, debris generation, and pool formation in the containment. If ECCS recirculation through the emergency sump is required, then debris transport to the sump becomes a concern. Although the false opening of a PORV is improbable, it is the transient progression from the time at which the PORV lifts and sticks that is of interest here. The effort was not made to model a more probable initiating event that would lead to a PORV opening. The PORV was assumed to stick in the full-open position instantaneously with the reactor at rated power.

2.2 Parameters of Interest

The parameters of interest in the simulations were the properties at the RCS breach and the conditions in containment thought to influence debris generation and transport. Those parameters are listed below, and each is followed by a description of the influence it may have on debris generation and transport. The transient behavior for each parameter (with the exception of pool pH) was calculated by either RELAP5 or MELCOR for each accident scenario listed in Sec. 2.1

RCS PRESSURE AND TEMPERATURE

The flow through an RCS breach would be choked as long as the RCS temperature (and hence pressure) remains elevated. The critical (choked) flow rate through the breach would depend strongly on upstream pressure and temperature, which define the thermodynamic state of the fluid. The state of the fluid largely determines the expansion characteristics of a two-phase flashing jet (Ref. 5).

BREACH FLOW CONDITIONS (FLOW RATE, VELOCITY, AND QUALITY)

The destructive potential of a break jet would depend strongly on break flow conditions. The velocities of both phases (liquid and vapor) are important here. The values calculated are the velocities at the choke plane. In addition, the moisture content of the fluid exiting the breach influences the damage potential of the jet. The quantity calculated here is the ratio of vapor mass flow rate to total mass flow rate at the choke plane.

ECCS SAFETY INJECTION FLOW

The rates of ECCS safety injection determine when the inventory of the RWST would be depleted, requiring switchover to ECCS recirculation through the emergency sump. The timing of switchover is important with regard to debris settling opportunities. Flow patterns in the water pool formed on the floor of containment would be influenced by injection rates. Injection rates determine accident progression as related to the rate at which the RCS is cooled down.

ECCS RECIRCULATION FLOW

The rate at which flow is recirculated through the emergency sump will determine the flow patterns, velocities, and turbulence levels in the containment pool. The potential for debris transport is governed by these traits. In addition, the recirculation rate is a principal factor in calculating the pressure drop across any debris bed that develops on the sump screen.

CONTAINMENT SPRAY FLOW

Containment sprays have the potential to wash settled debris from containment structures and suspended debris from the containment atmosphere down to the containment pool. Whether the sprays are operating or not largely determines the time at which the RWST inventory is expended and the magnitude of the recirculation flow through the emergency sump. The flow patterns and turbulence levels in the containment pool may be affected by where and how the sprays drain.

The potential for containment sprays to influence debris transport is thought to be considerable. As such, it is important to note the large variability in spray activation logic that exists from plant to plant, e.g., containment high-high pressure set points. Additionally, actions taken by the operators to terminate CS operation would also influence debris transport.

CONTAINMENT SPRAY TEMPERATURE

In some plants, recirculated spray water would pass through heat exchangers. The heat removal would influence containment pressure and temperature trends. This phenomenon is of particular interest in ice-condenser containments. Therefore, special emphasis was put on modeling residual heat removal (RHR) heat exchangers and determining the expected spray temperature.

POOL DEPTH AND TEMPERATURE

The available NPSH at the recirculation pumps depends on the depth of the containment pool and its temperature. The velocities, flow patterns, and turbulence levels (and hence debris transport potential) in the pool depend on pool depth.

POOL pH

The dependencies of containment coating stability on pool pH are being considered as part of a current NRC study distinct from GSI-191. Estimates of pool pH were not obtained in the course of the GSI-191 thermal-hydraulic analyses. The predicted integral break, injection, and spray flows could be used in hand calculations of the pH in the containment pool, but efforts to track pH in the thermal-hydraulic analyses were not made.

CONTAINMENT ATMOSPHERIC VELOCITY

The atmospheric velocities generated in the containment in response to an RCS breach determine to what degree generated debris initially disperses within the containment. These are the velocities developed as the containment is subjected to the shock and pressurizing effects of the flashing break jet.

PAINT TEMPERATURE

Sustained elevated temperatures may degrade containment paints. An elaborate paint representation model was included in the MELCOR input model.

3.0 MODEL DESCRIPTIONS

3.1 RELAP5 RCS Model

The RELAP5 model used in the PWR RCS calculations employed realistic initial and boundary conditions and a detailed representation of a Westinghouse four-loop plant. Figure 2 shows the nodalization of the RCS modeled. The model included accurate representations of the reactor core, reactor vessel, steam generators, pressurizer, RCPs, loop piping, and ECCS. Accumulators were included, as were steam generator ADVs, pressurizer PORVs, and safety valves. A pressurizer relief tank was incorporated complete with burst disks and piping from the PORVs. The metal mass of the RCS was represented.

Reactor transient power was calculated by RELAP5's point-kinetics solution with active density and Doppler reactivity feedback. Power was initialized at 3376 MW, and a chopped cosine (0.55, 1.145, 0.55) axial profile was imposed. A scram signal was set to actuate when pressure in the pressurizer steam space dropped below 1860 psia. Control rod insertion was represented by the addition of negative reactivity to the point-kinetic solution. The negative reactivity addition began 0.1 s after the scram signal. Decay heat was defined to follow proposed 1973 ANS standard data.

RELAP5's core reflood logic was active. The core grid spacer input affecting critical heat-flux determinations was defined carefully. Counter-current flow-limiting logic was enabled appropriately at the core inlet and exit.

Boundaries placed on the RELAP5 model downstream of the pipe breaks were filled with wet air. The air pressure was varied with time to reflect the containment response to the accidents. The time response of the pressure was refined through iteration between the RELAP5 RCS simulations and the MELCOR containment simulations. RELAP5's choking logic was enabled at the break junction(s). Discharge coefficients of unity were specified.

Maximum safeguard ECCS operation was assumed; i.e., the simulations do not reflect conservatisms such as single failures. The RWST temperature was assumed to be 105°F. Table 1 list the charging, safety injection (SI), and RHR pump characteristics used in the simulations.

All of the accident simulations were initiated from a steady condition arrived at by running RELAP5 for an extended period while holding core power, RCS pressure, steam generator pressure, and feedwater temperature constant and actively controlling steam generator level.

Table 2 shows the values of selected key parameters in the RELAP5 model at steady state. Table 3 presents miscellaneous characteristics of the RELAP model important to the simulations documented here and known to vary sizably from plant to plant.

Various operator actions were modeled in the RELAP5 accident simulations. The primary operator action is related to cooling the core slowly (50ºF/h to 100ºF/h) following a LOCA to minimize thermal stresses. Control variables and trips were added to address operator actions taken to

- open one or two pressurizer PORVs,
- open main steam ADVs, and
- trip the RCPs.

The RELAP5 model assumed that the PORVs would be piped to the PRT, which is equipped with burst disks. Table 4 is a summary of the geometric details of the PRT modeled in our study. Because assumptions regarding the PRT geometry may significantly influence the outcome of several accident scenarios, we decided to perform a brief literature search and compare the present PRT model with industry data. As shown in Table 4, the PRT assumed in this study is fairly representative of PRTs that exist at several plants.

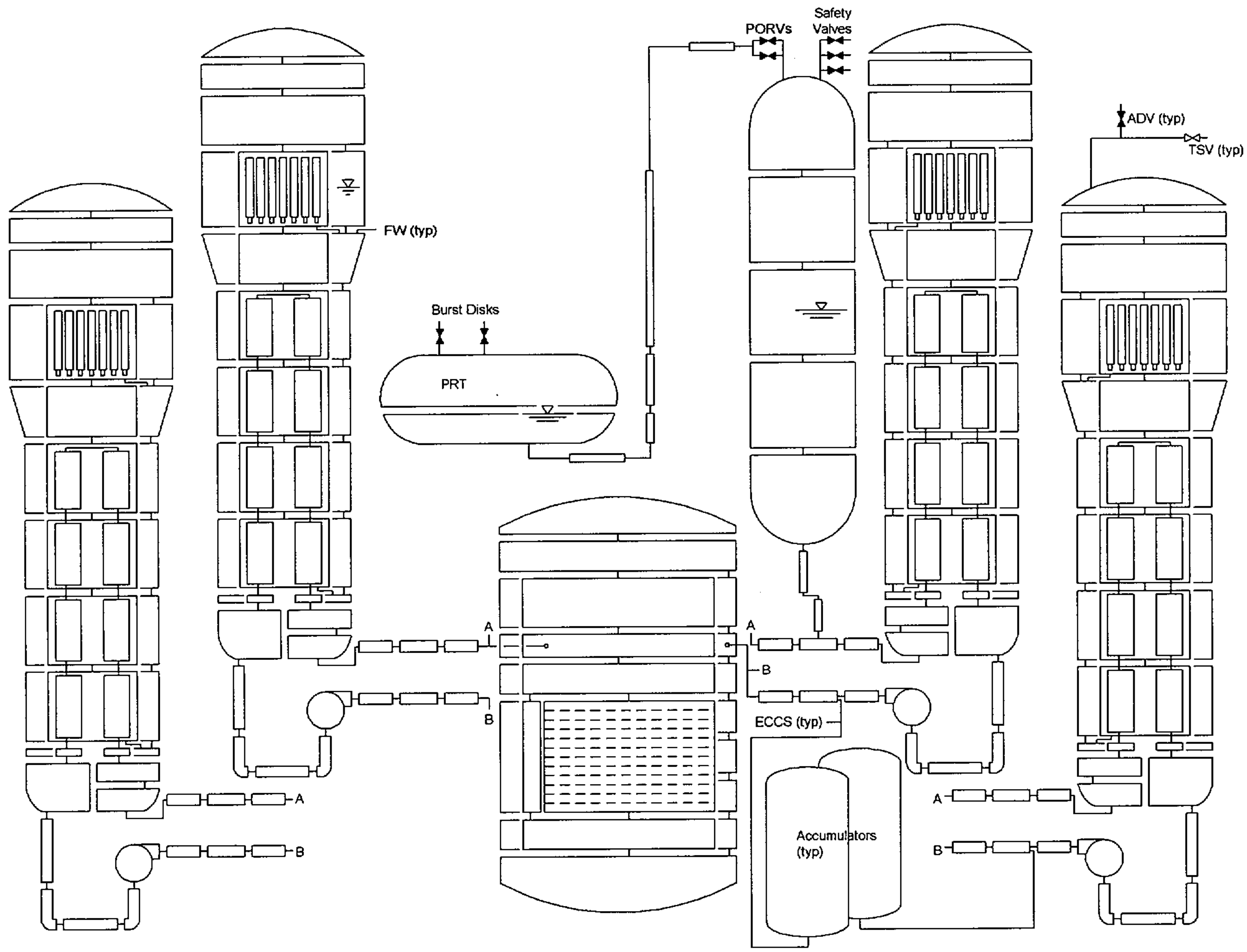


Fig. 2. RELAP5 RCS Model Nodalization.

Table 1. RELAP5 RCS Model ECCS Pump Characteristics.

	Charging Pumps	SI Pumps	RHR Pumps
Number	2	2	2
Design flow rate (gpm)	150	400	3000
Design head (ft)	5800	2500	350
Max. flow rate (gpm)	550	700	4500
Head at max. flow rate (ft)	1300	1500	300
Shutoff head (ft)	6329	3985	474
Startup delay (s after scram signal)	13	17	21

Table 2. RELAP5 RCS Model Steady-State Values.

RELAP5 Parameter	Value
Reactor power (MW)	3376
RCS pressure (pressurizer steam space, psia)	2250
Pressurizer level (% of hot-calibrated range)	50
Loop flow (lbm/s per loop)	9710
Hot-leg temperature (°F)	601.6
Cold-leg temperature (°F)	537.7
Steam generator outlet pressure (psia)	760
Steam generator level (% of narrow range)	44
Feedwater temperature (°F)	432

Table 3. RELAP5 RCS Model Miscellany.

RELAP5 Parameter	Value
PORVs: • Number • Rating • Set point	 2 210,000 lbm/h at 2335 psig each 2485 psia
Pressurizer safety valves: • Number • Rating • Set point	 3 420,000 lbm/h at 2485 psig each 2535 psia
PRT: • Volume • Initial liquid fraction • Initial temperature • Initial pressure (air)	 1800 ft^3 0.30 (volume of water ≈ 0.3 x 1800ft^3) 120 °F 14.7 psia
PRT burst disks: • Number • Rating • Break pressure	 2 800,000 lbm/h at 100 psig 100 psid

Steam generator ADVs: • Number • Rating • Set point	 1 per steam generator 68,000 lbm/h at 100 psia, not to exceed 1.05e6 lbm/h at 1300 psia 790 psia
Main steam isolation timing	Scram + 12.5 s
Feedwater temperature change timing	Scram
RCP trip	Variable—speed plots included

Table 4. Results of LANL Survey of PRTs in Existing Westinghouse PWRs.

Plant	Quench/Relief Tank Data	Other Related Information	Reference
Zion	Rupture disk release pressure is 100 psig Maximum allowed tank temperature is 120ºF Total volume is 1800 ft^3 Total rupture disk relief capacity is 1.60 x 10^6 lb/h	PRT normally contains water and predominantly nitrogen atmosphere; steam discharged through a sparger pipe under the water level; tank is equipped with an internal spray and drain used to cool tank following discharge; there are 2 rupture disks; if the temperature in the tank rises above 120ºF during operation, the tank is cooled by spraying water and draining out the warm mixture to waste disposal system; rupture disks have relief capacity equal to combined capacity of pressurizer safety valves	Zion Updated FSAR (June 1992), pp. 5.4-27 and 5.4-28 and Table 5.4-22
Ft. Calhoun	Rupture disk rating—75 psig	On the referenced date, the plant experienced a reactor trip with subsequent opening of a pressurizer relief valve; the quench tank pressure increased to approximately 13 psi; the estimated discharge to the quench tank was 200 gal.	Daily Event Report (DER) 24098 (8/22/92)
St. Lucie	Relief valve is set at 70 psig and the rupture disk blows at 100 psig Total volume is 1800 ft^3 Total rupture disk relief capacity is 1.60 x 10^6 lb/h		DER 29039 (7/8/95)
Braidwood	Rupture disk relieves at 100 psig		DER 27306 (5/26/94)
Sequoyah	The rupture disk blows at 100 psig Total volume is 1800 ft^3 Total rupture disk relief capacity is 1.60 x 10^6 lb/h	Reference made to a pressurizer drain tank (PDT) pump; incident involved PRT temperature in excess of Technical Specification limits.	DER 21423 (7/21/91)

3.2 MELCOR Large Dry Containment Model

The MELCOR model used in the large dry containment simulations accurately represented the typical structure and systems of a PWR large dry containment. The model included individual control volumes representing each of the following containment regions.

- Lower containment
- Upper containment
- Reactor cavity
- Emergency sump
- Pressurizer enclosure
- Each steam generator enclosure

The containment sprays and fan coolers were represented,[3] and the RHR heat exchangers were modeled. The assumption was made that the containment sprays would be isolated manually 2 h after being started.

The RCS was not represented explicitly in the MELCOR model. RCS breach flows to containment were modeled as time-dependent additions of water and energy to one of the control volumes representing a steam generator enclosure. As described earlier, the water and energy additions were determined by performing a related transient thermal-hydraulic calculation with RELAP5. The amount of water and associated energy flowing from the RCS breaches in the RELAP5 calculations were tracked over time and input to the MELCOR containment simulations.

The plant rating associated with the structures and systems represented in the MELCOR large dry containment model is 3893 MWt. This differs from the 3376 MWt rating of the RCS represented in the RELAP5 model. To reconcile this difference, the RELAP5 energy inputs to the MELCOR large dry DEGB containment calculation were scaled upward. The scale factor applied (1.3) increased the integral energy addition predicted by RELAP5 (up to the time of switchover to recirculation through the emergency sump) to the FSAR value reported for the containment represented in the MELCOR model. No mass-addition scaling was made in conjunction with the energy-addition scaling described.

At the time when switchover to ECCS recirculation through the emergency sump was indicated, i.e., when the RWST was expended, the RHR portion of recirculation flow (total recirculation flow less spray flow) was fixed at a rate equal to the combined charging, SI, and RHR flow rates in the RELAP5 calculation at that time. Energy addition rates from the time of switchover were set equal to the product of

1. the combined charging, SI, and RHR mass flow rate;
2. the enthalpy difference between the RWST water and water spilling from the break; and
3. a decay heat multiplier equal to the decay power associated with the current time since scram normalized to the decay power at the time of switchover to ECCS recirculation through the emergency sump.

With mass flow and energy addition managed in this way, the assumption has been made that by the time of switchover, water levels and pressures have stabilized in the RCS and SI flows have equilibrated with RCS conditions and break size.

In specifying break flows to MELCOR, a distinction was made between the liquid and vapor phases. The portion of break flow identified as liquid by RELAP5 was identified to MELCOR as liquid water in the atmosphere. The break flow portion identified as steam by RELAP5 was placed into MELCOR as water vapor.

The MELCOR model contained numerous heat structures representing the concrete and steel composing the containment structure. The heat structures were defined with paint layers to closely determine the temperatures to which containment paint would be exposed. Key attributes of the MELCOR large dry containment model are presented in Table 5. Figure 3 shows the nodalization of the MELCOR large dry containment model

The following aspects of the containment input model were judged to significantly influence the accident progression in many accidents. Considerable effort was taken in this study to simulate these features in a manner that is representative of operating US PWRs.

CONTAINMENT SPRAY SET POINT

The CS actuation set points in large dry containments are known to vary considerably from plant to plant. A lower point would imply that containment sprays may be actuated even after transients that slowly release steam into the containment. Actuation of containment sprays would mean higher debris transport, and thus the likelihood of sump screen blockage, is more likely.

A survey of existing PWR design documents was undertaken to select a set point that is more reflective of those of operating plants. Table 6 presents the results of the survey. As shown here, the set points for large dry containments vary from 3 psig (Waterford) to 30 psig (Point Beach). However, very few containments have set points lower than the 9.5 psig used in the current study. Hence, it is concluded that the current value is a reasonably conservative value.

RHR HEAT EXCHANGER

A realistic RHR model was used in this analysis based on a similar survey of existing system design documents for several large dry PWRs.

Table 5. MELCOR Large Dry Containment Model Miscellany.

Containment Parameter	Value
Free volume	3,200,000 ft^3
Basemat floor area	20,034 ft^2
Useable RWST capacity	457,700 gal
RWST temperature	105°F
Engineered safety feature (ESF) high pressure signal	4.75 psig
ESF high-high pressure signal	9.5 psig
Fan coolers: • Number of units • Capacity • Startup delay	 6 74,800,000 Btu/h per unit ESF high + 15 s
Sprays: • Flow rate • Startup delay • Shutdown	 5700 gpm ESF high-high + 70.1 s Manual after 2 h of operation
RHR heat exchangers: • Number of units • UA • Capacity	 3 2,000,000 Btu/h-°F 31,200,000 Btu/h per unit

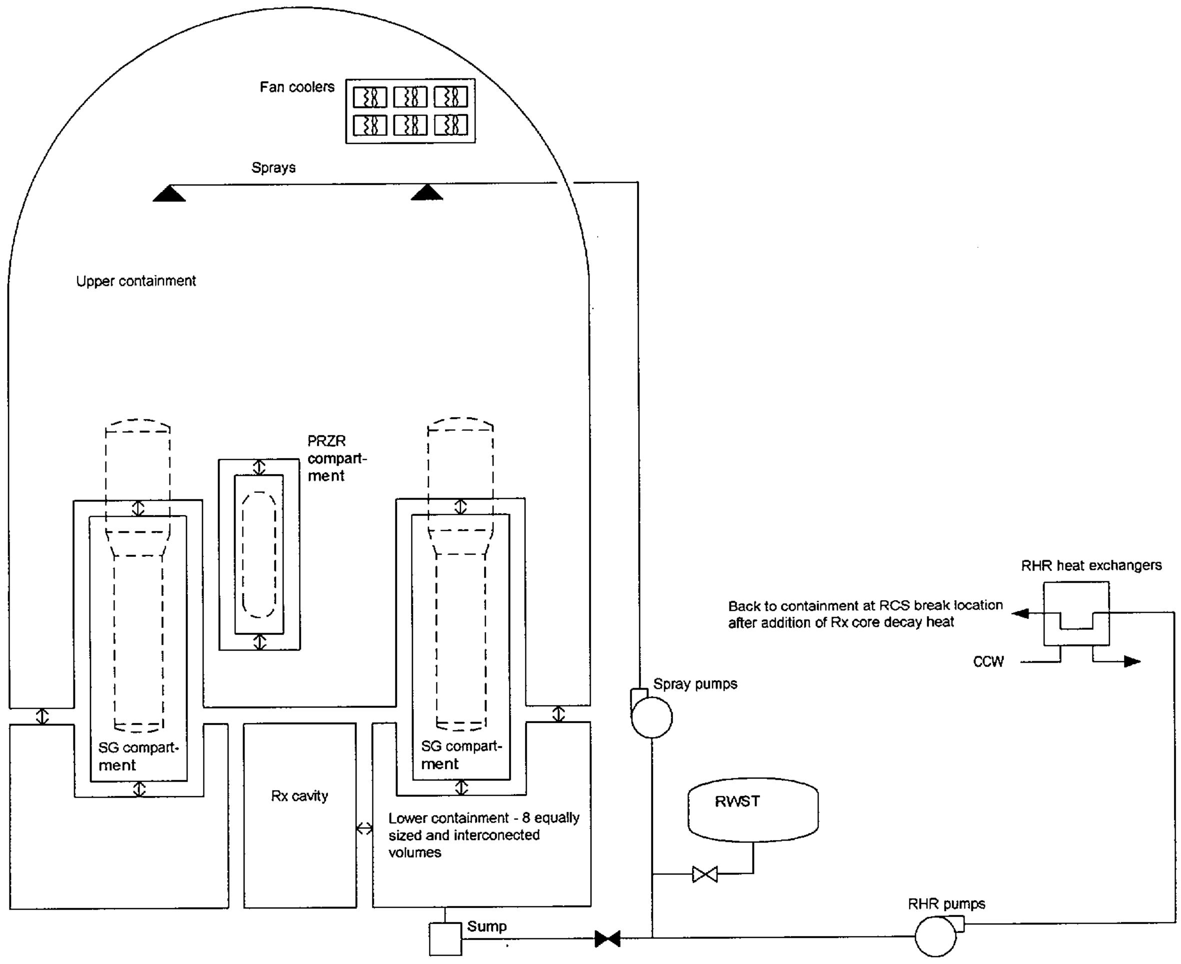


Fig. 3. MELCOR Large Dry Containment Nodalization.

Table 6. Containment Spray Set-Point Survey Results.

Containment Spray ESF Actuation Set Points for PWR Plants					
Plant	**Cont. Spray ESF Actuation Setpoint (psig)**	**Cont. Type**	**NSSS**	**Notes**	**References**
ANO-1	30	Dry-Amb	B&W		Interim Reliability Evaluation Program: Analysis of the Arkansas Nuclear One-Unit 1 Nuclear Power Plant, NUREG/CR-2878, pp. 3-2, B4-2; NRC's Website
ANO-2	8.6	Dry-Amb	CE	Stated as 23.3 psia	NRC's Website (Plant Information Books)
Beaver Valley 1 & 2	8	Dry-Sub	West 3LP		NRC's Website (Plant Information Books)
Braidwood 1 & 2	20	Dry-Amb	West 4LP		NRC's Website (Plant Information Books)
Byron 1 & 2	20	Dry-Amb	West 4LP		NRC's Website (Plant Information Books)
Callaway	27	Dry-Amb	West 4LP		NRC's Website (Plant Information Books)
Calvert Cliffs 1 & 2	4.75	Dry-Amb	CE		NRC's Website (Plant Information Books)
Catawba 1 & 2	3	Ice Cond	West 4LP		NRC's Website (Plant Information Books)
Comanche Peak 1 & 2	18.2	Dry-Amb	West 4LP		NRC's Website (Plant Information Books)
Crystal River	30	Dry-Amb	B&W	Actuates on simultaneous high-high containment pressure (30 psig) and HPI signal	NRC's Website (Plant Information Books)
D. C. Cook 1 & 2	2.9	Ice Cond	West 4LP		Individual Plant Examination (IPE), p. 3-73; NRC' s Website
Davis Besse	23	Dry-Amb	B&W	Setpoint is 38.4 psia (23.7 psig) per NRC Website	Per J. Darby file information
Diablo Canyon 1 & 2	22	Dry-Amb	West 4LP		Individual Plant Examination (IPE), p. 4.1-9; NRC's Website
Farley 1 & 2	27	Dry-Amb	West 3LP		NRC's Website (Plant Information Books)
Fort Calhoun	5	Dry-Amb	CE	Actuates on simultaneous high containment pressure (5 psig) and pressurizer low/low pressure	NRC's Website (Plant Information Books)
Ginna	28	Dry-Amb	West 2LP		NRC's Website (Plant Information Books)
Haddam Neck	Manually operated	Dry-Amb	West 4LP	Plant is permanently shutdown	Integrated Safety Assessment Report, Haddam Neck Plant, NUREG-1185, pp. 2-3 of Vol. 1and p. C 5-62 of Vol. 2
Indian Point 2	24	Dry-Amb	West 4LP		NRC's Website (Plant Information Books)
Indian Point 3	22	Dry-Amb	West 4LP		IPE, p. 3-27; NRC's Website
Kewaunee	23	Dry-Amb	West 2LP		NRC's Website (Plant Information Books)
Maine Yankee	20	Dry-Amb	CE	Plant is permanently shutdown	Daily Event Report No. 28555 dated 3/17/95; NRC's Website
McGuire 1 & 2	2.9	Ice Cond	West 4LP		NRC's Website (Plant Information Books)
Millstone 2	9.48	Dry-Amb	CE		NRC's Website (Plant Information Books)
Millstone 3	8	Dry-Sub	West 4LP		NRC's Website (Plant Information Books)
North Anna 1 & 2	13.05	Dry-Sub	West 3LP	Based on 27.75 psia setpoint	NRC's Website (Plant Information Books)
Oconee 1, 2, 3	10	Dry-Amb	B&W		IPE, p. A.3-6; Reactor Safety Study Methodology Applications Program: Oconee #3 PWR Power Plant, NUREG/CR-1659, Vol. 2, pp. B10-11, B11-4

Containment Spray ESF Actuation Set Points for PWR Plants

Plant	Cont. Spray ESF Actuation Setpoint (psig)	Cont. Type	NSSS	Notes	References
Palisades	3.7	Dry-Amb	CE	Information not totally clear, but appears that containment spray actuates on high containment pressure signal (3.7-4.4 psig)	NRC's Website (Plant Information Books)
Palo Verde 1, 2, 3	8.5	Dry-Amb	CE80		NRC's Website (Plant Information Books)
Point Beach 1 & 2	30	Dry-Amb	West 2LP		NRC's Website (Plant Information Books)
Prairie Island 1 & 2	23	Dry-Amb	West 2LP		NRC's Website (Plant Information Books)
Robinson	25	Dry-Amb	West 3LP		NRC's Website (Plant Information Books)
Salem 1 & 2	25.3	Dry-Amb	West 4LP		IPE, p. 4.3-6
San Onofre 2 & 3	14	Dry-Amb	CE		NRC's Website (Plant Information Books)
Seabrook	18	Dry-Amb	West 4LP		NRC's Website (Plant Information Books)
Sequoyah 1 & 2	2.81	Ice Cond	West 4LP		Analysis of Core Damage Frequency: Sequoyah, Unit 1 Internal Events, NUREG/CR-4550, Vol. 5, p. IV-124
Shearon Harris	10	Dry-Amb	West 3LP		NRC's Website (Plant Information Books)
South Texas 1 & 2	9.5	Dry-Amb	West 4LP		IPE, p. 4.1.1-11; NRC's Website
St. Lucie 1 & 2	Not avail	Dry-Amb	CE	No information available	
Summer	Not avail	Dry-Amb	West 3LP	No information available	
Surry 1 & 2	10.3	Dry-Sub	West 3LP	Also stated as 25 psia	Analysis of Core Damage Frequency: Surry, Unit 1 Internal Events, NUREG/CR-4550, Vol. 3, p. 4.6-41; Reactor Safety Study Methodology Applications Program: Calvert Cliffs #2 PWR Power Plant, NUREG/CR-1659, Vol. 3, pp. B10-10, B11-5
TMI-1	30	Dry-Amb	B&W		NRC's Website (Plant Information Books)
Turkey Point 3 & 4	Not avail	Dry-Amb	West 3LP	No information available	
Vogtle 1 & 2	21.5	Dry-Amb	West 4LP		NRC's Website (Plant Information Books)
Waterford	3	Dry-Amb	CE	Stated as 17.7 psia	NRC's Website (Plant Information Books)
Watts Bar 1	Not avail	Ice Cond	West 4LP	No information available	
Wolf Creek	27	Dry-Amb	West 4LP		NRC's Website (Plant Information Books)
Zion 1 & 2	23	Dry-Amb	West 4LP	Plant is permanently shutdown	Updated FSAR

PAINT SYSTEMS

All heat structures in the containment were modeled to include a layer of paint. The painted heat structures included concrete walls/floors and steel structures. A heat structure representing a concrete wall typically was defined with 11 nodes positioned to distinguish two layers of paint, a carbon steel liner, an air gap, and the concrete itself. One model representing a structure built from thin steel typically was configured with four nodes placed to distinguish two layers of paint from the steel. An illustrative concrete layering would be

1. an 8-mil coat of Americote 90 paint,
2. a 4-mil coat of Dimetcote 6 paint,
3. a 0.03125-ft carbon steel liner,
4. a 4.2-mil air gap, and
5. a 3-ft-thick concrete wall.

An illustrative thin-steel layering would be

1. an 8-mil coat of Americote 90 paint,
2. a 6-mil coat of Dimetcote 6 paint, and
3. a 0.1-in. thickness of carbon steel.

Physical properties were defined for each material based on vendor-provided data.

3.3 MELCOR Ice-Condenser Containment Model

The MELCOR model used in the ice-condenser containment simulations accurately represented the typical structure and systems of a PWR ice-condenser containment. The ice-condenser model was adapted from a comprehensive MELCOR model developed under other NRC support. Adaptations included facilitating the RELAP5 output as the source of water and energy additions to containment and reconfiguring the recirculative RHR and spray flows to account for heat removal by the RHR and spray heat exchangers. Penetrations low in the crane wall between the lower compartment and the annular compartment also were added.

The MELCOR ice-condenser model included individual control volumes representing each of the following containment regions.

- The lower compartment
- The annular compartment
- The reactor cavity
- The pressurizer enclosure
- The steam generator enclosures (combined)
- The upper dome
- The lower dome
- The cylindrical section
- The ice condensers (several control volumes)

Containment pressure suppression systems, i.e., containment sprays and ice condensers, were represented in detail. The fans for circulating the containment atmosphere through the ice condensers were defined carefully. Containment spray was portioned appropriately between the upper and lower regions of containment and the annular compartment. Dead-ended containment regions, where water could become trapped and made unavailable for ECCS recirculation, were represented physically in size and in how they connect with other containment regions. Specifically, the reactor cavity, the floor of the refueling pool, and the passages between these regions and other regions of containment were modeled carefully. Containment sprays were kept operating indefinitely once started (no action on the part of the operators to shut down the sprays was assumed).

In the course of running LOCAs of different sizes and comparing the containment response with accepted reference calculations, it was found that certain user-defined MELCOR parameters associated with ice-condenser modeling had very strong influences on containment pressure response. These ice-condenser parameters were varied with LOCA size to best match the pressure response of the reference calculations.

As described above for the large dry containment model, the RCS was not represented explicitly in the MELCOR ice-condenser model. The RCS breach flows to containment were modeled as time-dependent additions of water and energy to the control volume representing the lower containment. The water and energy additions described for the large dry containment model were determined identically for the ice-condenser model. Similarly, the considerations described above regarding switchover to ECCS recirculation through the emergency sump also apply to the ice-condenser model.

In specifying break flows to MELCOR, a distinction was made between the liquid and vapor phases. The portion of break flow identified as liquid by RELAP5 was identified to MELCOR as liquid water in the atmosphere. The break flow portion identified as steam by RELAP5 was placed into MELCOR as water vapor.

The MELCOR model contained numerous heat structures representing the concrete and steel composing the containment structure. Representative heat structures were defined with paint layers to closely determine the temperatures to which containment paint would be exposed. Key attributes of the MELCOR ice-condenser containment model are presented in Table 7. Figure 4 shows the nodalization used in the MELCOR ice-condenser model.

Table 7. MELCOR Ice-Condenser Containment Model Miscellany.

Containment Parameter	Value
Free volume	1,331,579 ft^3
Basemat floor area (lower compartment + annulus)	6,711 ft^2
Usable RWST capacity	295,000 gal.
RWST temperature	105 °F
Ice condensers: • Ice mass • Initial ice surface area	 2,429,984 lbm 85,314 ft^2
ESF high pressure signal	1.1 psig
ESF high-high pressure signal	2.9 psig
Recirculation fan startup	ESF high + 50 s
Sprays: • Flow rate • Startup delay • Shutdown	 6400 gpm ESF high-high + 50 s Sprays were kept running indefinitely once started
Spray heat exchangers: • Number of units • UA • Capacity	 2 4,314,000 Btu/h-°F 107,850,000 Btu/h per unit
RHR heat exchangers: • Number of units • UA • Capacity	 2 1,798,700 Btu/hr-°F 41,600,000 Btu/hr per unit

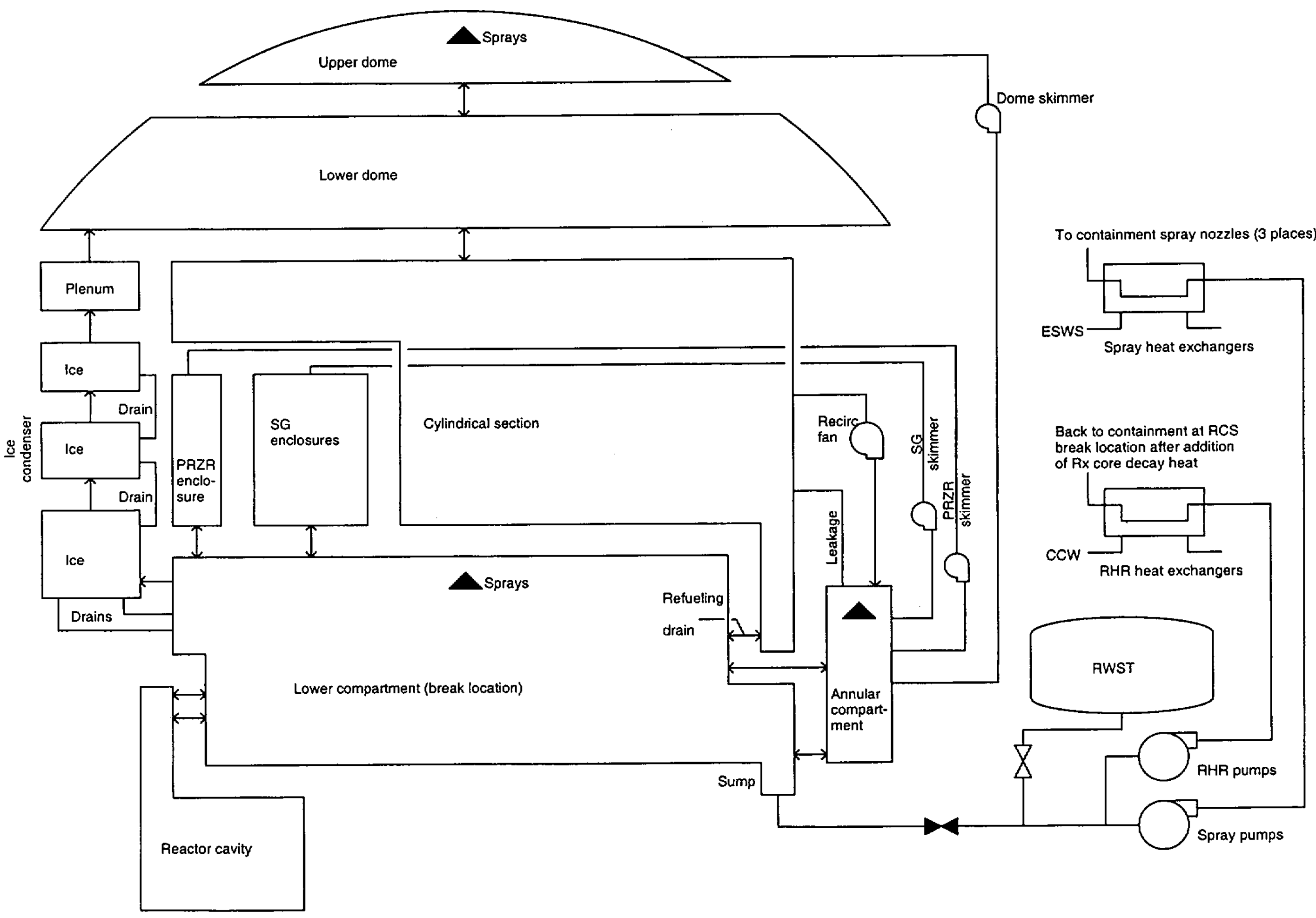


Fig. 4. MELCOR Ice-Condenser Containment Nodalization.

4.0 RESULTS

4.1 Overall Results

The results of the computer simulations are presented in Appendices A through D for each of the accidents analyzed. Appendix A presents the RELAP5 results for the RCS response; Appendices B and C present the thermal-hydraulic response of large dry and ice-condenser containments, respectively. Appendix D presents the response of the large-dry containment when fan coolers are assumed not to operate for a SLOCA. These results are presented as plots that capture the transient behavior of each key parameter (judged to influence debris generation or transport). Section 2.2 discusses the rationale for selecting the key parameters and provides a qualitative description of their effect on debris generation and transport.

This section summarizes the key results of the simulations in tabular form for easy understanding. Tables 8 and 9 present the important characteristics of the RCS blowdown and ECCS response for each accident simulated in large dry and ice-condenser containments, respectively. The results of the accident simulations are presented here in terms of three phases in the event progression: (1) the blowdown phase, (2) the ECCS injection phase, and (3) the sump recirculation phase. These phases are described and discussed in Secs. 4.1.1 through 4.1.3.

Tables 10 through 16 show the variation of key parameters at selected time intervals for accidents postulated in large dry containments. The last columns in Tables 11 through 17 lists the figure number in the appendix (A, B, or C) that plots the transient behavior of that parameter. Similar data are provided in Table 17 for the large dry containment sensitivity calculation (i.e., no fan coolers) and in Tables 18 through 24 for ice-condenser containments. Figures 5 through 11 are the event timelines for each accident simulated.

The data summarized in the tables and figures reveal that accident progression differs markedly with event and containment type. The important variables are as follows.

- *The time at which blowdown commences and the duration over which blowdown occurs vary considerably with accident type.* In one extreme, the RCS blowdown following an LLOCA commences immediately and terminates within 30 s. The stagnation pressure at the break plane over that time period varies between 2000 and 300 psia. On the other extreme, blowdown following the SLOCA occurs over the first hour of the transient; even after 1 h, it is possible that the pressure vessel remains at pressures as high as 500 psi. Debris generation estimates must account for these differences, especially for those insulations for which generation is driven by erosion. It is possible that a small-break zone of influence (ZOI) may be characterized by a larger L/D compared with large or medium breaks[4].
- *ECCS recirculation through the emergency sump is not required in all cases.* In an accident not requiring ECCS recirculation through the emergency sump, the RCS breach would have been above the centerline of the hot legs, and RHR entry conditions would have been achieved before the RWST inventory was expended. RHR entry would have been accomplished, and long-term recirculative cooling of the reactor would be managed where water was pulled from the hot legs, passed through the RHR heat exchangers, and redelivered to the reactor at the cold-leg safety injection points. The assumed RHR entry conditions for the calculations documented here are 350°F and 450 psig. In some of the calculations, RHR entry temperature is achieved at elevated pressure and with a water-solid system (including the pressurizer). In such cases, pressure would need to be reduced by throttling injection flow or opening pressurizer safety valves as needed to reduce system back pressure before realigning suction to the hot legs. Plant-specific EOPs would identify the proper procedure. In the calculations here, it has been assumed that after RHR entry temperature is achieved, RHR entry is manageable promptly thereafter.

Table 8. Key Debris Generation and Transport Parameters—Large Dry Containment.

Event	Peak Break Flow (lbm/s)	Peak Containment Compartment Velocity (ft/s)	Duration of Containment Spray Operation (h)	Terminal Pool Depth (ft)	Highest Emergency Sump Recirculation Flow (gpm))	Duration of Emergency Sump Recirculation (h)
LLOCA	79700	282	2	3.5	17500	Long term
MLOCA	4940	35	2	3.3	8250	Long term
SLOCA	2550	9	Not required	3	2500	Long term
Small-small LOCA	26	3.75	Not required	3	250	Long term
Surge line break	11100	236	2	3.3	17300	3.5
LOSP with LOFW	1480	22	Not required	1.5	Not required	Not required
False lifting/stuck PORV	1360	22.5	Not required	1.7	Not required	Not required

Table 9. Key Debris Generation and Transport Parameters—Ice-Condenser Containment.

Event	Peak Break Flow (lbm/s)	Peak Containment Compartment Velocity (ft/s)	Duration of Containment Spray Operation (h)	Terminal Pool Depth (ft)	Highest Emergency Sump Recirculation Flow (gpm)	Duration of Emergency Sump Recirculation
LLOCA	79700	184	Long term	10.1	18000	Long term
MLOCA	4940	30	Long term	9.6	9000	Long term
SLOCA	2550	2.8	Long term	8.9	9000	Long term
Small-small LOCA	26	1.25	Not required	6 to 9	250	Long term
Surge line break	11100	70	4	11.1	18000	4
LOSP with LOFW	1480	1	4.5	6.2	8900	3.75
False lifting/stuck PORV	1360	5.75	3.75	6.2	8000	3.25

Table 10. Debris Generation and Transport Parameters: Cold-Leg DEGB—Large Dry Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0+	20 s	45 s	45 s	15 min	27 min	27 min	2 h	24 h	
RCS pressure at break (psia)	2250	393	55							A.1-2
RCS temperature at break (°F)	531	291	250	250	173	144	144			A.1-9
Break flow (lbm/s)	7.97e4	1.28e4	4.89e3							A.1-6
Break flow velocity (ft/s)	296	930	100							A.1-8
Break flow quality	0	0.25	0.3	0.3	0					A.1-7
Safety injection (gpm)				11500	11500	11500				A.1-5
Recirculation flow (gpm)							17500	11800	11800	B.1-20
Spray flow (gpm)				0	5700	5700	5700	0		B.1-18
Spray temperature (°F)					105	190	190			B.1-19
Containment pressure (psig)	0	36	33	33	11.5	7	7	1.5	0	B.1-14
Containment temperature (°F)	110	305	250	250	190	163	163	115	95	B.1-15
Pool depth (ft)					2	3.5	3.5	3.5	3.5	B.1-16
Pool temperature (°F)					212	187	187	125	100	B.1-17
Containment atmosphere velocity (ft/s)	282		7							B.1-22
Containment relative humidity (%)	50	100	100	100	100	90	90	100	100	B.1-23
Paint temperature (°F)	100			215	240	220	220	145	112	B.1-24

Peak break flow: 7.97e4 lbm/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure: 36 psig at 20 sec

Peak break flow velocity: 930 ft/s at 21 s
Quality at peak break flow velocity: 0.25
Peak containment atmosphere velocity: 282 ft/s at 0+ s

Table 11. Debris Generation and Transport Parameters: Medium LOCA—Large Dry Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0+	30 s	180 s	20 s	15 min	57 min	57 min	2 h	24 h	
RCS pressure at break (psia)	2250	900	508							A.2-2
RCS temperature at break (°F)	537	521	392		330	274	274			A.2-9
Break flow (lbm/s)	4940	1670	1000							A.2-6
Break flow velocity (ft/s)	510	190	108							A.2-8
Break flow quality	0	0	0		0.03	0.03	0.03	0		A.2-7
Safety injection (gpm)				885	2500	2500				A.2-5
Recirculation flow (gpm)							8250	2550	2550	B.2-20
Spray flow (gpm)		0	5700		5700	5700	5700	0		B.2-18
Spray temperature (°F)			105		105	150	150	150		B.2-19
Containment pressure (psig)	0	6	9.5		5	3	3	4.2	1.5	B.2-14
Containment temperature (°F)	110	170	182		160	140	140	148	120	B.2-15
Pool depth (ft)					0.9	3.3	3.3	3.3	3.3	B.2-16
Pool temperature (°F)					170	145	145	147	125	B.2-17
Containment atmosphere velocity (ft/s)	35	10	5							B.2-22
Containment relative humidity (%)	50	100	100		98	98	98	98	100	B.2-23
Paint temperature (°F)	110		160		175	160	160	155	121	B.2-24

Peak break flow: 4940 lbm/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure: 10.2 psig at 2 min

Peak break flow velocity: 510 ft/s at 0+ s
Quality at peak break flow velocity: 0
Peak containment atmosphere velocity: 35 ft/s at 0+ s

Table 12. Debris Generation and Transport Parameters: Small LOCA – Large Dry Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0+	**30 min**	**1 h**	**60 s**	**2 h**	**3 h**	**3 h**	**12 h**	**24 h**	
RCS pressure at break (psia)	2250	605	512							A.3-2
RCS temperature at break (°F)	538	354	371		270	236	236			A.3-9
Break flow (lbm/s)	550	343	300							A.3-6
Break flow velocity (ft/s)	320	320	320							A.3-8
Break flow quality	0	0	0							A.3-7
Safety injection (gpm)				1500	2500	2500				A.3-5
Recirculation flow (gpm)							2500	2500	2500	B.3-8
Spray flow (gpm)	Sprays not required									B.3-7
Spray temperature (°F)										
Containment pressure (psig)	0	5	5		4	3	3	1	0.75	B.3-3
Containment temperature (°F)	110	160	160		150	140	140	115	110	B.3-4
Pool depth (ft)			0.8		1.5	2.25	2.25	3	3	B.3-5
Pool temperature (°F)			157		157	150	150	125	118	B.3-6
Containment atmosphere velocity (ft/s)	9	4	4							B.3-10
Containment relative humidity (%)	50	100	100		100	100	100	100	100	B.3-11
Paint temperature (°F)	100	160	160		157	153	153	127	117	B.3-12

Peak break flow: 550 lbm/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure: 6 psig at 38 min

Peak break flow velocity: 320 ft/s at 0+
Quality at peak break flow velocity: 0
Peak containment atmosphere velocity: 9 ft/s at 20 s

Table 13. Debris Generation and Transport Parameters: Small-Small LOCA—Large Dry Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0+	2 h	4 h	0+	10 h	20 h	20 h	22 h	24 h	
RCS pressure at break (psia)	2250	1350	450							A.4-2
RCS temperature at break (°F)	538	444	350							A.4-9
Break flow (gpm)	250	250	250							A.4-6
Break flow velocity (ft/s)	350									A.4-8
Break flow quality	0									A.4-7
Safety injection (gpm)				250	250	250				A.4-5
Recirculation flow (gpm)							250	250	250	B.4-8
Spray flow (gpm)									Sprays not required	B.4-7
Spray temperature (°F)										
Containment pressure (psig)	0	<2	<2		0					B.4-3
Containment temperature (°F)	110		120			120			120	B.4-4
Pool depth (ft)							3			B.4-5
Pool temperature (°F)							130			B.4-6
Containment atmosphere velocity (ft/s)	3.75									B.4-10
Containment relative humidity (%)	50	100				100			100	B.4-11
Paint temperature (°F)	110		120			120			120	B.4-12

Peak break flow: 26 lbm/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure:2 psig at 30 min

Peak break flow velocity: 350 ft/s at 0+
Quality at peak break flow velocity: 0
Peak containment atmosphere velocity: 3.75 ft/s at 2 min

Table 14. Debris Generation and Transport Parameters: Surge Line Break—Large Dry Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0+	20 s	5 min	20 s	15 min	30 min	30 min	2 h	4 h	
RCS pressure at break (psia)	2250	756	203							A.5-2
RCS temperature at break (°F)	653	514	384		278	173	173			A.5-9
Break flow (lbm/s)	11100	3050	875							A.5-6
Break flow velocity (ft/s)	317	217	143							A.5-8
Break flow quality	0.05	0.05	0.05		0					A.5-7
Safety injection (gpm)				1930	11500	11500				A.5-5
Recirculation flow (gpm)							17300	11600	0	B.5-9
Spray flow (gpm)			5700		5700	5700	5700	0		B.5-7
Spray temperature (°F)			105		105	190	190	132		B.5-8
Containment pressure (psig)	0	9	20		12.5	5	5	2.5	1.25	B.5-3
Containment temperature (°F)	110	185	222		200	160	160	132	117	B.5-4
Pool depth (ft)					1.25	3.25	3.25	3.25	3.25	B.5-5
Pool temperature (°F)					210	190	190	140	124	B.5-6
Containment atmosphere velocity (ft/s)	236	18	12							B.5-11
Containment relative humidity (%)	50	100	100		98	80	80	92	100	B.5-12
Paint temperature (°F)	110	115	222		218	204	204	158	135	B.5-13

Peak break flow: 1.11e4 lbm/s at 0+ s
Quality at peak break flow: 0.05
Peak containment pressure: 22.5 psig at 180 s

Peak break flow velocity: 415 ft/s at 148 s
Quality at peak break flow velocity: 0.05
Peak containment atmosphere velocity: 236 ft/s at 0+ s

Table 15. Debris Generation and Transport Parameters: LOSP with LOFW—Large Dry Containment (1 PORV Held Open at First Lift).

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0	66 min	67 min	72 min	2 h	4 h				
PRT pressure (psia)	14.7	90	25.5							A.6a-15
PRT temperature (°F)	120	275	235	239	274	265				A.6a-19
Burst disk flow (lbm/s)	0	1480	76.5							A.6a-16
Burst disk flow velocity (ft/s)		621	591							A.6a-18
Burst disk flow quality		0.4	0.4	0.4	0.3	0.06				A.6a-17
Safety injection (gpm)				1015	1280	0				A.6a-4
Recirculation flow (gpm)	ECCS recirculation through emergency sump not required—RHR entry accomplished at 4 h									B.6a-8
Spray flow (gpm)	Sprays not required									B.6a-7
Spray temperature (°F)										
Containment pressure (psig)	0	0+	1	2.5	4	4				B.6a-3
Containment temperature (°F)	110			135	152	150				B.6a-4
Pool depth (ft)				0	0.25	1.5				B.6a-5
Pool temperature (°F)					142	152				B.6a-6
Containment atmosphere velocity (ft/s)		18	11							B.6a-11
Containment relative humidity (%)	50	100	100	100	100	100				B.6a-12
Paint temperature (°F)	110			110+	150	155				B.6a-13

Peak break flow: 1.48e3 lbm/s at 66.3 min
Quality at peak break flow: 0.0015
Peak containment pressure: 5 psig at 82.5 min

Peak break flow velocity: 621 ft/s at 66.3+ min
Quality at peak break flow velocity: 0.45
Peak containment atmosphere velocity: 18 ft/s at 66.3 min

Table 15. Debris Generation and Transport Parameters: LOSP with LOFW —Large Dry Containment (cont) (Fast Cooldown from 30 min).

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0	32 min	33 min	30 min	1 h	2 h				
PRT pressure (psia)	14.7	111	25							A.6b-15
PRT temperature (°F)	120	250	228		298	270				A.6b-19
Burst disk flow (lbm/s)	0	1480	75							A.6b-16
Burst disk flow velocity (ft/s)		860	567							A.6b-18
Burst disk flow quality		0.45	0.45		0.1	0.008				A.6b-17
Safety injection (gpm)				2200	2360	2500				A.6b-4
Recirculation flow (gpm)	ECCS recirculation through emergency sump not required—RHR entry accomplished at 4 h									B.6b-8
Spray flow (gpm)									Sprays not required	B.6b-7
Spray temperature (°F)										
Containment pressure (psig)	0	0+	1		5	4				B.6b-3
Containment temperature (°F)	110		120		160	150				B.6b-4
Pool depth (ft)			0		0.25	1.4				B.6b-5
Pool temperature (°F)					160	152				B.6b-6
Containment atmosphere velocity (ft/s)		20	11							B.6b-11
Containment relative humidity (%)	50	100	100		100	100				B.6b-12
Paint temperature (°F)	110		110+		160	155				B.6b-13

Peak break flow: 1.48e3 lbm/s at 32 min
Quality at peak break flow: 0.0012
Peak containment pressure: 5.25 psig at 66 min

Peak break flow velocity: 860 ft/s at 32+ min
Quality at peak break flow velocity: 0.83
Peak containment atmosphere velocity: 20 ft/s at 32 min

Table 15. Debris Generation and Transport Parameters: LOSP with LOFW —Large Dry Containment (cont) (No Operator Action for 2.5 h).

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0	**79 min**	**80 min**	**86 min**	**4.5 h**	**6 h**				
PRT pressure (psia)	14.7	97	25							A.6c-15
PRT temperature (°F)	120	287	230	232	261	226				A.6c-19
Burst disk flow (lbm/s)	0	1480	77							A.6c-16
Burst disk flow velocity (ft/s)		706	575							A.6c-18
Burst disk flow quality		0.6	0.6	0.6	0.06	0				A.6c-17
Safety injection (gpm)				317	2500	2035				A.6c-4
Recirculation flow (gpm)	ECCS recirculation through emergency sump not required—RHR entry accomplished at 6 h									B.6c-8
Spray flow (gpm)	Sprays not required									B.6c-7
Spray temperature (°F)										
Containment pressure (psig)	0	0+	1		4.3	2.5				B.6c-3
Containment temperature (°F)	110		125		150	133				B.6c-4
Pool depth (ft)					1.2	2.3				B.6c-5
Pool temperature (°F)					160	140				B.6c-6
Containment atmosphere velocity(ft/s)		22	11							B.6c-11
Containment relative humidity (%)	50	100			100	100				B.6c-12
Paint temperature (°F)	110		100+		170	148				B.6c-13

Peak break flow: 1.48e3 lbm/s at 79 min
Quality at peak break flow: 0.015
Peak containment pressure:8 psig at 4 h

Peak break flow velocity: 706 ft/s at 79+ min
Quality at peak break flow velocity: 0.57
Peak containment atmosphere velocity: 22 ft/s at 79 min

Table 16. Debris Generation and Transport Parameters: PORV Lifts Falsely and Sticks Open—Large Dry Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0	257 s	600 s	122 s	1 h	3 h				
PRT pressure (psia)	14.7	105	50							A.7-15
PRT temperature (°F)	120	283	280		280	269				A.7-19
Burst disk flow (lbm/s)	0	1360	182							A.7-16
Burst disk flow velocity (ft/s)		134	404							A.7-18
Burst disk flow quality		0.02	0.2		0.2	0.08				A.7-17
Safety injection (gpm)				884	1512	1696				A.7-4
Recirculation flow (gpm)	ECCS recirculation through emergency sump not required—RHR entry accomplished at 3 h									B.7-8
Spray flow (gpm)	Sprays not required									B.7-7
Spray temperature (°F)										
Containment pressure (psig)	0		2		4.5	4.3				B.7-3
Containment temperature (°F)	110		122		157	152				B.7-4
Pool depth (ft)					0.4	1.7				B.7-5
Pool temperature (°F)					150	152				B.7-6
Containment atmosphere velocity (ft/s)		22.5	11							B.7-11
Containment relative humidity (%)	50	100	100		100	100				B.7-12
Paint temperature (°F)	110				156	153				B.7-13

Peak break flow: 1360 lbm/s at 257 s
Quality at peak break flow: 0.02
Peak containment pressure: 5 psig at 18 min

Peak break flow velocity: 709 ft/s at 525 s
Quality at peak break flow velocity: 0.35
Peak containment atmosphere velocity: 22.5 ft/s at 257+ s

Table 17. Debris Generation and Transport Parameters: SLOCA w/no Fan Coolers—Large Dry Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0+	30 min	1 h	60 s	1 h	3 h	3 h	12 h	24 h	
PRT pressure (psia)	2250	605	512							A.3-2
PRT temperature (°F)	538	354	371		270	236	236			A.3-9
Burst disk flow (lbm/s)	550	343	300							A.3-6
Burst disk flow velocity (ft/s)	320	320	320							A.3-8
Burst disk flow quality	0	0	0							A.3-7
Safety injection (gpm)				1500	2500	2500				A.3-5
Recirculation flow (gpm)							2500	2500	2500	D-8
Spray flow (gpm)										D-7
Spray temperature (°F)					105	150	150	125	120	
Containment pressure (psig)	0	5	5		4	3	3	1	0.75	D-3
Containment temperature (°F)	110	160	160		150	140	140	115	110	D-4
Pool depth (ft)			0.8		1.5	2.25	2.25	3	3	D-5
Pool temperature (°F)			157		157	150	150	125	118	D-6
Containment atmosphere velocity (ft/s)	9	4	4							D-10
Containment relative humidity (%)	50	100	100		100	100	100	100	100	D-11
Paint temperature (°F)	100	160	160		157	153	153	127	117	D-12

Peak break flow: 550 lb/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure: 6 psig at 38 min

Peak break flow velocity: 320 ft/s at 0+
Quality at peak break flow velocity: 0
Peak containment atmosphere velocity: 9 ft/s at 20 s

Note: Results for this calculation should be used for all sub-atmospheric containments for SLOCA events.

Table 18. Debris Generation and Transport Parameters: Cold Leg DEGB—Ice Condenser Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0+	**20 s**	**45 s**	**45 s**	**10 min**	**17 min**	**17 min**	**2 h**	**24 h**	
RCS pressure at break (psia)	2250	393	55							A.1-2
RCS temperature at break (°F)	531	291	250	250	200	160	160			A.1-9
Break flow (lbm/s)	7.97e4	1.28e4	4.89e3							A.1-6
Break flow velocity (ft/s)	296	930	100							A.1-8
Break flow quality	0	0.25	0.3	0.3	0					A.1-7
Safety injection (gpm)				11500	11500	11500				A.1-5
Recirculation flow (gpm)							18000	18000	18000	
Spray flow (gpm)				6400	6400	6400	6400	6400	6400	
Spray temperature (°F)				105	105	97	97	95	89	
Containment pressure (psig)	0+	14	10.1	10.1	4.5	4.5	4.5	3	2	
Containment temperature (°F)	100	168	160	160	103	105	105	98	100	
Pool depth (ft)				4	8.5	10.75	10.75	10.8	10.1	
Pool temperature (°F)				180	157	159	159	148	126	
Containment atmosphere velocity (ft/s)	184	18	1							
Containment relative humidity (%)	0	50	100	100	80	96	96	97	98	
Paint temperature (°F)	100	106	112	112	113	112	112	90	90	

Peak break flow: 7.97e4 lbm/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure: 14.4 psig at 15 s

Peak break flow velocity: 930 ft/s at 21 s
Quality at peak break flow velocity: 0.25
Peak containment atmosphere velocity: 184 ft/s at 0+ s

Table 19. Debris Generation and Transport Parameters: Medium LOCA—Ice Condenser Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0+	30 s	180 s	20 s	15 min	34 min	34 min	2 h	24 h	
RCS pressure at break (psia)	2250	900	508							A.2-2
RCS temperature at break (°F)	537	521	392		330	300	300			A.2-9
Break flow (lbm/s)	4940	1670	1000							A.2-6
Break flow velocity (ft/s)	510	190	108							A.2-8
Break flow quality	0	0	0		0.03	0.03	0.03	0		A.2-7
Safety injection (gpm)				885	2500	2500				A.2-5
Recirculation flow (gpm)							9000	9000	9000	
Spray flow (gpm)		0	6400		6400	6400	6400	6400	6400	
Spray temperature (°F)			105		105	105	92.5	86.5	84	
Containment pressure (psig)	0+	9.8	7.8		4	4	4	1.8	1.4	
Containment temperature (°F)	100	145	151		110	110	110	87	90	
Pool depth (ft)					4	7.9	7.9	8	9.6	
Pool temperature (°F)					150	146	146	117	104	
Containment atmosphere velocity (ft/s)	30	2.5	1.25							
Containment relative humidity (%)	0	10	40		80	97	97	97	98	
Paint temperature (°F)	100	101	125		130	125	125	95	90	

Peak break flow: 4940 lbm/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure: 11 psig at 55 s

Peak break flow velocity: 510 ft/s at 0+ s
Quality at peak break flow velocity: 0
Peak containment atmosphere velocity: 30 ft/s at 0+ s

Table 20. Debris Generation and Transport Parameters: Small LOCA—Ice Condenser Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0+	30 min	1 h	60 s	15 min	35 min	35 min	5 h	24 h	
RCS pressure at break (psia)	2250	605	512							A.3-2
RCS temperature at break (°F)	538	354	371		391	362	362			A.3-9
Break flow (lbm/s)	550	343	300							A.3-6
Break flow velocity (ft/s)	320	320	320							A.3-8
Break flow quality	0	0	0							A.3-7
Safety injection (gpm)				1500	2500	2500				A.3-5
Recirculation flow (gpm)							9000	9000	9000	
Spray flow (gpm)		6400	6400	0	6400	6400	6400	6400	6400	
Spray temperature (°F)		105	91		105	105	91	87.5	86	
Containment pressure (psig)	0+	4.1	3.6	3.4	4.4	4.2	4.2	2.25	1.8	
Containment temperature (°F)	100	111	96.5	94	112	110	110	92	95	
Pool depth (ft)		5.5	6.75		2.5	6.5	6.5	9	8.9	
Pool temperature (°F)		137	132		137	137	137	120	114	
Containment atmosphere velocity (ft/s)	2.9	0.7	0.7							
Containment relative humidity (%)	0	97	97	6	100	97	97	97	97	
Paint temperature (°F)	100	110	104	100	106	110	110	92	96	

Peak break flow: 550 lbm/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure: 4.4 psig at 15 min

Peak break flow velocity: 320 ft/s at 0+
Quality at peak break flow velocity: 0
Peak containment atmosphere velocity: 2.9 ft/s at 23 s

Table 21. Debris Generation and Transport Parameters: Small-Small LOCA—Ice Condenser Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0+	2 h	4 h	0+	10 h	20 h	20 h	22 h	24 h	
RCS pressure at break (psia)	2250	1350	450							A.4-2
RCS temperature at break (°F)	538	444	350							A.4-9
Break flow (gpm)	250	250	250							A.4-6
Break flow velocity (ft/s)	350									A.4-8
Break flow quality	0									A.4-7
Safety injection (gpm)				250	250	250				A.4-5
Recirculation flow (gpm)							250	250	250	
Spray flow (gpm)	Sprays not required									
Spray temperature (°F)										
Containment pressure (psig)	0		<1		0					
Containment temperature (°F)	100		100			100			100	
Pool depth (ft)							6 to 9			
Pool temperature (°F)							110			
Containment atmosphere velocity (ft/s)	0.3									
Containment relative humidity (%)	0	100				100			100	
Paint temperature (°F)	100					100			100	

Peak break flow: 26 lbm/s at 0+ s
Quality at peak break flow: 0
Peak containment pressure: 1.3 psig at 6 min

Peak break flow velocity: 350 ft/s at 0+
Quality at peak break flow velocity: 0
Peak containment atmosphere velocity: 1.2 ft/s at 5.75 min

Table 22. Debris Generation and Transport Parameters: Surge Line Break—Ice Condenser Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0+	20 s	5 min	20 s	10 min	20 min	20 min	2 h	4 h	
RCS pressure at break (psia)	2250	756	203							A.5-2
RCS temperature at break (°F)	653	514	384		301	241	241			A.5-9
Break flow (lbm/s)	11100	3050	875							A.5-6
Break flow velocity (ft/s)	317	217	143							A.5-8
Break flow quality	0.05	0.05	0.05		0					A.5-7
Safety injection (gpm)				1930	11500	11500				A.5-5
Recirculation flow (gpm)							18000	18000	0	
Spray flow (gpm)		0	6400		6400	6400	6400	6400	0	
Spray temperature (°F)			105		105	105	93	95		
Containment pressure (psig)	0+	9.3	5.9		4.4	4.5	4.5	3	3.6	
Containment temperature (°F)	100	137	117		102.5	106	106	97	114	
Pool depth (ft)			3.75		7	10.4	10.4	11.2	11.1	
Pool temperature (°F)			127		122	142	142	147	148	
Containment atmosphere velocity (ft/s)	70	7	2							
Containment relative humidity (%)	0	15	70		83	96	96	98	97	
Paint temperature (°F)	100	101	114		93	92	92	101	114	

Peak break flow: 1.11e4 lbm/s at 0+ s
Quality at peak break flow: 0.05
Peak containment pressure: 9.6 psig at 15 s

Peak break flow velocity: 415 ft/s at 148 s
Quality at peak break flow velocity: 0.05
Peak containment atmosphere velocity: 70 ft/s at 0+ s

Table 23. Debris Generation and Transport Parameters: LOSP with LOFW—Ice Condenser Containment (1 PORV Held Open at First Lift).

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0	66 min	67 min	72 min	1.5 h	1.9 h	1.9 h	3 h	4 h	
PRT pressure (psia)	14.7	90	25.5							A.6a-15
PRT temperature (°F)	120	275	235	239	259	274				A.6a-19
Burst disk flow (lbm/s)	0	1480	76.5							A.6a-16
Burst disk flow velocity (ft/s)		621	591							A.6a-18
Burst disk flow quality		0.4	0.4	0.4	0.39	0.3				A.6a-17
Safety injection (gpm)				1015	1280	927				A.6a-4
Recirculation flow (gpm)							7700	7700	0	
Spray flow (gpm)				0	6400	6400	6400	6400	0	
Spray temperature (°F)					105	105	88	82.5		
Containment pressure (psig)	0	1	1.6	2.25	3.15	4	4	0.85	0.8	
Containment temperature (°F)	100	105	105	90	106	108	108	80	79	
Pool depth (ft)					2	6	6	6.1	6.2	
Pool temperature (°F)					121	125	125	100	96	
Containment atmosphere velocity (ft/s)	0	1	0.75							
Containment relative humidity (%)	0	7	10	84	100	99	80	99	99	
Paint temperature (°F)	100	98	98	96	102.5	102.5	102.5	91	87	

Peak break flow: 1.48e3 lbm/s at 66.3 min
Quality at peak break flow: 0.0015
Peak containment pressure: 4 psig at 1.9 h

Peak break flow velocity: 621 ft/s at 66.3+ min
Quality at peak break flow velocity: 0.45
Peak containment atmosphere velocity: 1 ft/s at 66.3 min

Table 23. Debris Generation and Transport Parameters: LOSP with LOFW– Ice Condenser Containment (cont) (Fast Cooldown from 30 min).

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0	32 min	33 min	30 min	45 min	70 min	70 min	2 h	4 h	
PRT pressure (psia)	14.7	111	25							A.6b-15
PRT temperature (°F)	120	250	228		301	294				A.6b-19
Burst disk flow (lbm/s)	0	1480	75							A.6b-16
Burst disk flow velocity (ft/s)		860	567							A.6b-18
Burst disk flow quality		0.45	0.45		0.18	0.08				A.6b-17
Safety injection (gpm)				2200	2200	2420				A.6b-4
Recirculation flow (gpm)							8900	8900	0	
Spray flow (gpm)				0	6400	6400	6400	6400	0	
Spray temperature (°F)					105	105	92	88		
Containment pressure (psig)	0	0+	2		4.2	4.25	4.25	2.25	1.8	
Containment temperature (°F)	100	100	100		113	111	111	91	88	
Pool depth (ft)					1.8	6	6	6.5	7.5	
Pool temperature (°F)					133	135	135	124	117	
Containment atmosphere velocity (ft/s)	0	3.3	0.5							
Containment relative humidity (%)	0	0	20		100	98	80	98	98	
Paint temperature (°F)	100	100	100		103	110	110	100	92	

Peak break flow: 1.48e3 lbm/s at 32 min
Quality at peak break flow: 0.0012
Peak containment pressure: 4.25 psig at 1 h

Peak break flow velocity: 860 ft/s at 32+ min
Quality at peak break flow velocity: 0.83
Peak containment atmosphere velocity: 3.3 ft/s at 32 min

Table 23. Debris Generation and Transport Parameters: LOSP with LOFW– Ice Condenser Containment (cont) (No Operator Action for 2.5 h).

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0	79 min	80 min	86 min	2 h	2.42 h	2.42 h	4 h	6 h	
PRT pressure (psia)	14.7	97	25							A.6c-15
PRT temperature (°F)	120	287	230	232	234	234				A.6c-19
Burst disk flow (lbm/s)	0	1480	77							A.6c-16
Burst disk flow velocity (ft/s)		706	575							A.6c-18
Burst disk flow quality		0.6	0.6	0.6	0.55	0.55				A.6c-17
Safety injection (gpm)				317	312	312				A.6c-4
Recirculation flow (gpm)							6750	6750	0	
Spray flow (gpm)				0	6400	6400	6400	6400	0	
Spray temperature (°F)					105	105	87	78.5		
Containment pressure (psig)	0	0	2	2	2.5	3	3	0.4	0.3	
Containment temperature (°F)	100	100	100	100	104	104	104	75	73	
Pool depth (ft)					3	6.2	6.2	6.2	6.2	
Pool temperature (°F)					116	117	117	85	82	
Containment atmosphere velocity (ft/s)	0	0.67	0.6							
Containment relative humidity (%)	0	30	100	100	100	100	70	100	100	
Paint temperature (°F)	100	100	100	100	102.5	103	103	87	86	

Peak break flow: 1.48e3 lbm/s at 79 min
Quality at peak break flow: 0.015
Peak containment pressure: 3 psig at 2.4 h

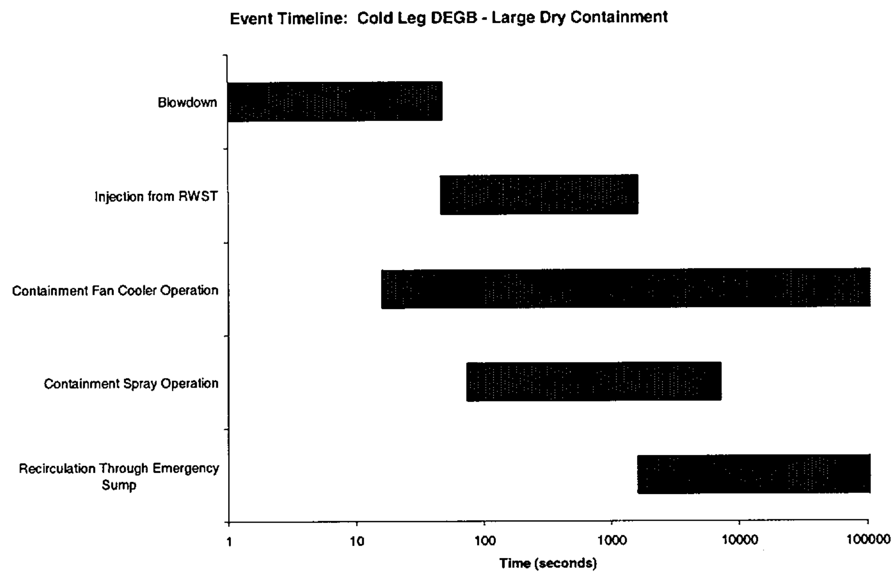
Peak break flow velocity: 706 ft/s at 79+ min
Quality at peak break flow velocity: 0.57
Peak containment atmosphere velocity: 0.67 ft/s at 79 min

Table 24. Debris Generation and Transport Parameters: PORV Lifts Falsely and Sticks Open—Ice Condenser Containment.

Parameter	Blowdown Phase			Injection Phase			Recirculation Phase			Figure
	0	257 s	600 s	122 sec	15 min	48 min	48 min	2 h	4 h	
PRT pressure (psia)	14.7	105	50							A.7-15
PRT temperature (°F)	120	283	280		281	281				A.7-19
Burst disk flow (lbm/s)	0	1360	182							A.7-16
Burst disk flow velocity (ft/s)		134	404							A.7-18
Burst disk flow quality		0.02	0.2		0.24	0.21				A.7-17
Safety injection (gpm)				884	1397	1479				A.7-4
Recirculation flow (gpm)							7900	7900	0	
Spray flow (gpm)				0	6400	6400	6400	6400	0	
Spray temperature (°F)					105	105	90	84		
Containment pressure (psig)	0	1.1	2.1		3.25	4.1	4.1	1.2	0.9	
Containment temperature (°F)	100	106	80		109	110	110	83	81	
Pool depth (ft)					0.5	6	6	6.1	6.2	
Pool temperature (°F)					128	130	130	105	98	
Containment atmosphere velocity (ft/s)	0	0.5	0.8							
Containment relative humidity (%)	0	6	93		90	100	100	99	99	
Paint temperature (°F)	100	100	96		100	108	108	92	87	

Peak break flow: 1360 lbm/s at 257 s
Quality at peak break flow: 0.02
Peak containment pressure: 4.1 psig at 48 min

Peak break flow velocity: 709 ft/s at 525 s
Quality at peak break flow velocity: 0.35
Peak containment atmosphere velocity: 5.75 ft/s at 225 s



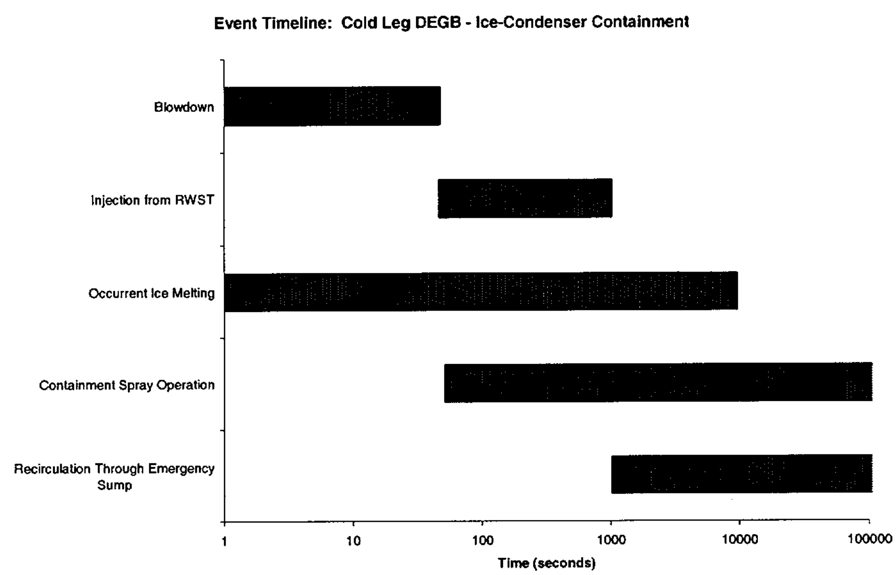
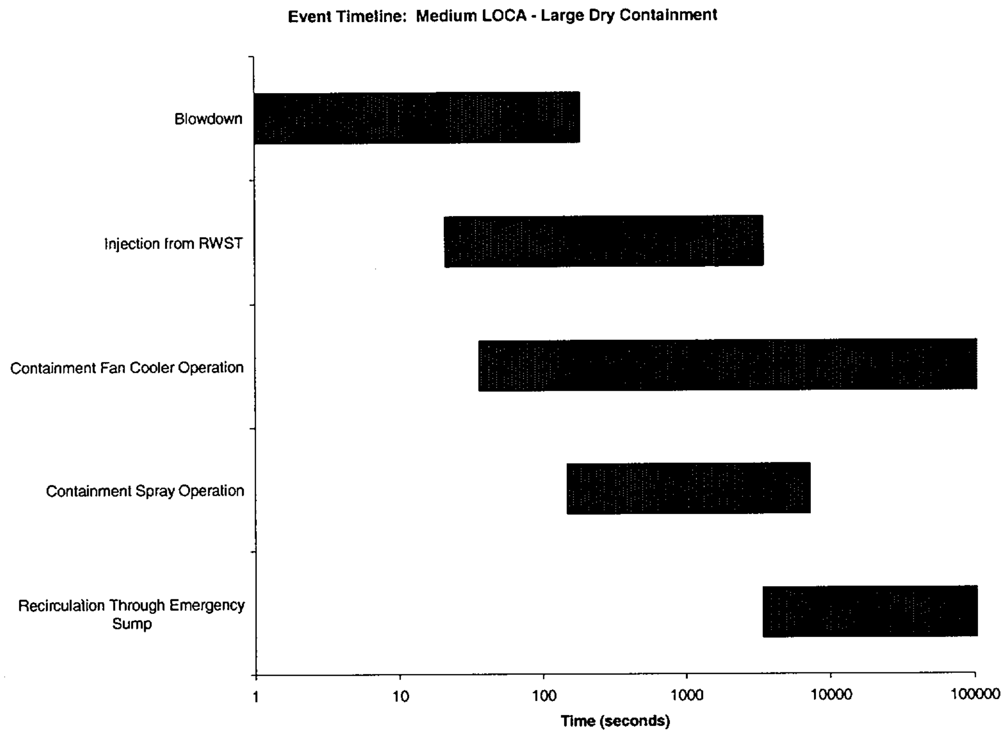


Fig. 5. Event Timeline for LLOCA Accident Progression.



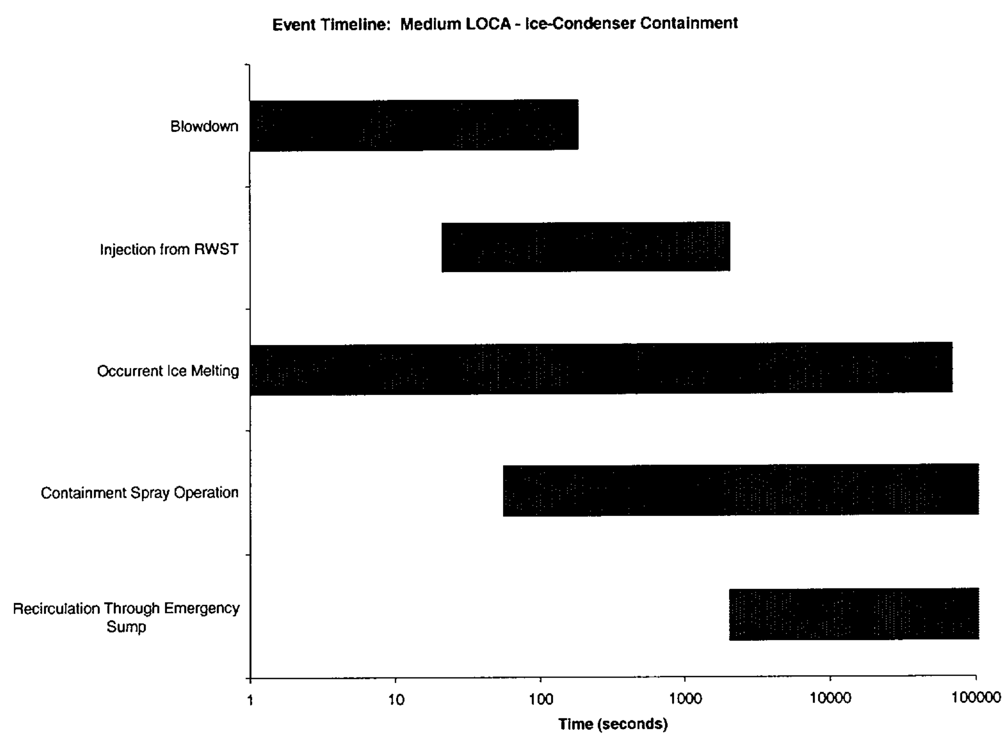


Fig. 6. Event Timeline for MLOCA Accident Progression.

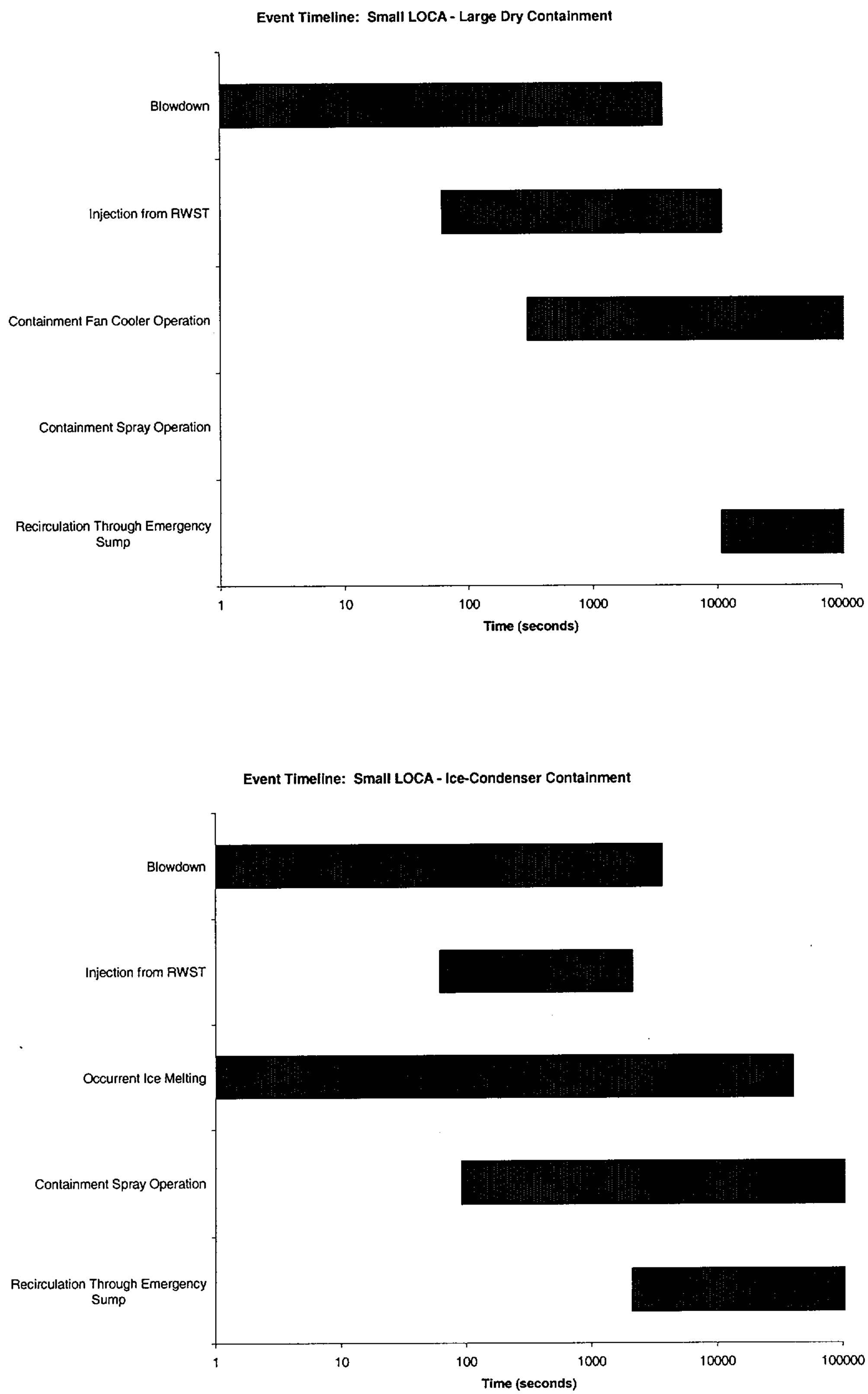
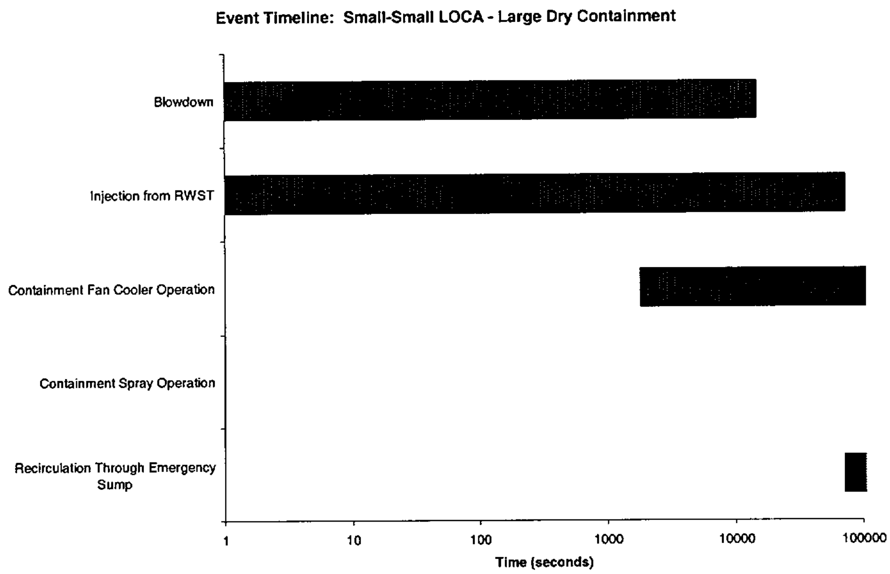


Fig. 7. Event Timeline for SLOCA Accident Progression.



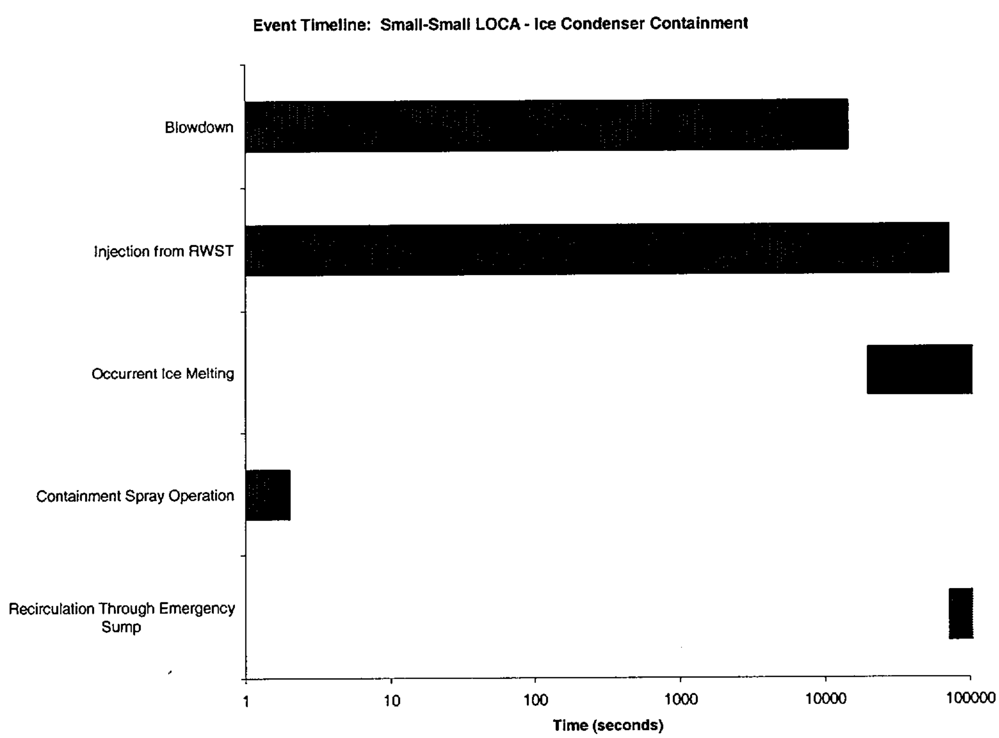
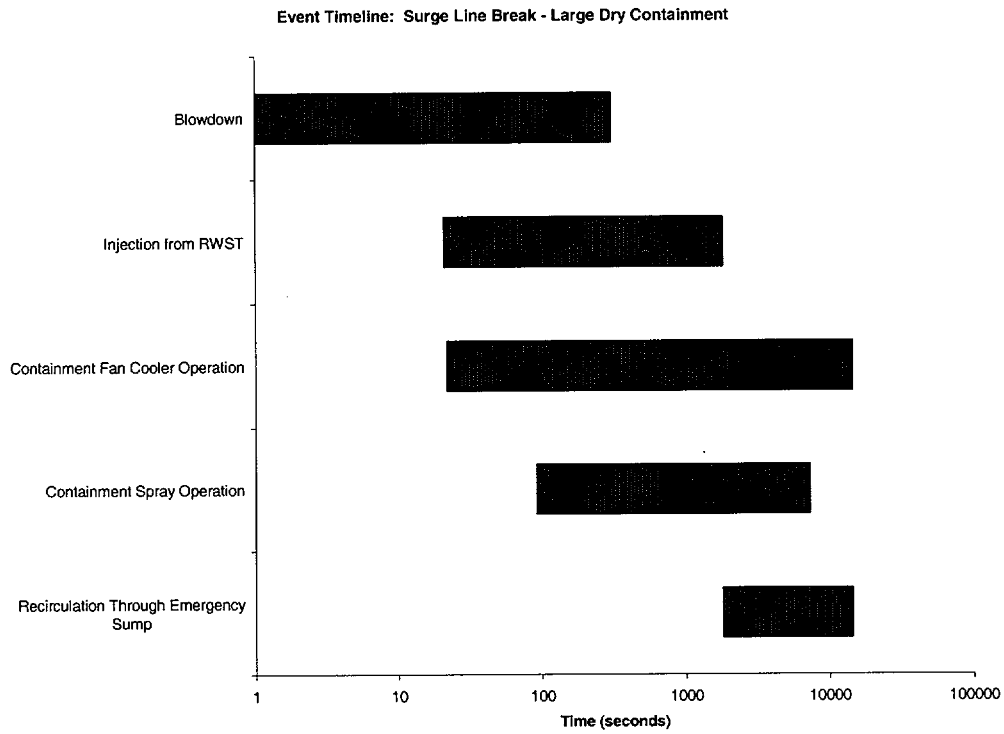


Fig. 8. Event Timeline for Small-Small LOCA Accident Progression.



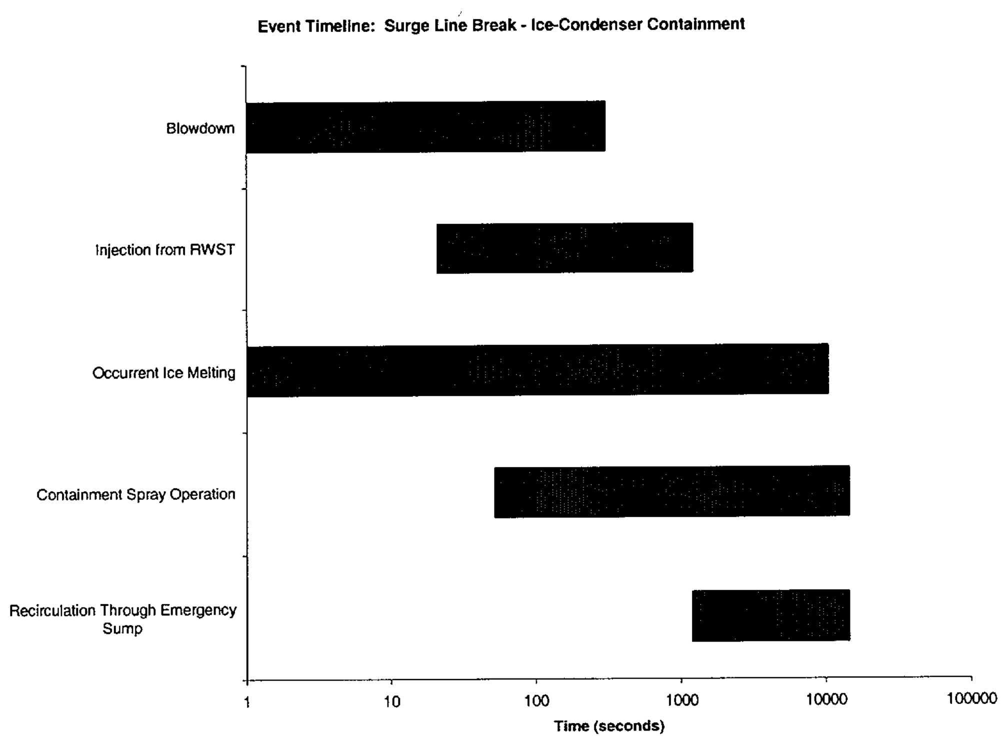


Fig. 9. Event Timeline for Surge Line Break Accident Progression.

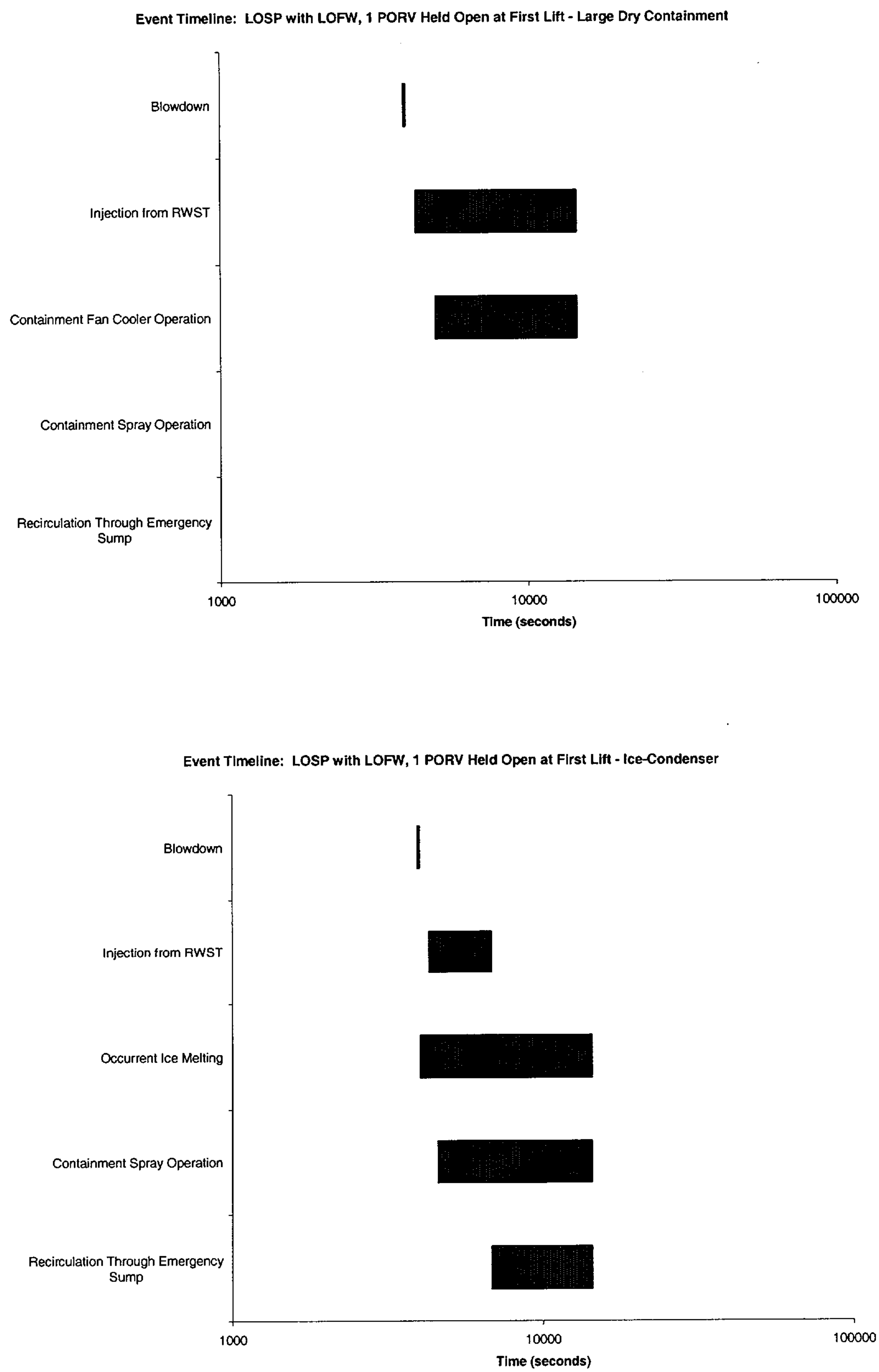
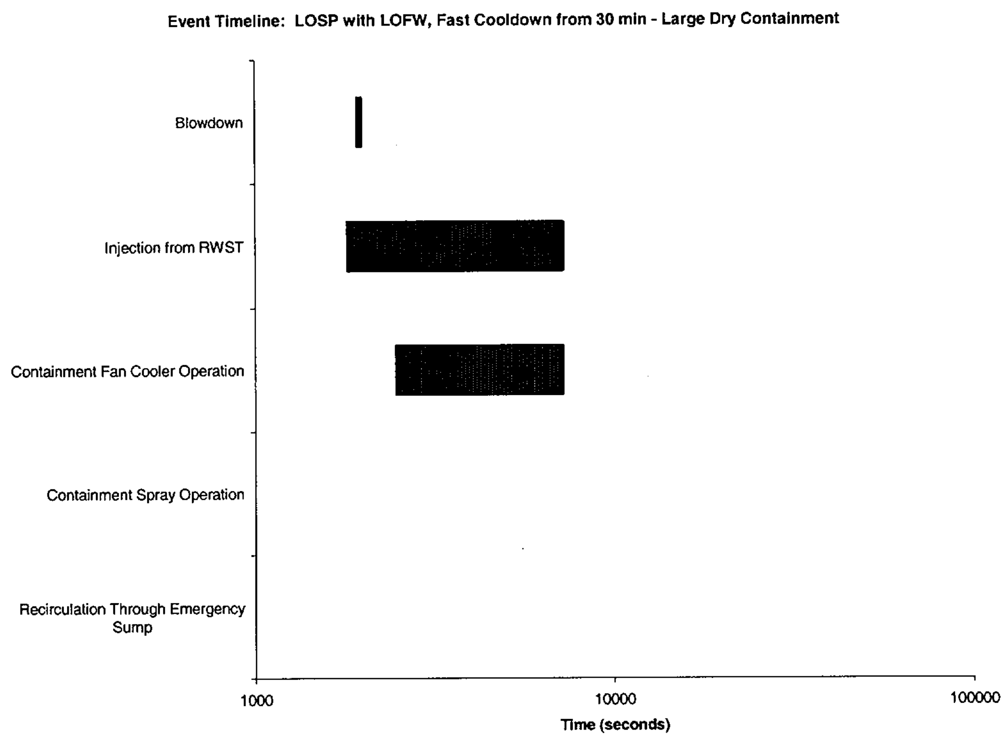


Fig. 10. Event Timeline for Transient Accident Progression.



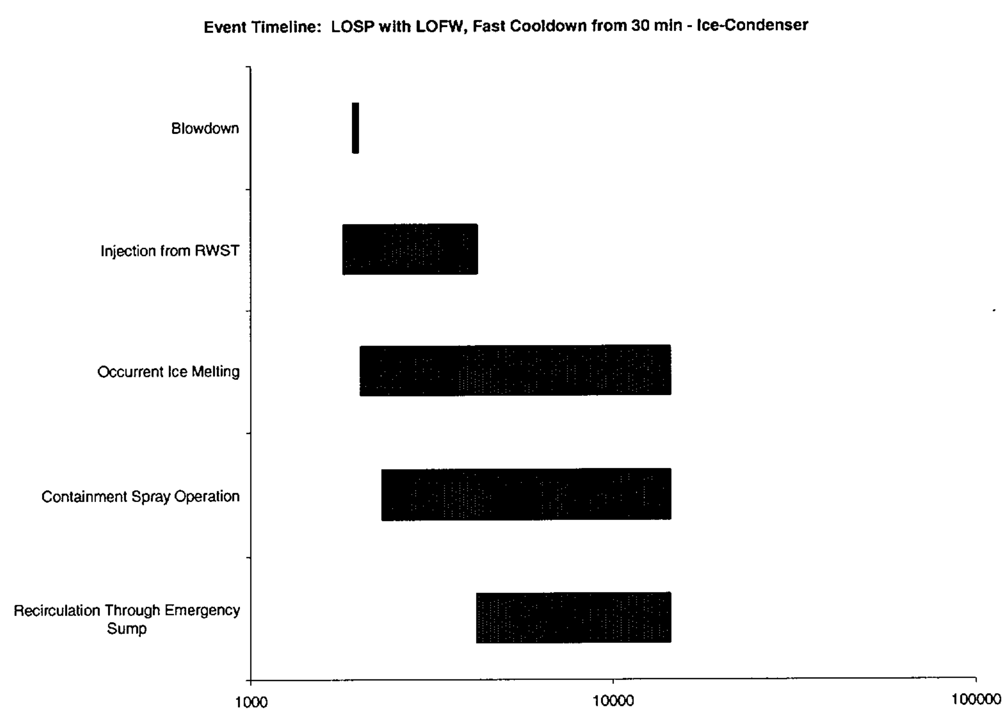
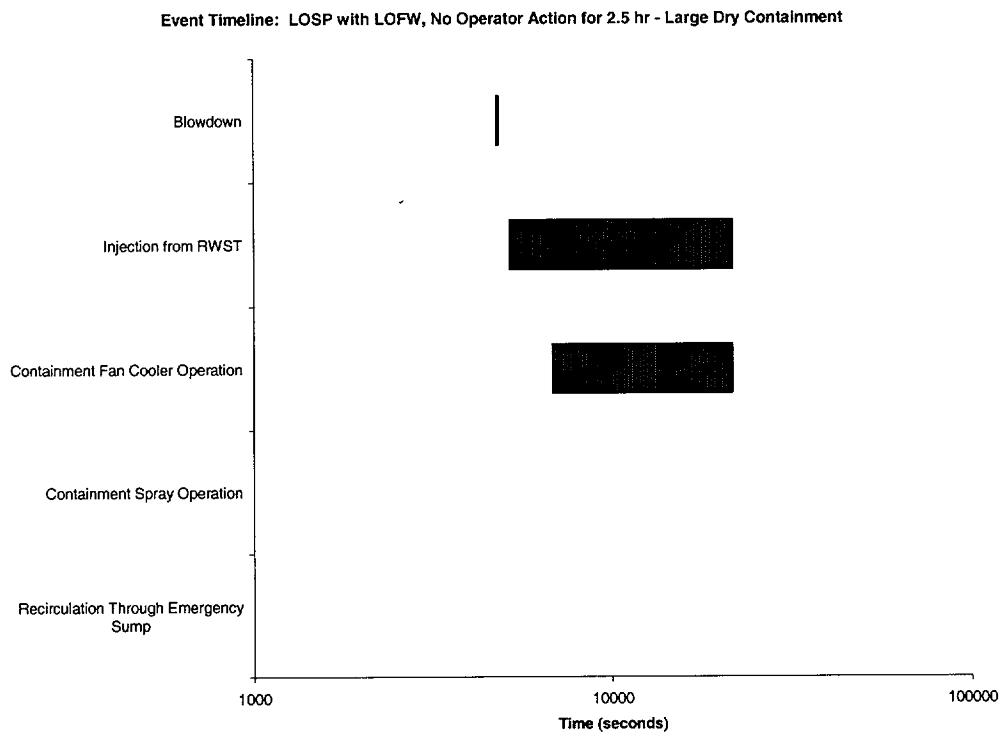


Fig. 10. Event Timeline for Transient Accident Progression (cont).



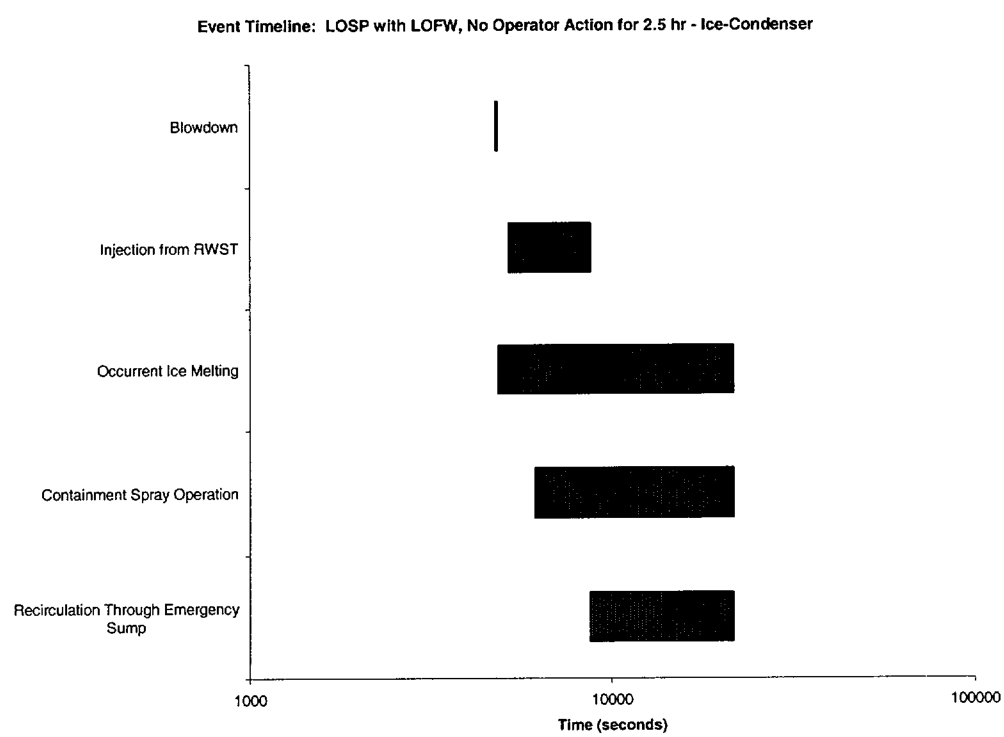
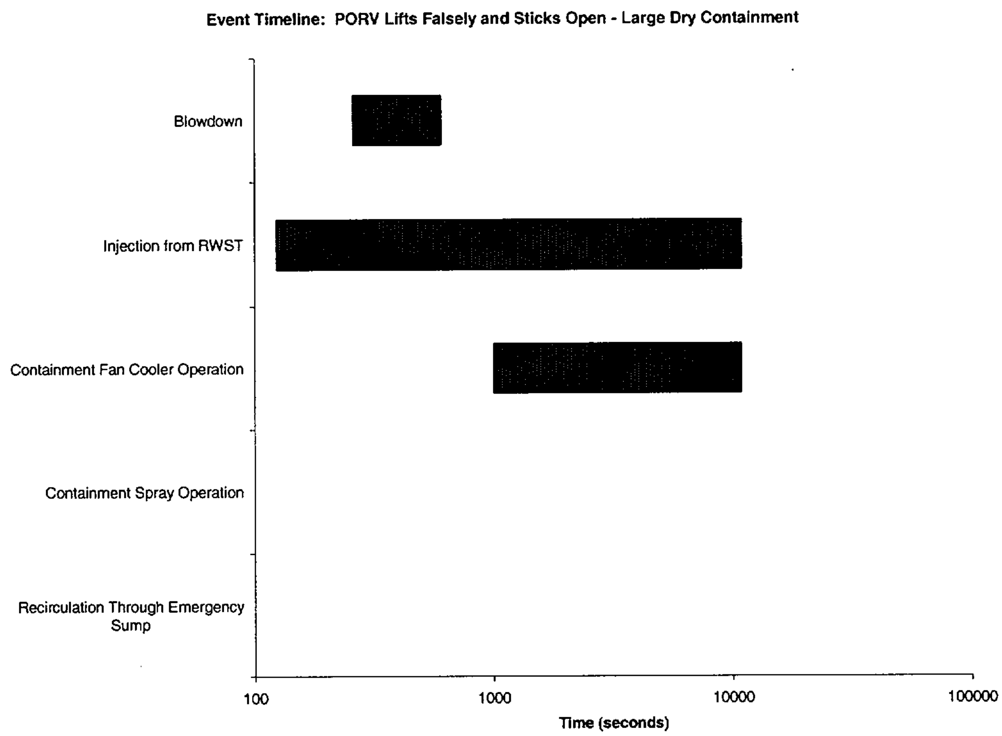


Fig. 10. Event Timeline for Transient Accident Progression (cont).



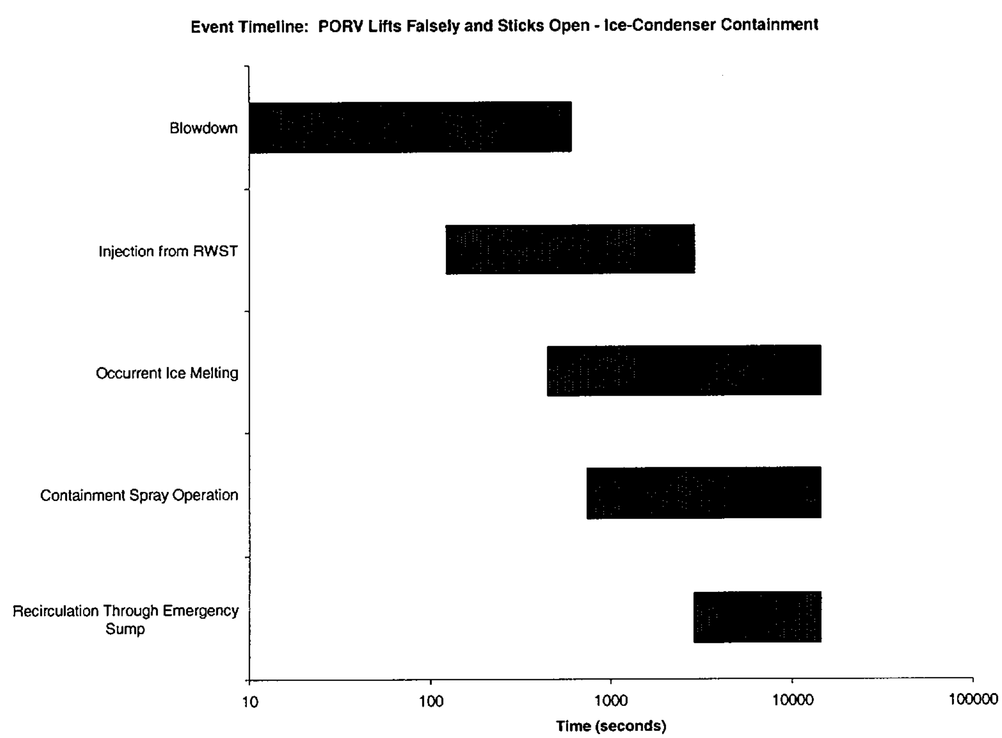


Fig. 11. Event Timeline for PORV Accident Progression.

- *In some cases, although ECCS recirculation through the emergency sump is required, it is only necessary for a few hours.* In an accident where ECCS recirculation through the emergency sump was required for only a few hours, the RCS breach would again have been above the centerline of the hot legs. In this case, RHR entry would be accomplished but only sometime after the RWST inventory had been expended. Upon RHR entry conditions being achieved, the ECCS pumps would be realigned from taking suction from the containment sump to taking suction from the hot legs.
- *Results differ markedly with containment type.* In large dry containments, sump recirculation is not required following LOSP with LOFW and a stuck-open PORV. In these accidents, the RCS breach is above the centerline of the hot legs, and therefore, makeup water is not required. The RHR entry conditions were achieved before the RWST inventory was expended during feed and bleed. In the RHR cooling mode of operation, decay heat is removed by pulling water from the hot legs, passing it through the RHR heat exchangers, and redelivering it to the reactor at the cold-leg SI points. On the other hand, in ice-condenser containments, sump recirculation is required for all accident scenarios simulated. The primary reason for this difference is that ice-condenser containments have a low CS actuation set point (2.9 psig) that would actuate containment sprays after every accident analyzed. In the large dry containments, the sprays would not actuate (CS set point > 9.5 psig), and the containment fans are sufficiently sized to manage containment pressure and temperature. If the sprays were not used or were used only sparingly, the length of time that ECCS injection could draw from the RWST would be increased greatly. The implication is that the potential for debris transport would be higher in the case of ice-condenser containments as compared with large dry containments.
- *The magnitude of the ECCS recirculation flow through the emergency sump varies between events.* In the case of a small-small LOCA, the maximum flow through the sump is expected to be about 250 gpm or less. This flow is required only for making up the RCS inventory leaking out through the breach. On the other hand, following a large-break LOCA and surge line break, the maximum sump flow approaches the design flow (which is approximately 18,000 gpm for the plants simulated). The implication is that the potential for debris transport would be higher following a large-break LOCA and a surge line break compared with all other accidents analyzed.
- *CS actuation is accident- and plant-specific.* In an accident where the containment fan coolers sufficiently managed containment pressure and temperature to below the ESF actuation set point, sprays would not actuate. If the sprays were not used or were used only sparingly, the length of time that ECCS injection could draw from the RWST would be largely increased. This also would minimize the potential for debris washdown by the cascading spray water. Sprays were required for the ice condenser containment, resulting in sump flow rates nearly 4 times that required for the large dry plants. Note that for SLOCA events, sprays may not be required for large dry containments whose actuation set points are higher than 10-15 psi if fan coolers do not operate, thereby limiting the maximum flow expected through the sump. This is because of the following.

    - In several plants, the chilled water supply to the fan coolers is isolated following the LOCA, which reduces the efficiency of the fan coolers for removing containment heat. The ultimate heat sink is the component cooling water (CCW), which may not be sufficiently sized to handle such heat loads.
    - Degradations in fan coolers may also be possible if LOCA debris reaches or deposits on the fan cooler heat exchangers.
    - Fan coolers are not safety-class equipment in most PWRs. It is not clear that fan coolers can be relied on for pressure control for a variety of reasons ranging from the fact that their functionality is not tested for these conditions to the fact that the heat removal source for fan coolers may be isolated as a result of a high-high or high containment pressure set point (differs from containment to containment).

Important technical considerations that should be addressed in the debris generation and transport models are presented below for each phase of accident progression. General results for LLOCA, MLOCA and SLOCA are provided in Figs. 12-14.

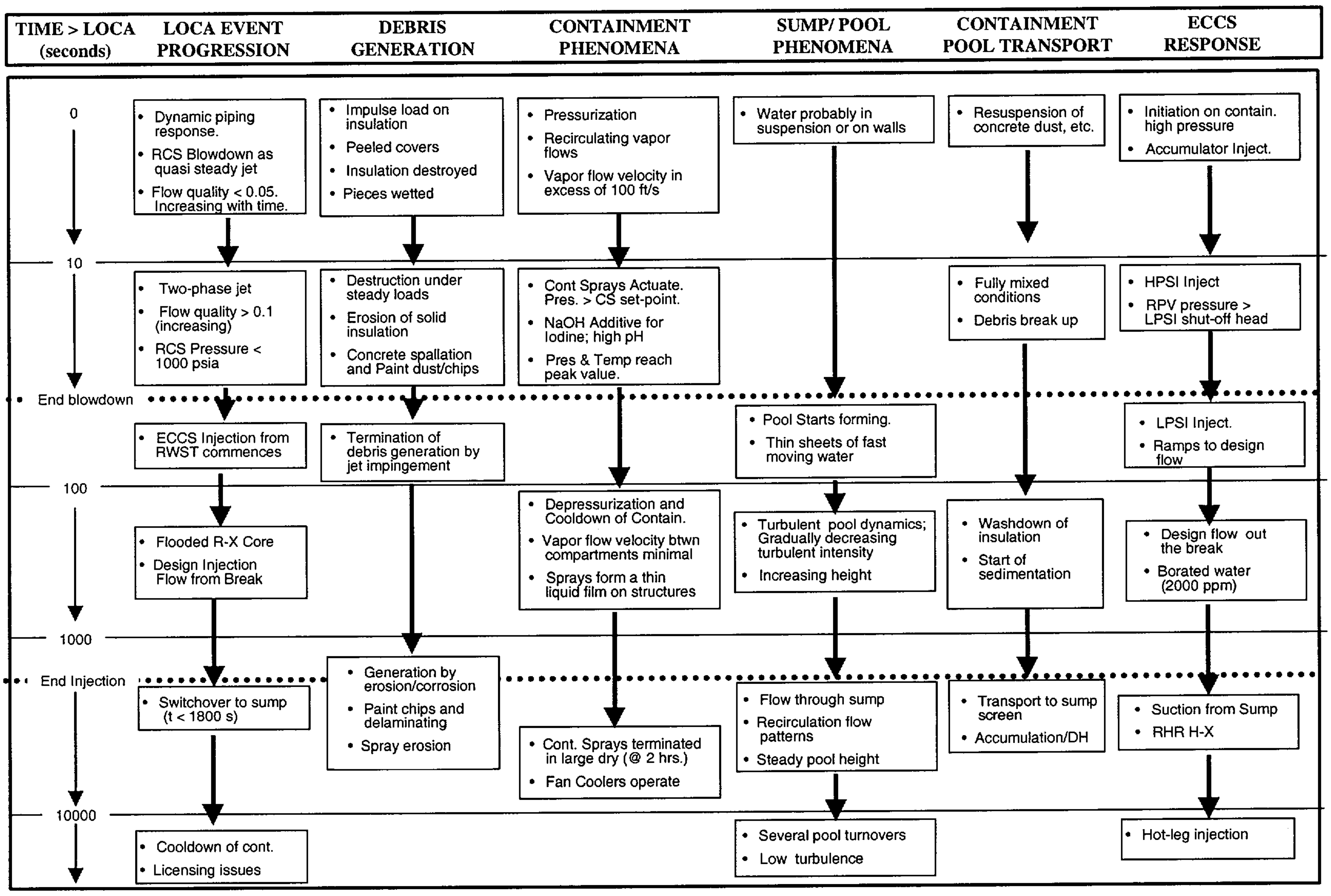


Fig. 12. PWR LLOCA Accident Progression in a Large Dry Containment.

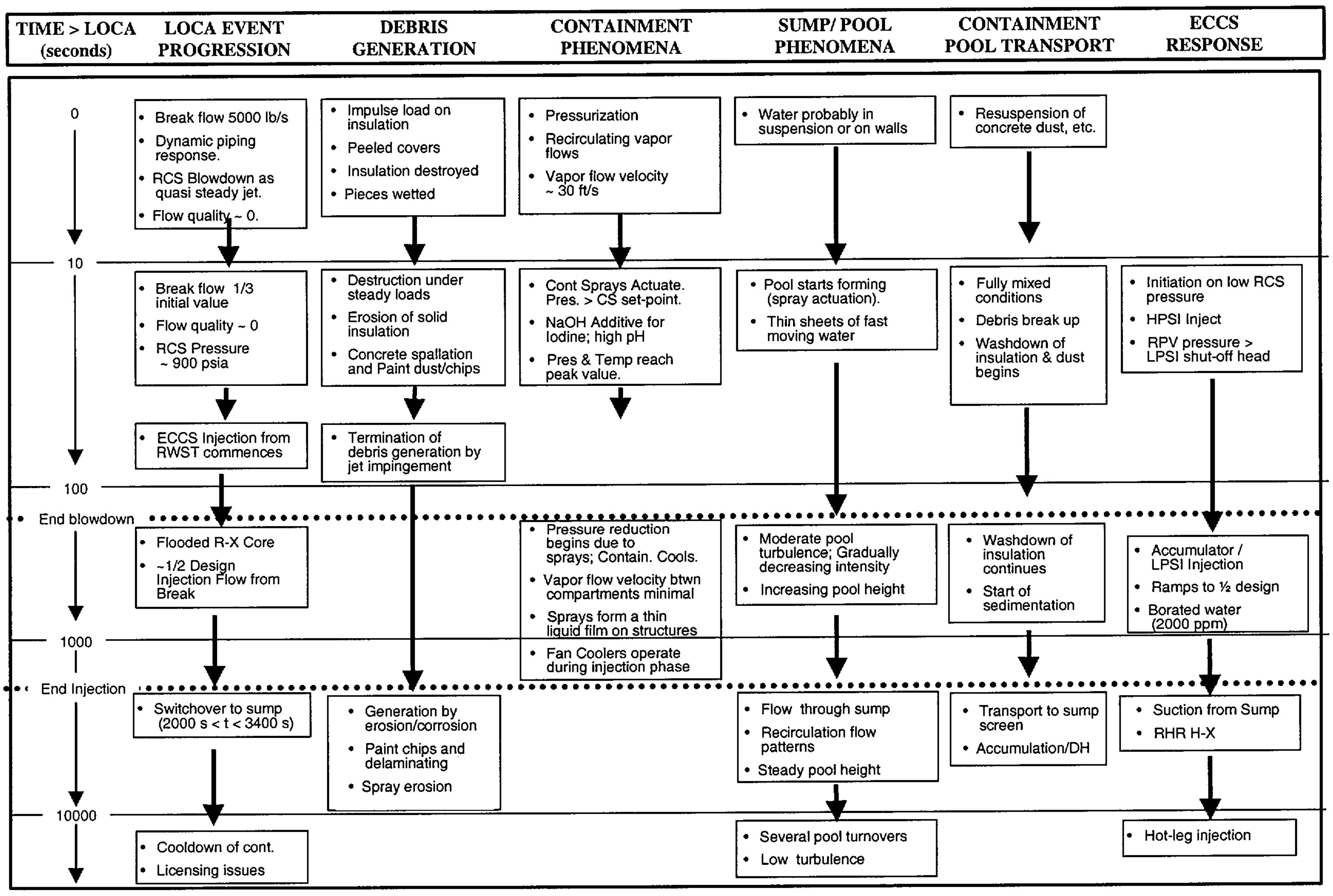


Fig. 13. PWR MLOCA Accident Progression in a Large Dry Containment.

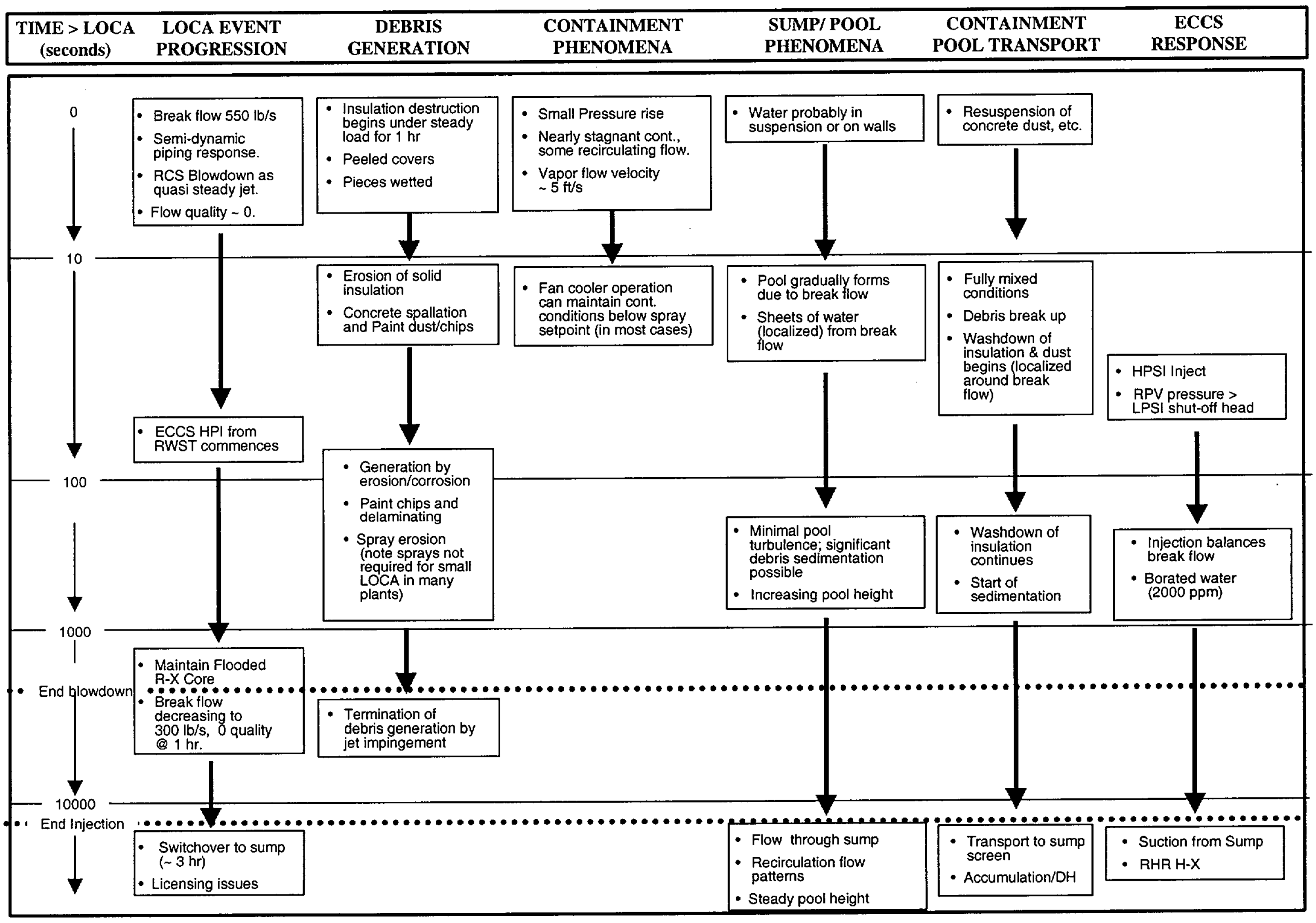


Fig. 14. PWR SLOCA Accident Progression in a Large Dry Containment.

4.1.1 RCS Blowdown. In this report, the RCS blowdown refers to the event (or process) by which elevated energy in the RCS inventory is vented to containment as the RCS vents through the breach. It is during RCS blowdown that the highest (and most destructive) energy is released and breach flows occur. Therefore, debris generation by jet impingement would be greatest during this time. Also, debris could be displaced from the breach vicinity as the flashing two-phase break jet expands into the containment. Large atmospheric velocities may develop in the containment as breach effluent quickly expands to all regions of containment. In the vicinity of the breach, containment structures would be drenched by water flowing from the breach. Throughout the containment, condensing steam would wet structures, and water would begin to pool on the containment floor. The time at which blowdown begins and when it is terminated depends strongly on the type of initiator and plant-specific details, such as the design/capacity of the ECCS and the plant type.

Accurate characterizations of conditions that exist during the blowdown phase are important for estimating debris generation and, to some degree, debris transport. The duration and severity of blowdown vary considerably with each accident type.

Large-Break LOCA. RCS blowdown following an LLOCA occurs over a period of 30 s, during which time the vessel pressure drops from 2000 psia to near atmospheric pressure. During this time, the reactor pressure vessel thermodynamic conditions undergo a rapid change. Initially, the break flow is subcooled at the break plane and flashes as it expands into the containment. Within 2 s, the vessel pressure drops below 2000 psi and the flow in the pipes and the vessel becomes saturated. Thereafter, the break flow quality is equal to or higher than 10%. On the other hand, the void fraction increases to approximately 1.0, clearly indicating that the water content would be dispersed in the vapor continuum in the form of small droplets. The corresponding flow velocity at the break plane reaches a maximum of about 930 ft/s. This clearly indicates that jets would reach supersonic conditions during their expansion upon exiting the break. Based on these simulations, the energetic blowdown terminates within 25 s as the vessel pressure decreases to near ambient (pressure < 150 psig). Although steam at high velocities continues to exit, the stagnation pressure is not sufficient to induce very high pressures at distances far from the break. Thus, it is reasonable to assume that debris generation following an LLOCA occurs within the first minute. (Note: Debris generation by non-jet-related phenomena may occur over a prolonged period of time as a result of high temperature and corrosion.)

Other LOCAs. RCS blowdown in the case of an MLOCA, pressurizer surge line-break LOCA, and SLOCAs occurs over a prolonged period (15 min for the MLOCA and 60 min for the SLOCA). In all these cases, blowdown starts at 0 s when the vessel is at 2000 psia and terminates mainly as the RCS pressure and liquid subcooling decrease. Another significant observation is that following an MLOCA/SLOCA, the exit flow at the break plane remains subcooled throughout the blowdown (at least until the vessel pressure falls to a point where blowdown would have little effect on debris generation). This may affect the ZOI over which debris would be generated.

Small-Small LOCA. RCS blowdown occurs over several hours during which the RCS depressurizes gradually from 2000 psia to 300 psia. Once again, the fluid exit conditions remain subcooled throughout the blowdown.

Transients. In all the transients modeled, the RCS relief water was assumed to enter the PRT, which is fitted with a rupture disk rated to withstand 100 psid in Westinghouse plants. (The PRT model details are Volume: 1800 ft^3, Number: 2, Break Pressure: 100 psid, Rating: 800, 000 lbm/h at 100 psig.) In all these accidents, the PRT tank gets overwhelmed well into the accident and releases two-phase mixtures at a quality of about 0.4. However, the stagnation pressure in the tank is very low (about 100 psid).

4.1.2 ECCS Injection Phase. The injection phase refers to the period during which the RCS relies on SI, drawing on the RWST for decay heat removal. The following phenomena occur during the injection phase. Core reflood is accomplished, and quasi-steady conditions are arrived at in the reactor, where decay heat is removed continually by injection flow. Containment sprays actuate, condensing steam and washing structures. Spray water drains over and down containment walls and equipment, carrying debris to a growing water pool on the containment floor. Containment fan coolers not operating before the accident start. In ice-condenser containments, the recirculation fans move the containment atmosphere through the ice condensers. Opportunities would exist for debris to settle in the pool during this relatively quiescent time before ECCS recirculation. Containment pressure would largely decrease from its maximum value reached in the blowdown phase. The injection phase is considered to be over when the RWST inventory is expended.

Accurate characterization of conditions that exist during injection phase is vital for estimating the quantity of debris transported from the upper containment to the pool and for estimating the quantity of debris that may remain in suspension. As shown in Tables 6 and 7, the injection phase in the case of large LOCA succeeds the RCS blowdown. In other accidents, the injection phase overlaps with the RCS blowdown. The duration of the injection phase was found to be a strong function of three factors: (a) the capacity of the RWST *vis-à-vis* ECCS sizing, (b) the CS actuation set point, and (c) the accident type.

LLOCA. Following an LLOCA, SI begins immediately because of the combined operation of the accumulators, the charging pump, the high-pressure safety injection (HPSI) pumps, and the low-pressure safety injection (LPSI)/RHR pumps. The SI flow approaches the design value (which is 11,500 gpm in the plant we simulated) in about a minute and continues at that rate until switchover. Current simulations did not take credit for reduction in the injection flow because either the operator throttles the ECCS train(s) or there are active systems failures (e.g., single-failure scenarios). After a LLOCA, the containment pressure also increases to a point where containment sprays would be turned on automatically (irrespective of containment type) and start injecting water into the containment within the first minute as well.

In conclusion, it has been determined that large quantities of water would be introduced into the containment within few minutes following an LLOCA. As a result, the water pool depth on the containment floor increases steadily. In the case of a large dry containment, the peak pool height is reached at the end of injection; in an ice-condenser containment, the peak value is reached several hours into the accident when all the ice melts.

Other Accidents. There are two fundamental differences between the LLOCA and the other LOCAs.

- The LPSI does not inject significant quantities of water into the core, at least for several hours. In the case of the MLOCA, the LPSI (or RHR) pumps start injecting into the core at about 1 h and reach steady state after 3 h (see Fig. A.2-5). In other breaks, the LPSI does not inject into the core at all; the HPSI and charging pumps are sufficient to make up for lost inventory.
- Actuation of containment sprays is highly plant specific and may not be needed at all. In the current plant (which has a CS actuation set point of 9.5 psig), spray actuation occurs only for the MLOCA. Even then, the operator may terminate sprays to prolong RWST availability and rely on fan coolers (or the ice condenser) for decay heat removal from the containment.

4.1.3 Recirculation Phase. After the inventory of the RWST had been expended, the ECCS pumps would be realigned to take suction from the emergency sump in the containment floor. This would begin the ECCS recirculation phase in which water would be pulled from the containment pool, passed through heat exchangers, and delivered to the RCS, where it would pick up decay heat from the reactor core, flow out the breach, and return to the containment pool. Pool depth would reach a steady state during the recirculation phase, and containment pressure and temperature would be gradually decreasing. It would be during the ECCS recirculation phase that potential would exist for debris resulting from an RCS breach (or residing in containment beforehand) to be transported to the containment emergency sump, accumulate on the sump screens, restrict flow, and either consume available NPSH or starve the ECCS recirculation pumps.

Three observations regarding the RCS and containment conditions during the recirculation phase can be made.

- Only LOCAs (large, medium, small, and surge line break) induce large flow rates through the sump. In the case of large breaks, the sump flow rate reaches the design capacity of all the pumps (which in our case is 17,500 gpm for the large dry containment and 18,000 gpm for the ice-condenser containment).
- In the case of large dry containments, other accidents (small-small LOCA, and transients) do not need sump recirculation because switchover to RHR cooling is possible within a few hours and containment sprays either would not be actuated or would be terminated by the operator after RWST switchover.
- In the case of ice-condenser containments, sump recirculation following accidents other than LOCAs is limited to supplying water to the containment sprays (which is about 6400 gpm).

4.2 Accident Progression Following a LLOCA

Figure 12 and Table 25 present a phenomenological description of events that would occur following a LLOCA.

4.2.1 Systems Response. A postulated break in the primary system initiates a high-pressure blowdown of the RCS liquid inventory. The blowdown and the subsequent flashing[5] in the containment cause a rapid decay in RCS pressure and rapid buildup of containment pressure. Either of these initiates reactor scram, and with delay built in, it is expected that reactor scram would occur within the first 1 s. Accident progression in sequences in which scram does not occur is significantly different and will not be discussed here.

The RCS blowdown continues until the vessel pressure falls below the shut-off head for accumulator tank,[6] the HPSI, and the LPSI. This causes increasingly large quantities of cooler borated RWST water to quench the core and terminate blowdown. The duration of blowdown phase is inversely proportional to the size of the break and other systematic considerations such as hot-leg vs cold-leg break. For a DEGB, the blowdown occurs roughly over the first 30 s.

An increase in containment pressure causes actuation of containment sprays, and in the case of ice condenser containment, it also results in opening of the ice-condenser compartment doors. The results indicate that CS actuation would occur in all containments in spite of the fact that in some large dry containments, the CS actuation set point is 27 psig. The containment spray adds water over the entire containment. In most containments, NaOH liquid stored in the spray additive tank (SAT) will be added to the borated water to facilitate absorption of iodine that may be released to the containment. Therefore, a secondary effect of the containment spray is that it may increase the pH of the liquid in the pool, which in turn could play a role in particulate debris precipitation.

During the injection phase, the HPSI, LPSI, and CS pumps take suction from the RWST. The break overflow and the CS flow fill up the containment sump and collect on the containment floor, forming a large pool of water. The height of the water pool is dependent on the water resources available for core reflood and selected operator actions regarding switchover. Simulations have shown that pool water height is highly plant-specific—varying from 2 to 15 ft.

The injection phase of ECCS operation continues until the RWST level falls below a preset point, at which time the LPSI and HPSI pumps switch over suction from the RWST to the containment sump. Switchover can be manual, semi-automatic, or automatic, depending on the vintage of the plant. In the plants simulated in our study, switchover occurred between 17 min (for an ice-condenser plant equipped with an RWST of 457,000 gal.) and 28 min (for a large-dry plant equipped with an RWST of 295,000 gal.).

Results from an industry survey conducted by the Nuclear Energy Institute (NEI) suggest that switchover time can vary between 5 and 40 min following an LLOCA, with a median value of 20 min (Ref. 6).

Table 25. PWR Large-Break LOCA Sequences.

<table>
<tr><th>Time after LOCA (s)</th><th>Accum. (SI Tanks)</th><th>HPSI</th><th>LPSI</th><th>CS</th><th>Comments</th></tr>
<tr><td>0-1</td><td colspan="5">Reactor scram. Initially high containment pressure. Followed by low pressure in the pressurizer. Debris generation commences caused by the initial pressure wave, followed by jet impingement. The blowdown flow rate is large. But mostly saturated water. Quality ≤0.05. Saturated jet-models are appropriate. SNL/ANSI Models suggest wider jets, but pressures decay rapidly with distance.</td></tr>
<tr><td>2</td><td></td><td>Initiation signal</td><td>Initiation signal</td><td>Initiation signal</td><td>Initiation signal from low pressurizer pressure or high containment pressure/temperature</td></tr>
<tr><td>5</td><td>Accumulator injection begins</td><td>Pumps start to inject into vessel (bypass flow out)</td><td>Pumps start (RCS P > pump dead head)</td><td>Pump start and sprays on</td><td>In cold-leg break, ECCS bypass is caused by counter-current injection in the downcomer. Hot leg does not have this problem.</td></tr>
<tr><td>10</td><td colspan="5">The blowdown flow rate decreases steadily from ≈20,000 lb/s to 5000 lb/s. Cold-leg pressure falls considerably to about 1000 psia. At the same time, effluent quality increases from 0.1 to 0.5 (especially that from steam generator side of the break). Flow is vapor continuum with water droplets suspended in it. Saturated water or steam jet-models are appropriate. At these conditions, SNL/ANSI models show that jet expansion induces high pressures far from the break location.</td></tr>
<tr><td>25</td><td></td><td>End of bypass; HPSI injection</td><td></td><td></td><td></td></tr>
<tr><td>25-30</td><td colspan="5">Break velocity reaches a maximum > 1000 ft/s. Quality in excess of 0.6. Steam flow at less than 500 lb/s. Highly energetic blowdown is probably complete. However, blowdown continues as residual steam continues to be vented.</td></tr>
<tr><td>35</td><td></td><td></td><td>Vessel LPSI ramps to design flow.</td><td></td><td></td></tr>
<tr><td>40</td><td colspan="5">Blowdown is terminated, and therefore, debris generation is complete. Blowdown pressure at the nozzle less than 150 psi. Debris would be distributed throughout the containment. Pool is somewhat turbulent. Height < 1 ft.</td></tr>
<tr><td>45</td><td>Accumula-tors empty</td><td></td><td></td><td></td><td></td></tr>
<tr><td>55-200</td><td colspan="5">Reflood and quenching of the fuel rods (T_{max} 1036 °F). In cold-leg break, quenching occurs between 125 and 150 s. In the case of hot-leg break, quenching occurs between 45 and 60 s (T_{max} 950 °F).</td></tr>
<tr><td>200-1200</td><td colspan="5">Debris added to lower containment pool by spray washdown drainage and break washdown. The containment floor keeps filling. No directionality to the flow. Heavy debris may settle down.</td></tr>
<tr><td>1200</td><td colspan="5">RWST low level indication received by the operator. Operator prepares to turn on ECCS in sump recirculation mode. Actual switchover when the RWST low-low level signal is received.</td></tr>
<tr><td>1500</td><td></td><td>Switch suction to sump</td><td>Switch suction to sump</td><td>Terminate or to sump</td><td>Many plants have containment fan coolers for long-term cooling.</td></tr>
<tr><td>1500-18000</td><td colspan="5">Debris may be brought to the sump screen. Buildup of debris on the sump screen may cause excessive head loss. Containment sprays may be terminated in large dry containments at the 2-h mark.</td></tr>
<tr><td>>36000</td><td></td><td>Switch to hot-leg recirculation.</td><td>Switch to hot-leg recirculation</td><td></td><td></td></tr>
</table>

In some plants, the containment sprays also switch over from the RWST to the sump, whereas in other plants, containment sprays would be turned off after RWST water resources are exhausted and containment heat removal would be accomplished by the fan coolers. The current simulations suggest that in many large dry containments, CS operation is not necessary because fan coolers have a sufficient size to remove decay heat.

During the recirculation phase, the ECCS pumps take suction from the containment floor, force it through heat exchanger(s), and inject cooler water into the pressure vessel. Further heat removal is provided by the fan cooler operation in the case of large dry containments and ice melting in the case of ice-condenser plants. No simulations were performed of how long ECCS recirculation operation is necessary for core/containment heat removal. However, the simulations do suggest that single-train injection is sufficient over the long term for RCS decay heat removal.

4.2.2 Thermal-Hydraulic Conditions During the Blowdown Phase. Following a large break, blowdown occurs immediately as the RCS blows down from 2100 psia to atmospheric pressure. The blowdown is completed in its entirety within 30 s. Blowdown is characterized by continual change in the thermodynamic state of the exiting fluid. The results of the current calculations, which were done for a Westinghouse four-loop plant, show the following trends.

- $t_{LOCA} < 1$ s. Primarily, subcooled water[7] ($\Delta T_{sub} \approx 20^{\circ}$F and $P_{stag} \approx 2100$ psia) exits the break. During this short interval, the break flow reaches a maximum value of about 80,000 lbm/s, although the fluid velocity at the break is relatively small (296 ft/s).
- 1 s $< t_{LOCA} < 10$ s. During this time, the flow stagnation conditions undergo a rapid change. Within a second or two, the vessel pressure drops below 2000 psi and the flow becomes saturated. Thereafter, the break flow quality is equal to or higher than 10%. On the other hand, the void fraction increases to approximately 1.0, clearly indicating that the water content would be dispersed in the vapor continuum in the form of small droplets. The corresponding flow velocity of the jet at the break plane is about 930 ft/s at an RCS pressure between 1500 and 1000 psi. This clearly indicates that jets would reach supersonic conditions during their expansion upon exiting the break.
- 10 s $< t_{LOCA} < 25$ s. About 10 s after a LOCA, the vessel pressure drops below 1000 psi, and the flow quality can vary between 10% and 40%, depending on the location of the break and response of the HPSIs. The flow velocities reach near-sonic level at the break plane, and for all practical purposes, these flows behave very similar to steam flows.
- $t_{LOCA} > 25$ s. Based on these simulations, the energetic blowdown terminates within 25 s as the vessel pressure decreases to near ambient (pressure < 150 psig). Although steam at high velocities continues to exit, the stagnation pressure is not sufficient to induce very high pressures at distances far from the break.

The containment pressure and temperature reach their maximum values either at the end of the blowdown phase or soon thereafter. In the case of large dry containment(s), the maximum pressure and temperature are 36 psig and 305°F; for ice condensers, they are 14 psig and 168°F, respectively.

4.2.3 Thermal-Hydraulic Conditions During the Injection Phase. Initially, the accumulator flow enters the core, followed by the SI flow (i.e., charging, HPSI, and LPSI flow). The SI flow increases steadily, reaching a steady state within the first minute. The combined ECCS flow for the RCS modeled is 11,500 gpm (see Fig. A.1-5 for the individual contributions of each system).

The high-high signal for actuation of containment sprays also is generated during blowdown. However, our conservative assumptions regarding the switching sequence resulted in the actual actuation of containment spray at about 50 s into the accident. Thereafter, the CS flow remained at a steady value of 5700 gpm, which is the CS flow rate for the plant being simulated.

In the plants simulated in our study, switchover occurred between 17 min (for an ice-condenser plant equipped with an RWST of 295,000 gal.) and 28 min (for a large-dry plant equipped with an RWST of

497,000 gal.). During this time frame, the pool depth increased from 0 to 3.5 ft in the case of a large dry containment and to 10 ft in the case of an ice-condenser containment.

The containment pressure and temperature (including that of the containment pool) decreased steadily with time from 36 psig to 7 psig and from 305°F to 170°F in the case of large dry containment analyzed.

4.2.4 Thermal-Hydraulic Conditions During the Recirculation Phase. The ECCS and CS flows remain fairly steady during recirculation at the design values of 11,800 gpm and 5700 gpm. These flow rates continue until the operators throttle either ECCS or CS flow rates. In our simulations, we assumed that operator would throttle containment spray after 2 h as the containment pressure and temperature fall well below its actuation set point. The turnover time of the sump volume (the volume of sump water/net ECCS + CS flow) is about 40 min, indicating that sump transport (if any) would have been completed within the first 2 h.

5.0 REFERENCES

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2. J. Darby, W. Thomas, and D. V. Rao, "Selection of Pressurized Water Reactor Accident Sequences for Evaluation of the Effect of Debris in the Sump," Los Alamos National Laboratory, Probabilistic Risk Analysis Group, letter report (April 30, 1999).

3. The RELAP5 Code Development Team, "RELAP5/MOD3 Code Manual," Volumes I through VII, Idaho National Engineering Laboratory/US Nuclear Regulatory Commission report NUREG/CR-5535 (June 1995).

4. R. M. Summers et al., "MELCOR Computer Code Manuals," Volumes 1 and 2, US Nuclear Regulatory Commission/Sandia National Laboratories report NUREG/CR-6119/SAND93-1285 (September 1994).

5. C. J. Shaffer and D. V. Rao, "Confirmatory Calculations of the Donald C. Cook Sump Water Level," Science and Engineering Associates, Inc., Albuquerque, NM, Technical Evaluation Report SEA 97-3703-A:5 (January 5, 1998).

6. "Results of Industry Survey on PWR Design and Operations," Compiled Database of Plant Responses, Nuclear Energy Institute (June 1997).

APPENDIX A
RELAP5 PREDICTIONS OF RCS RESPONSE

Fig. A.1-1: Cold Leg DEGB - Core Power

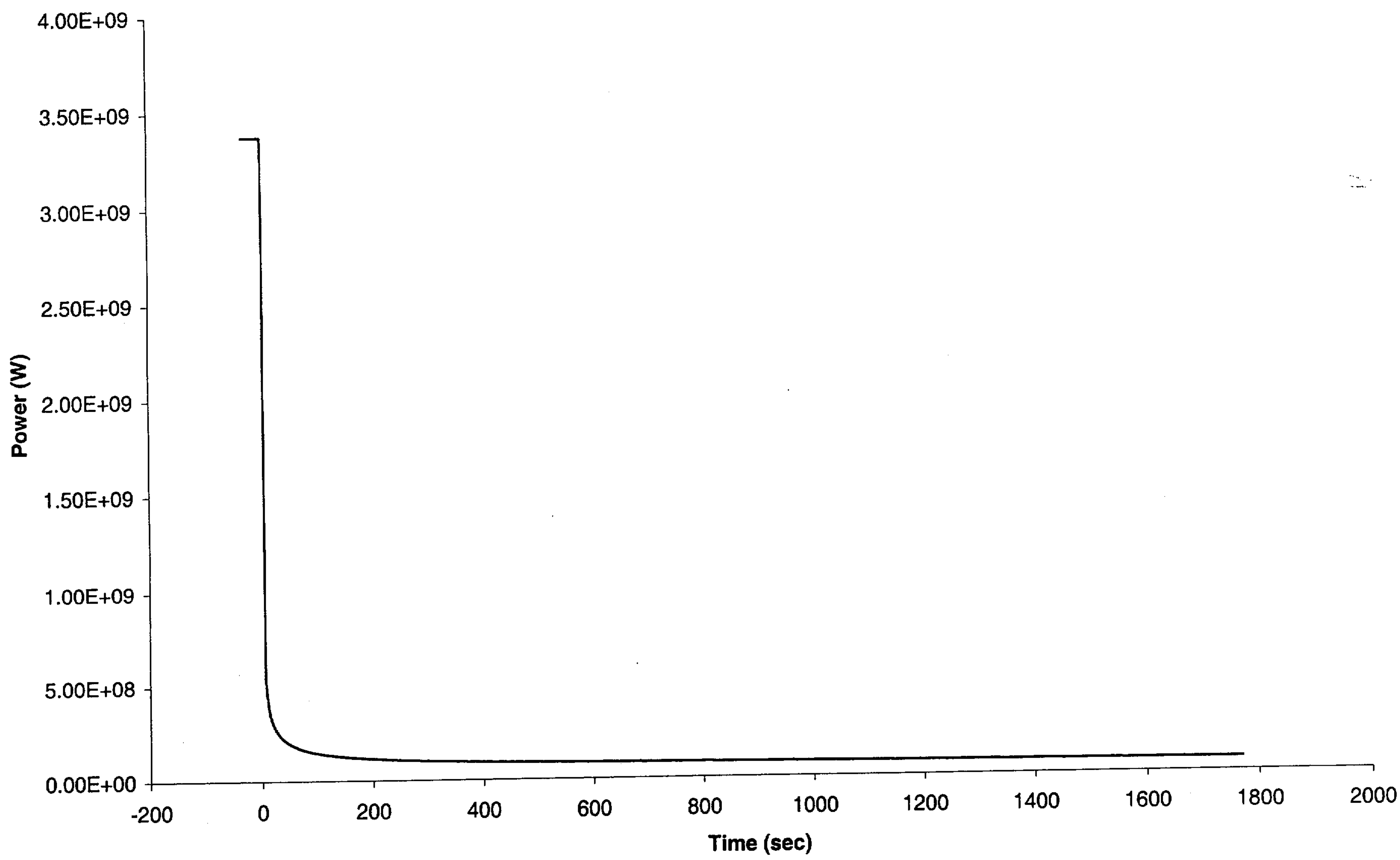

Fig. A.1-2: Cold Leg DEGB - RCS Pressure

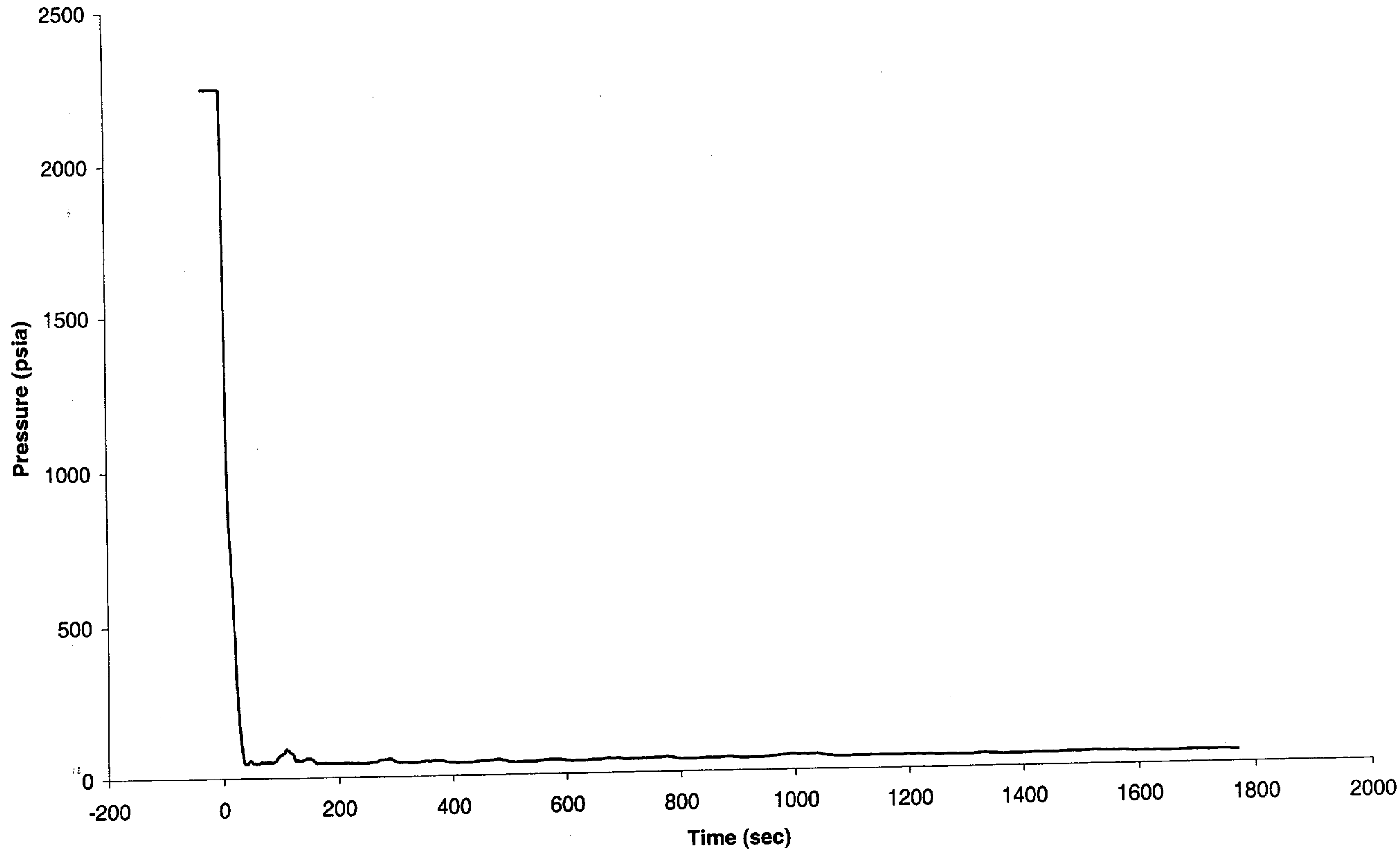

Fig. A.1-3: Cold Leg DEGB - Peak Cladding Temperature

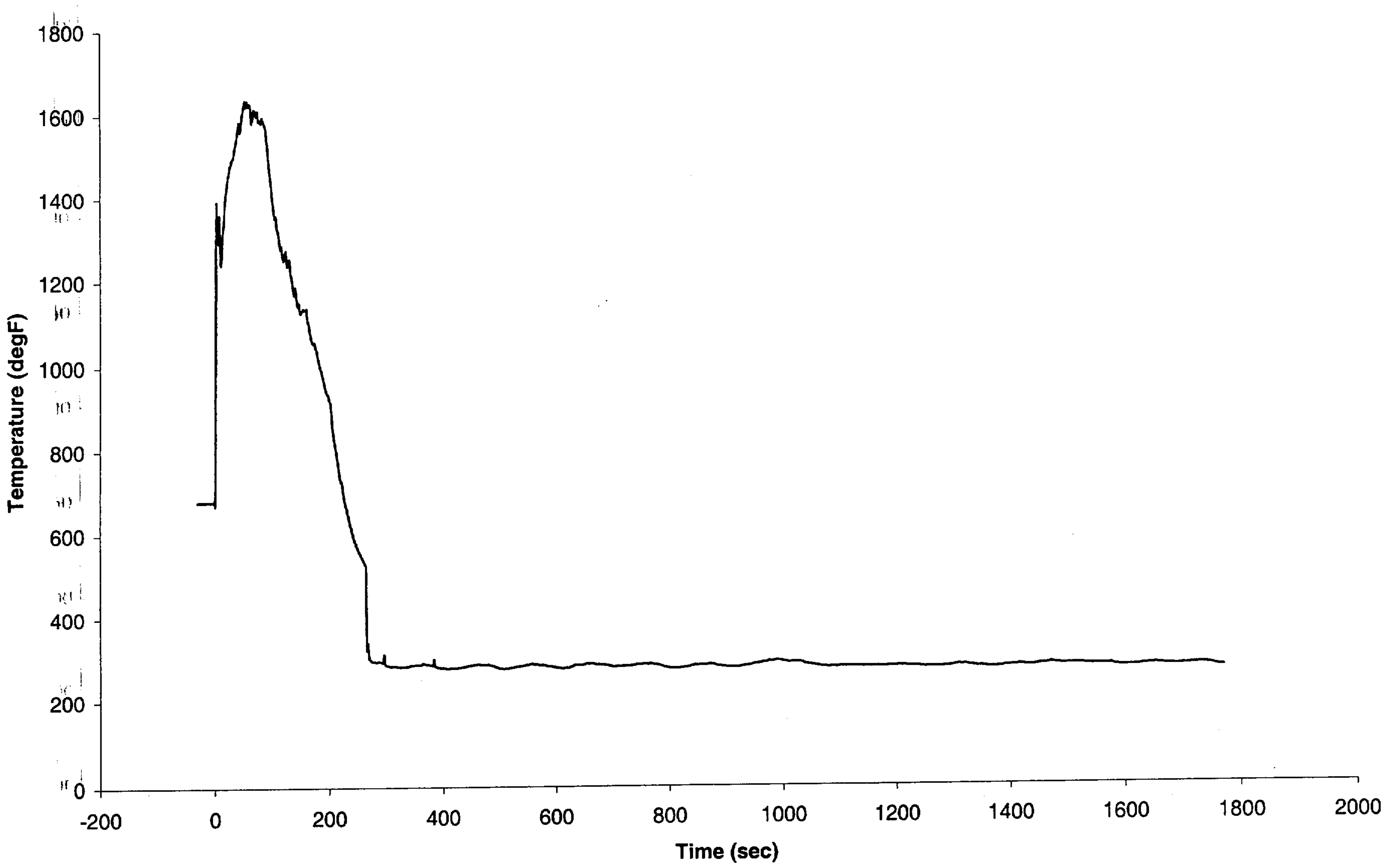

Fig. A.1-4: Cold Leg DEGB - Core Void

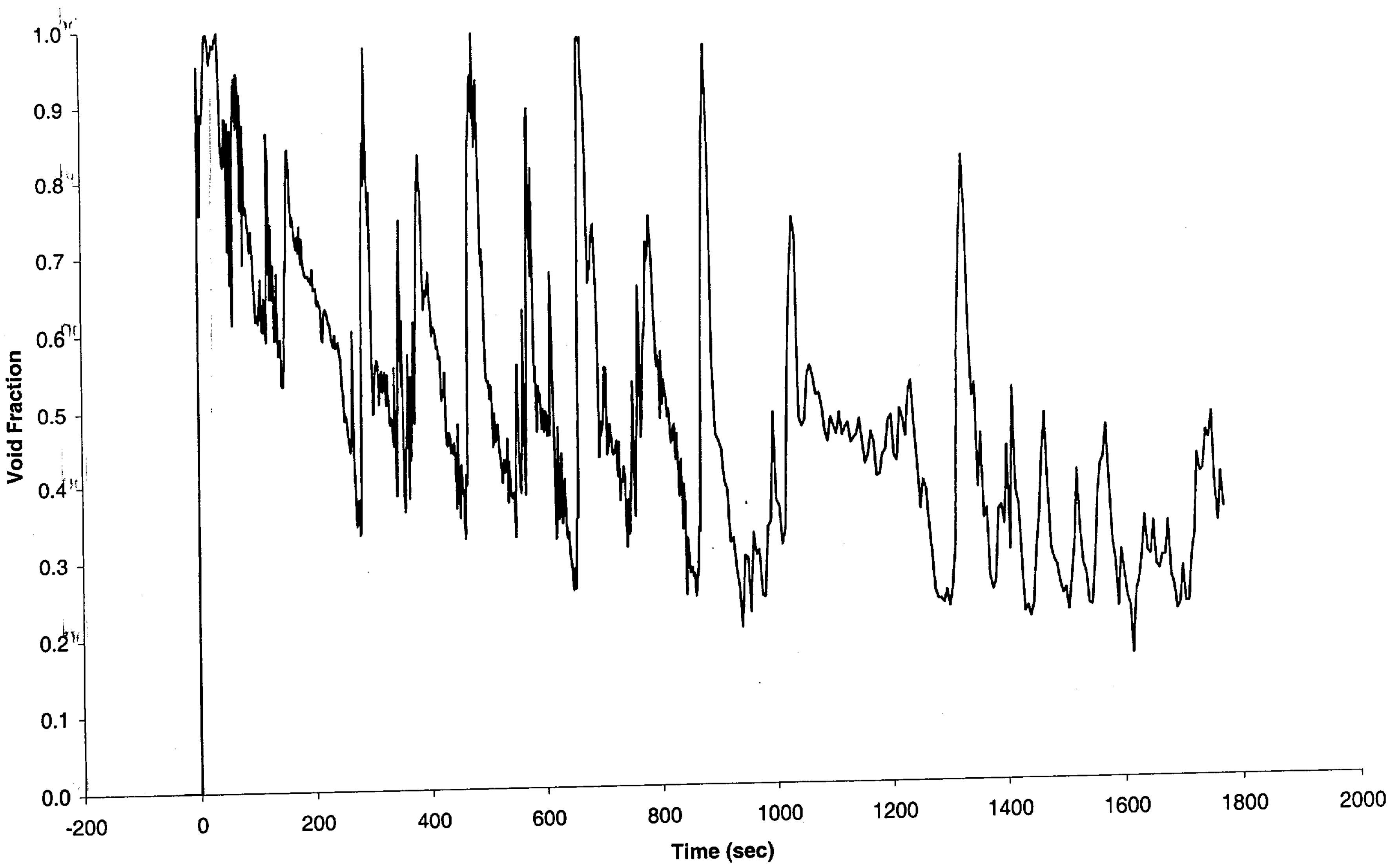

Fig. A.1-5: Cold Leg DEGB - Injection

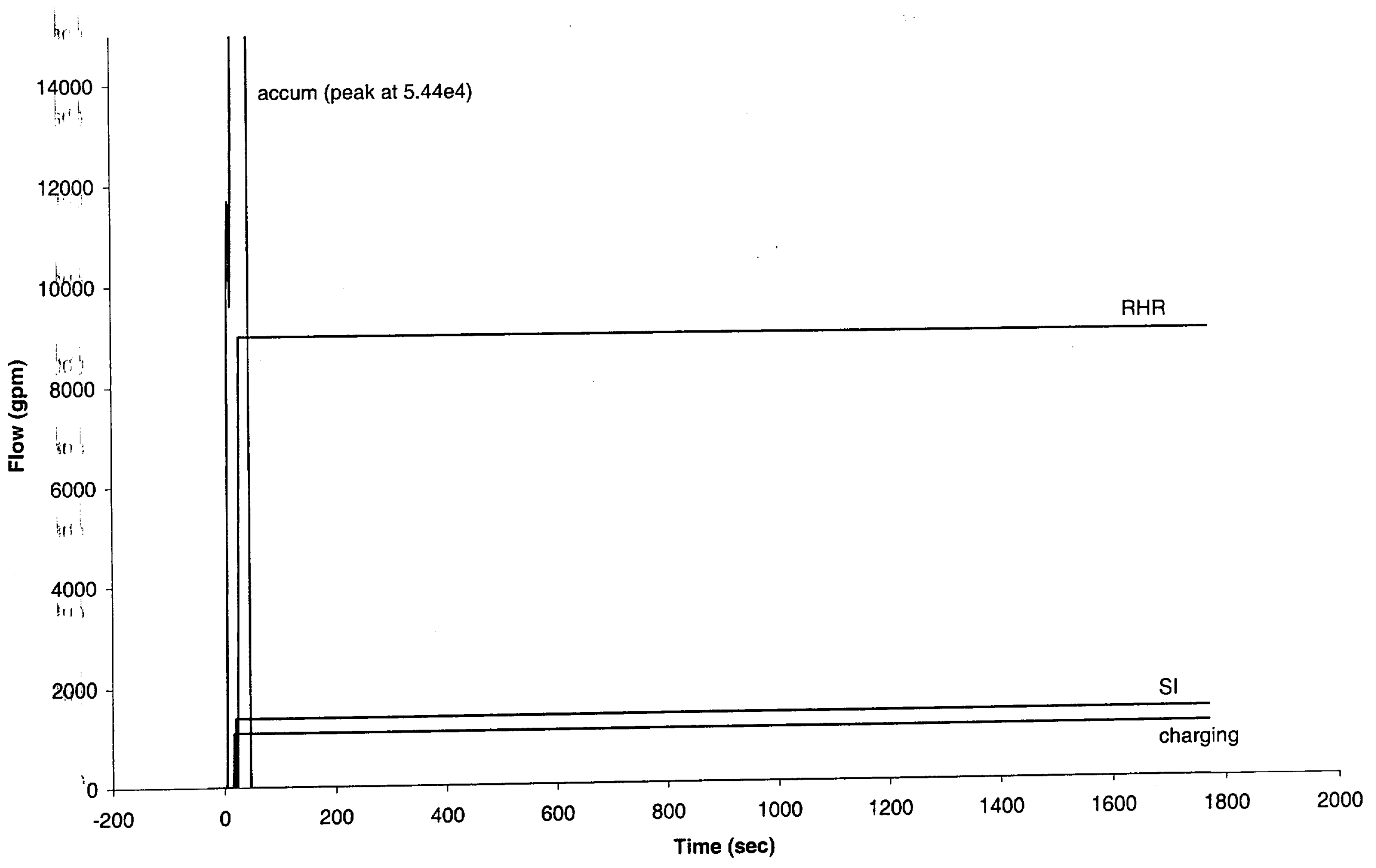

Fig. A.1-6: Cold Leg DEGB - Flow Rate at the Break

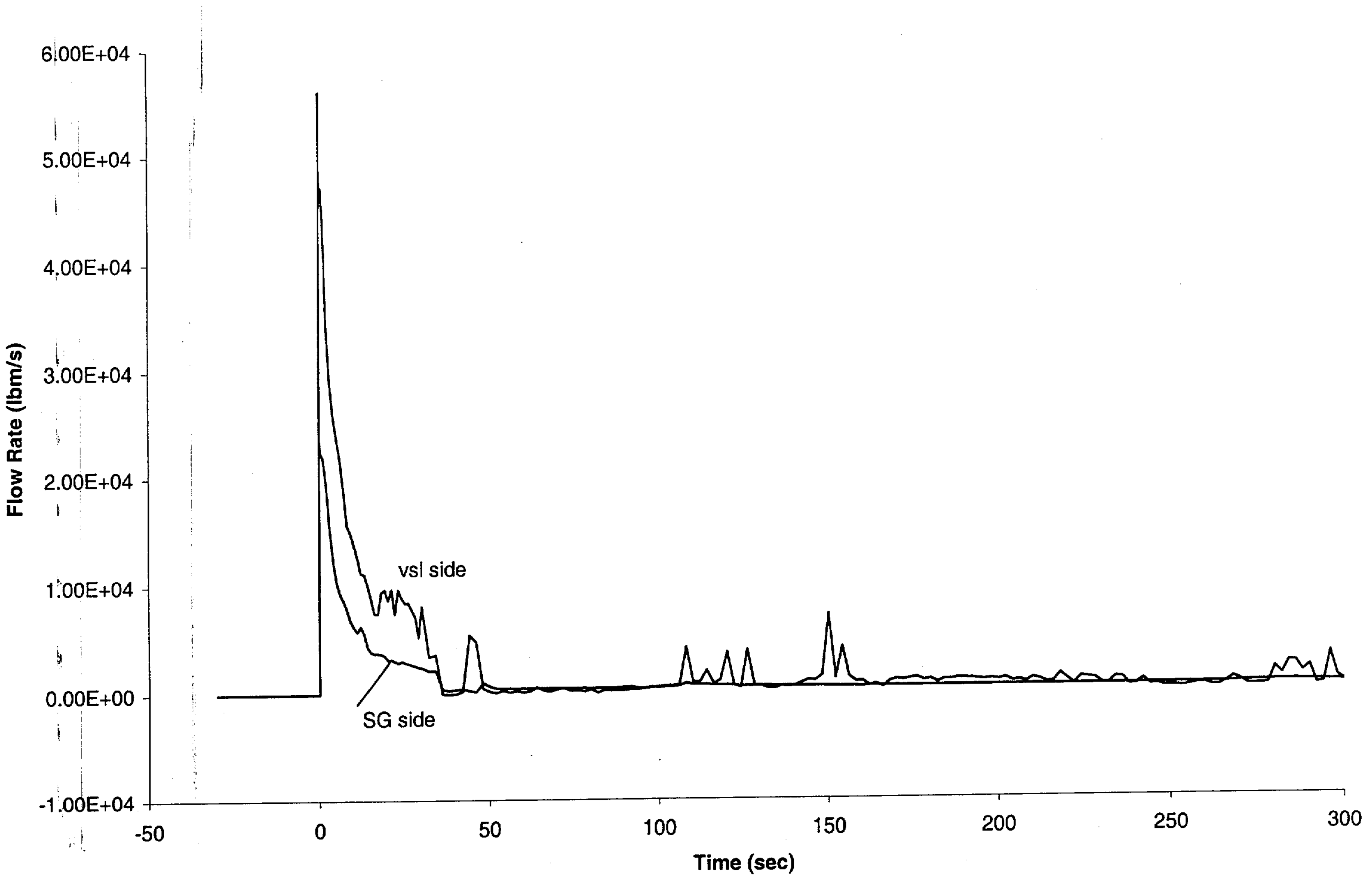

Fig. A.1-7: Cold Leg DEGB - Quality at the Break

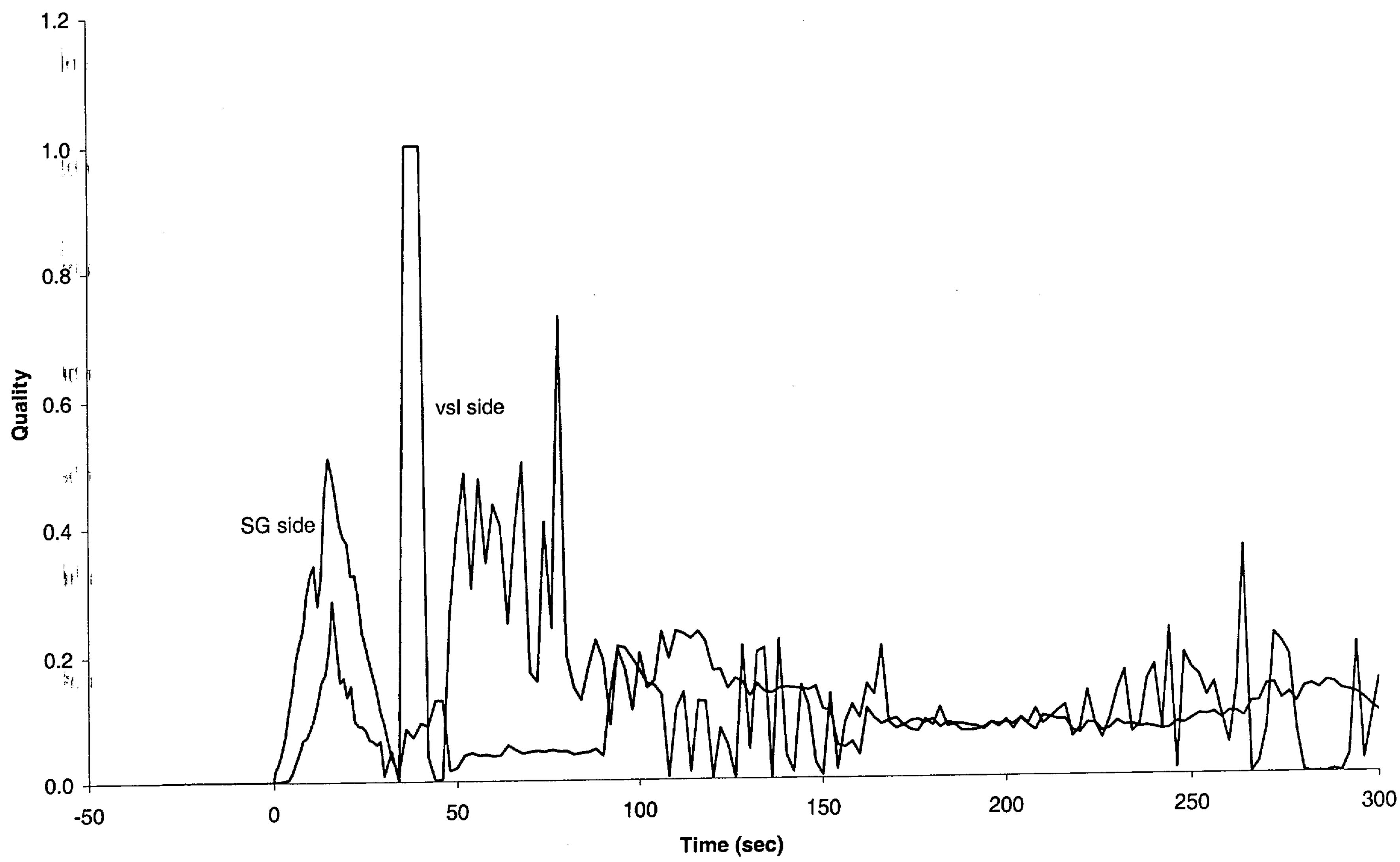

Fig. A.1-8: Cold Leg DEGB - Phasic Velocity at the Vessel Side of the Break

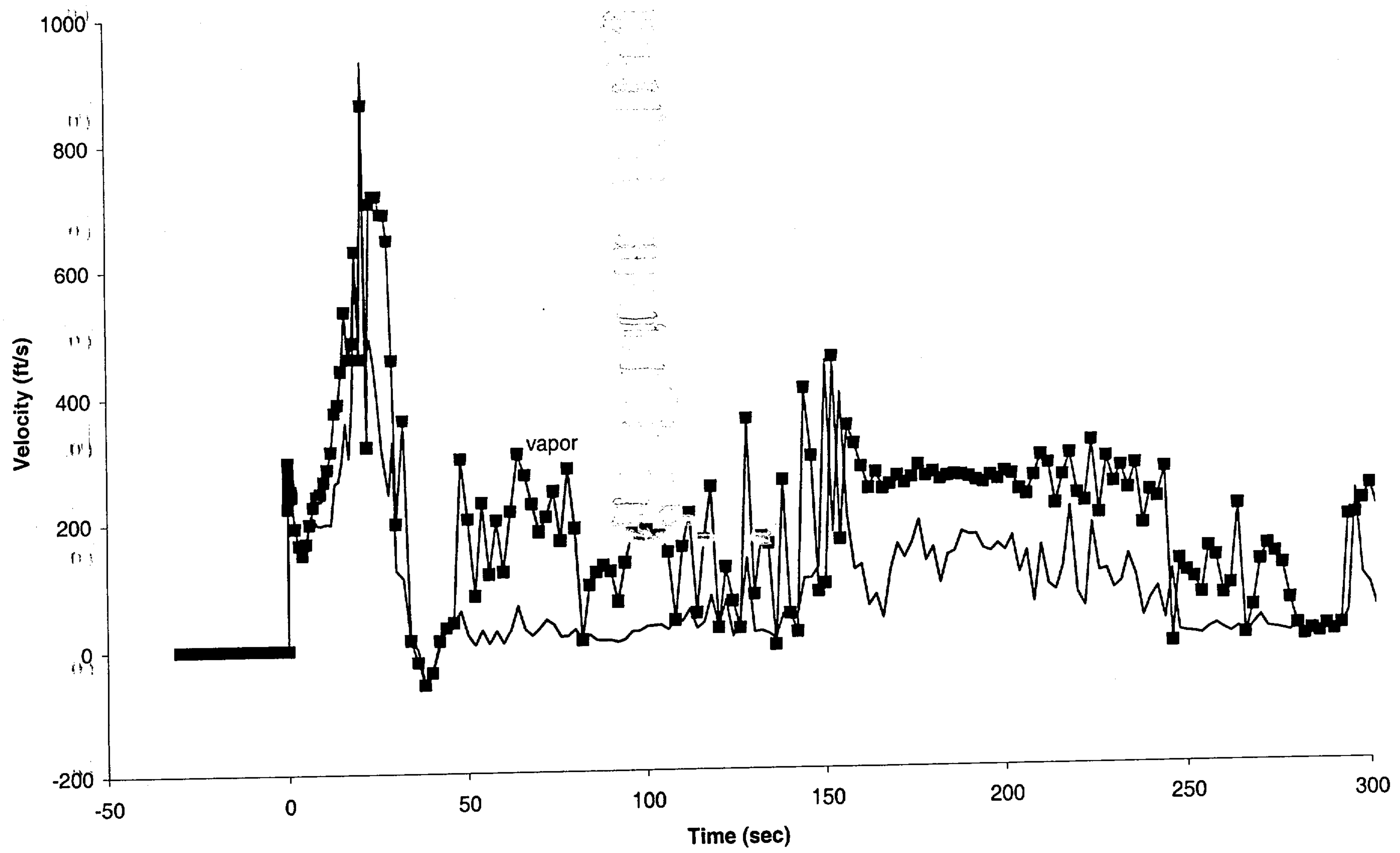

Fig. A.1-9: Cold Leg DEGB - Liquid Temperature at the Break

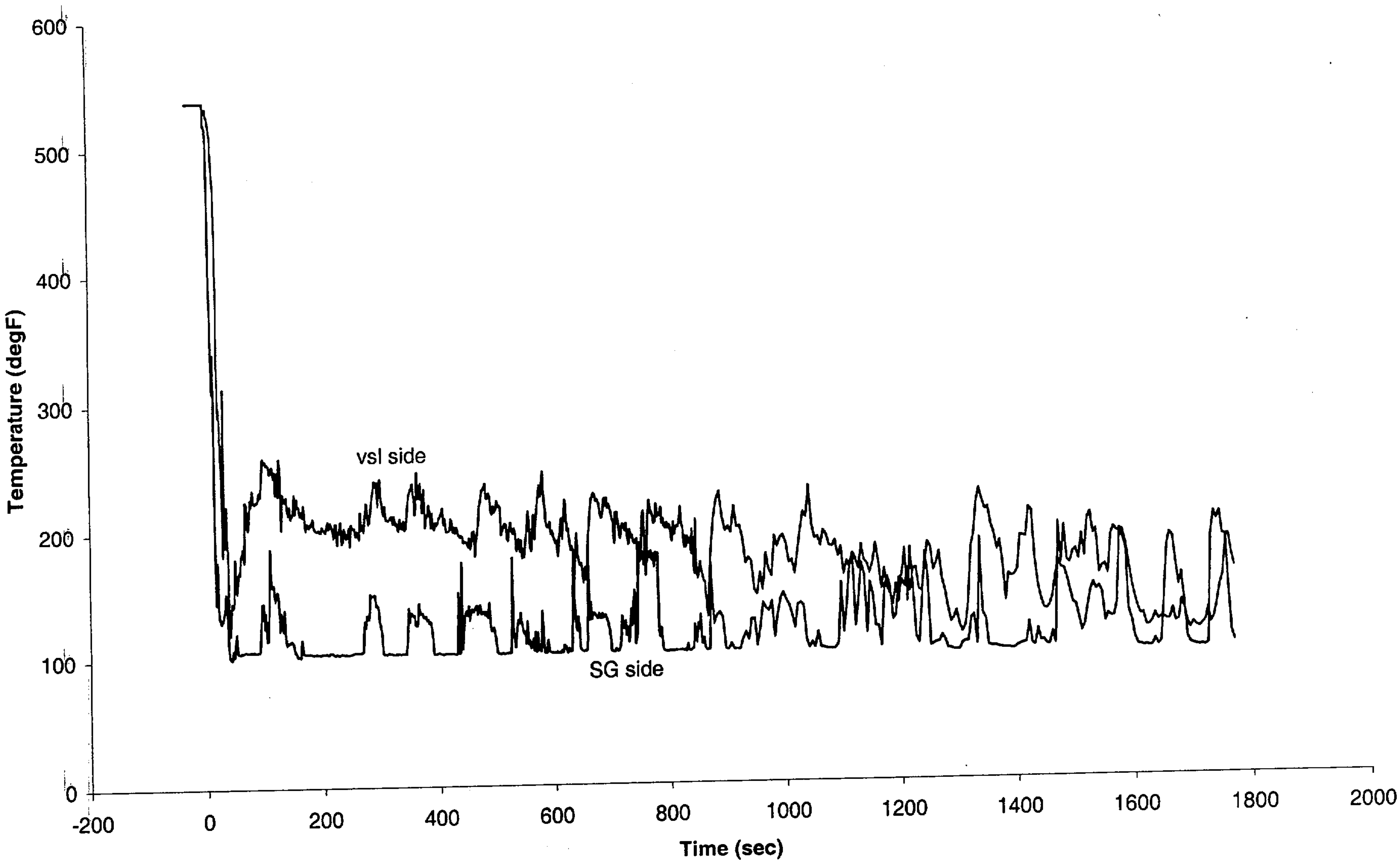

Fig. A.1-10: Cold Leg DEGB - RCP Speed

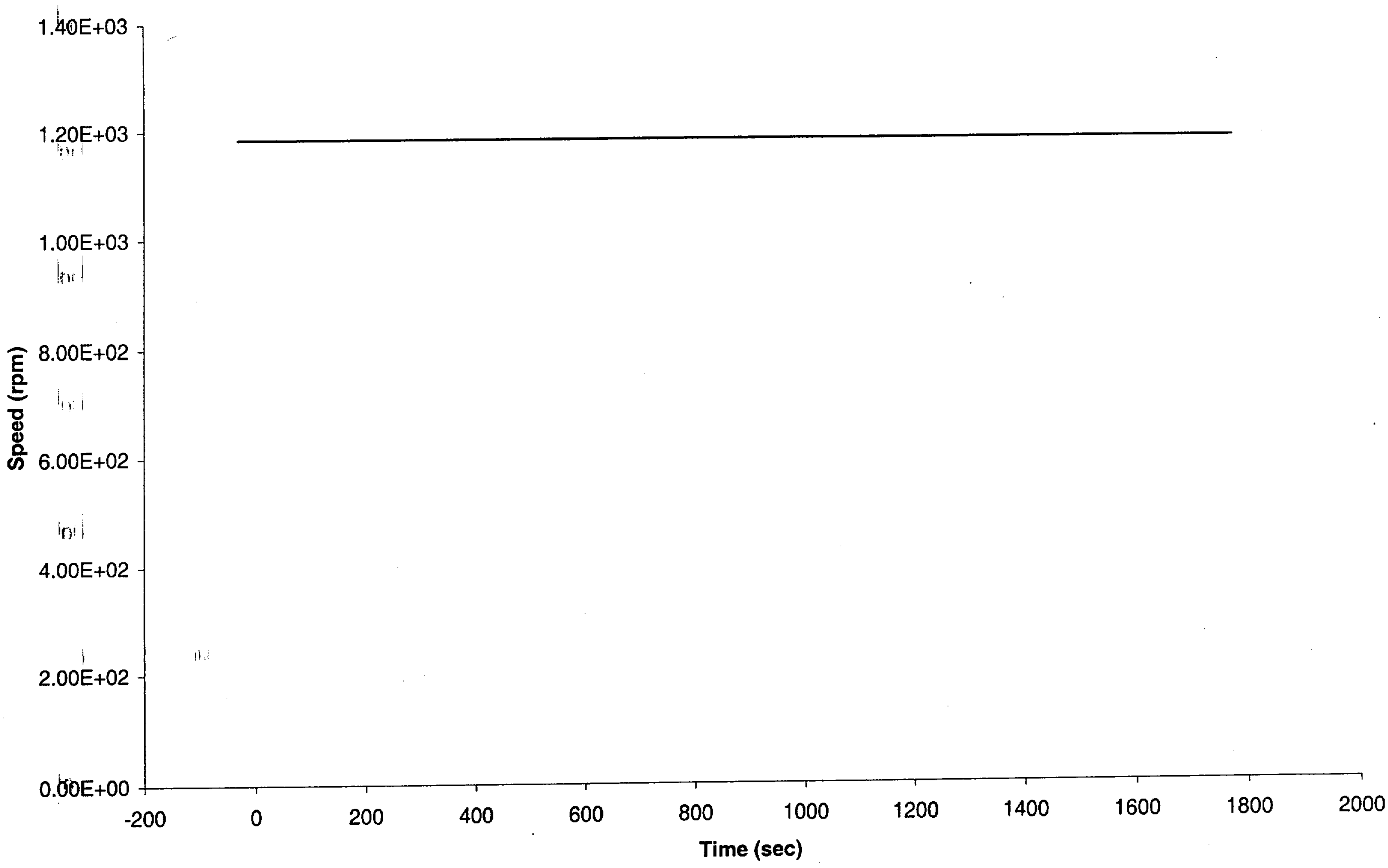

Fig. A.2-1: Medium LOCA - Core Power

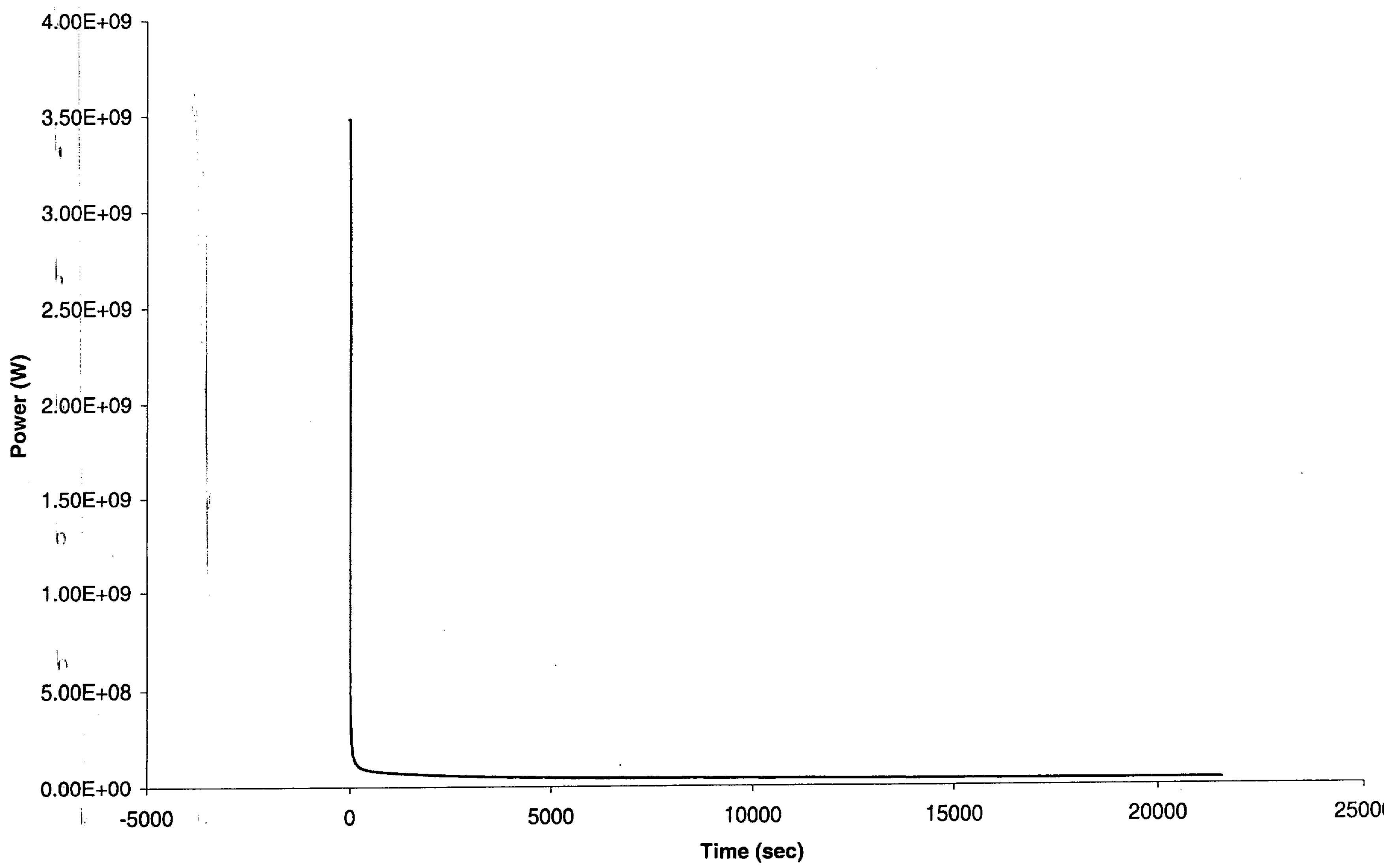

Fig. A.2-2: Medium LOCA - RCS Pressure

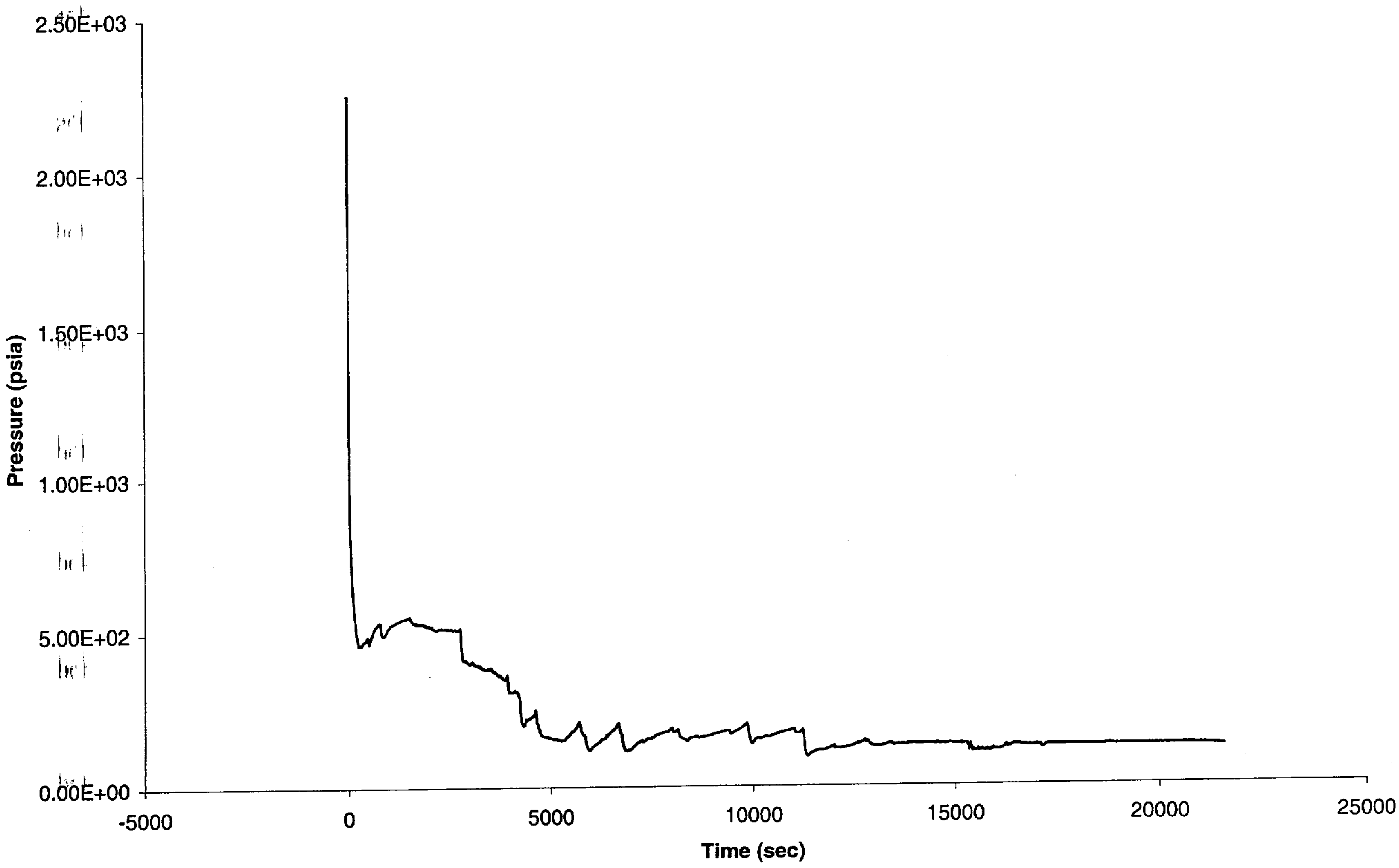

Fig. A.2-3: Medium LOCA - Peak Cladding Temperature

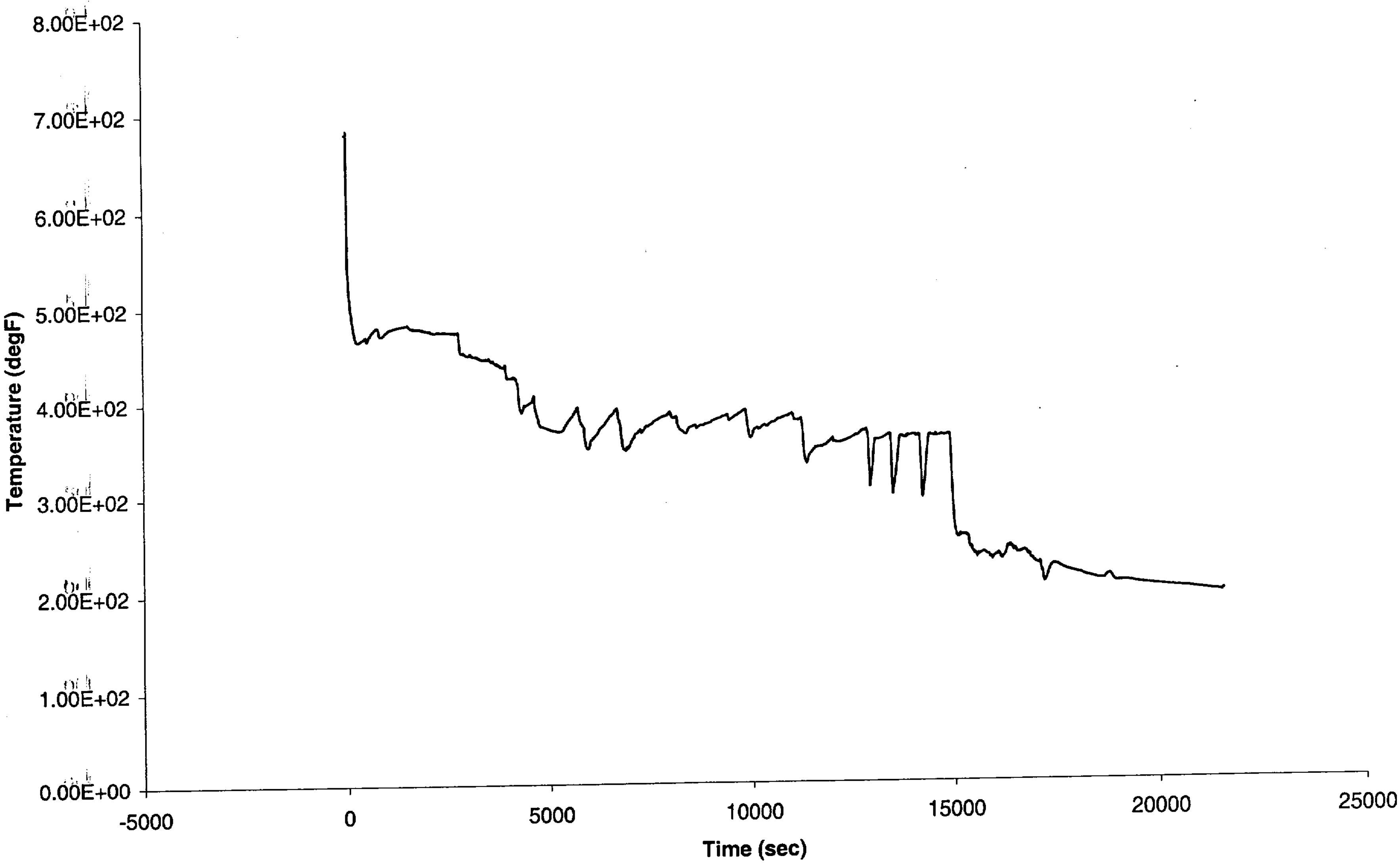

Fig. A.2-4: Medium LOCA - Core Void

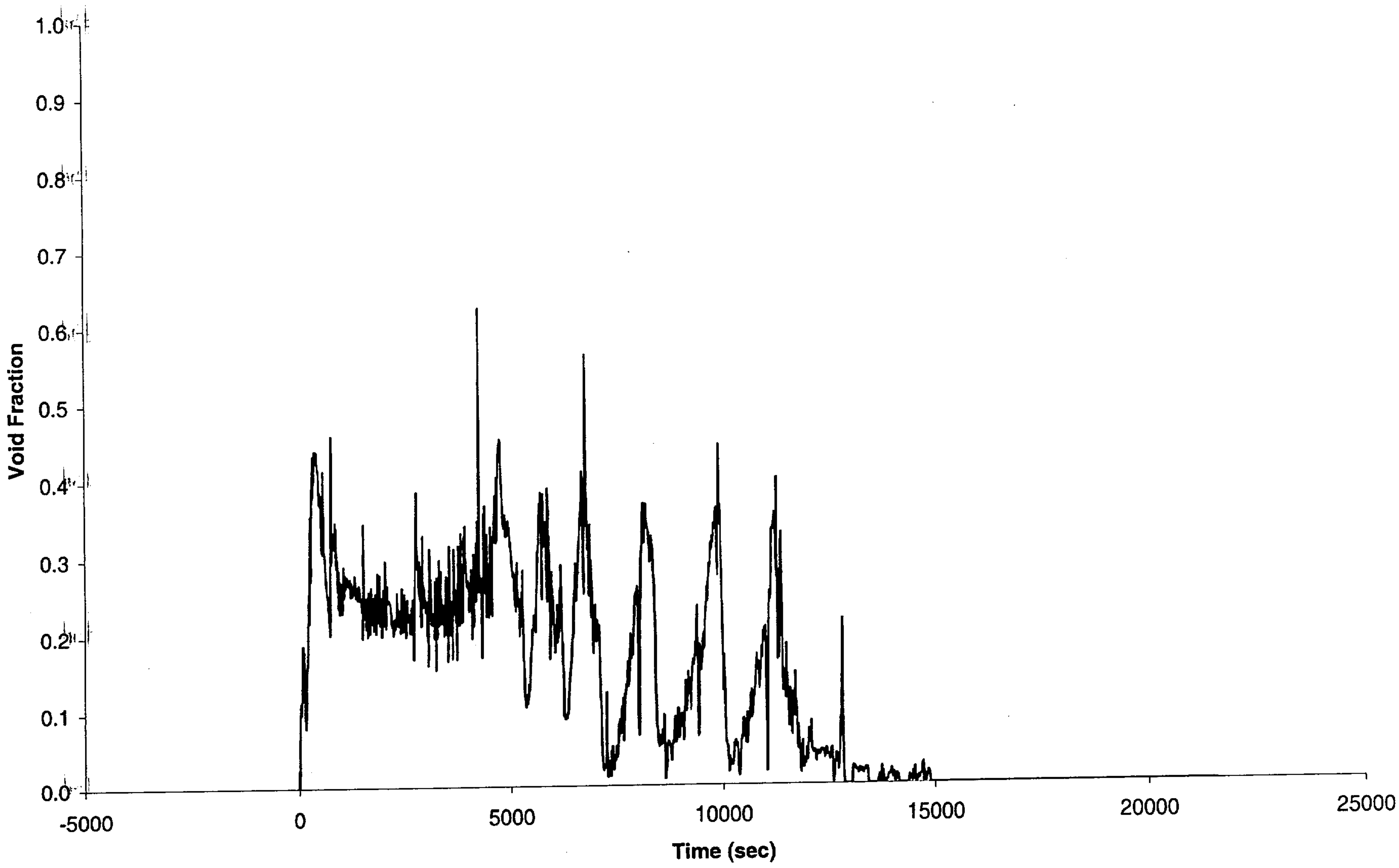

Fig. A.2-5: Medium LOCA - Injection

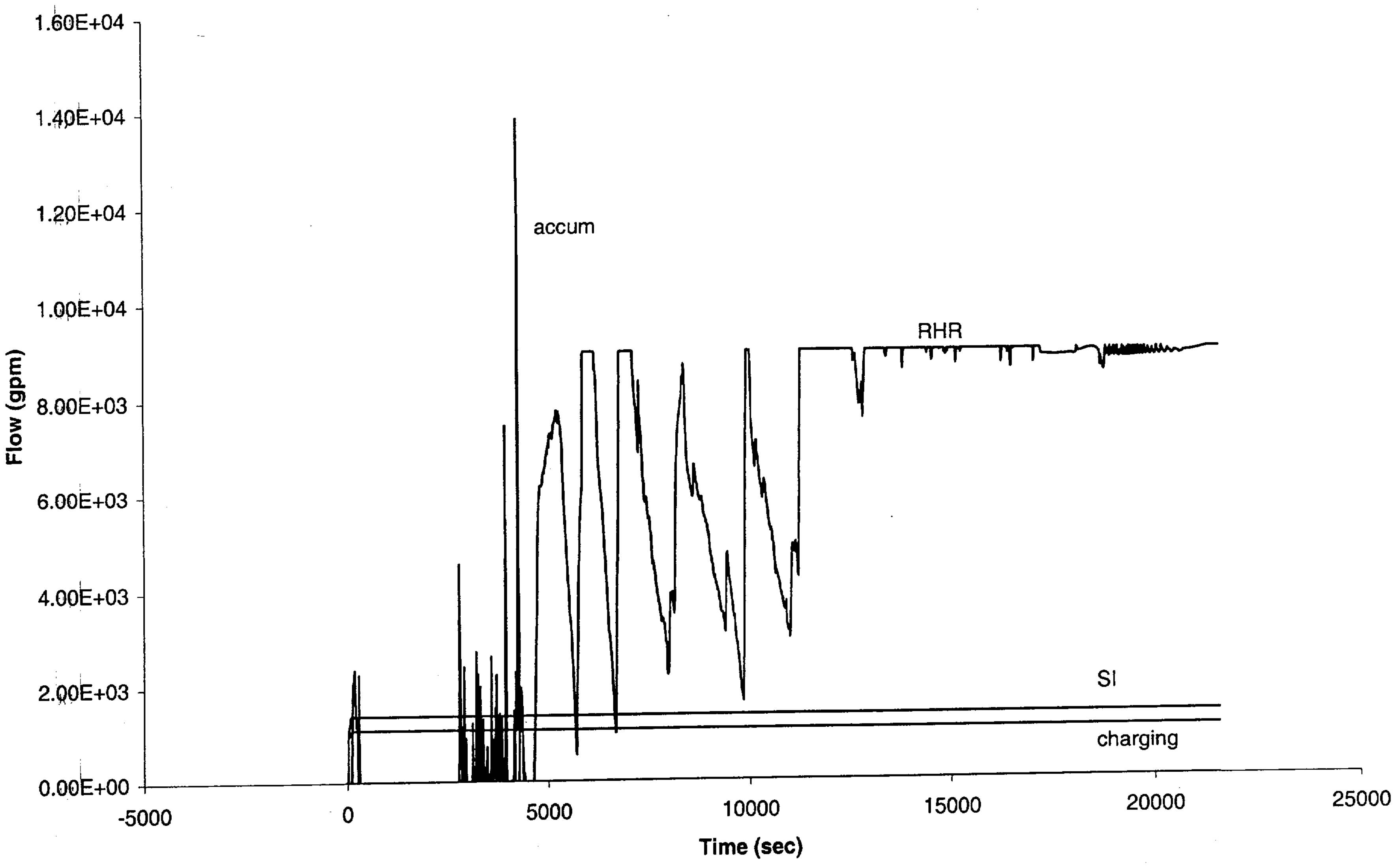

Fig. A.2-6: Medium LOCA - Break Flow

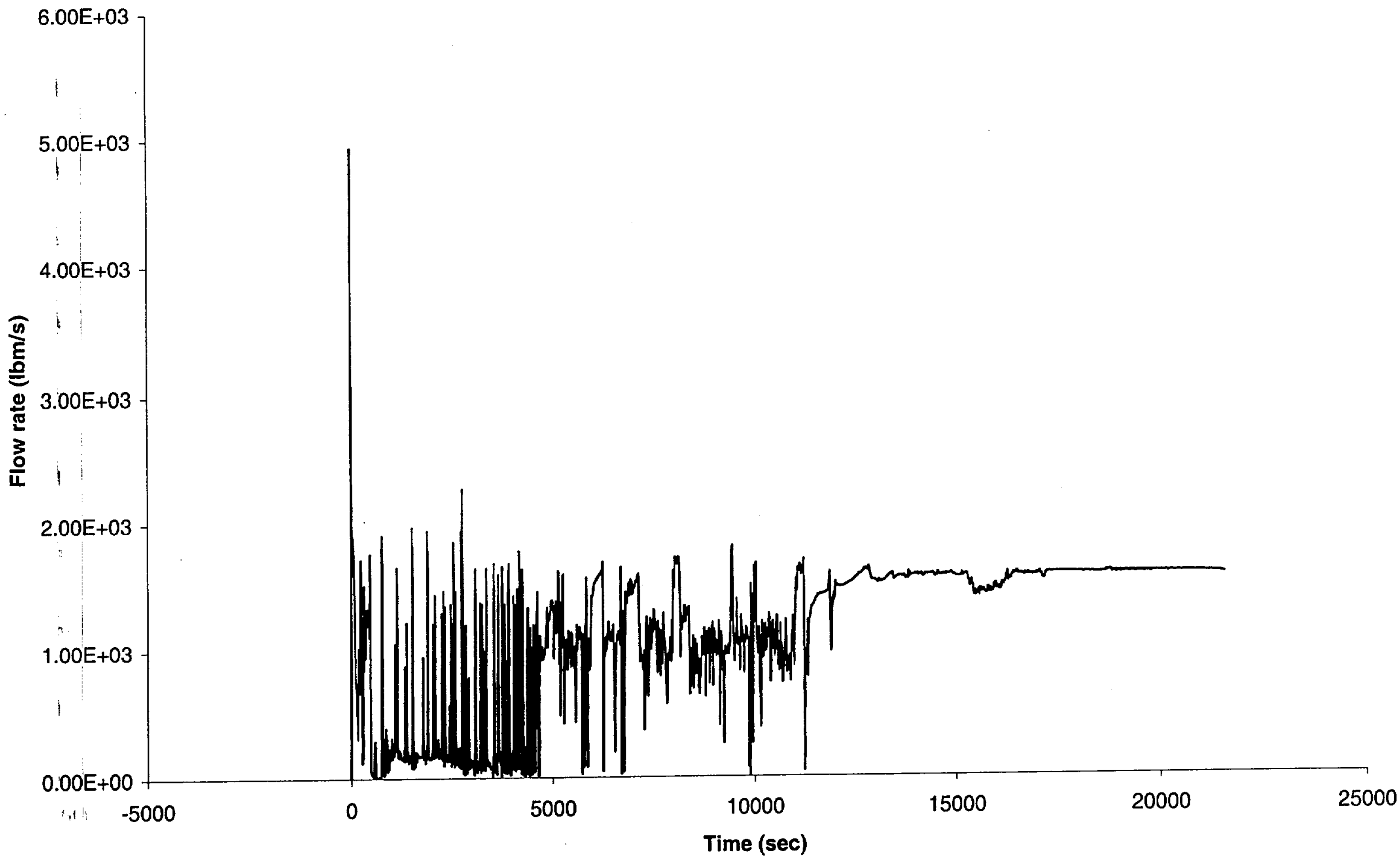

Fig. A.2-7: Medium LOCA - Quality at the Break

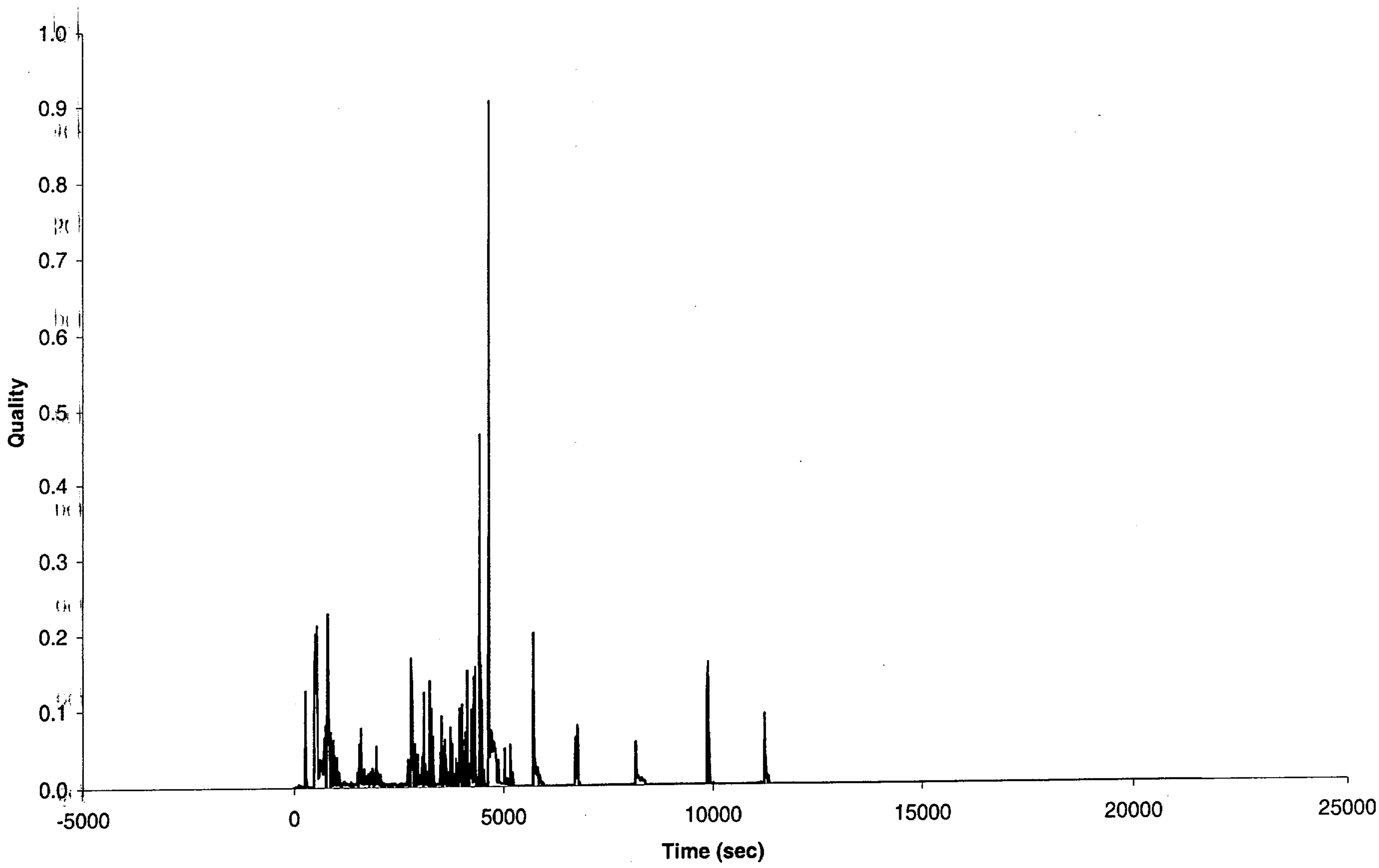

Fig. A.2-8: Medium LOCA - Phasic Velocity at the Break

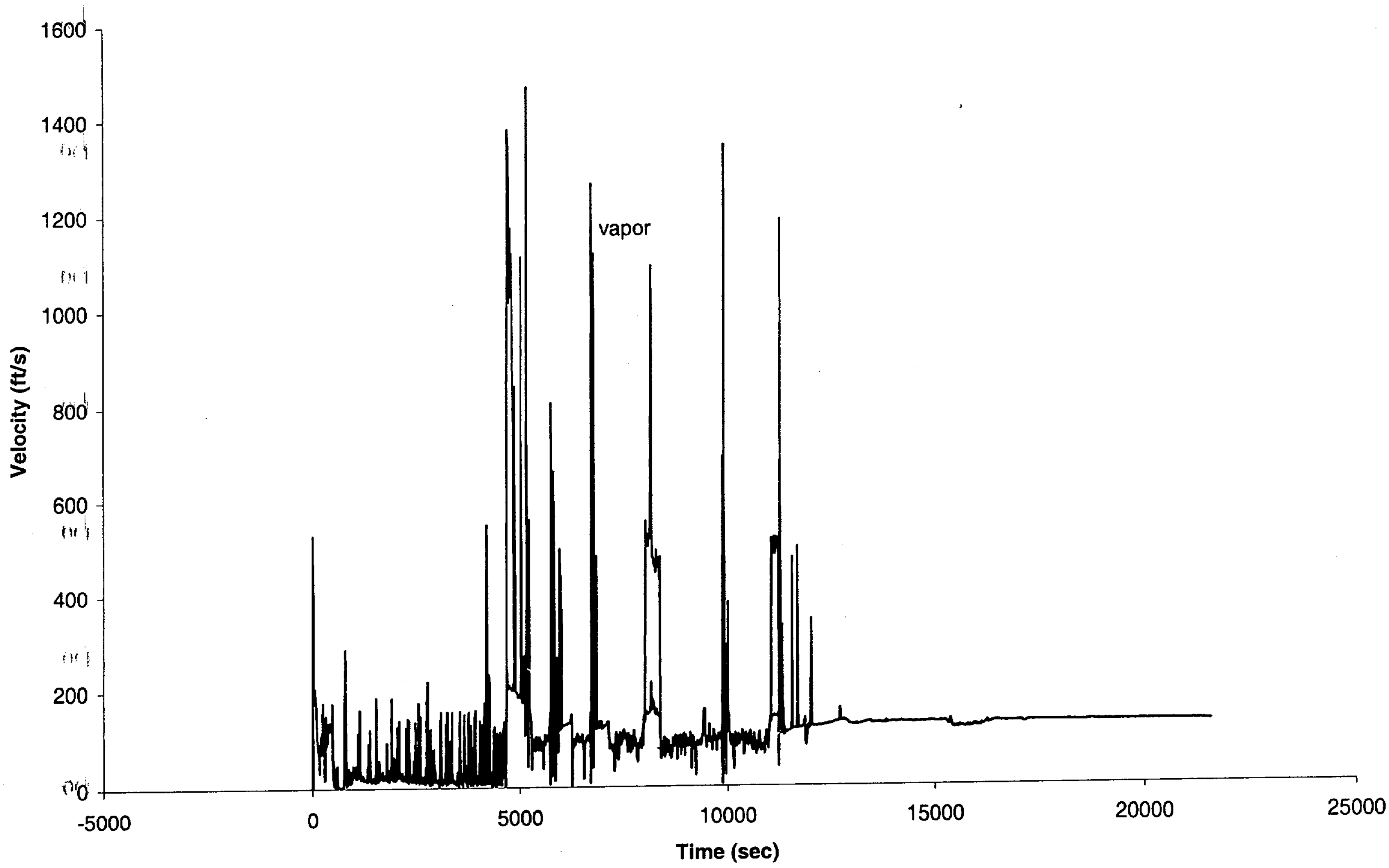

Fig. A.2-9: Medium LOCA - Liq Temp at the Break

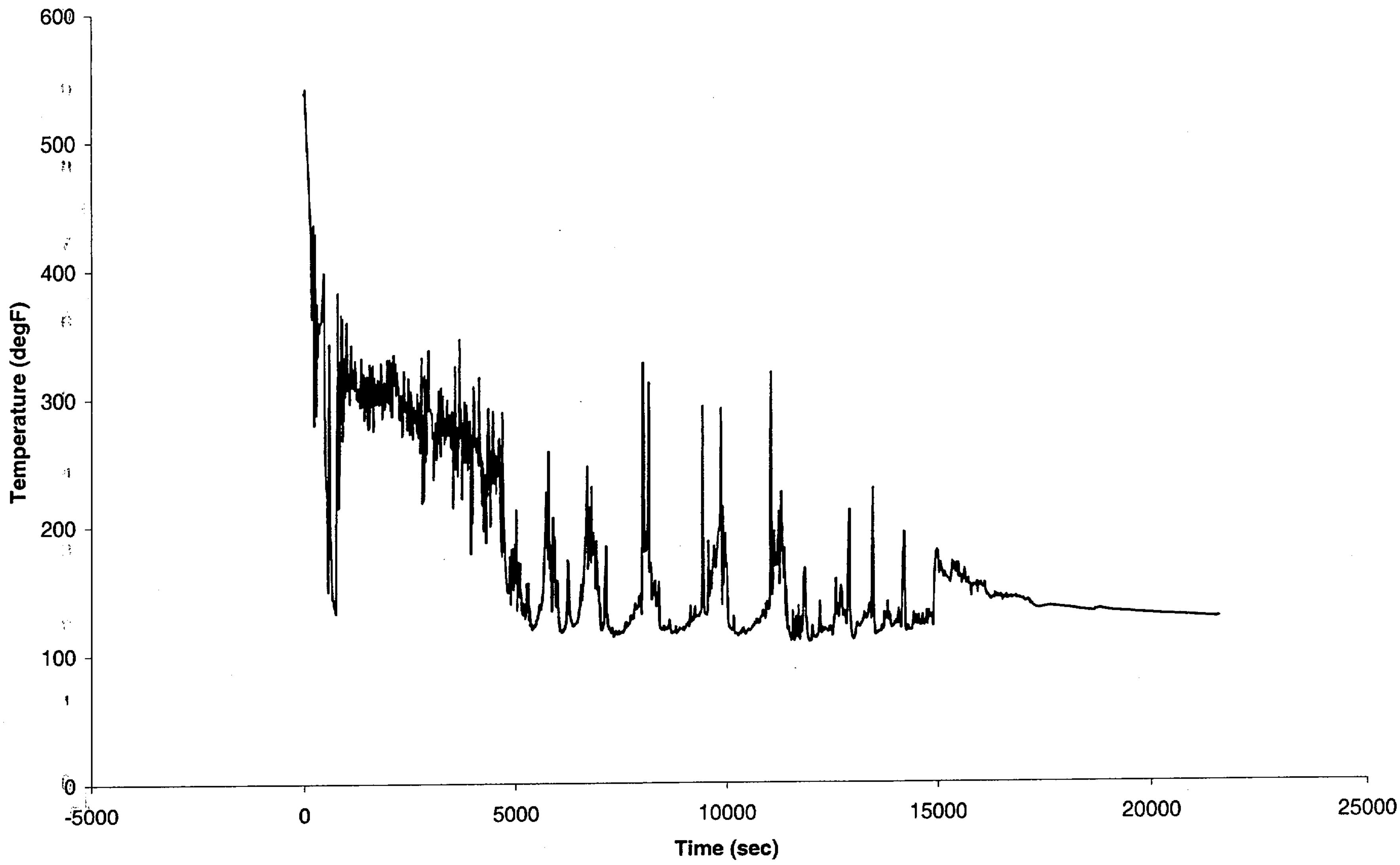

Fig. A.2-10: Medium LOCA - RCP Speed

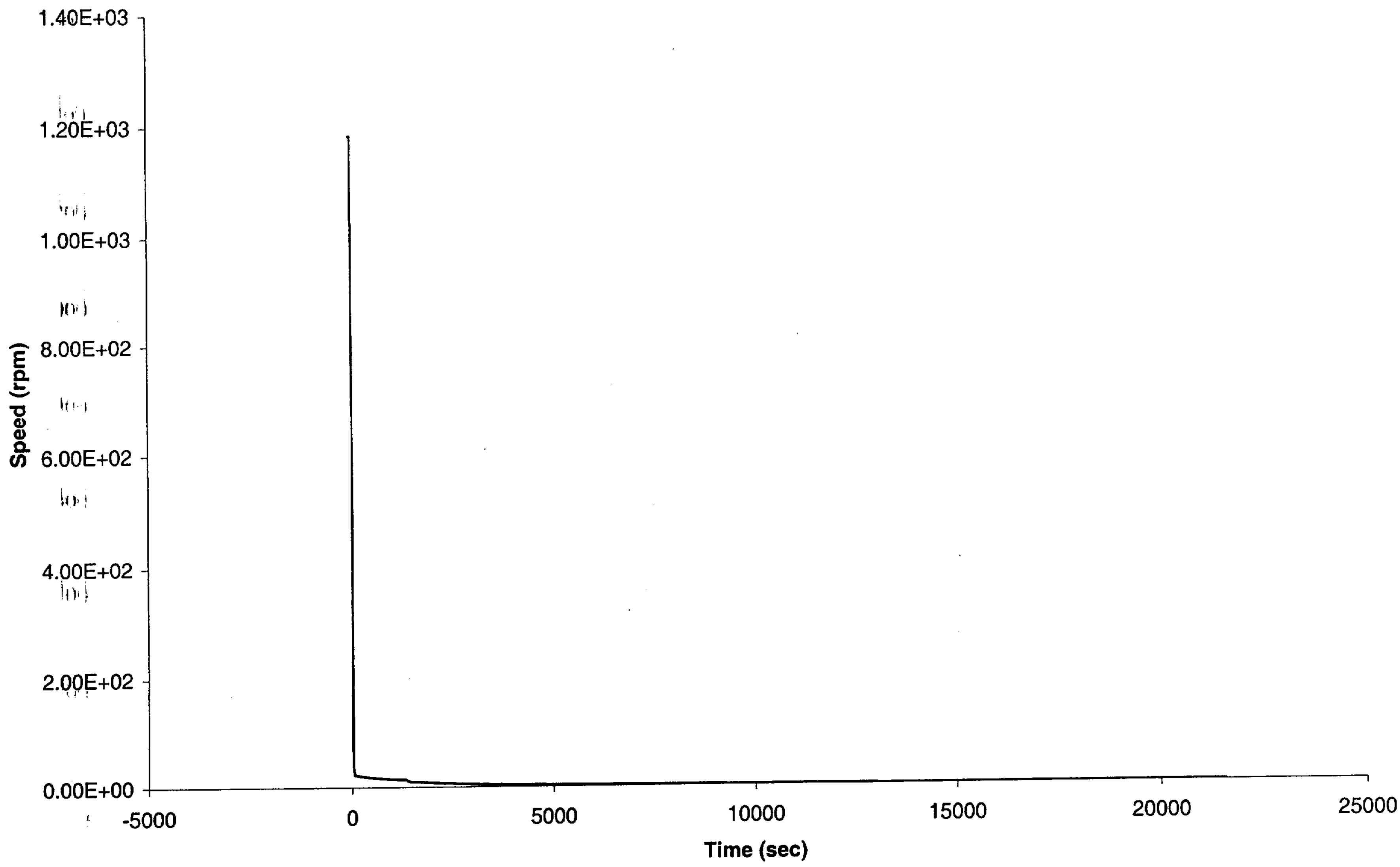

Fig. A.3-1: Small LOCA - Core Power

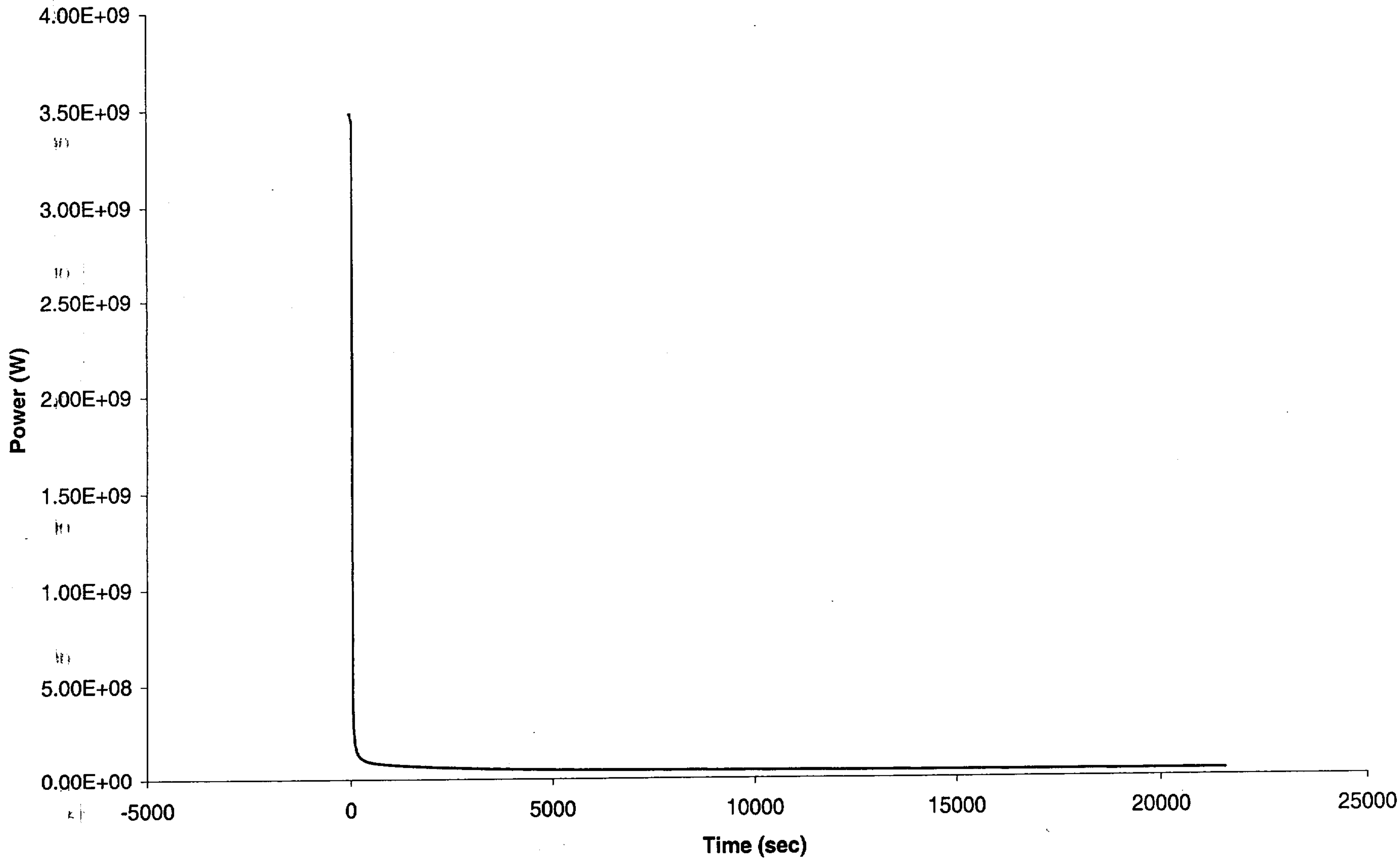

Fig. A.3-2: Small LOCA - RCS Pressure

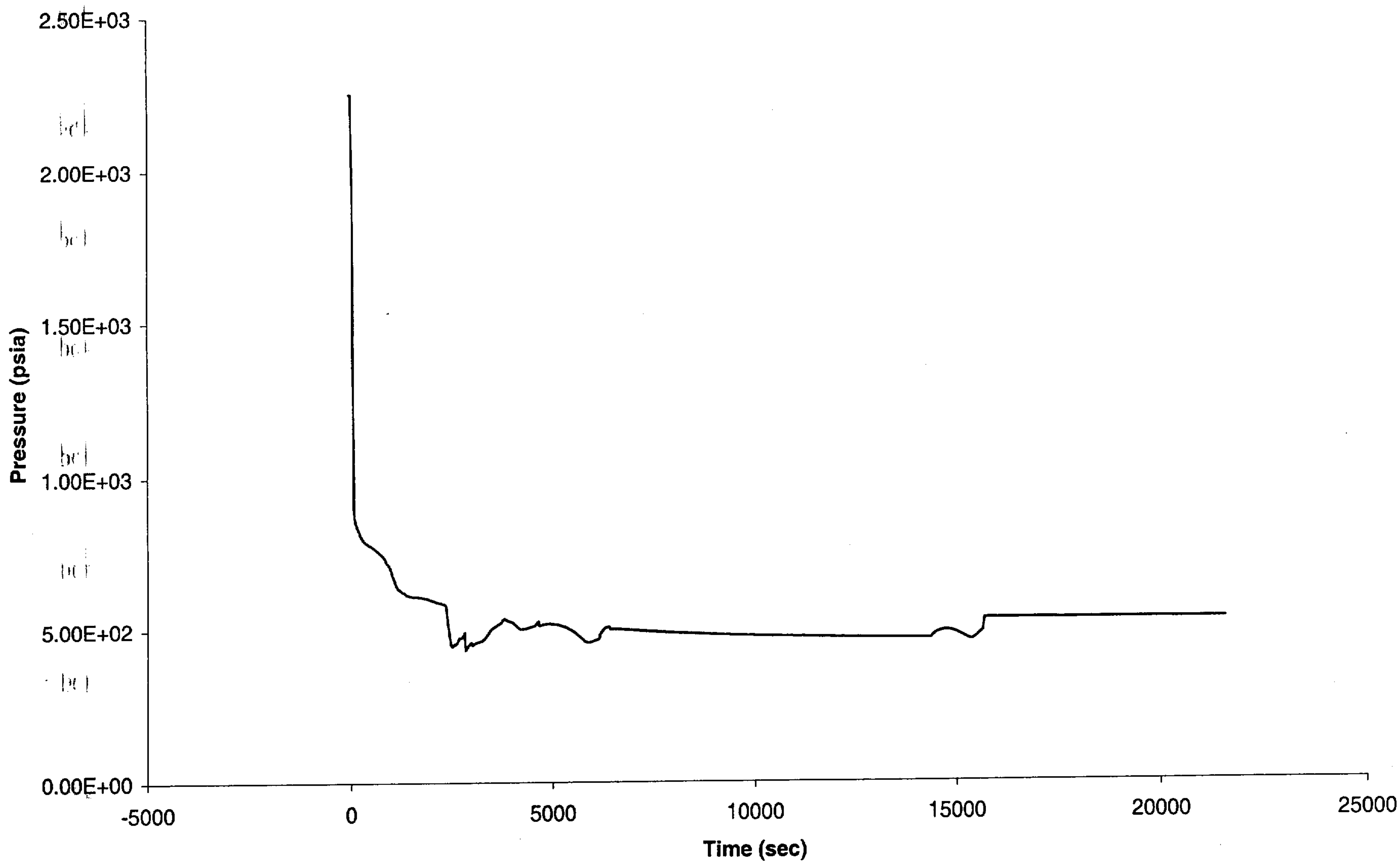

Fig. A.3-3: Small LOCA - Peak Cladding Temperature

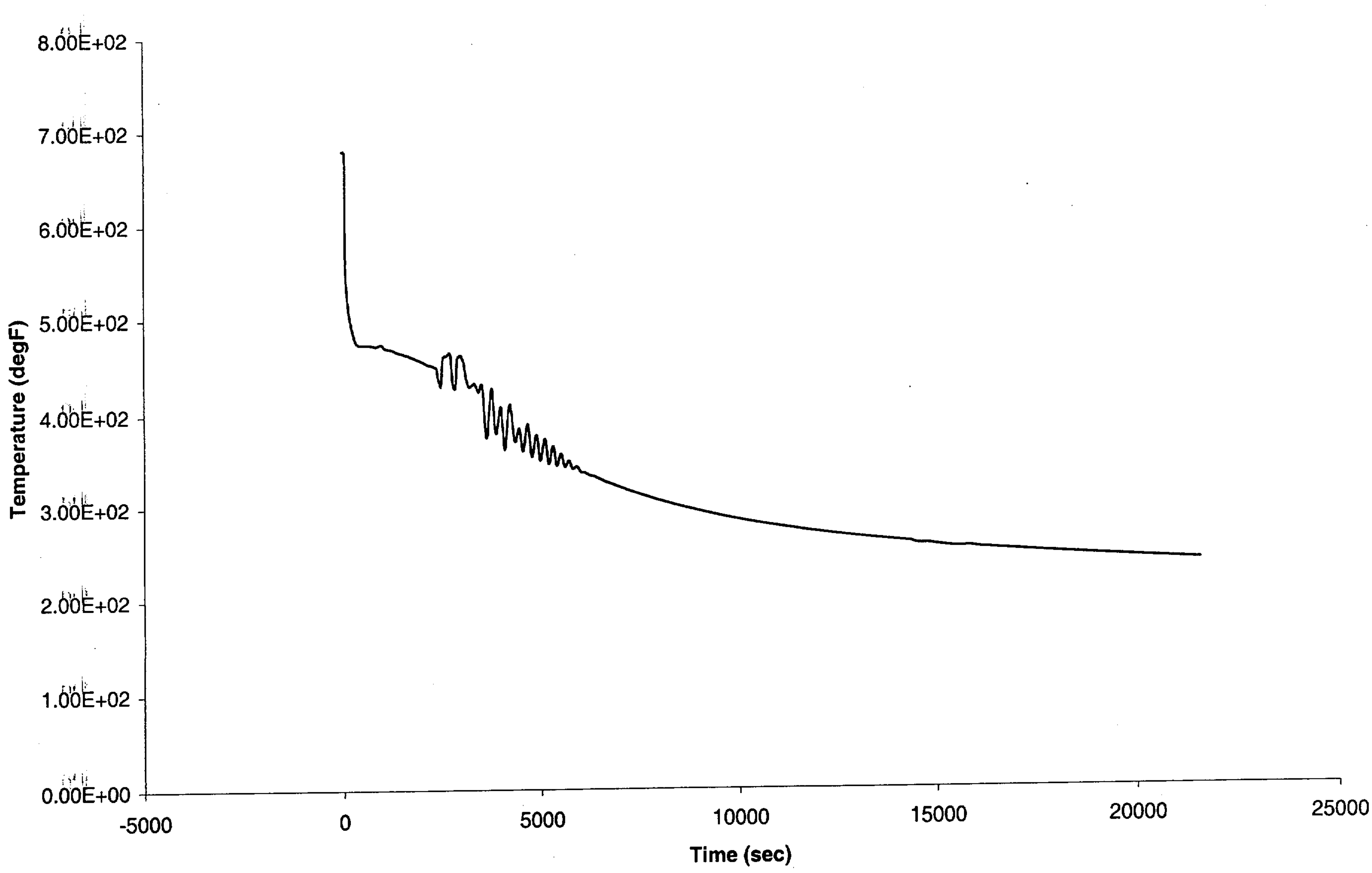

Fig. A.3-4: Small LOCA - Core Void

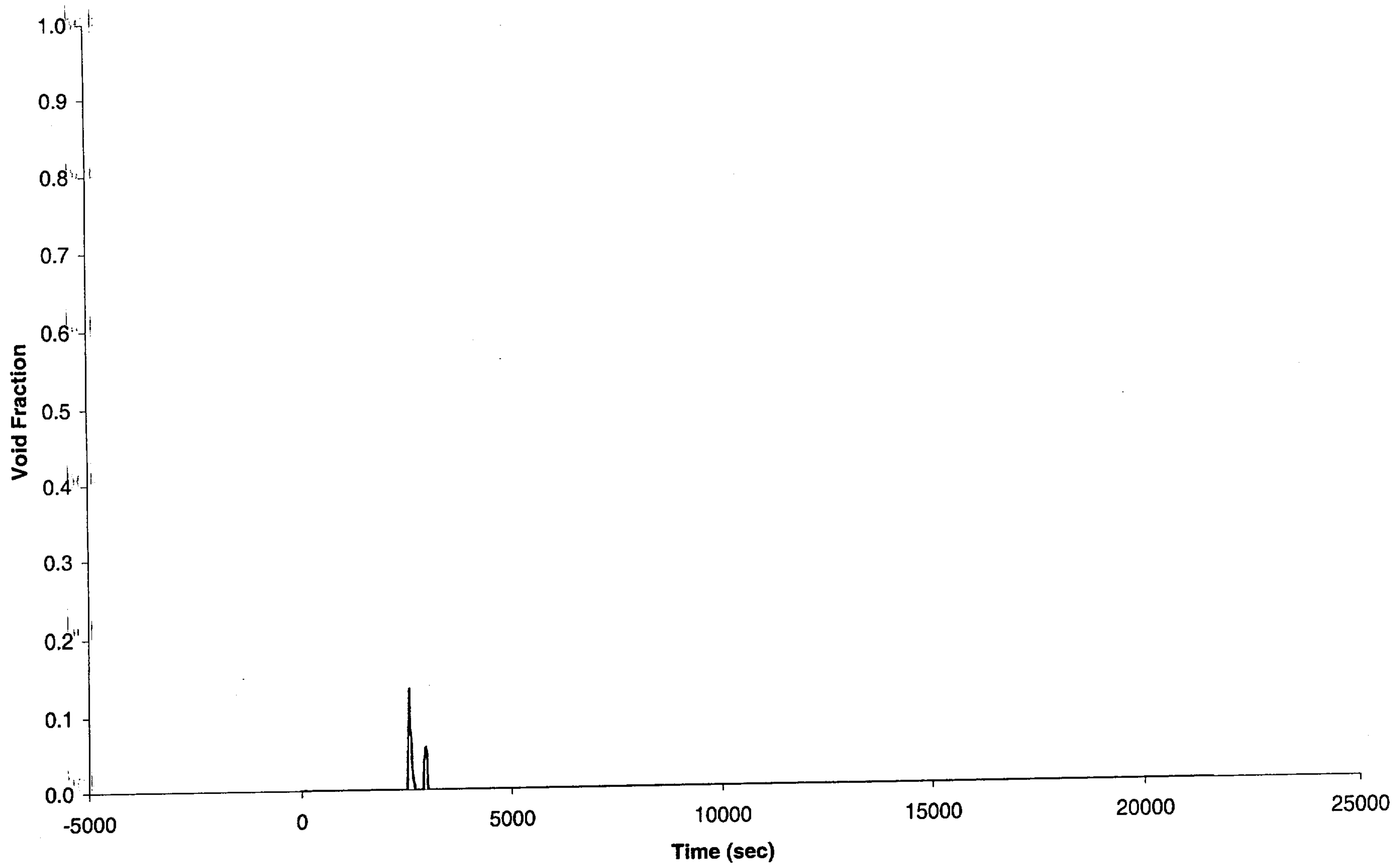

Fig. A.3-5: Small LOCA - Injection

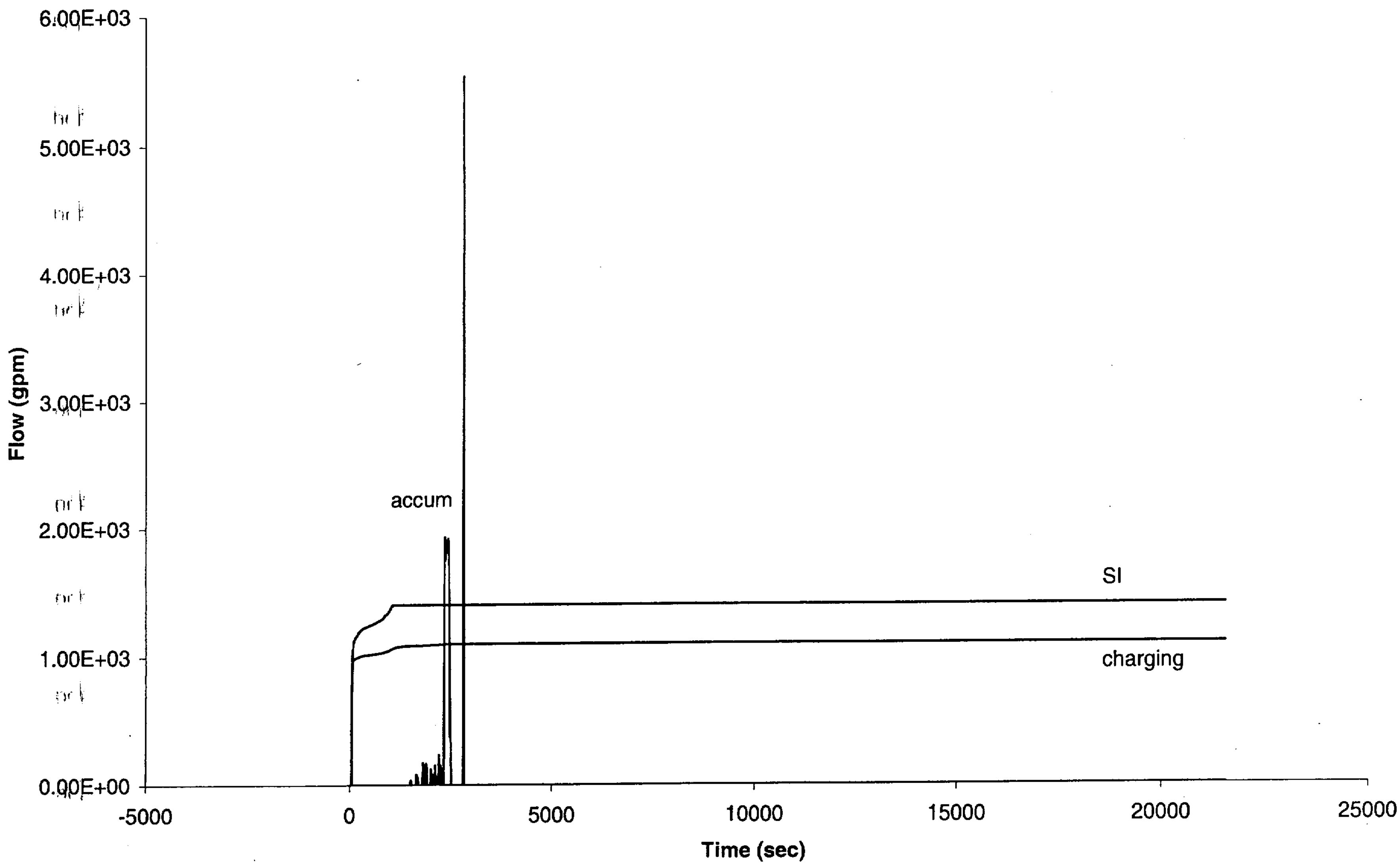

Fig. A.3-6: Small LOCA - Break Flow

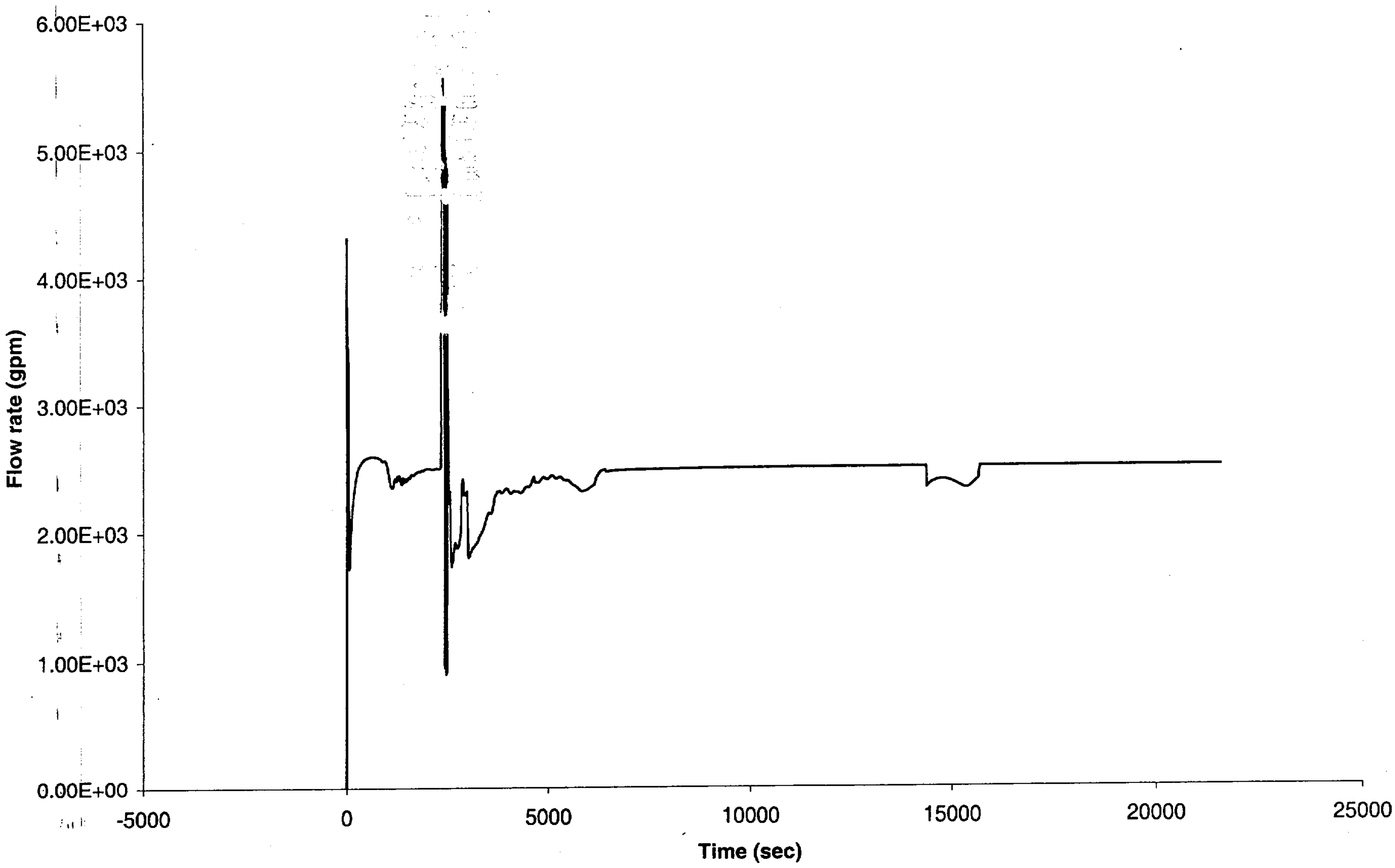

Fig. A.3-7: Small LOCA - Quality at the Break

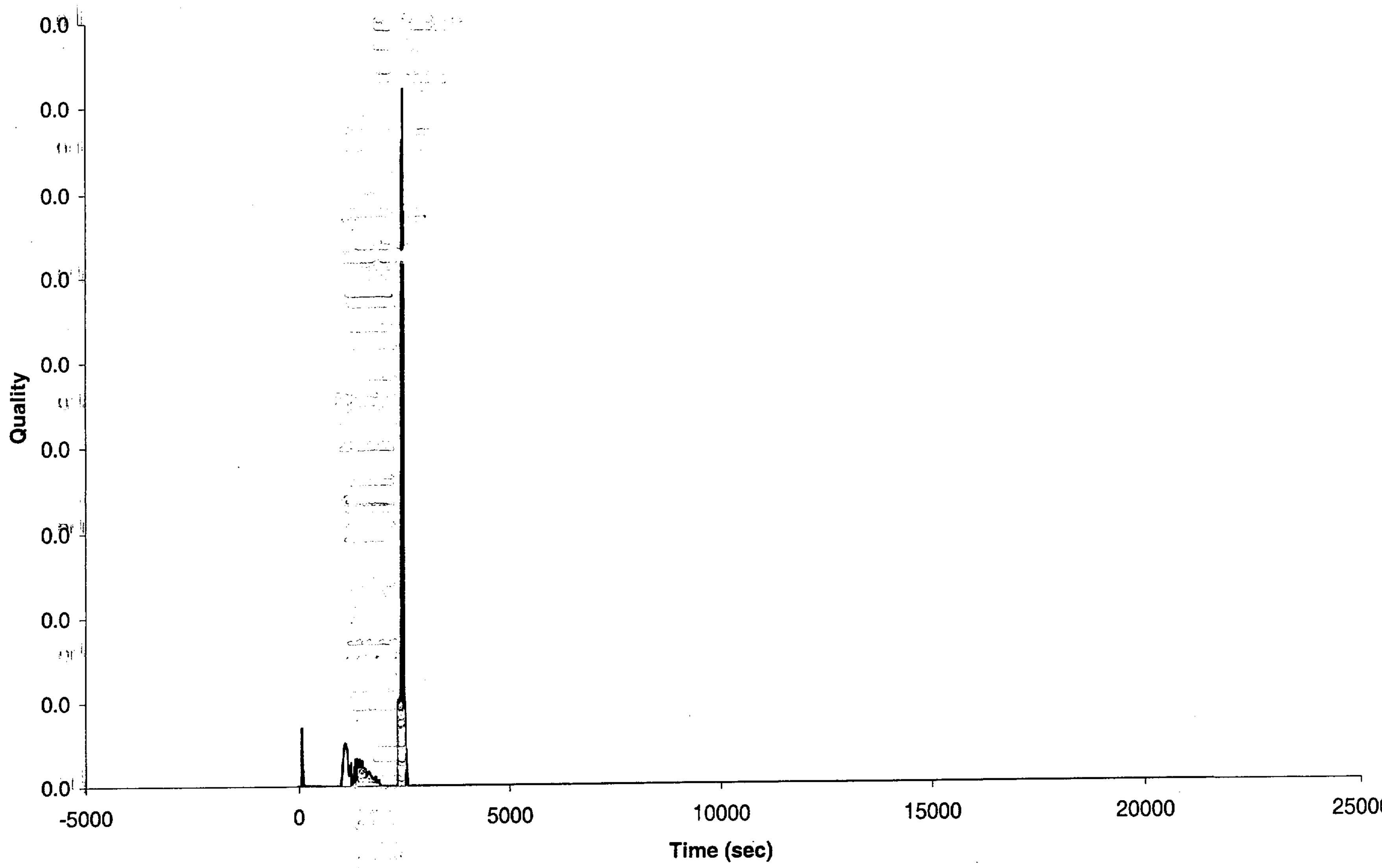

Fig. A.3-8: Small LOCA - Phasic Velocity at the Break

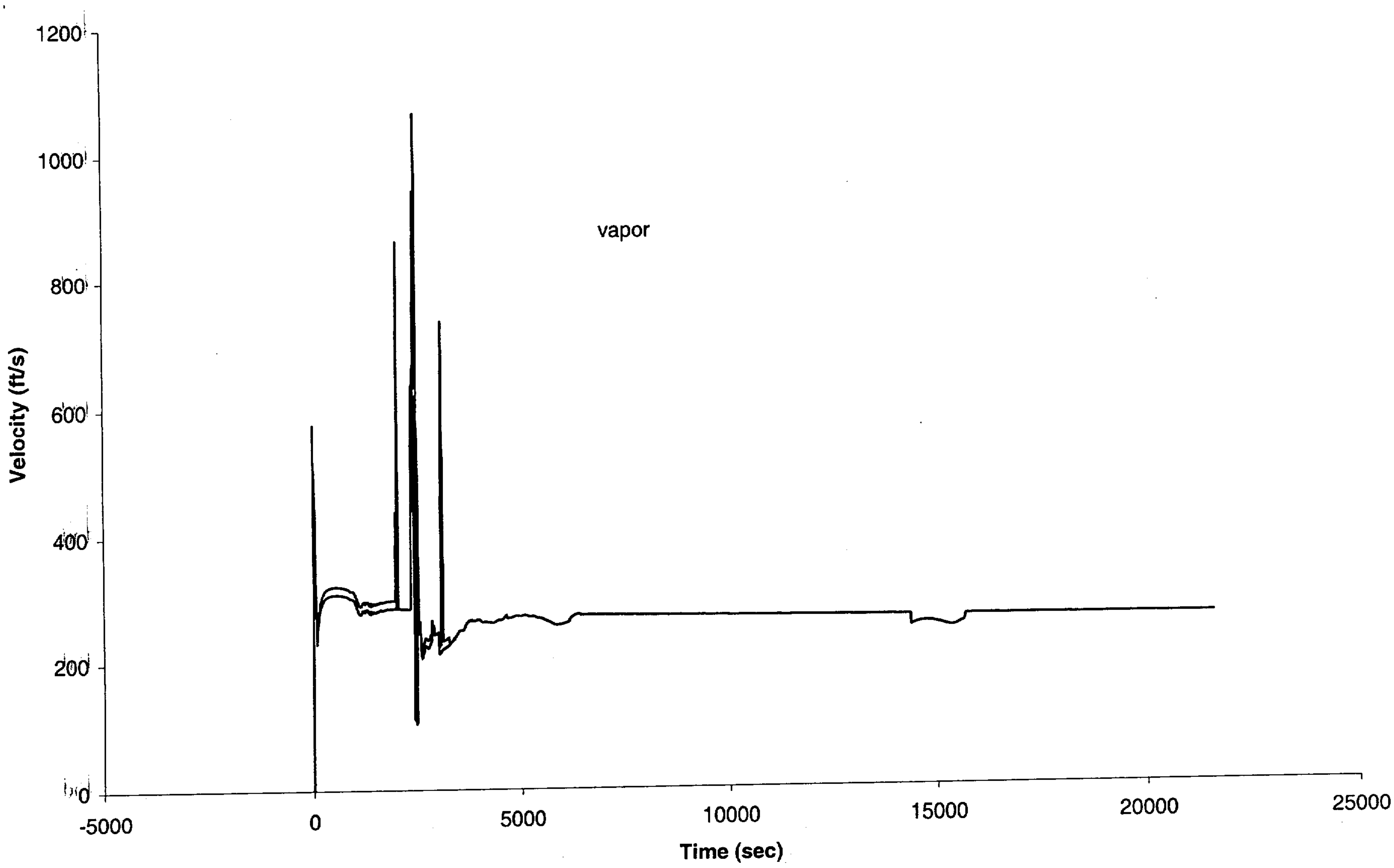

Fig. A.3-9: Small LOCA - Liq Temp at the Break

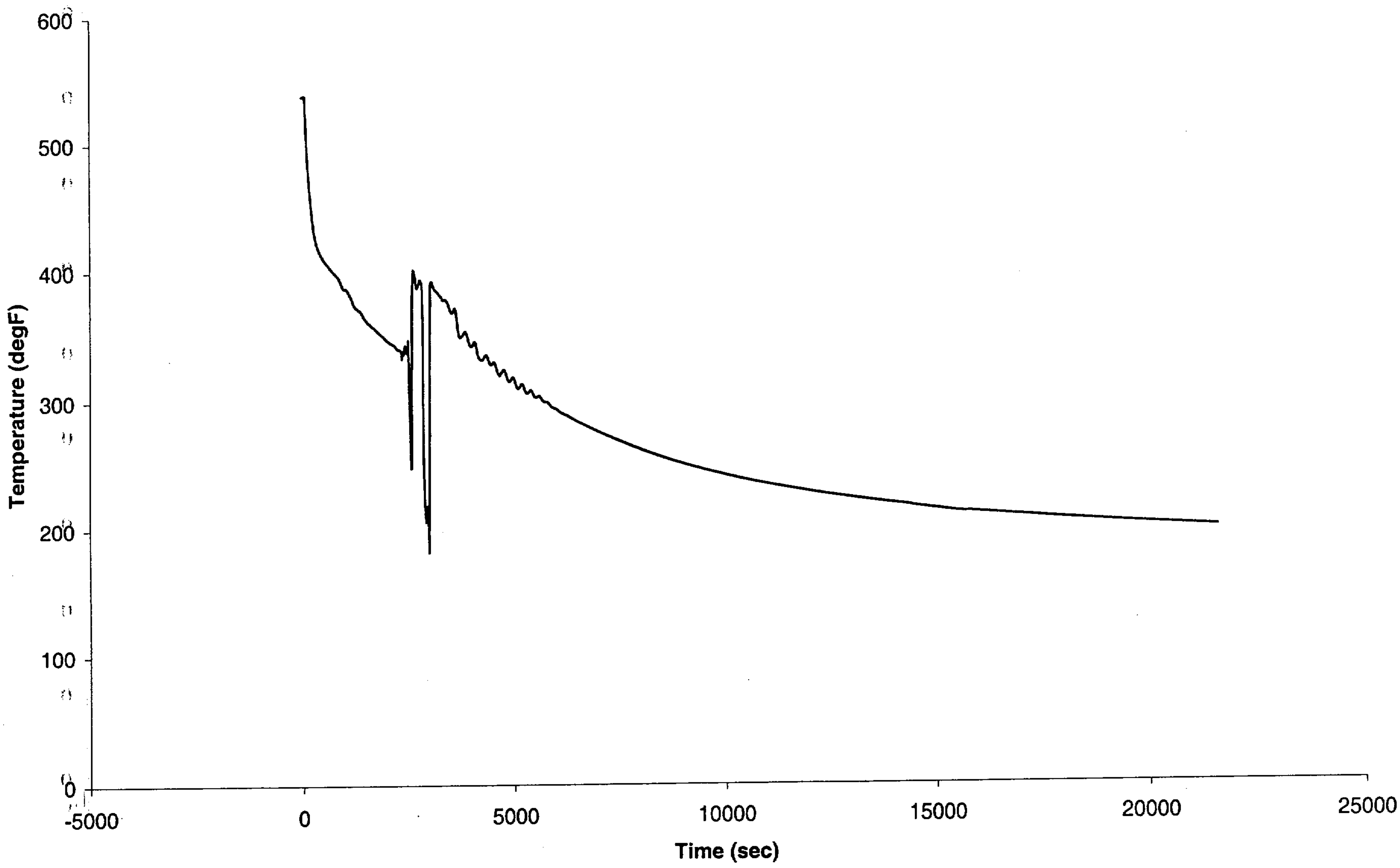

Fig. A.3.10: Small LOCA - RCP Speed

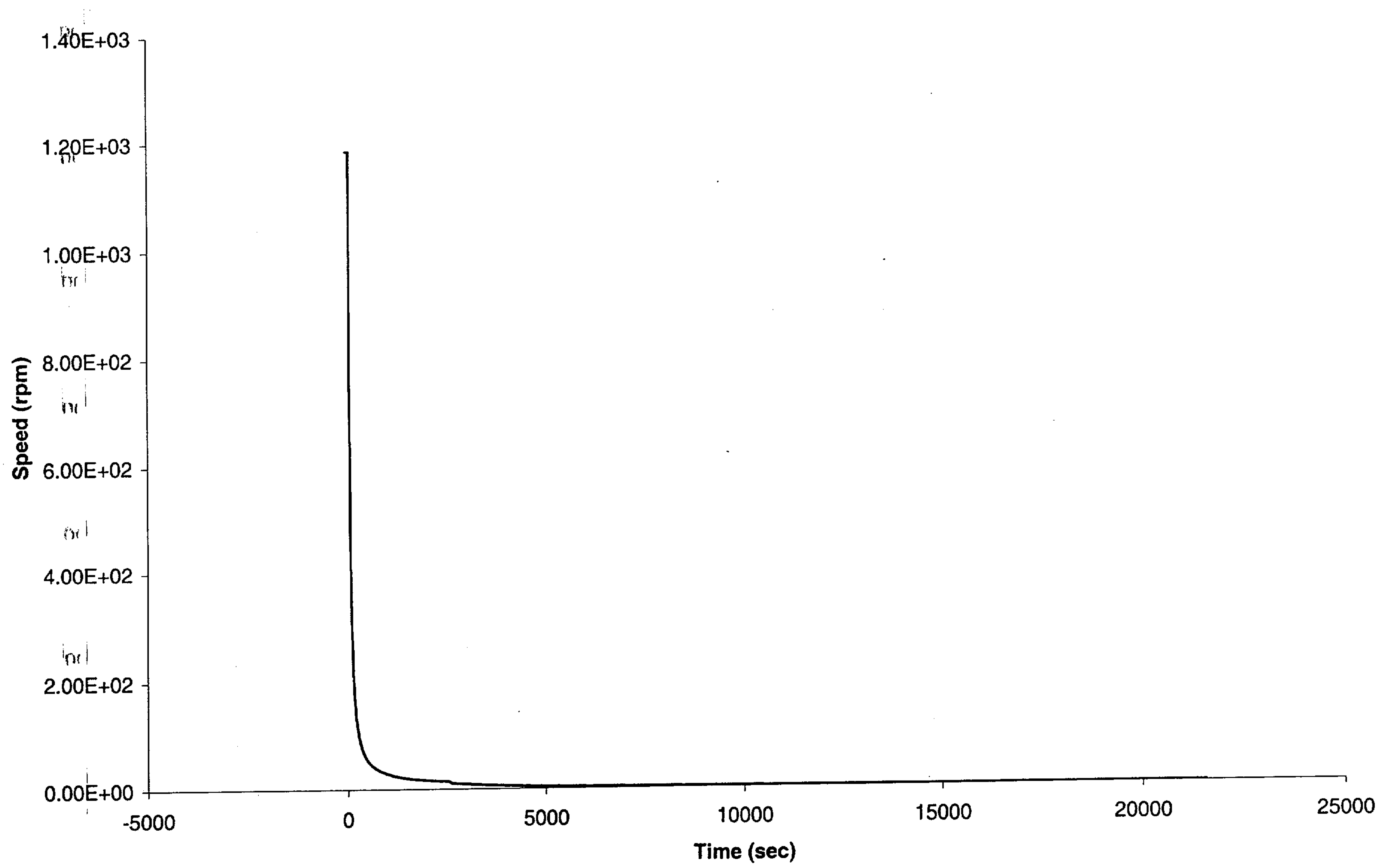

Fig. A.4-1: Small-Small LOCA - Core Power

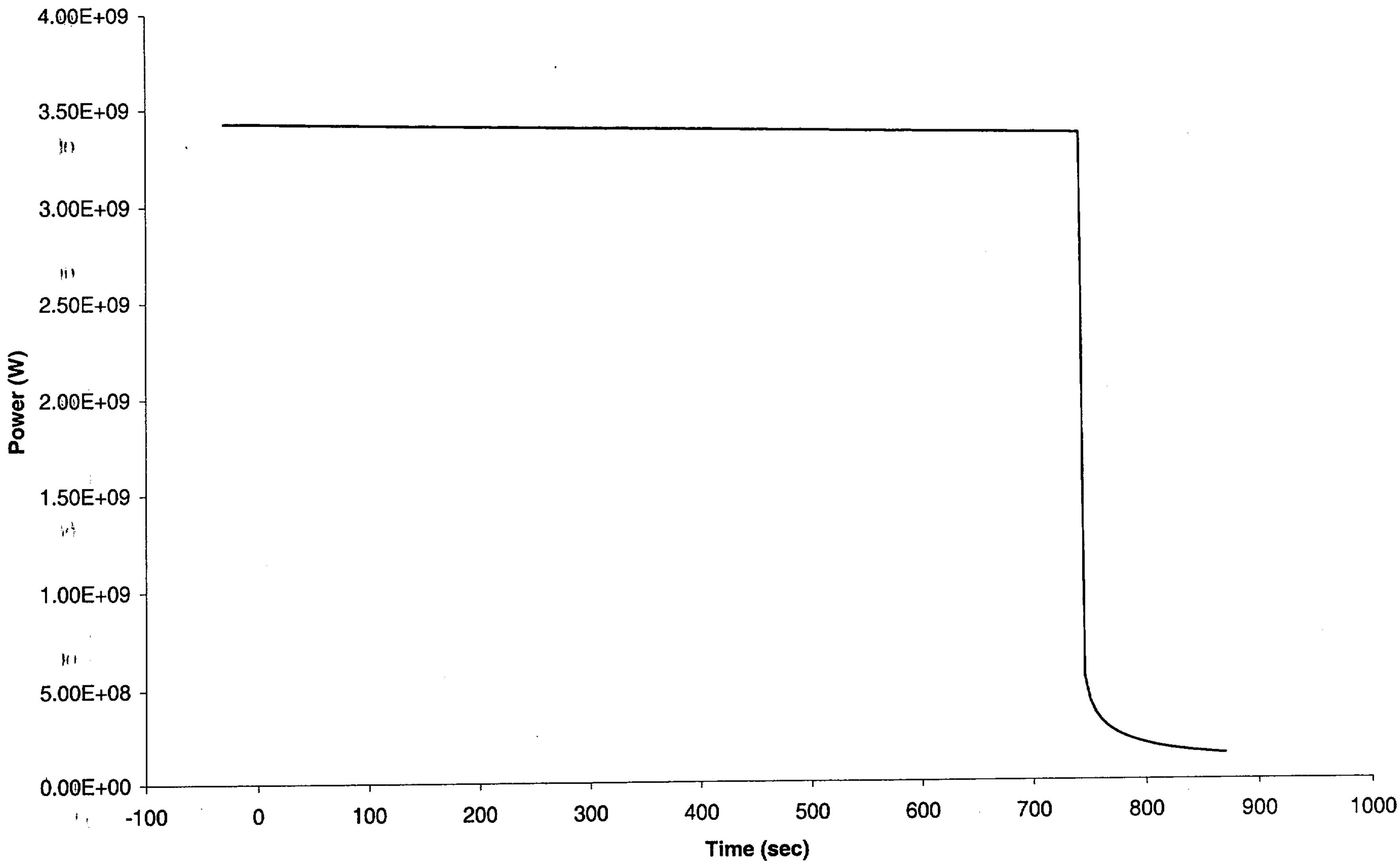

Fig. A.4-2: Small-Small LOCA - RCS Pressure

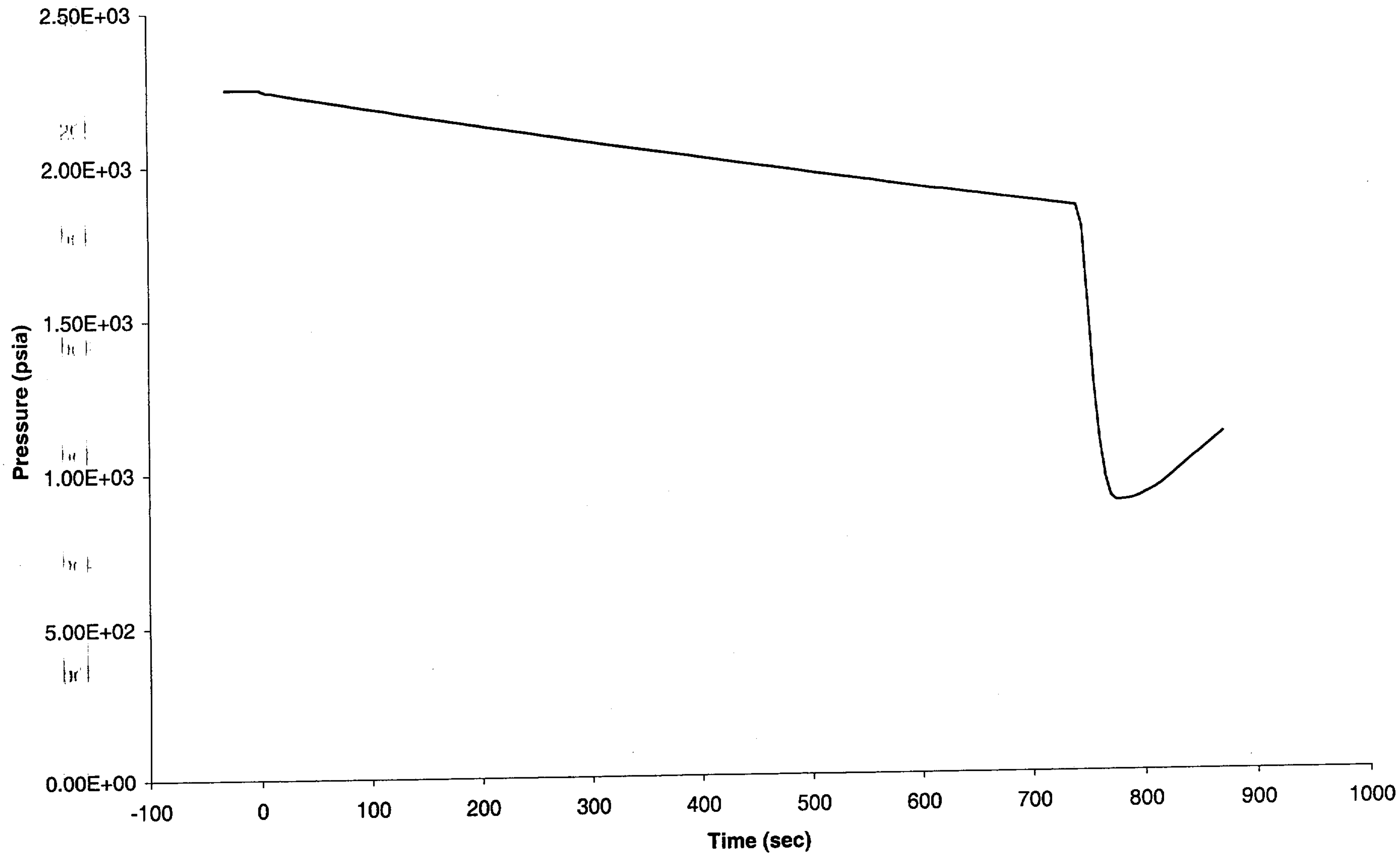

Fig. A.4-3: Small-Small LOCA - Peak Cladding Temperature

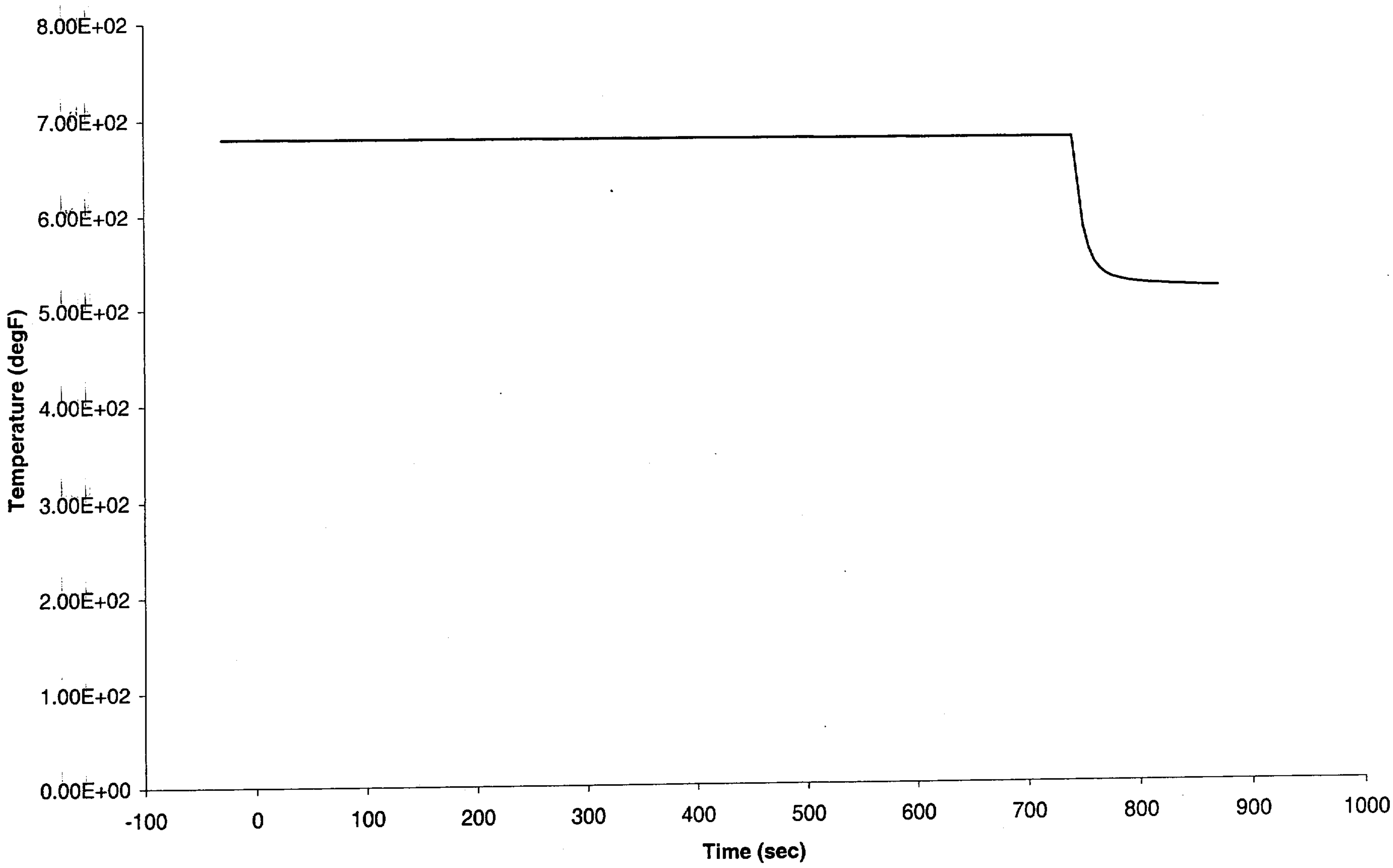

Fig. A.4-4: Small-Small LOCA - Core Void

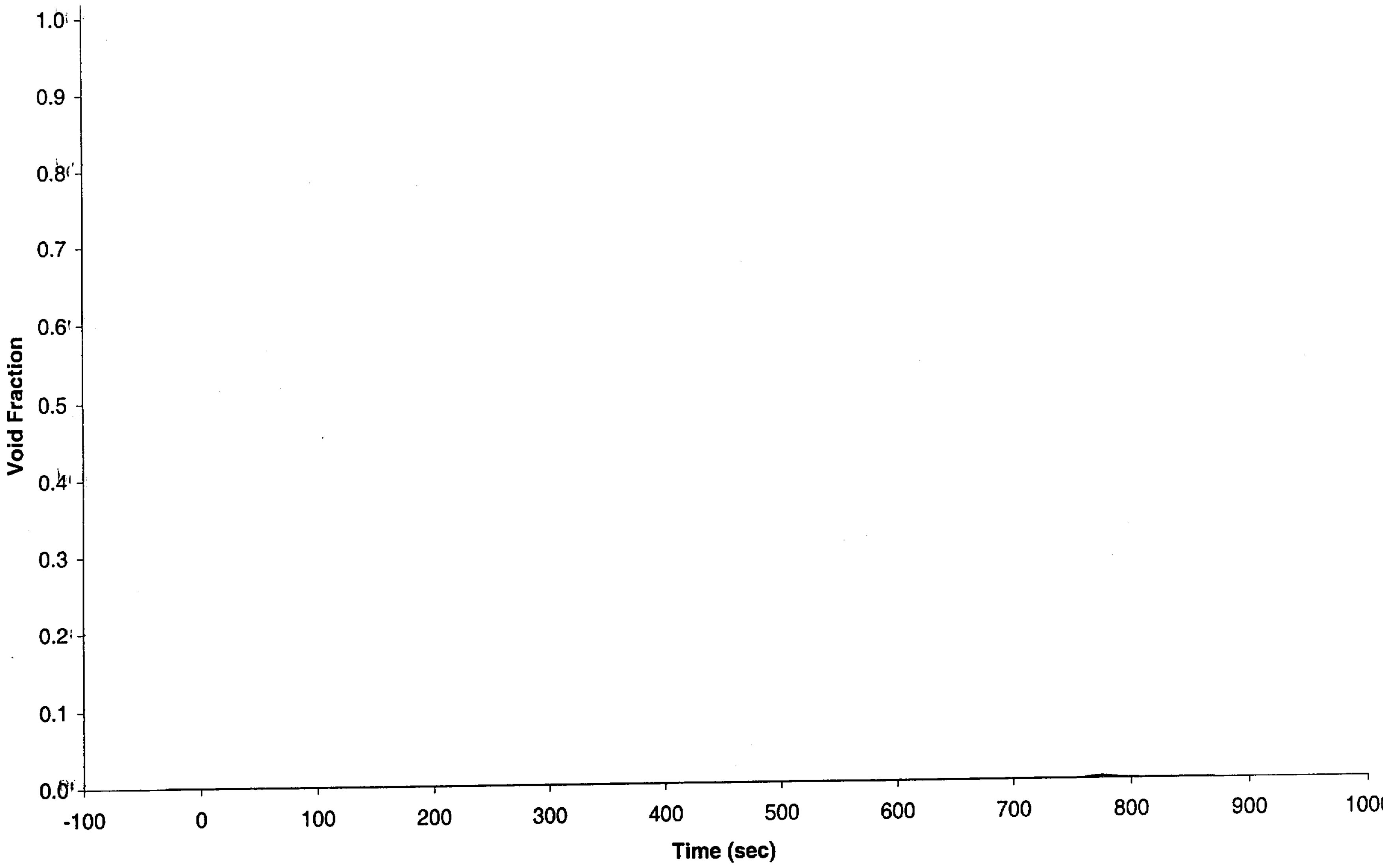

Fig. A.4-5: Small-Small LOCA - Injection

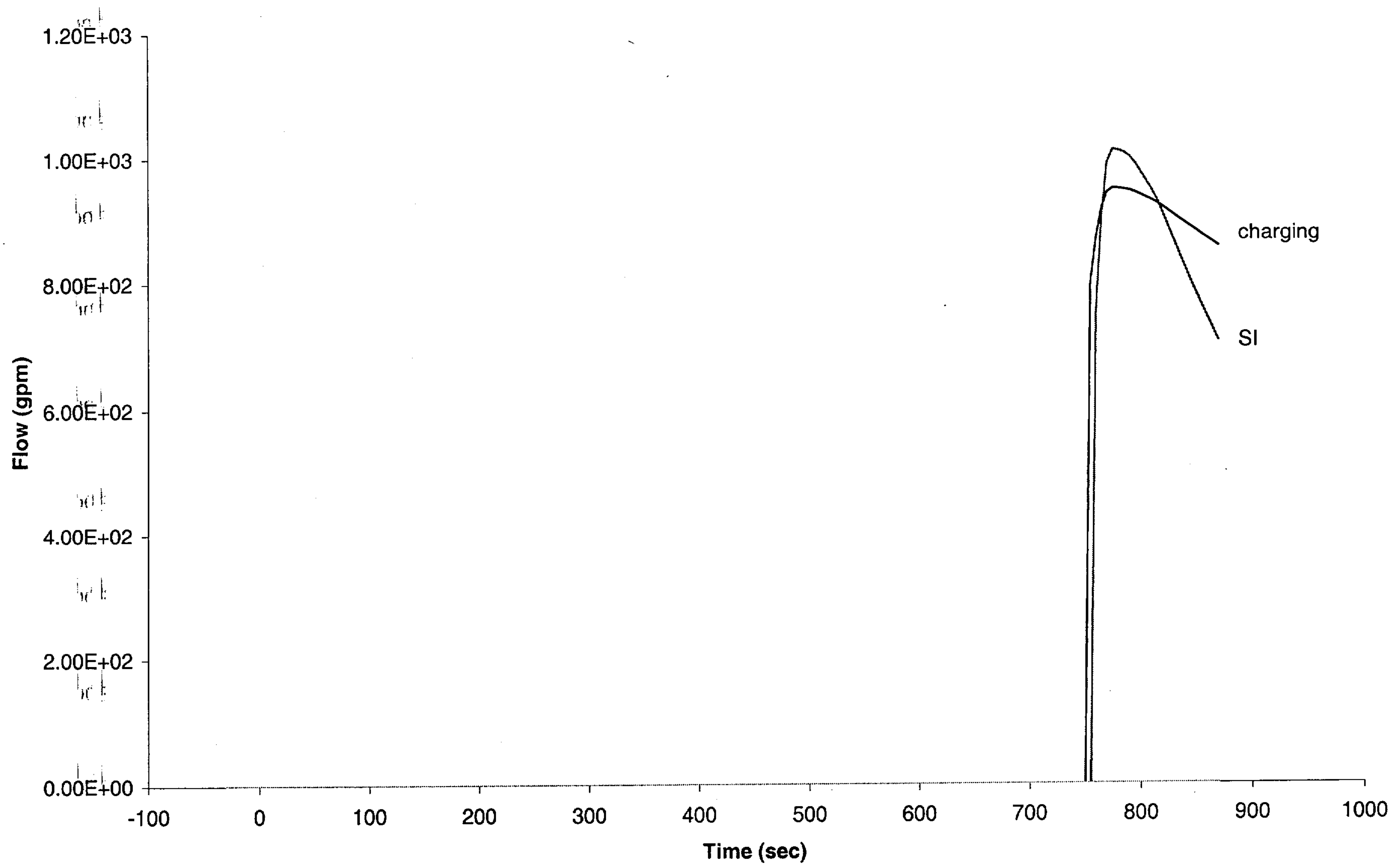

Fig. A.4-6: Small-Small LOCA - Volumetric Flow at the Break

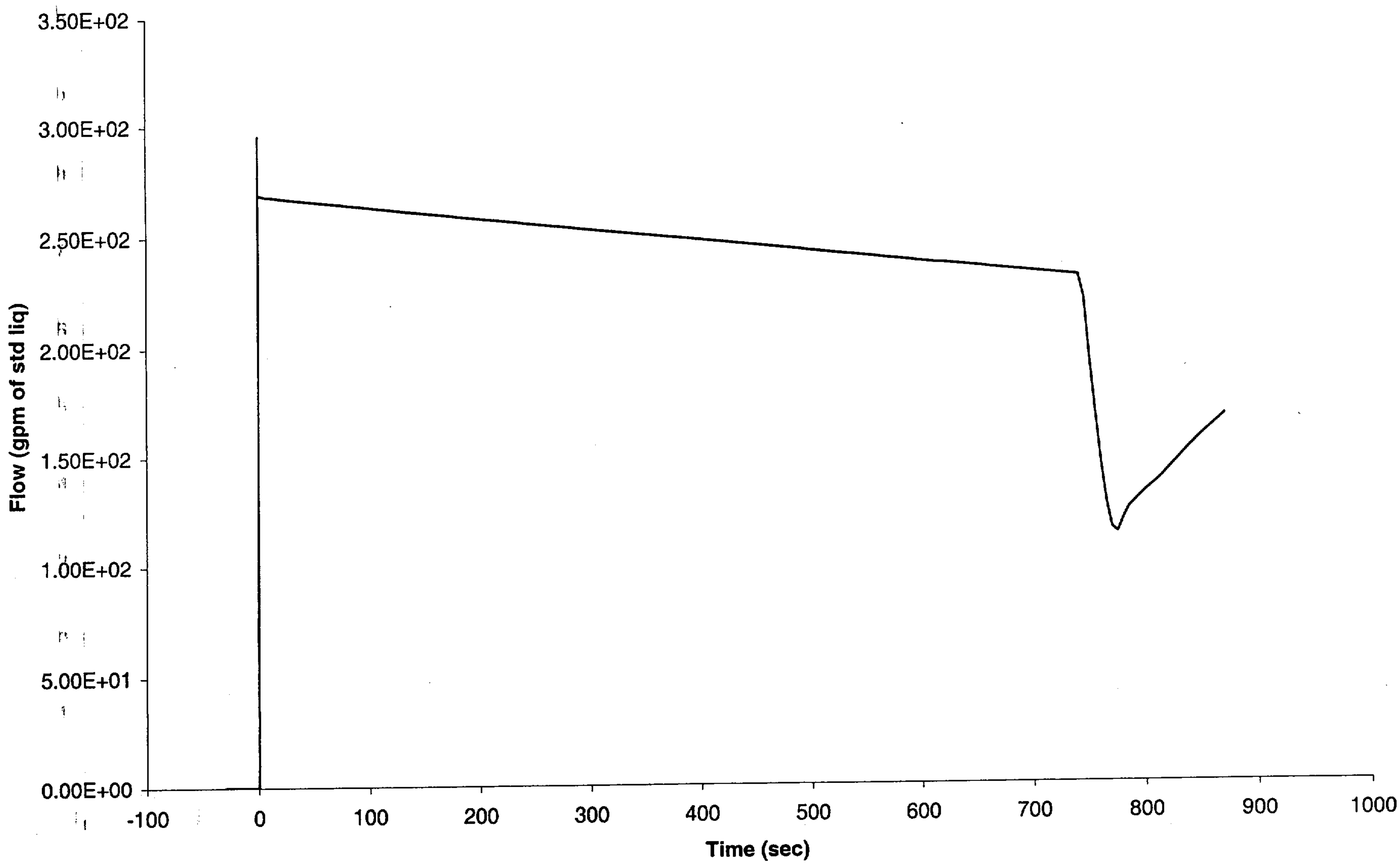

Fig. A.4-7: Small-Small LOCA - Quality at the Break

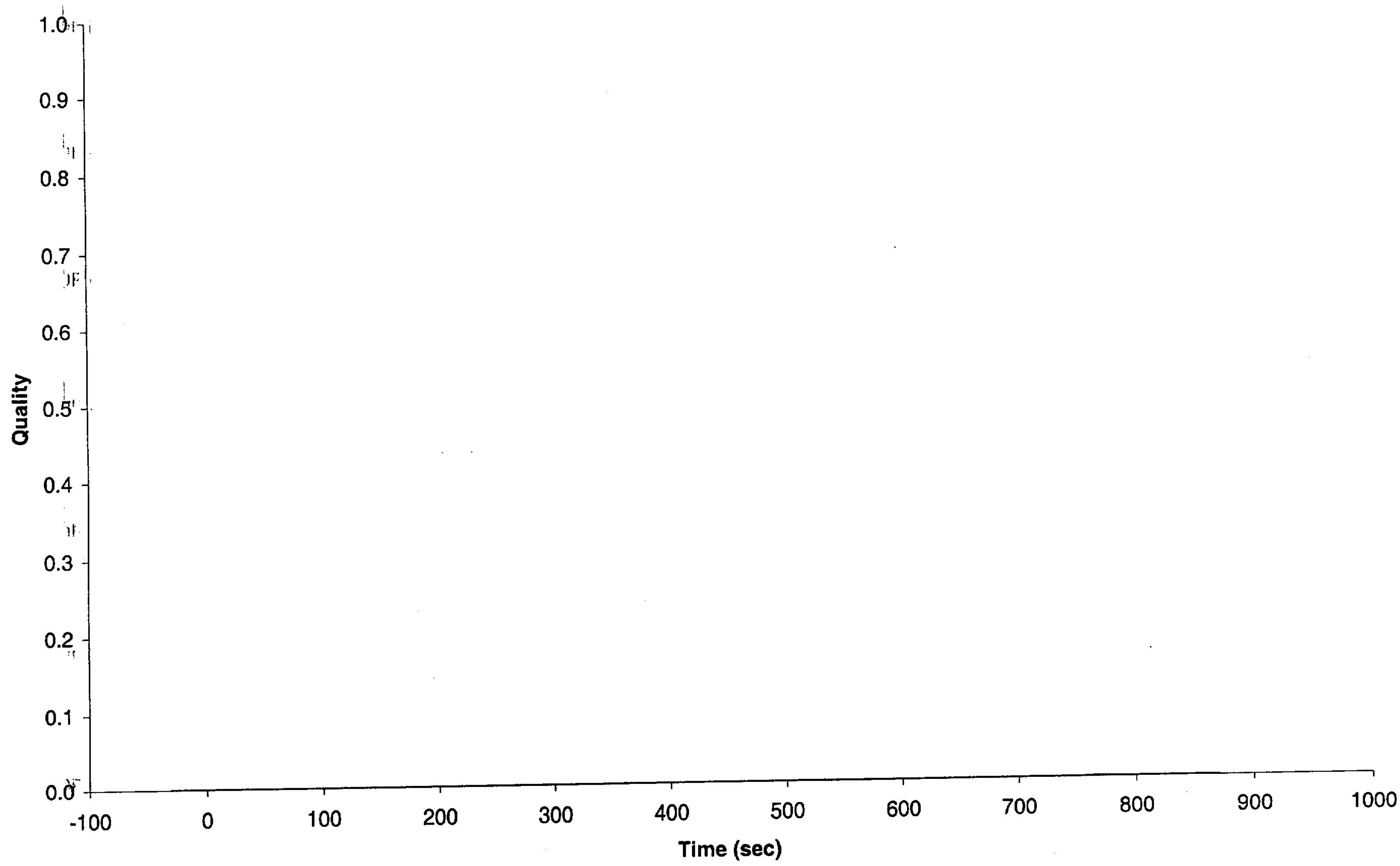

Fig. A.4-8: Small-Small LOCA - Phasic Velocity at the Break

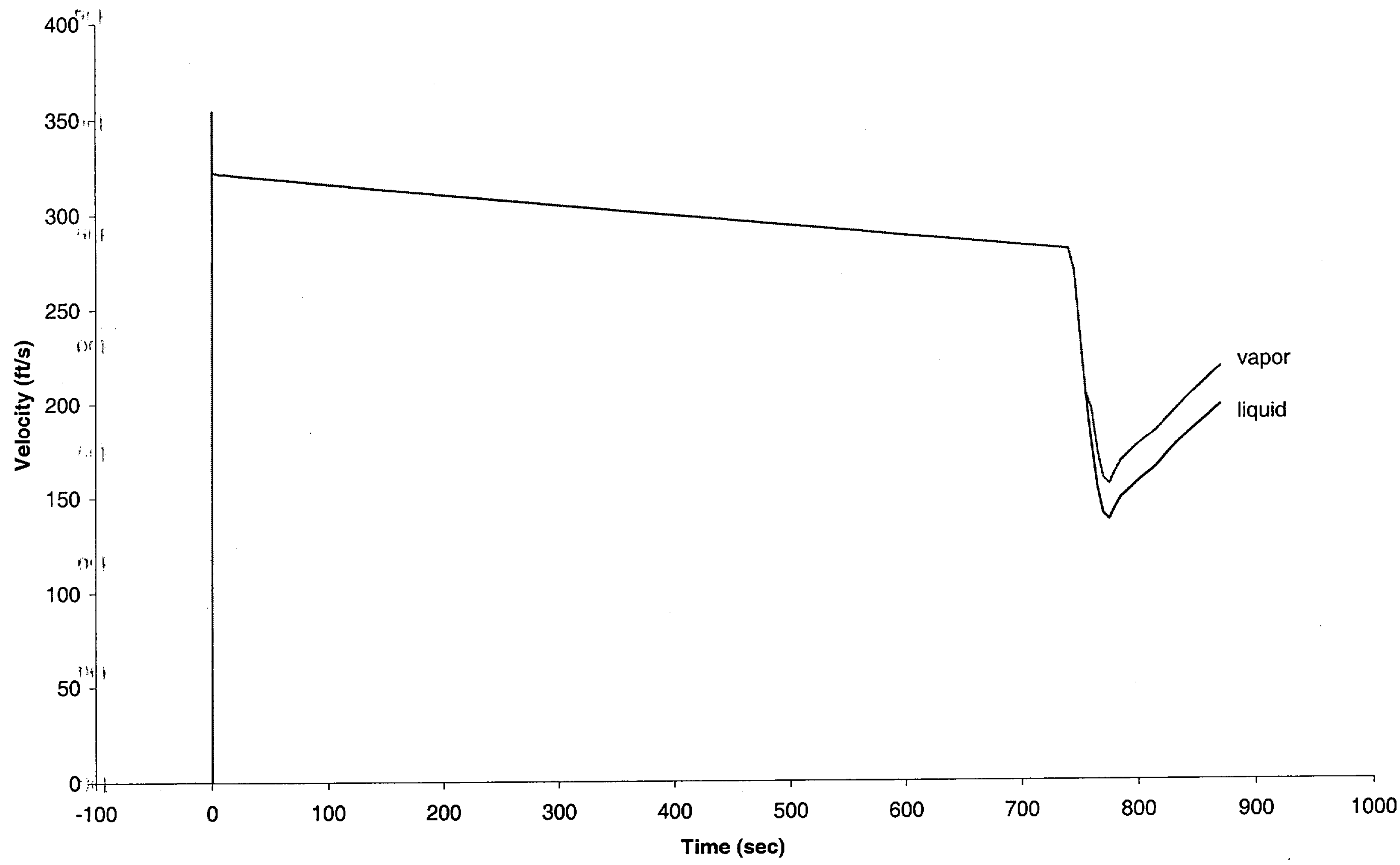

Fig. A.4-9: Small-Small LOCA - Liquid Temperature at the Break

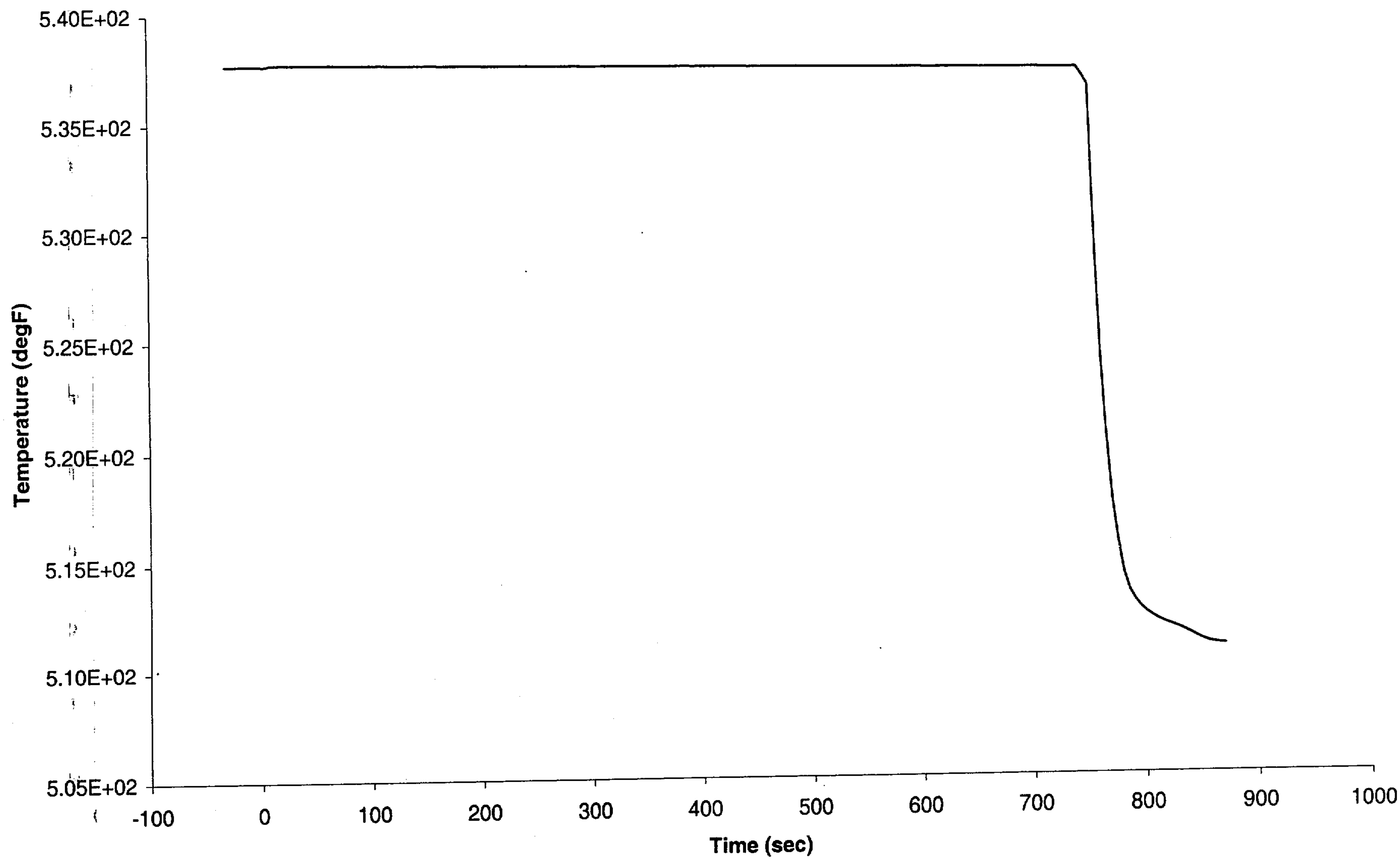

Fig. A.4-10: Small-Small LOCA - Pressurizer Level

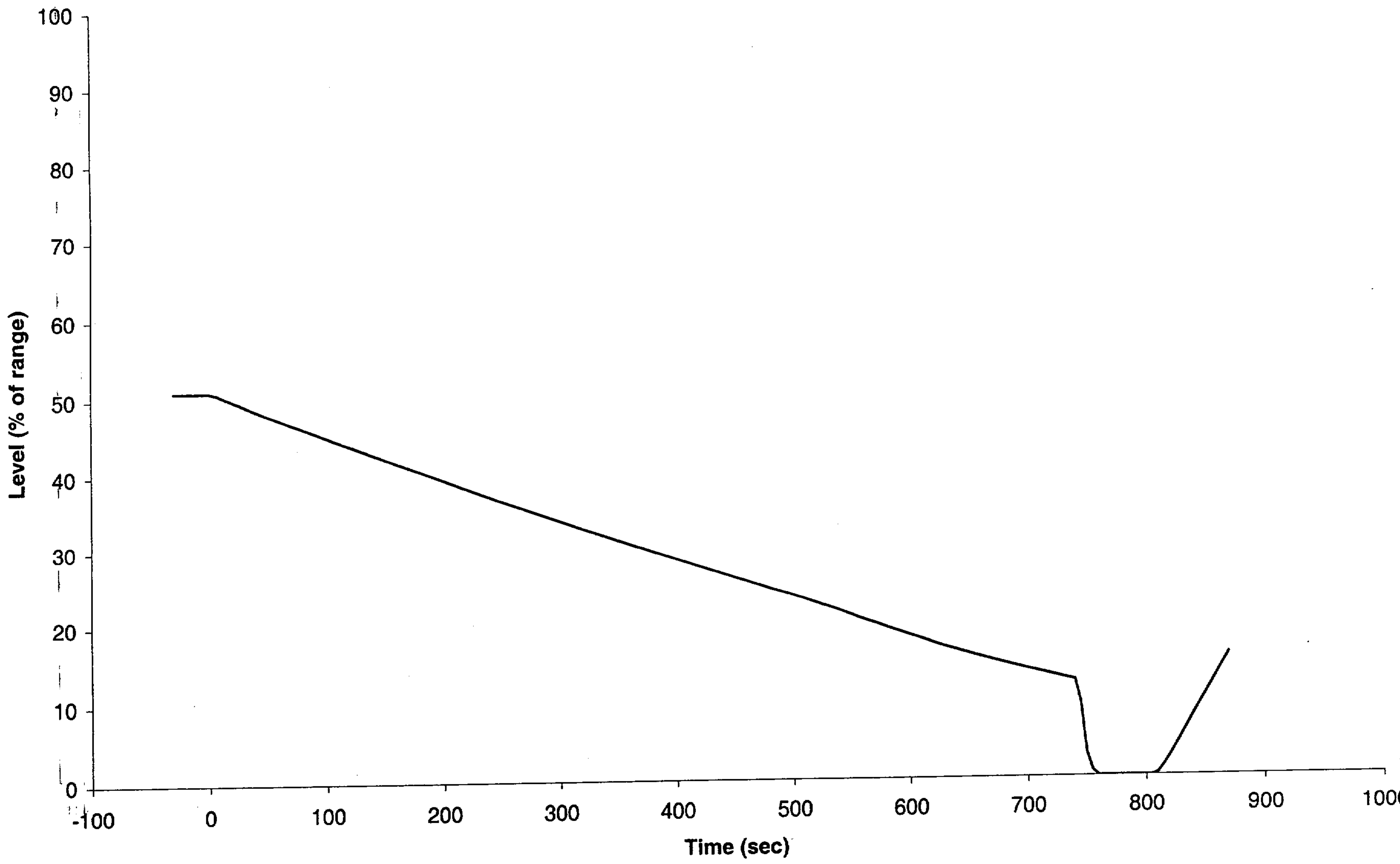

Fig. A.4-11: Small-Small LOCA - RCP Speed

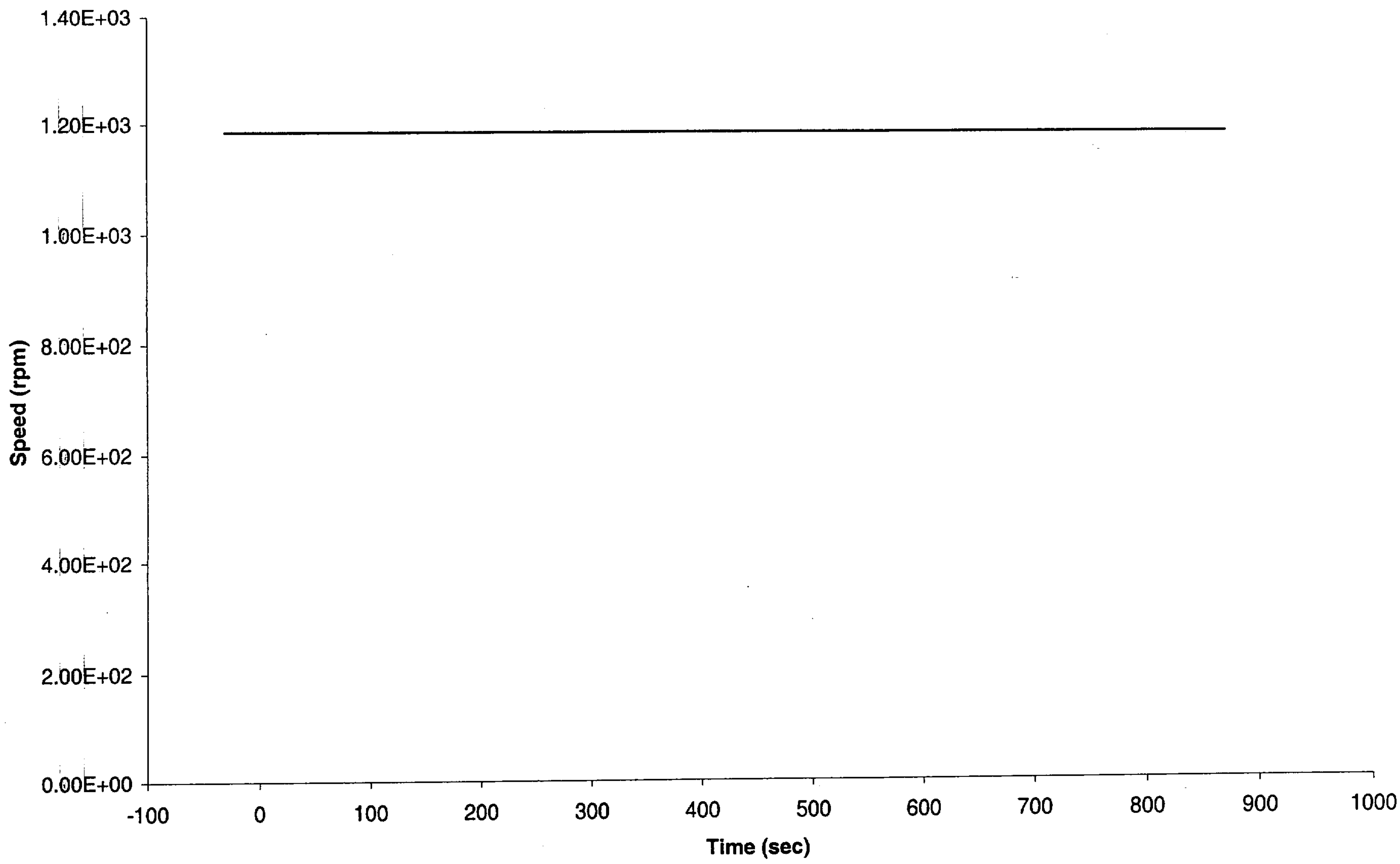

Fig. A.5-1: Surge Line Break - Core Power

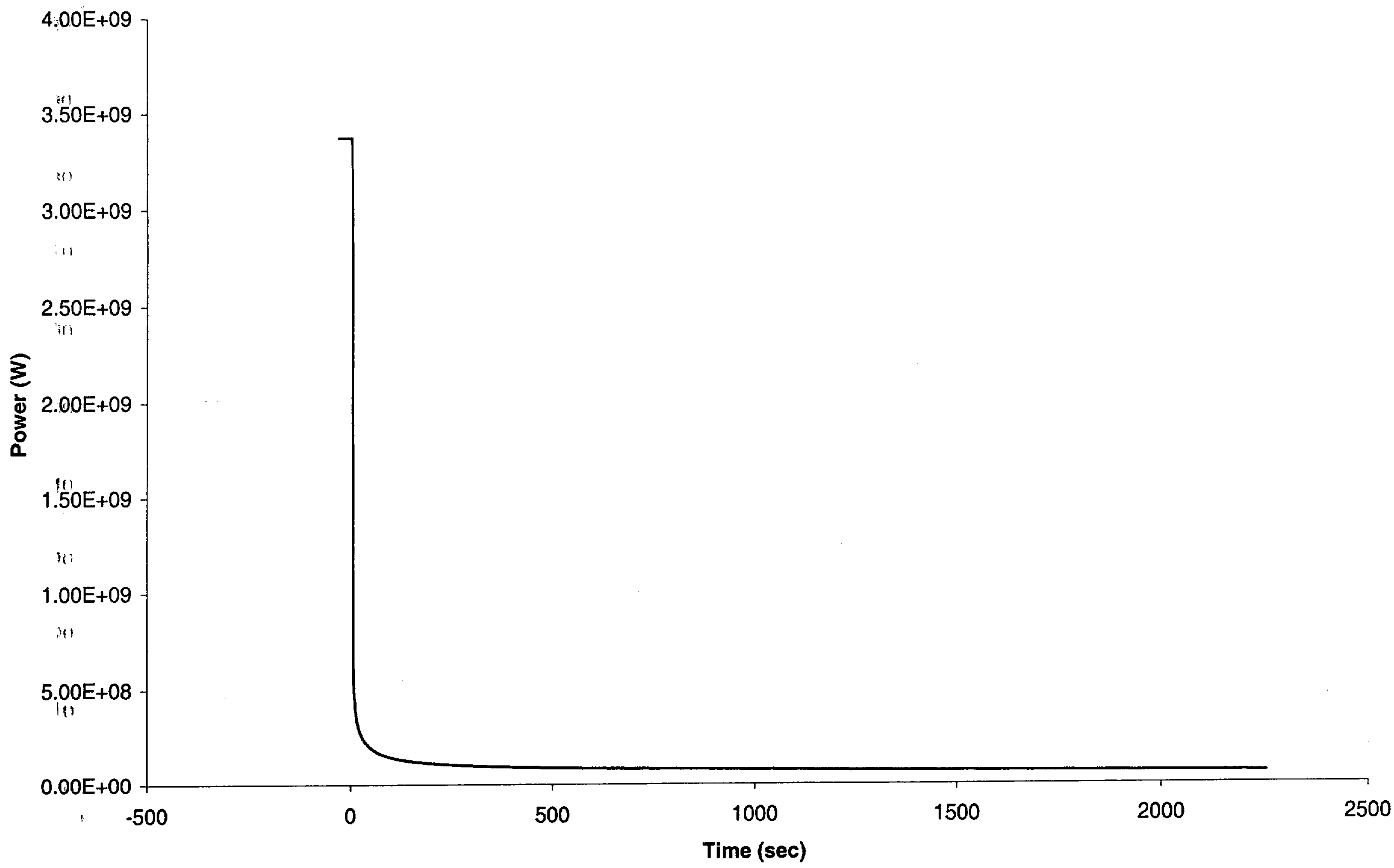

Fig. A.5-2: Surge Line Break - RCS (PRZR) Pressure

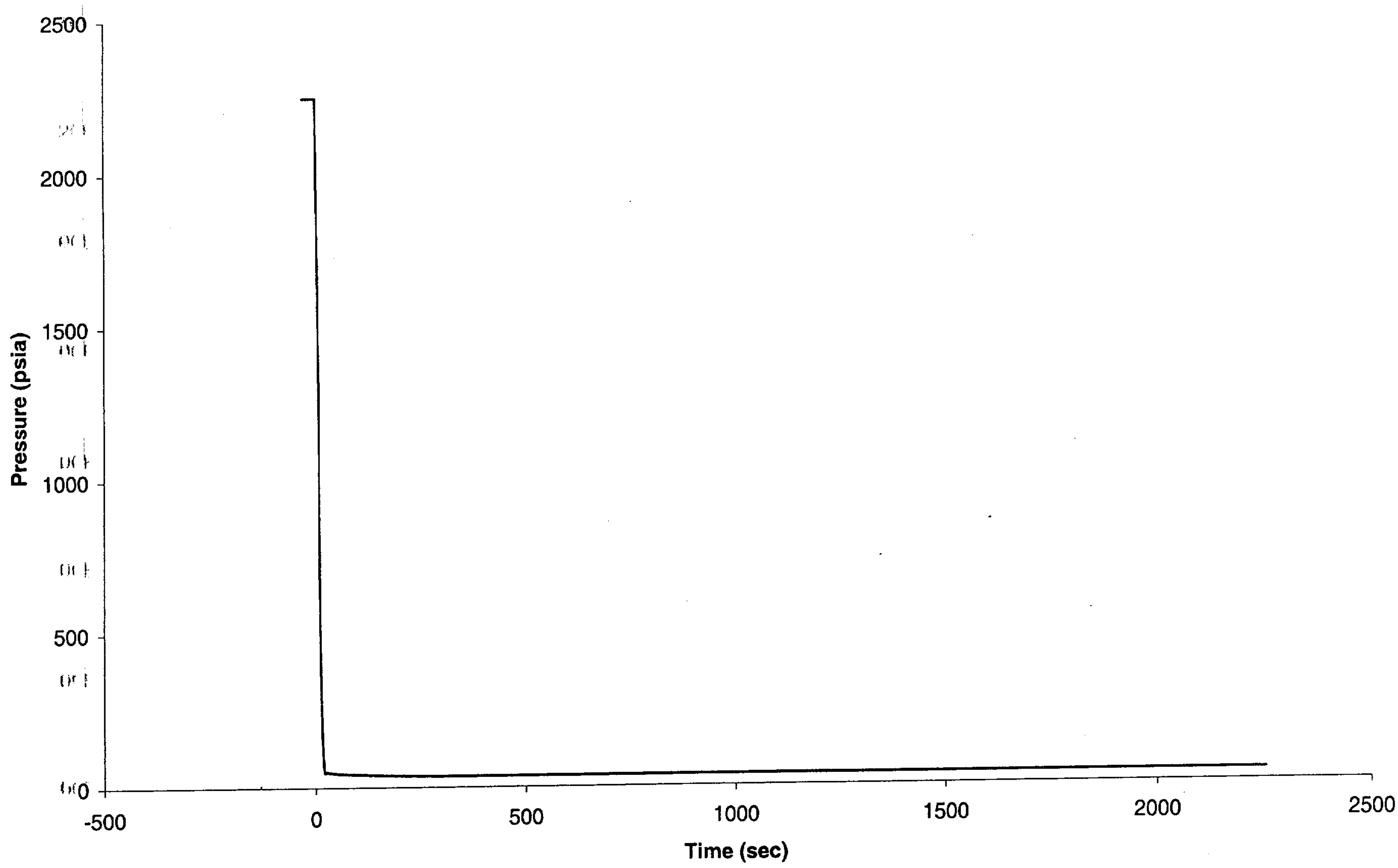

Fig. A.5-3: Surge Line Break - Peak Cladding Temperature

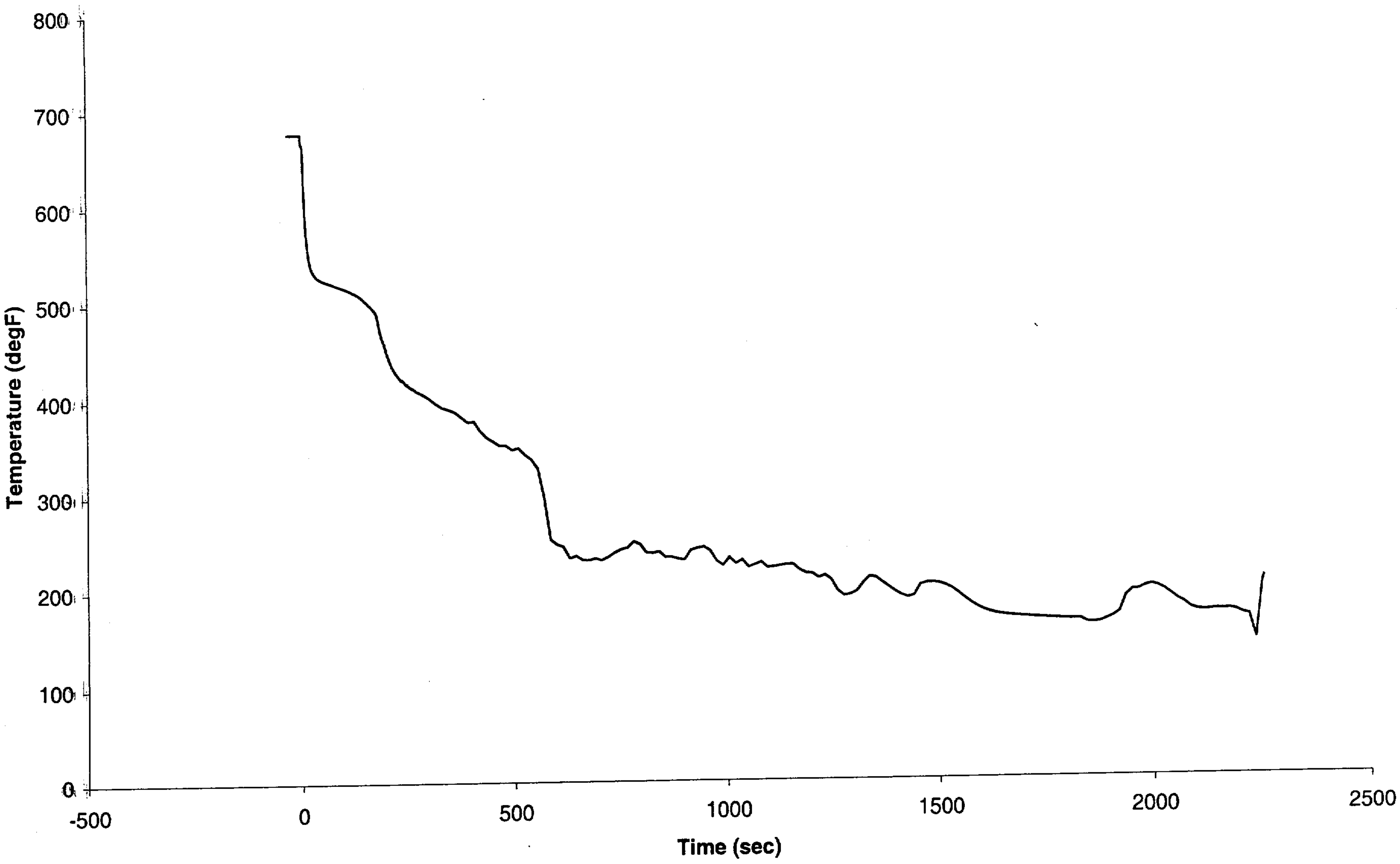

Fig. A.5-4: Surge Line Break - Core Void

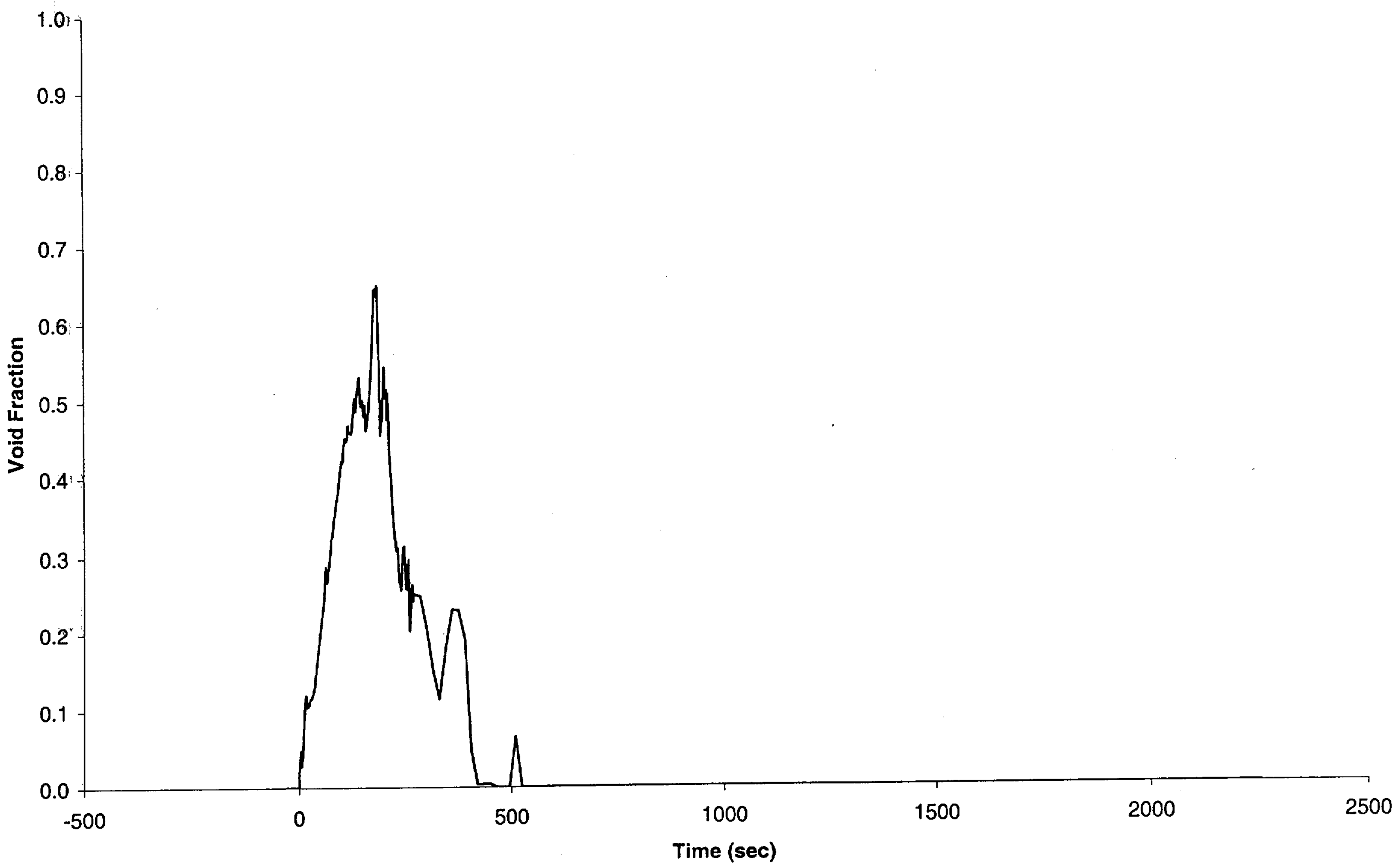

Fig. A.5-5: Surge Line Break - Injection

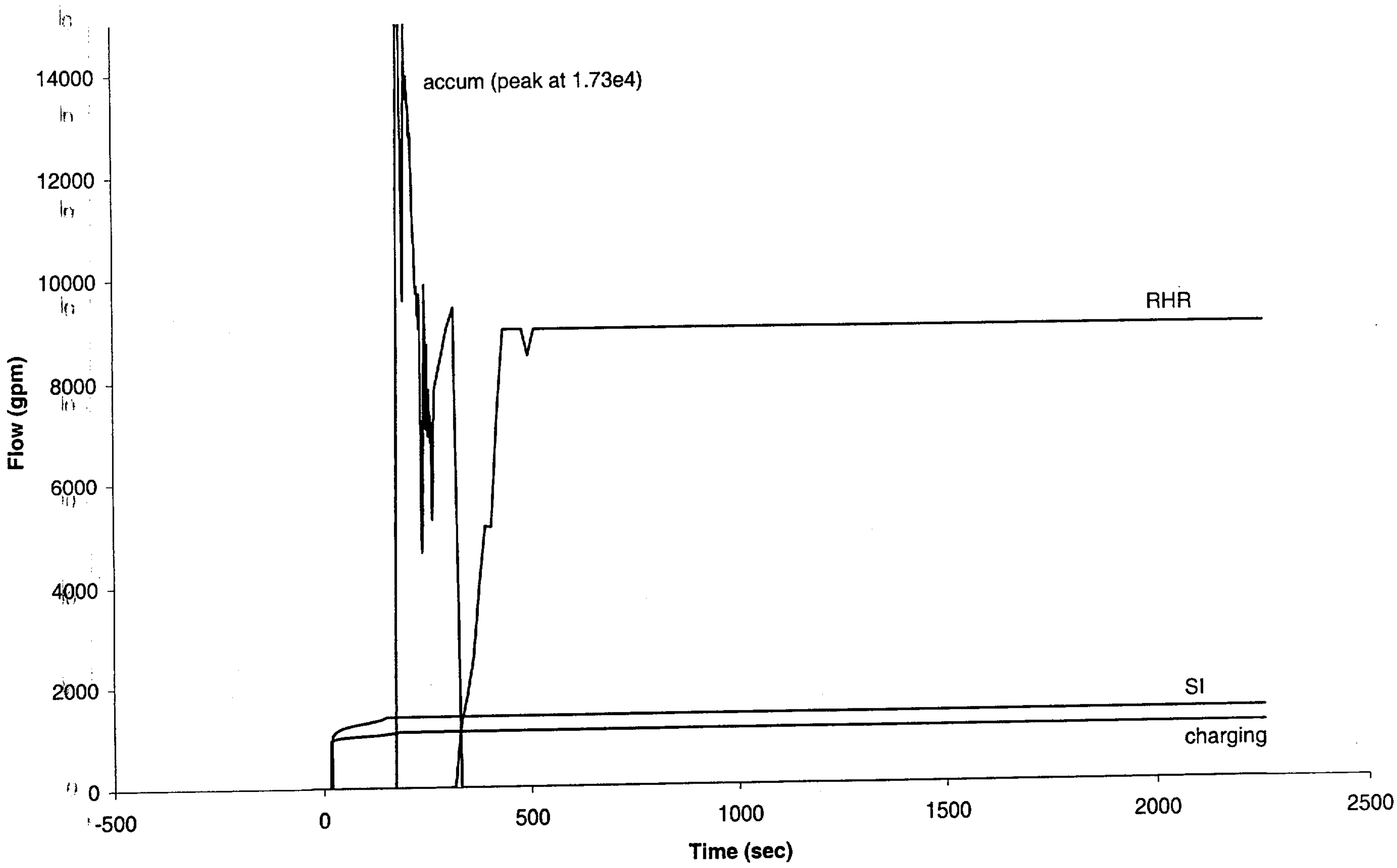

Fig. A.5-6: Surge Line Break - Flow Rate at the Break

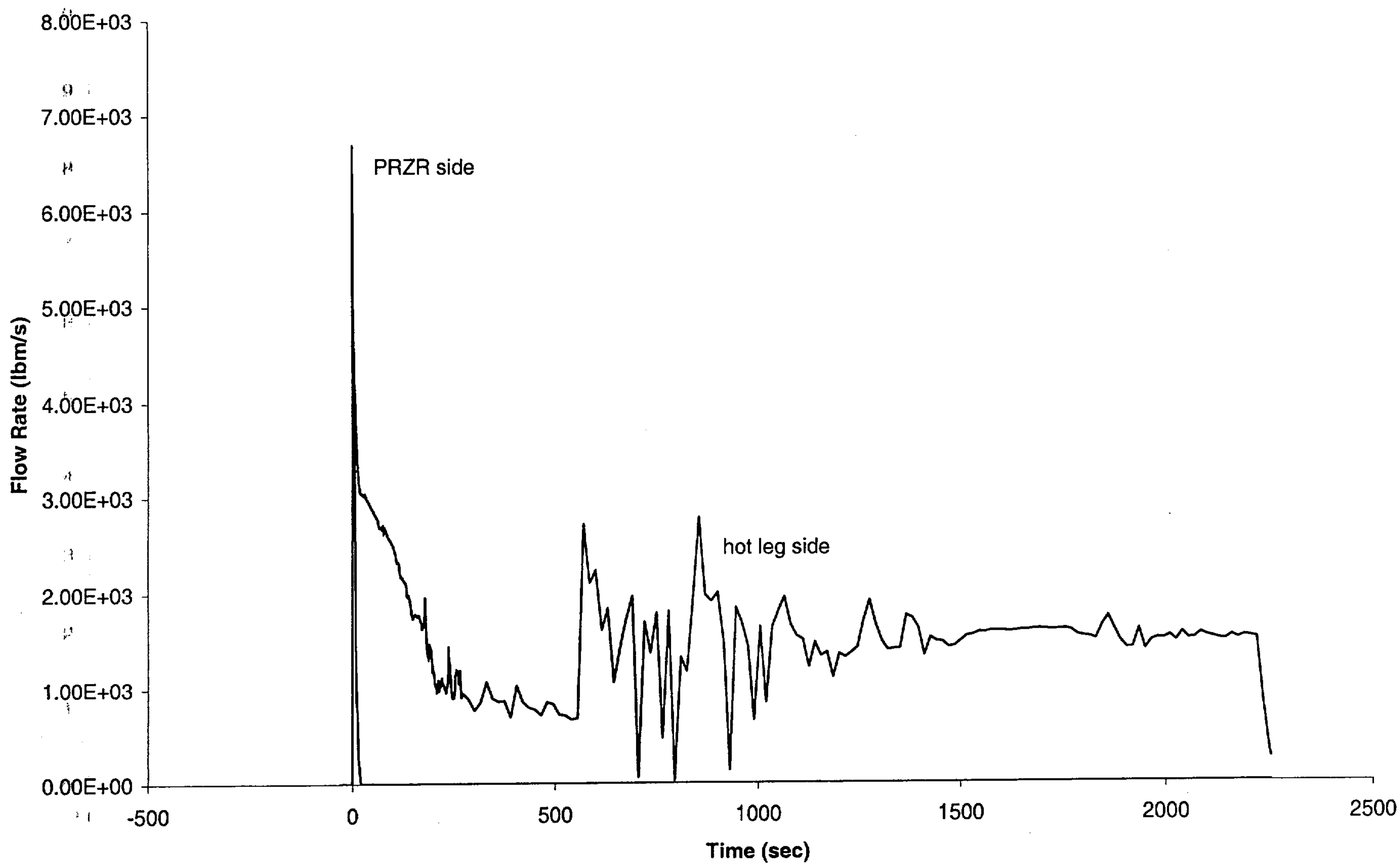

Fig. A.5-7: Surge Line Break - Quality at the Break

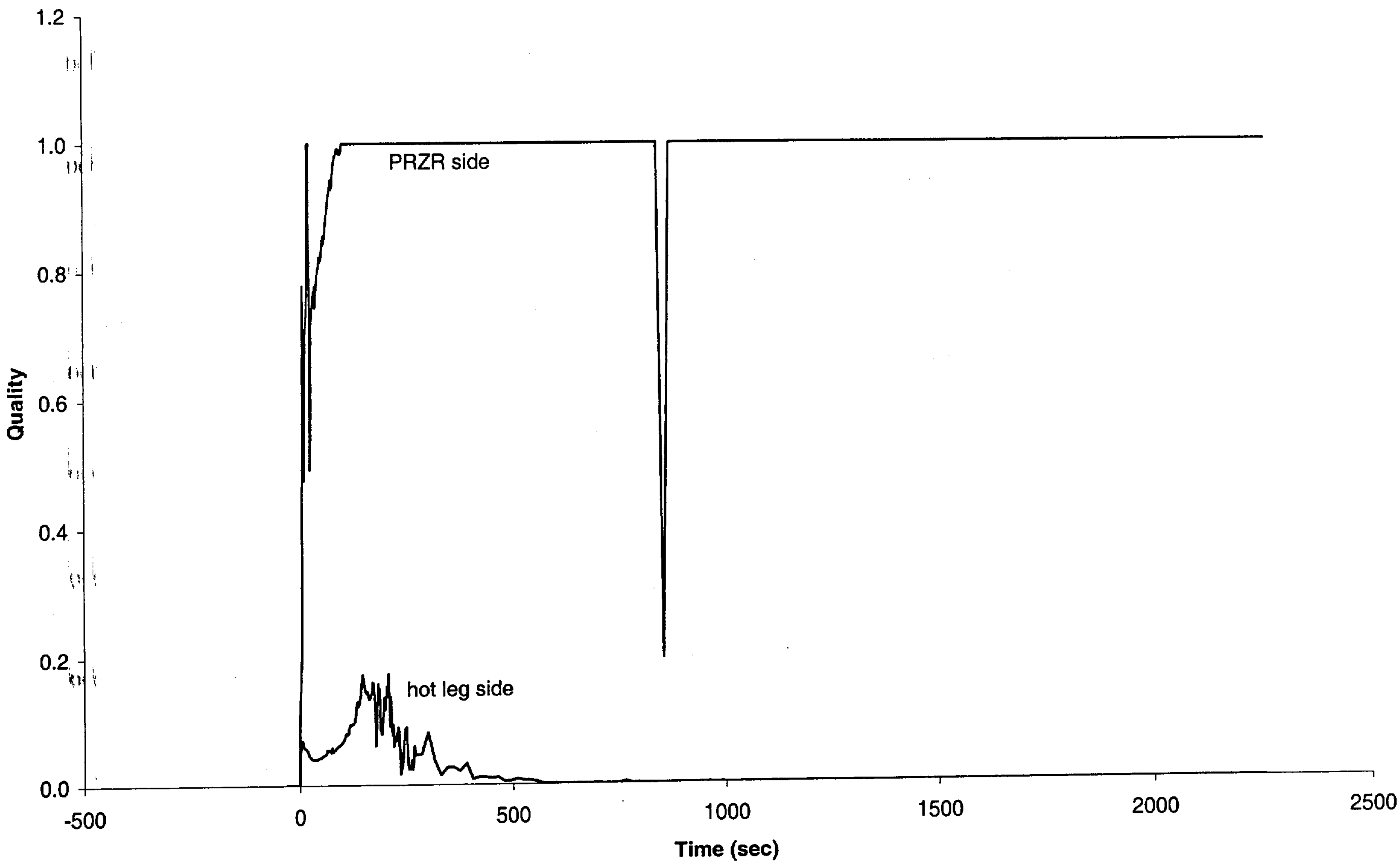

Fig. A.5-8: Surge Line Break - Phasic Velocity at the Hot Leg Side of the Break

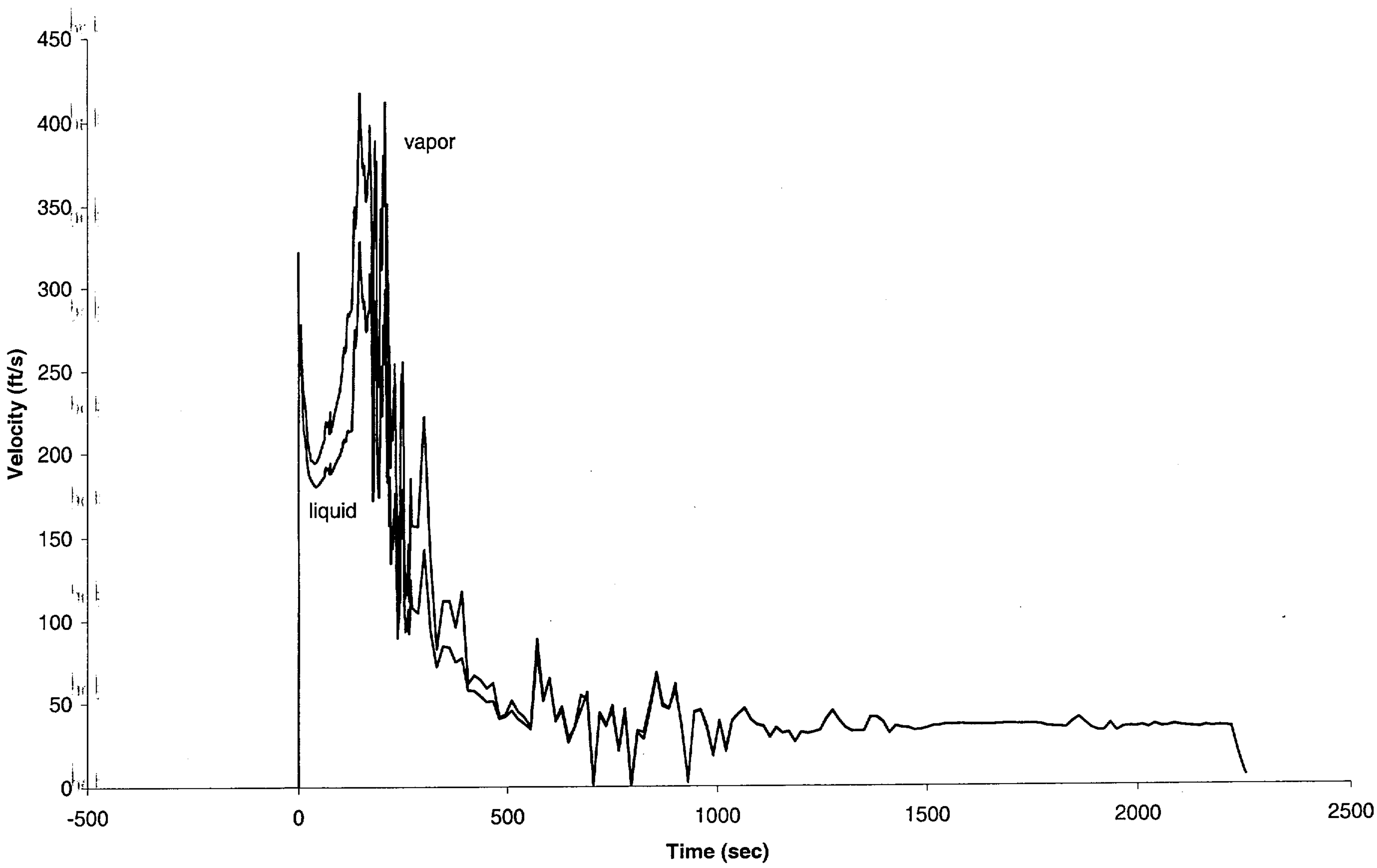

Fig. A.5-9: Surge Line Break - Liquid Temperature at the Break

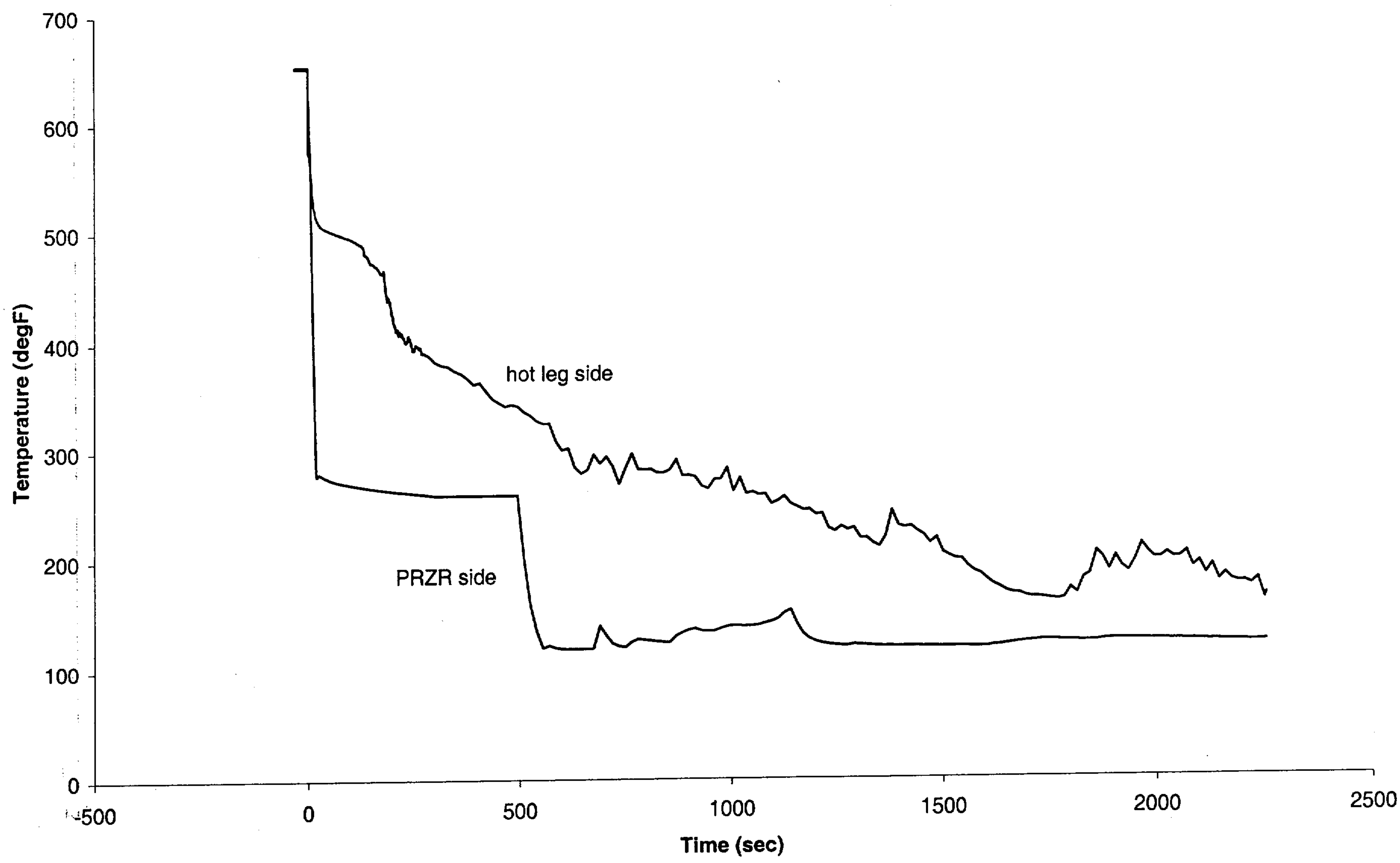

Fig. A.5-10: Surge Line Break - RCP Speed

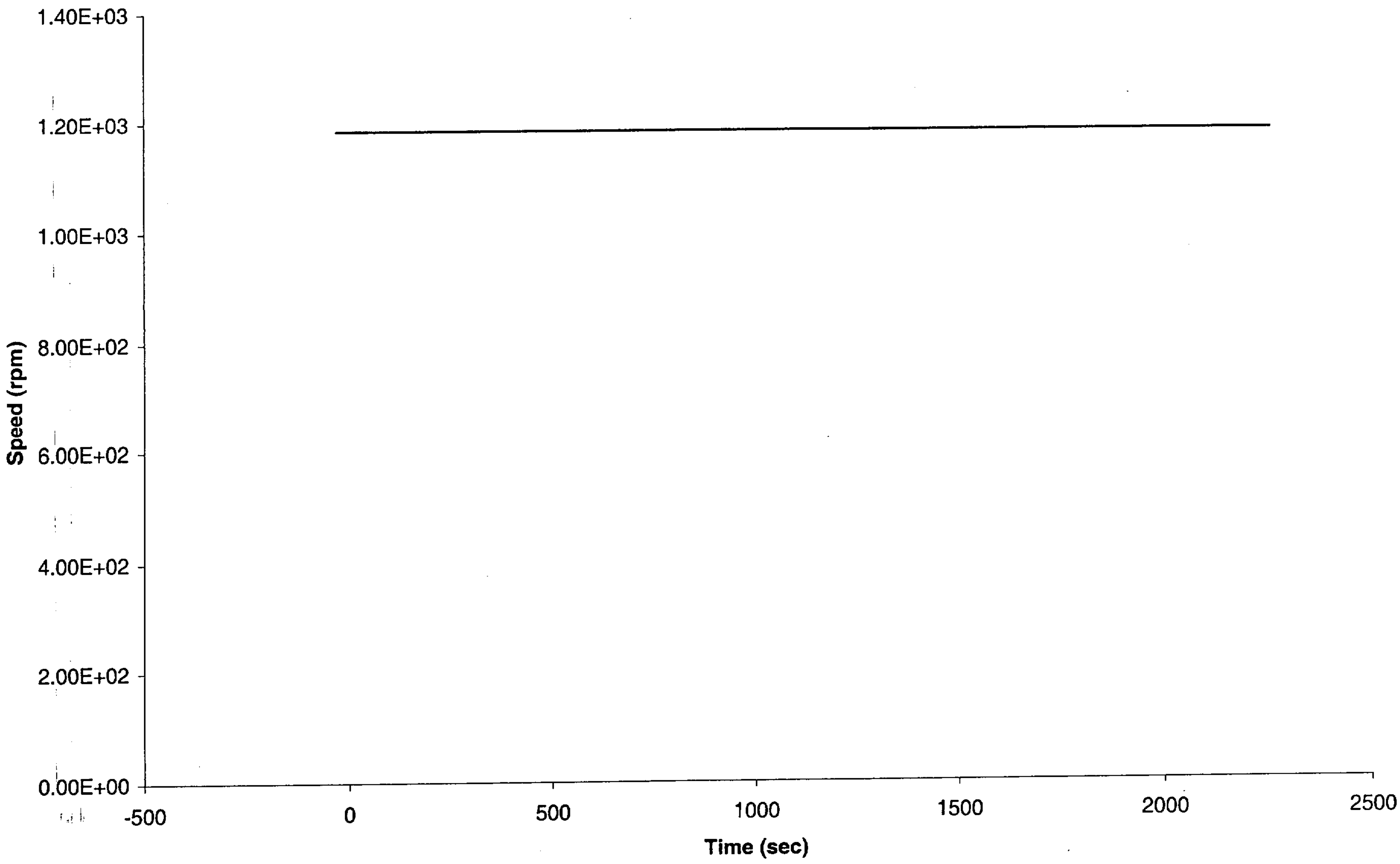

Fig. A.6a-1: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - Core Power

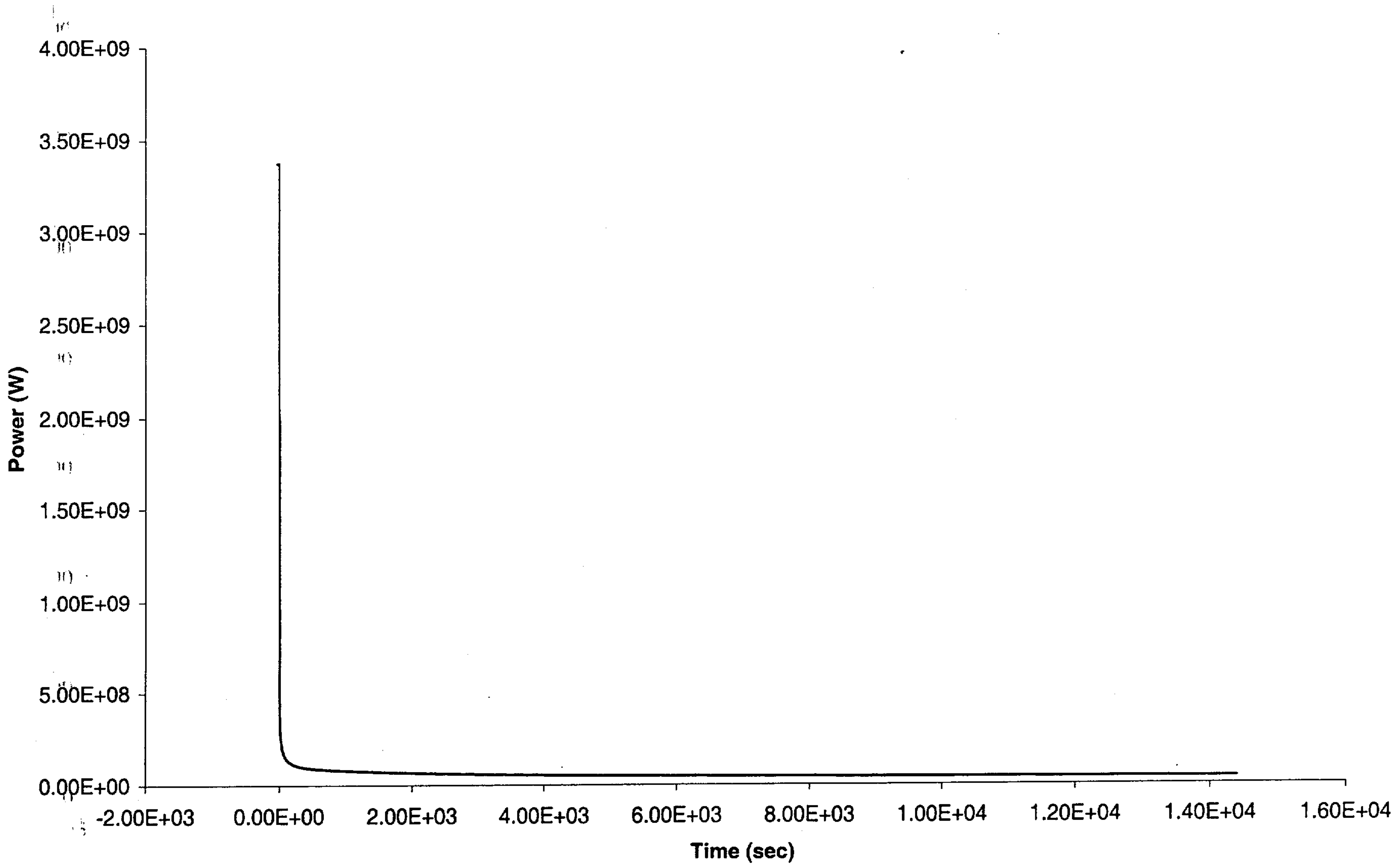

Fig. A.6a-2: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - <u>RCS Pressure</u>

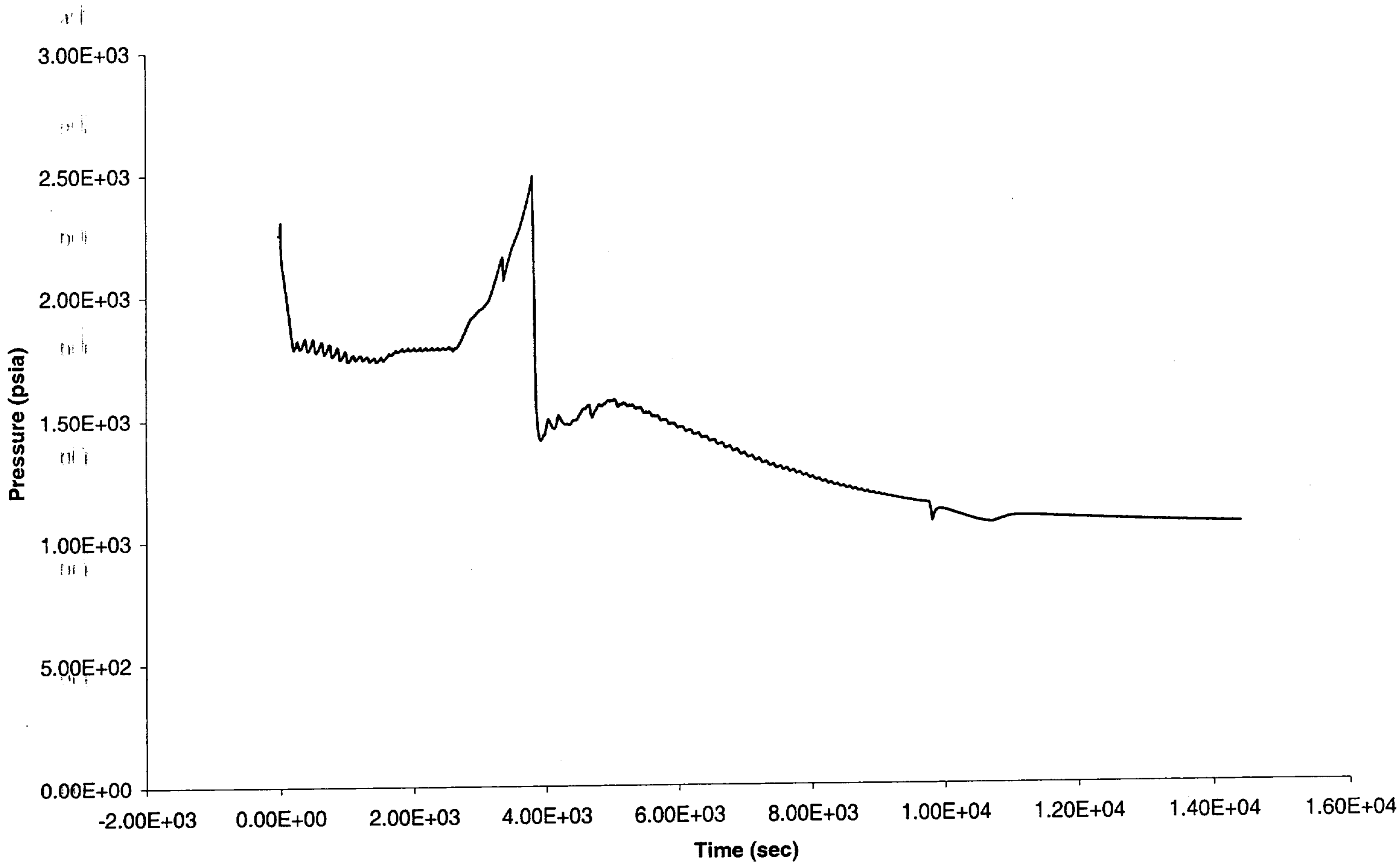

Fig. A.6a-3: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - <u>Feed/Steam Flows</u>

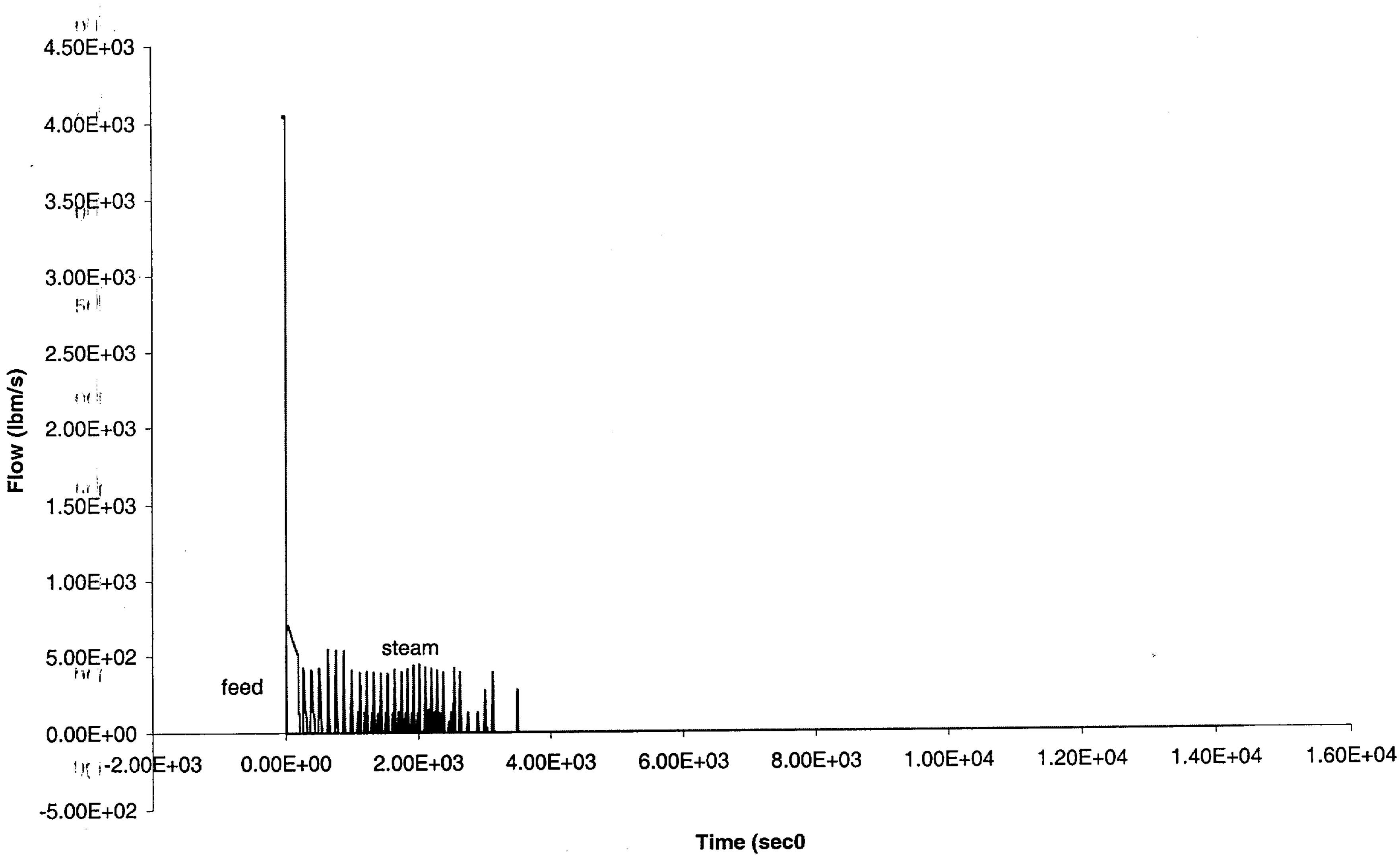

Fig. A.6a-4: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - Charging and SI Flows

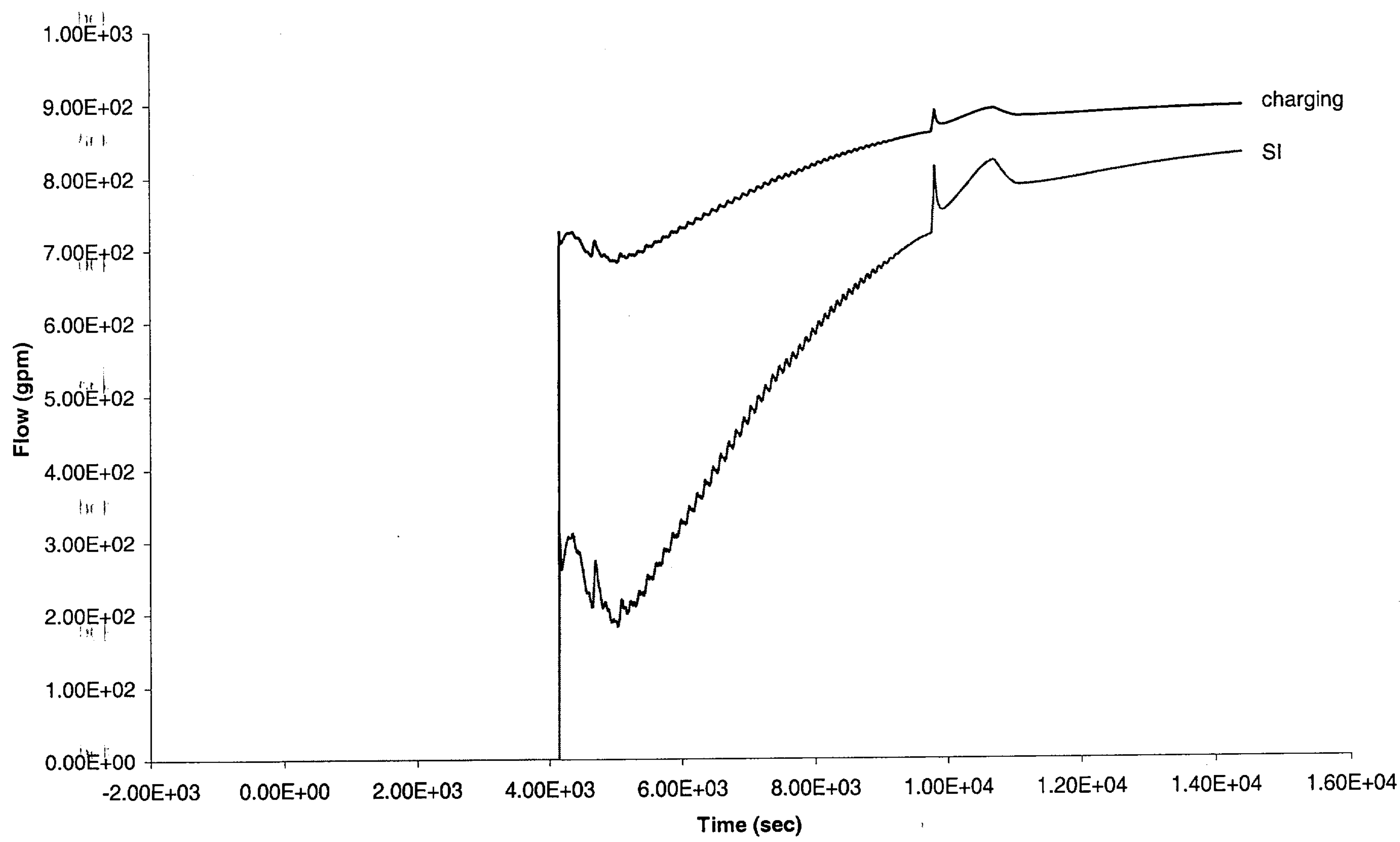

Fig. A.6a-5: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - RCS Temperatures

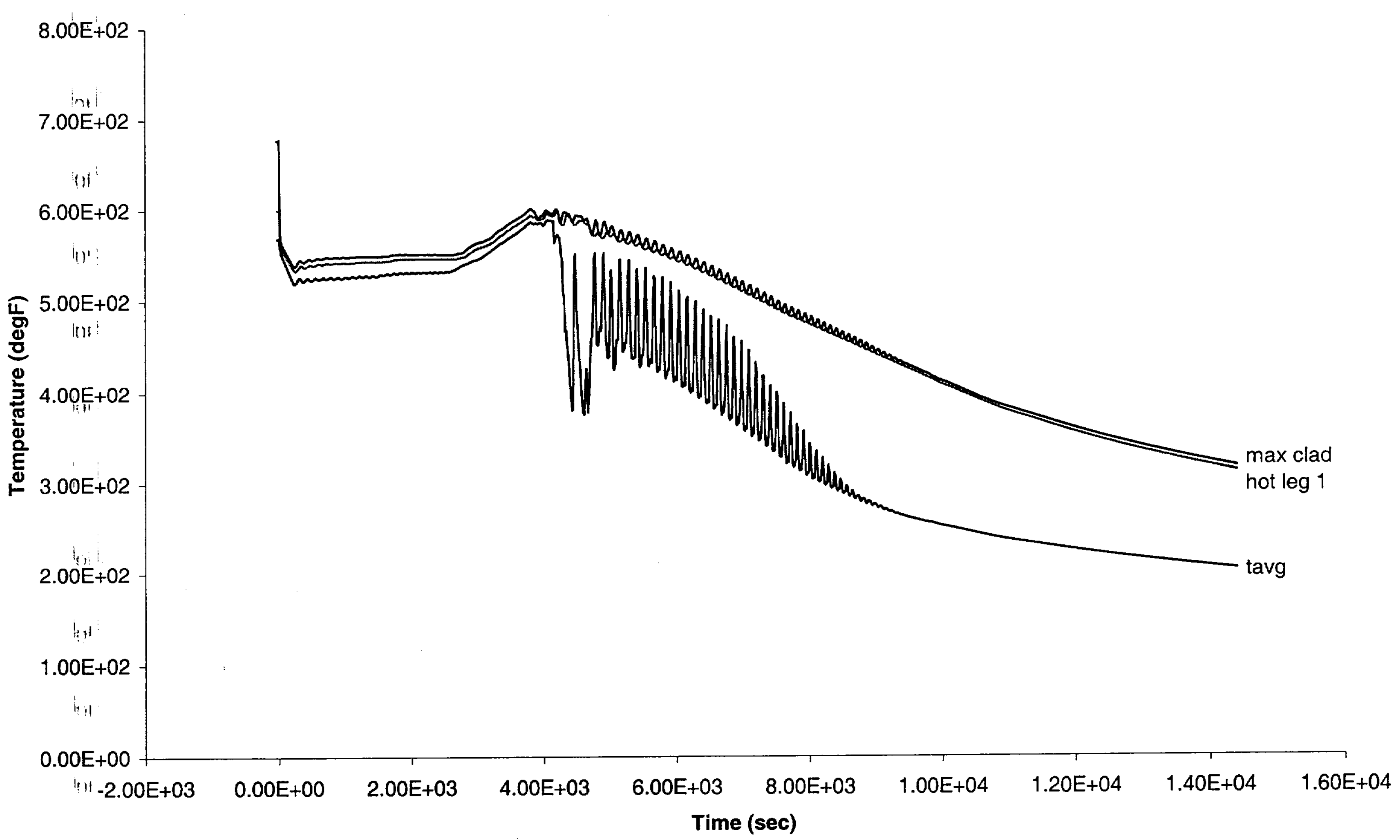

Fig. A.6a-6: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - <u>PRZR Level</u>

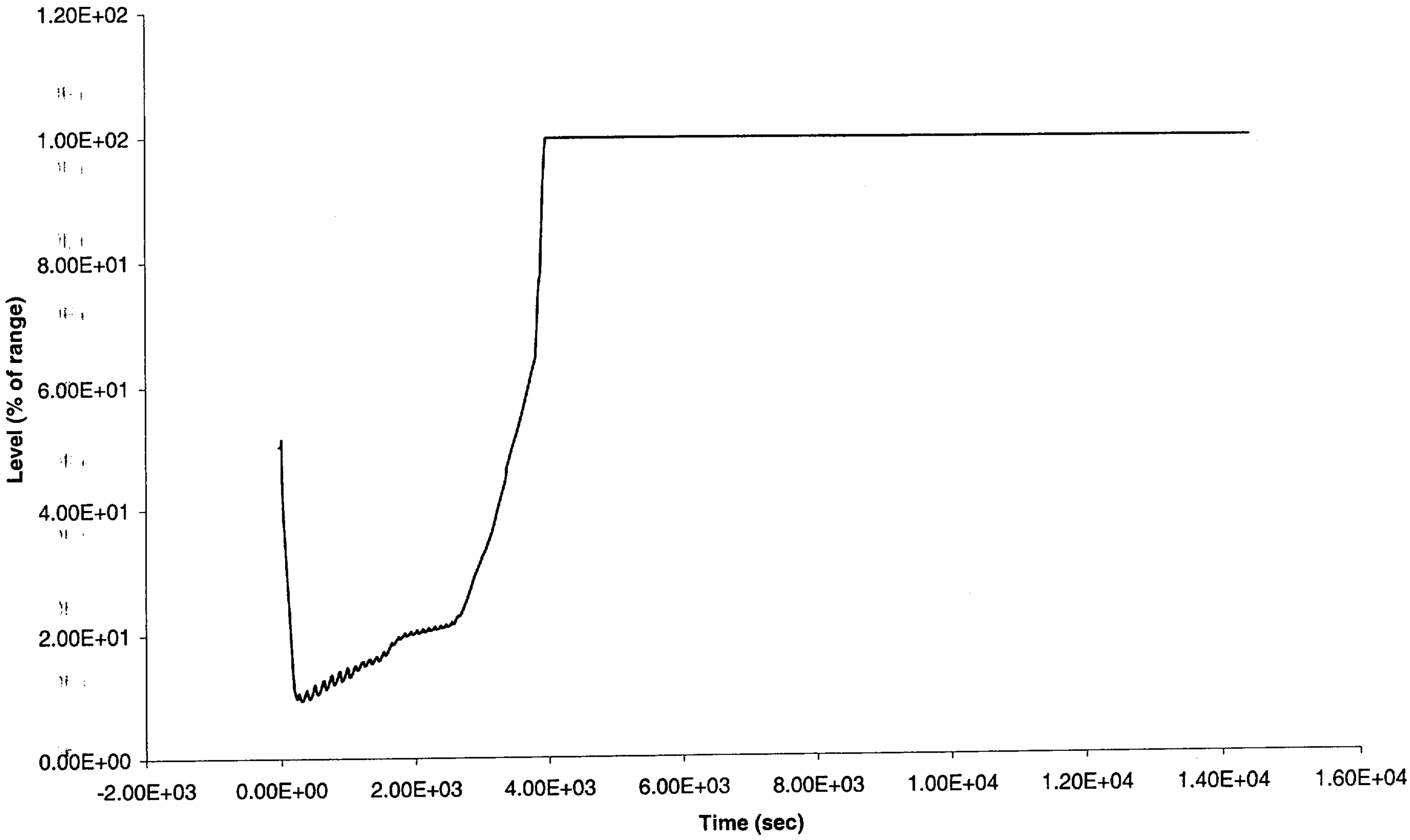

Fig. A.6a-7: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - <u>PORV Flow</u>

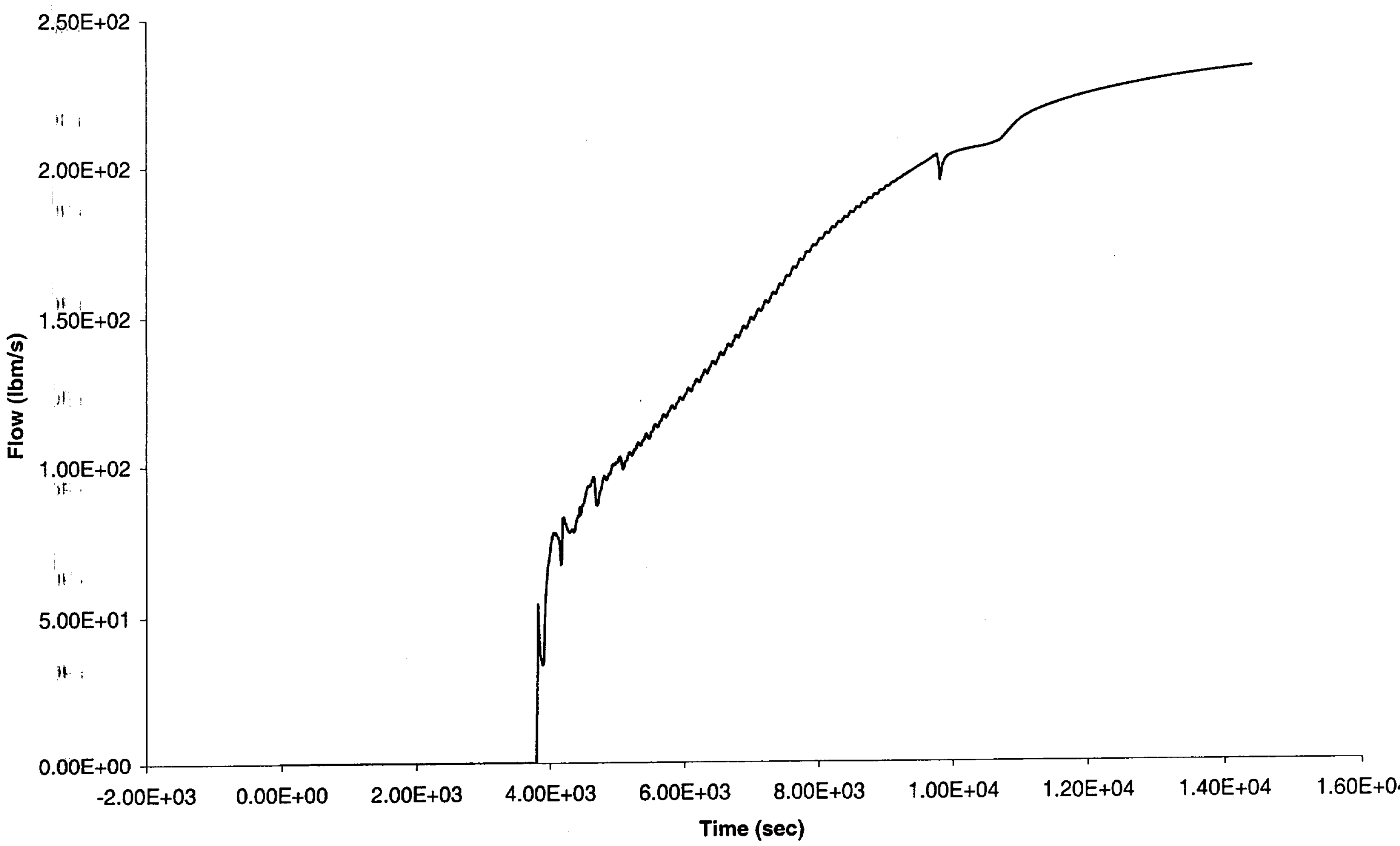

Fig. A.6a-8: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - <u>SG 1 WR Level</u>

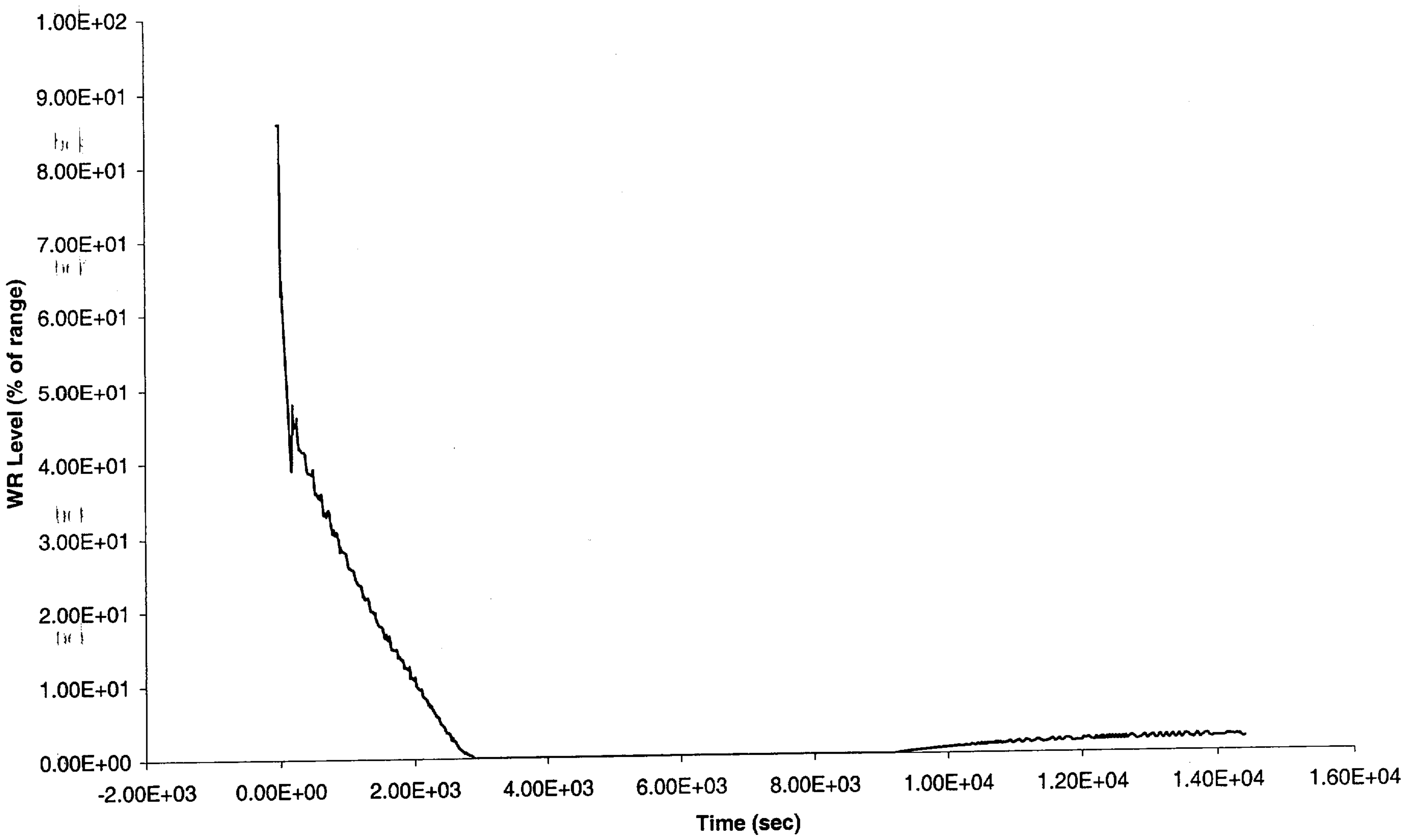

Fig. A.6a-9: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - SG 1 Pressure

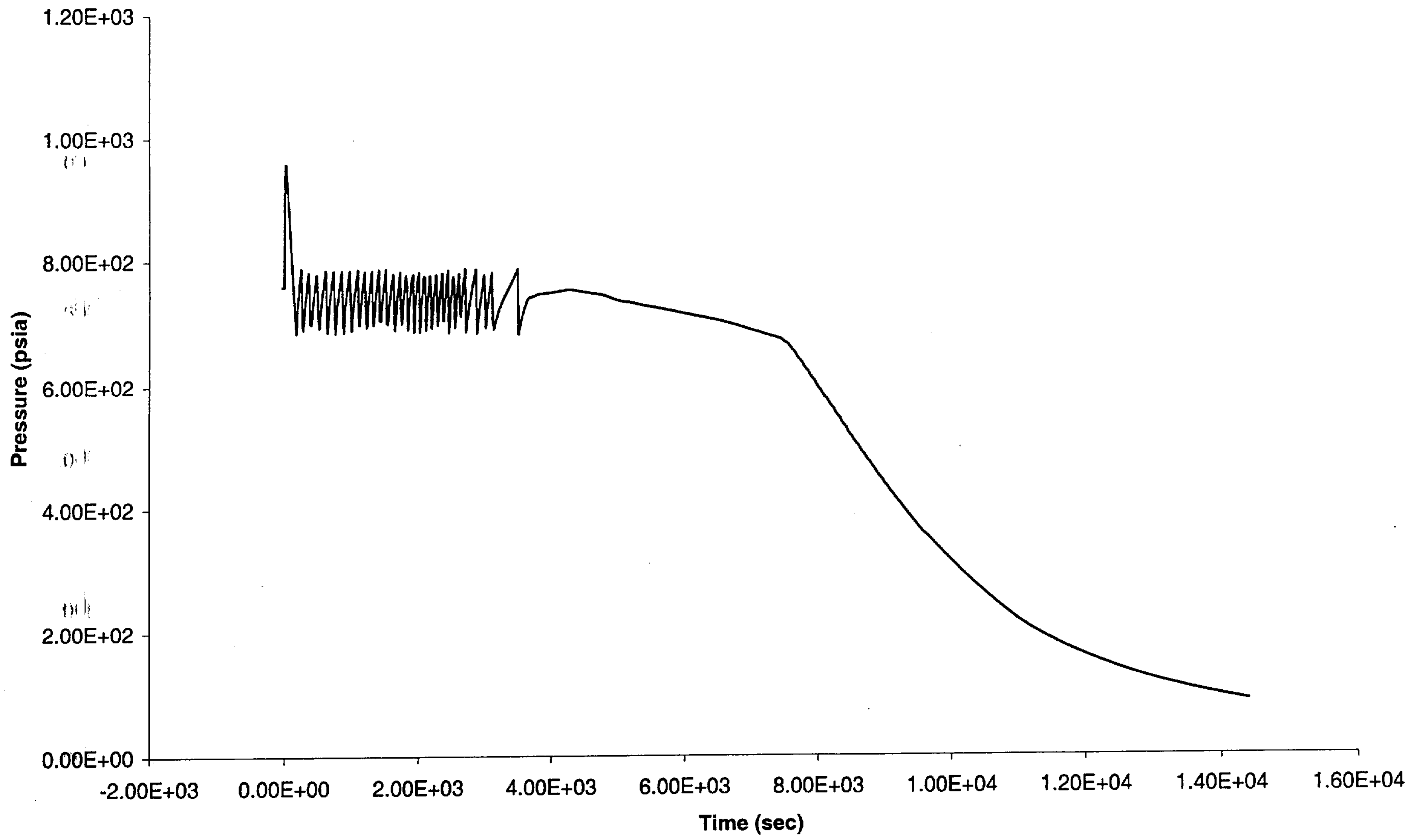

Fig. A.6a-10: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - SG 1 Temperature

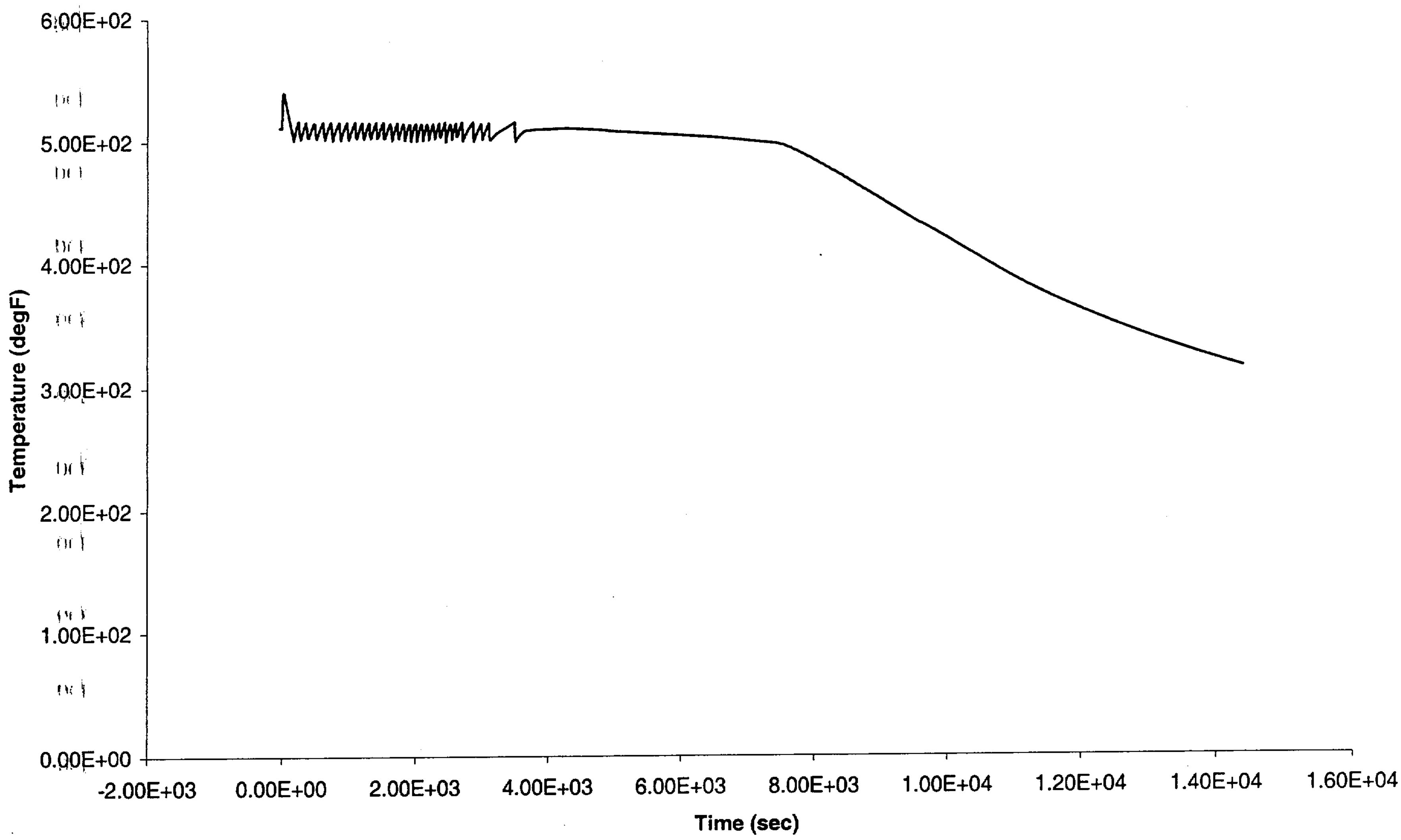

Fig. A.6a-11: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - <u>RCP Speed</u>

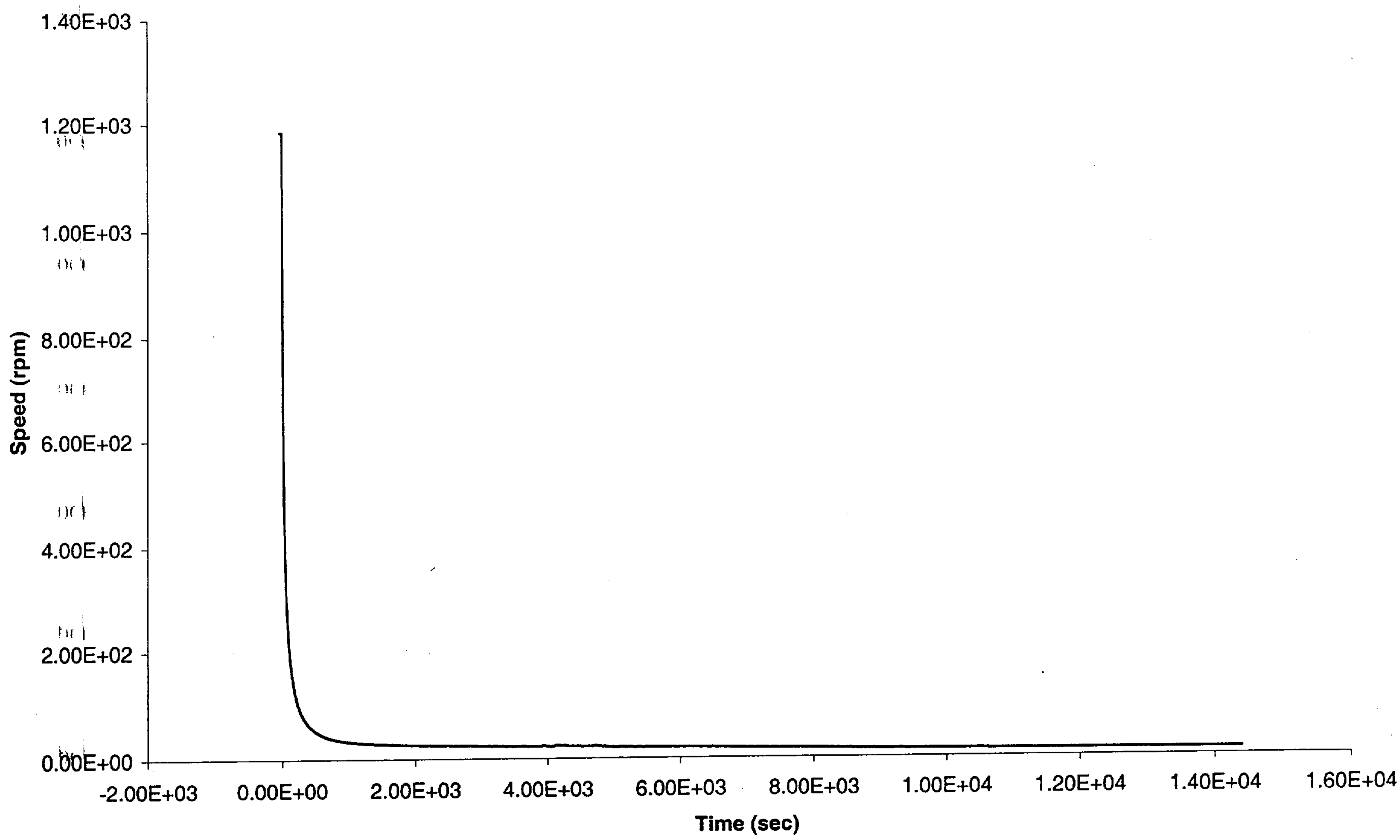

Fig. A.6a-12: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - <u>Core Exit Subcooling</u>

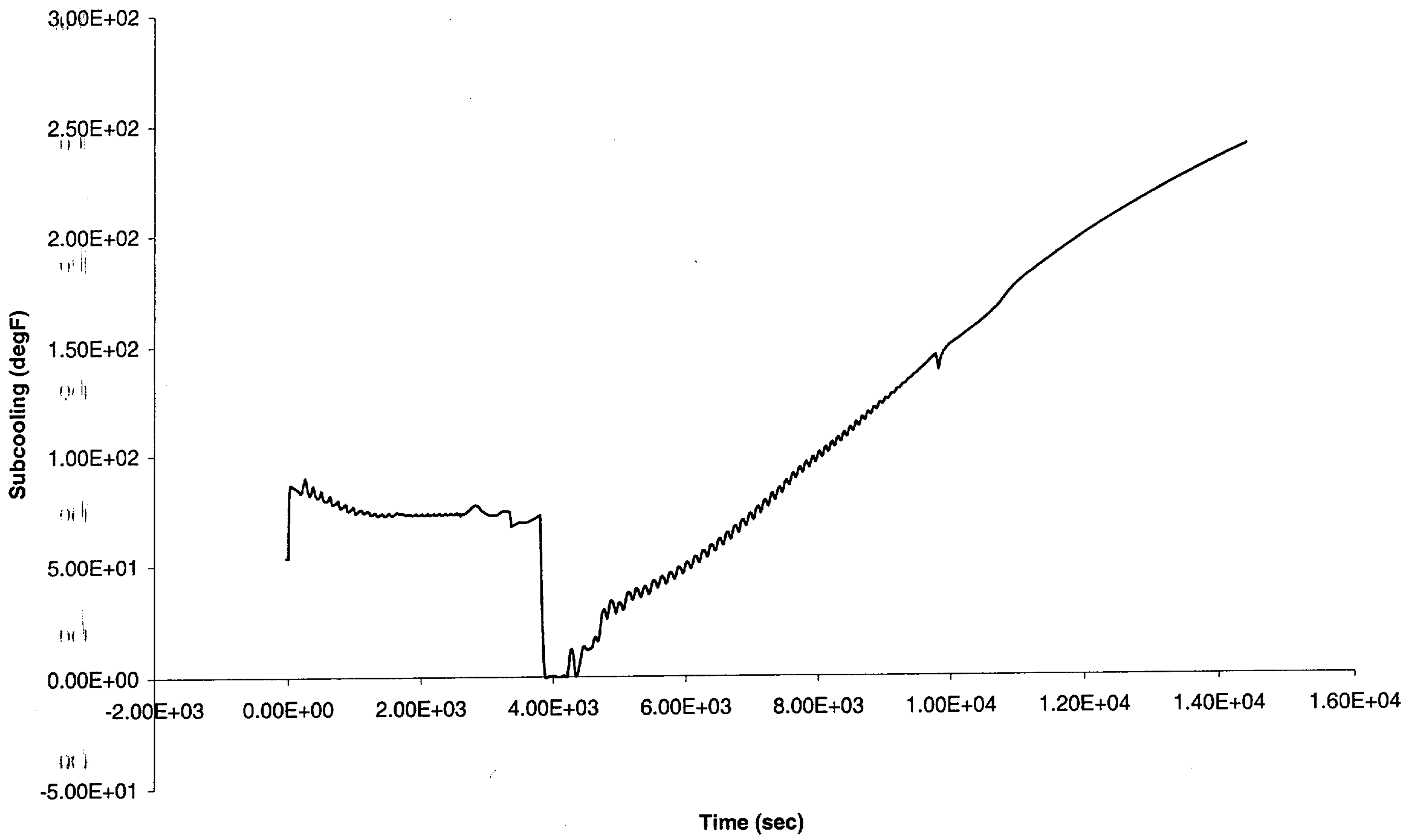

Fig. A.6a-13: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - <u>RCS Cooling Rate</u>

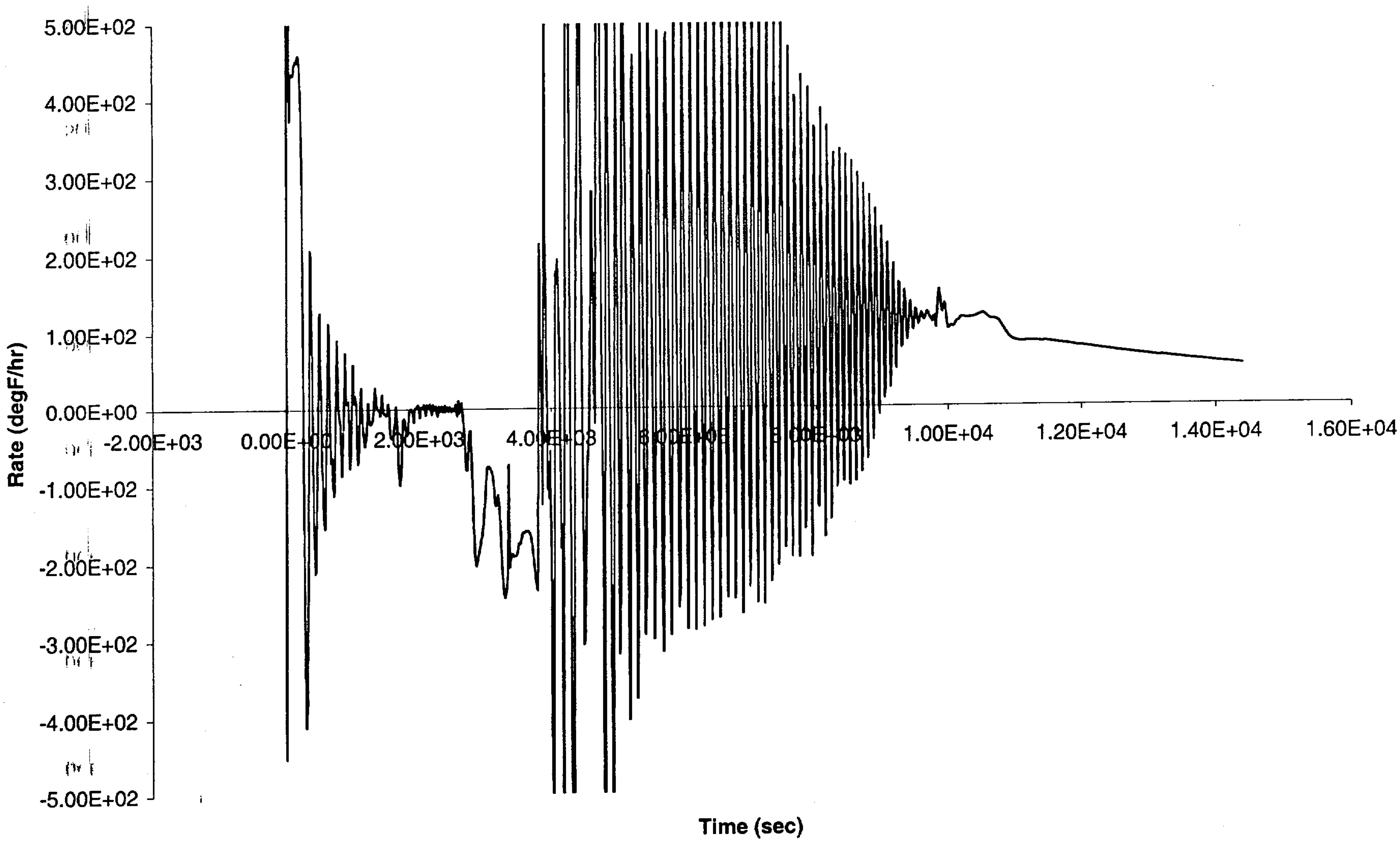

Fig. A.6a-14: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - Cummulative Charging + SI Flow

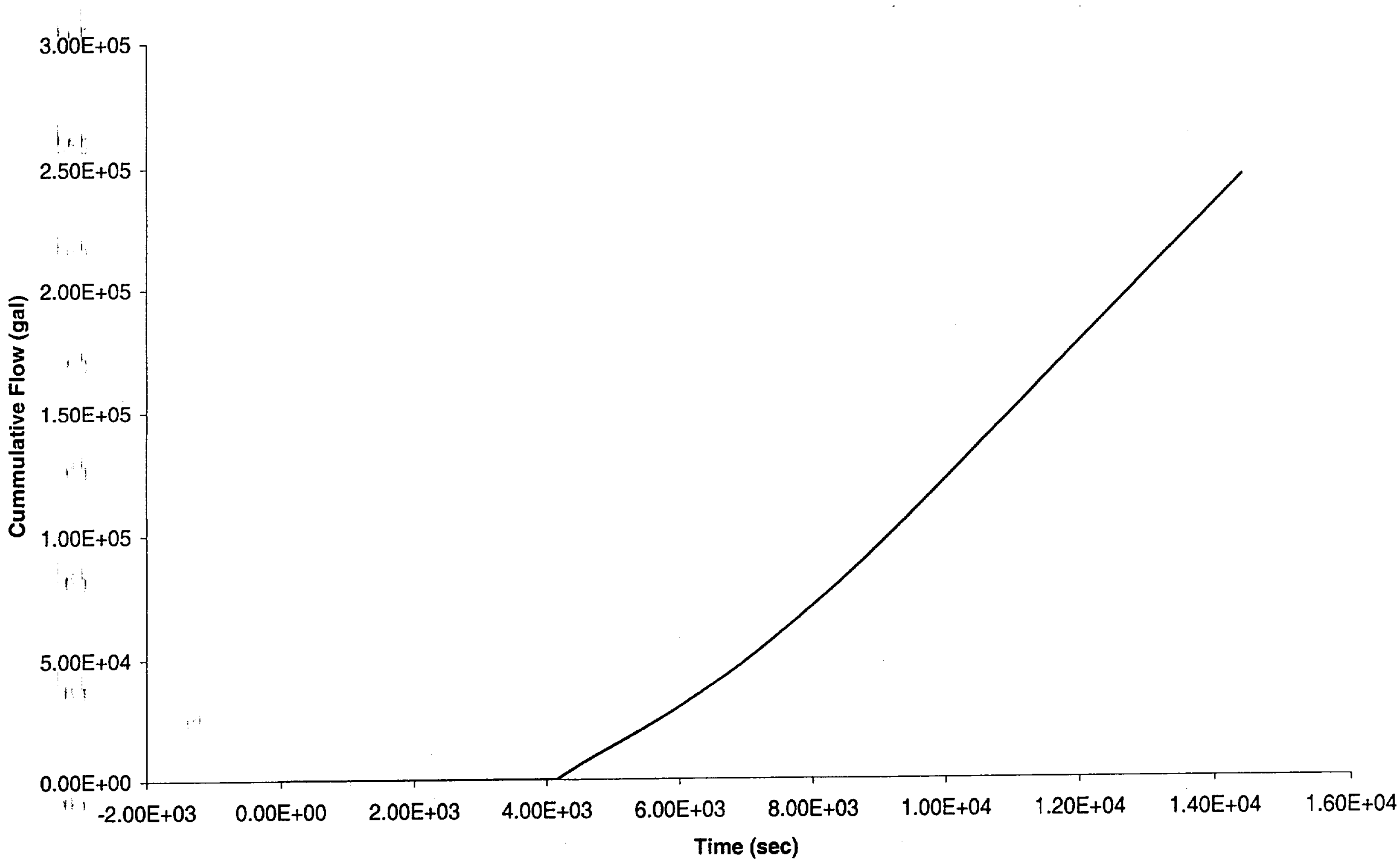

Fig. A.6a-15: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - <u>PRT Pressure</u>

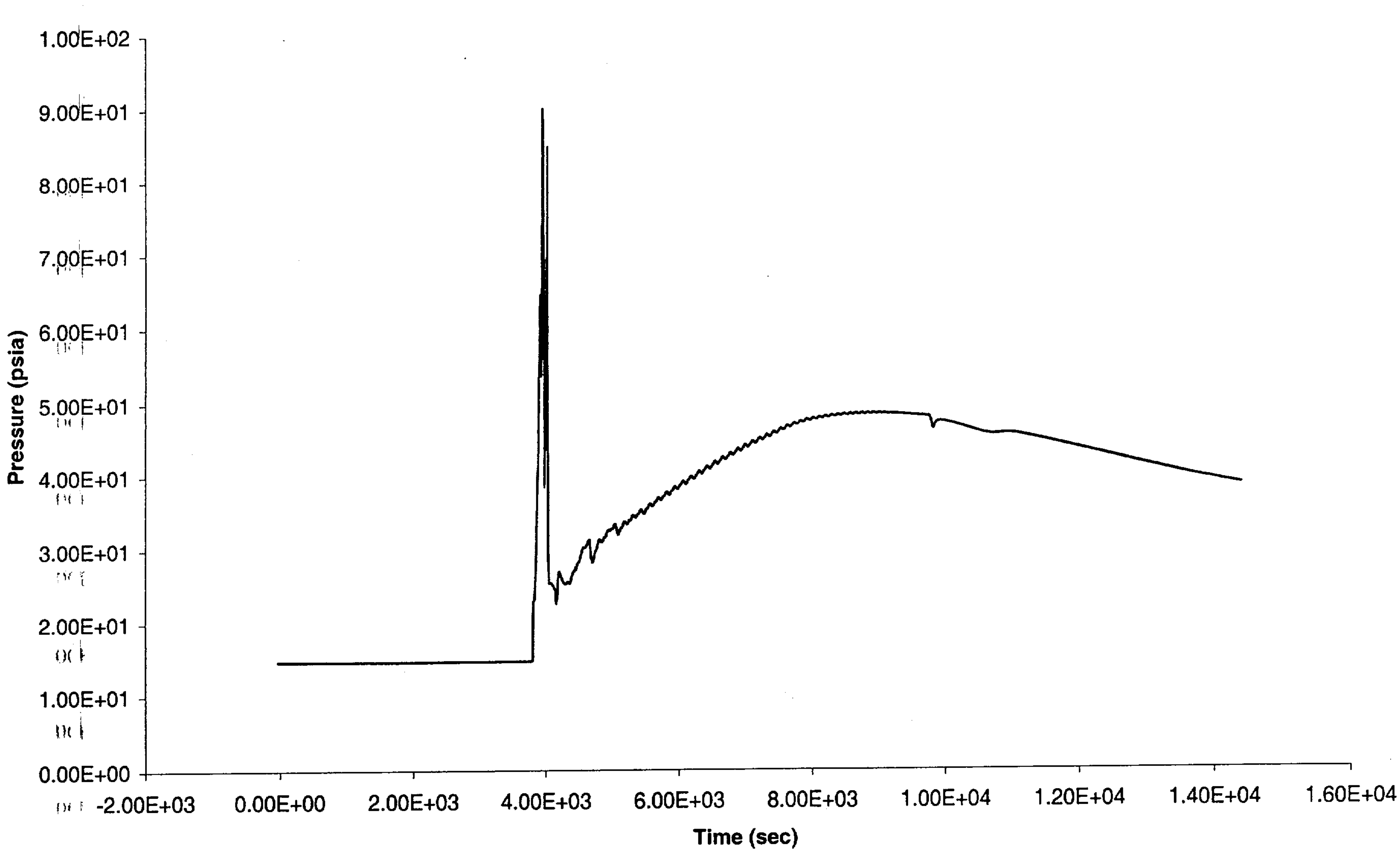

Fig. A.6a-16: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - <u>PRT Burst Disk Flow</u>

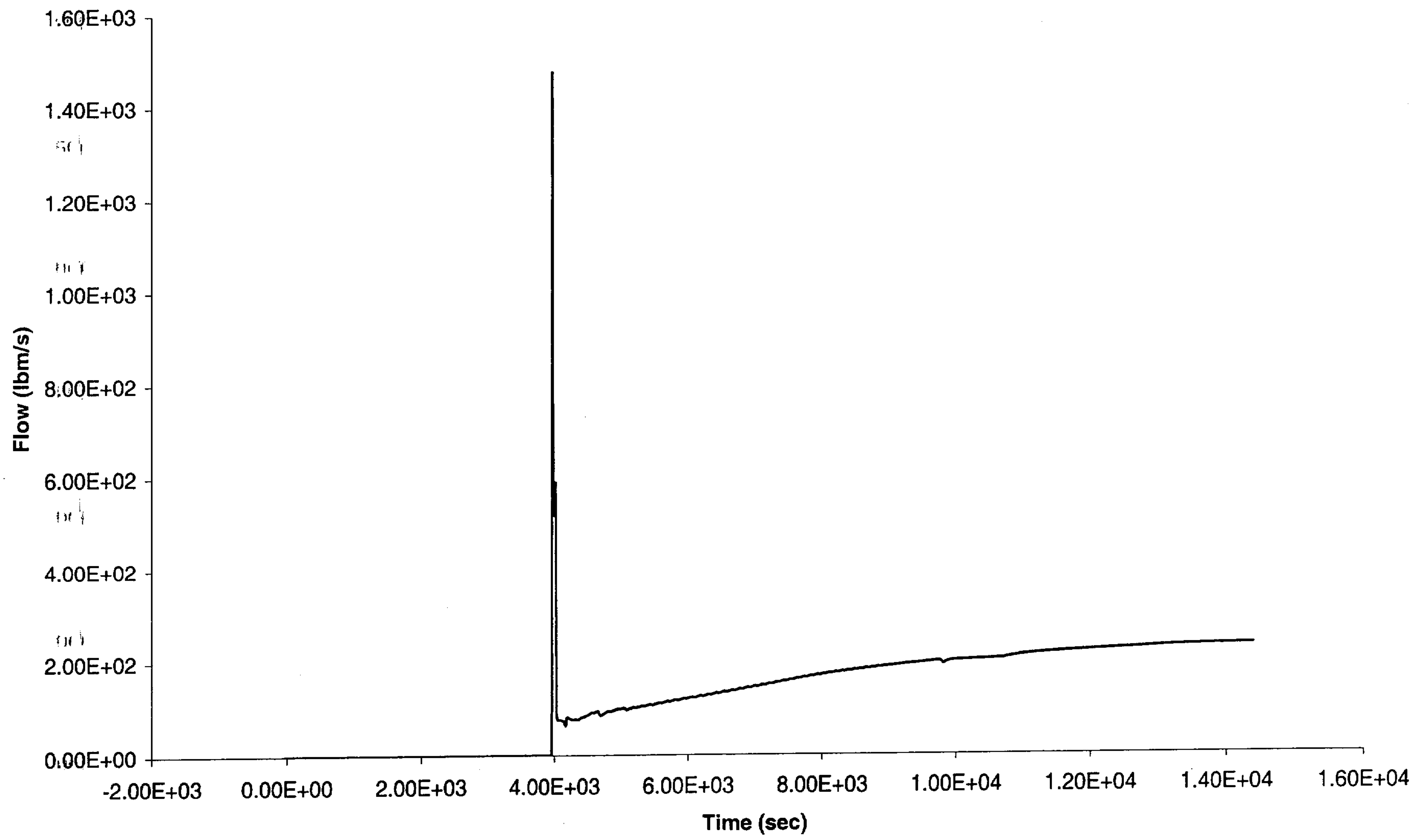

Fig. A.6a-17: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - Burst Disk Flow Quality

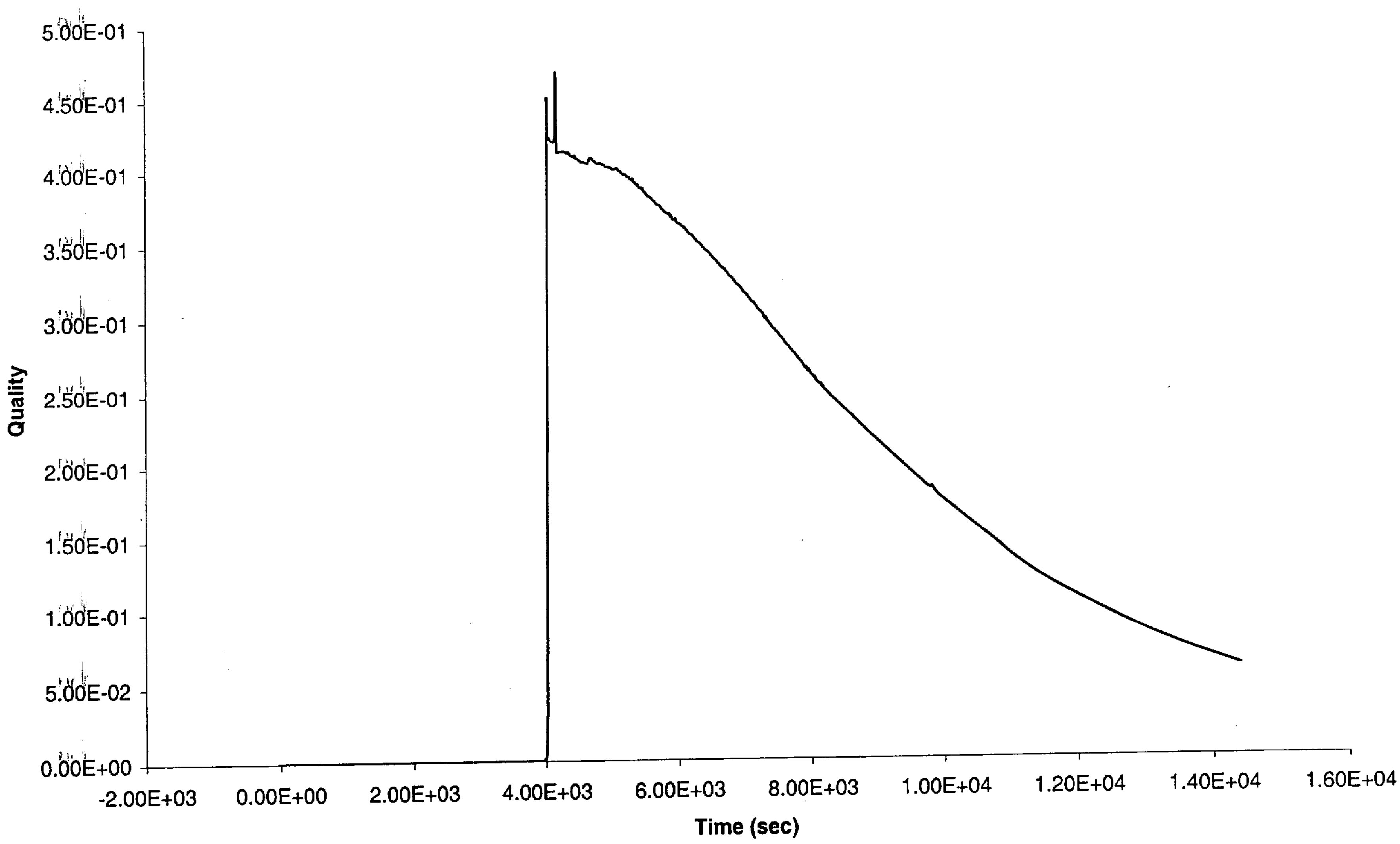

Fig. A.6a-18: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - **Burst Disk Phasic Velocities**

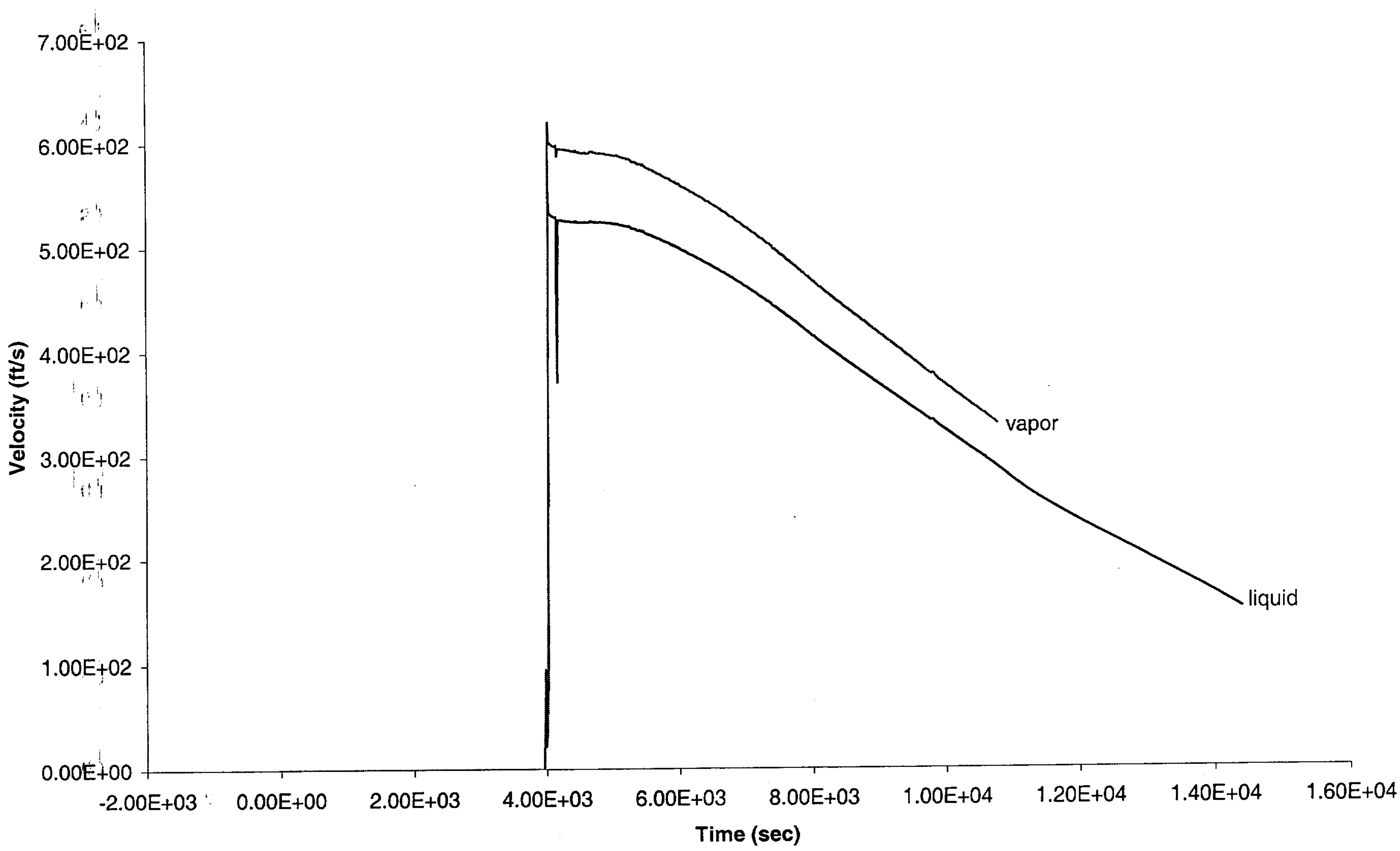

Fig. A.6a-19: LOSP with Subsequent AFW Failure, 1 PORV Held Open when it First Lifts - <u>PRT Liquid Temperature</u>

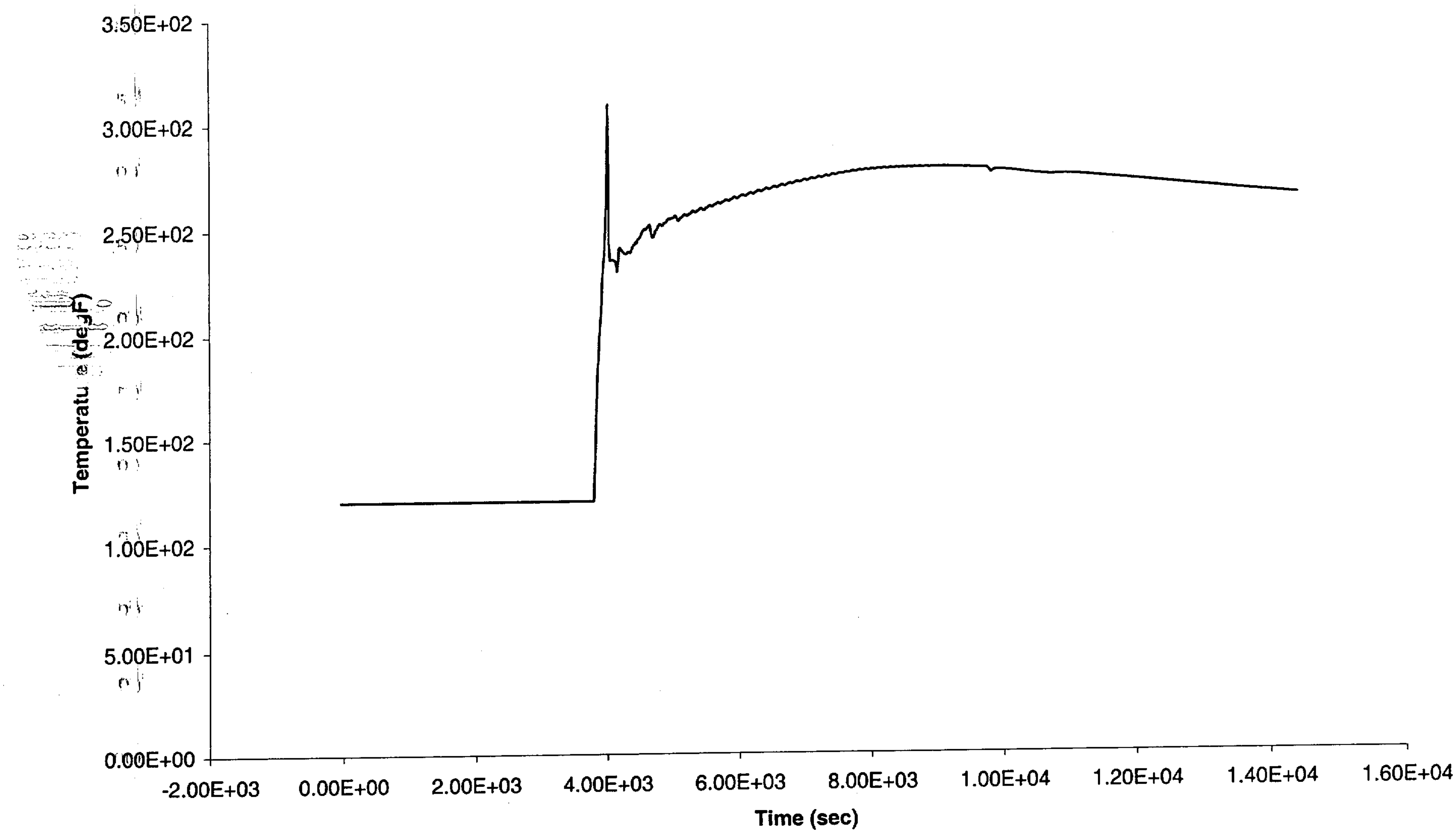

Fig. A.6b-1: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - Core Power

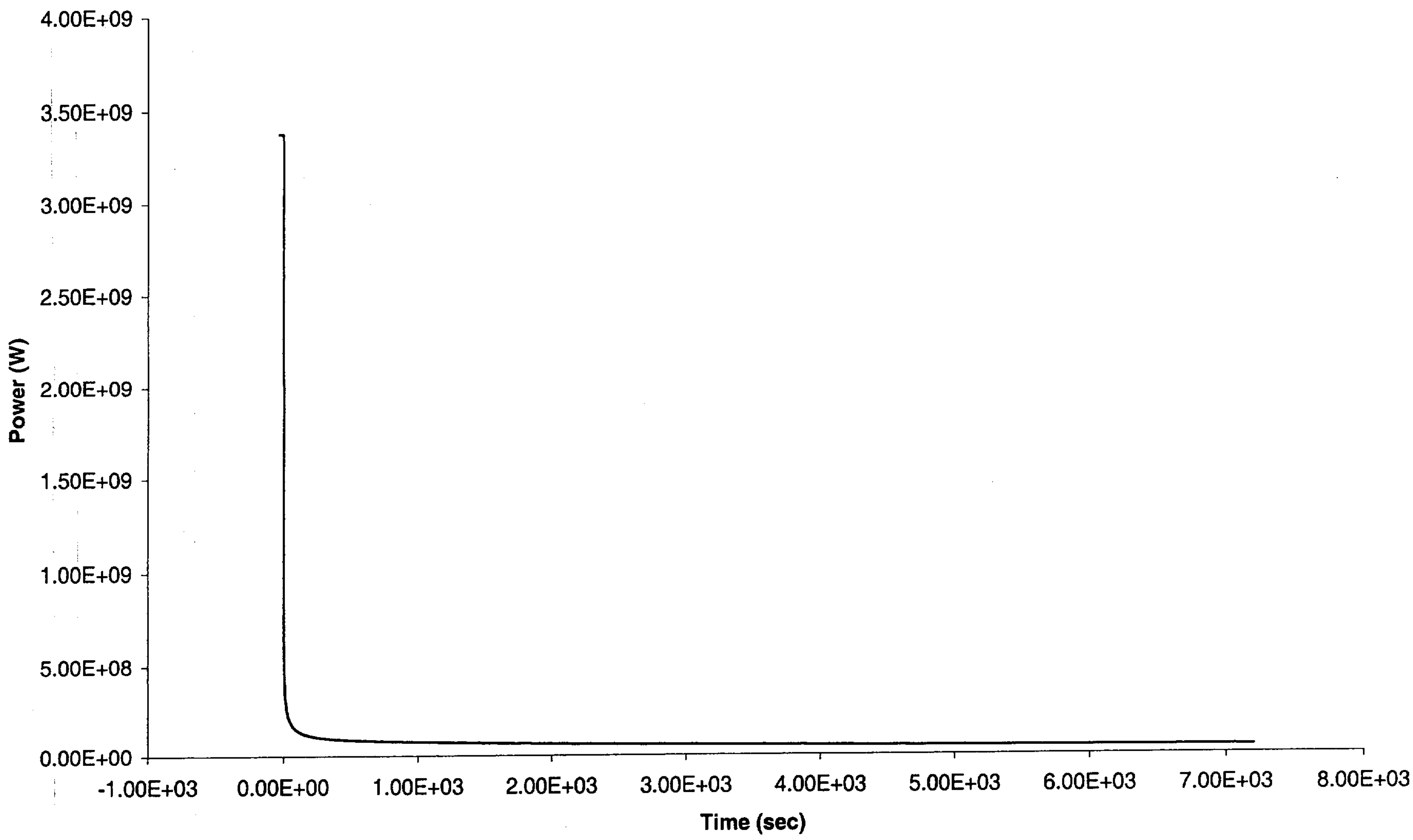

Fig. A.6b-2: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - RCS Pressure

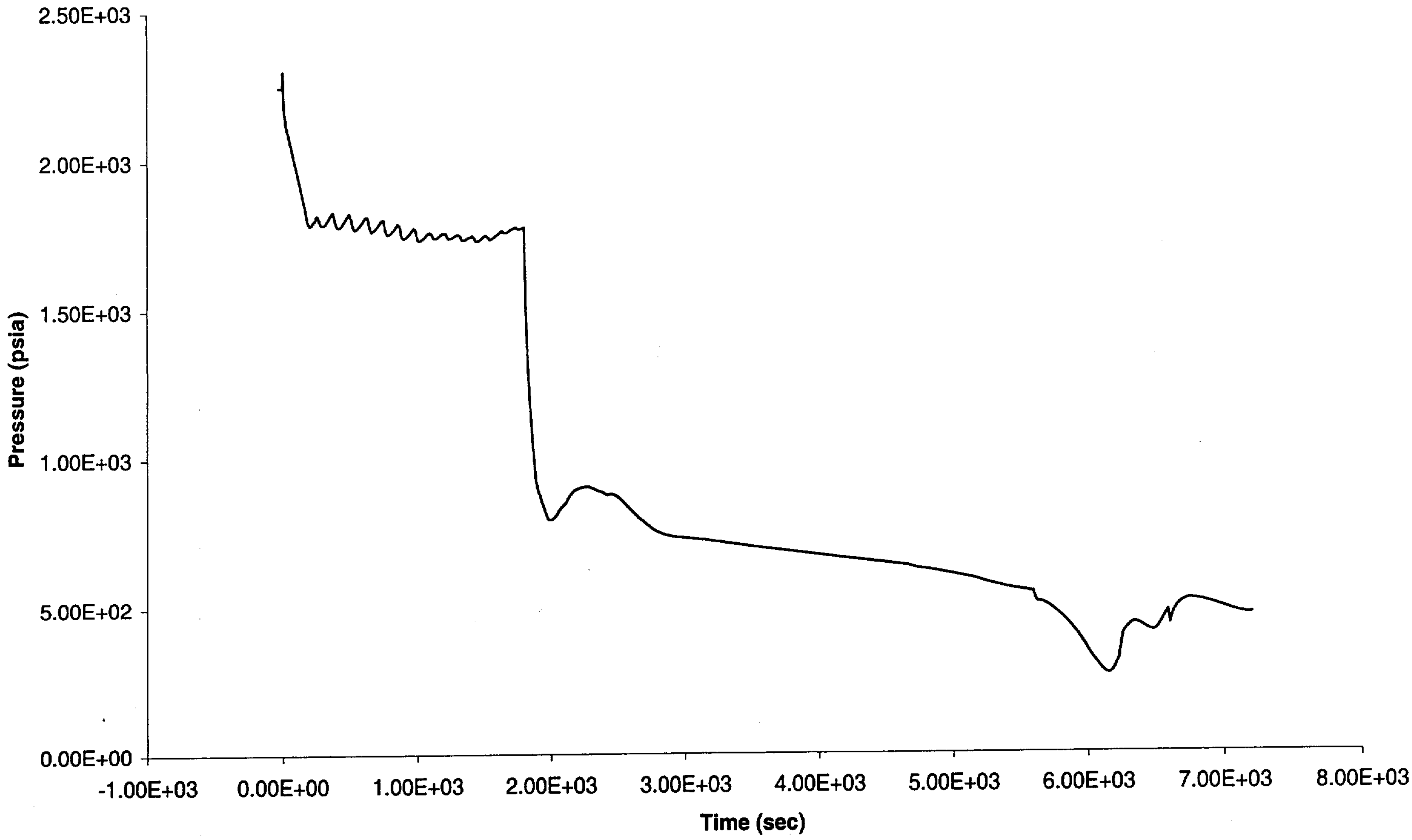

Fig. A.6b-3: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - Feed/Steam Flows

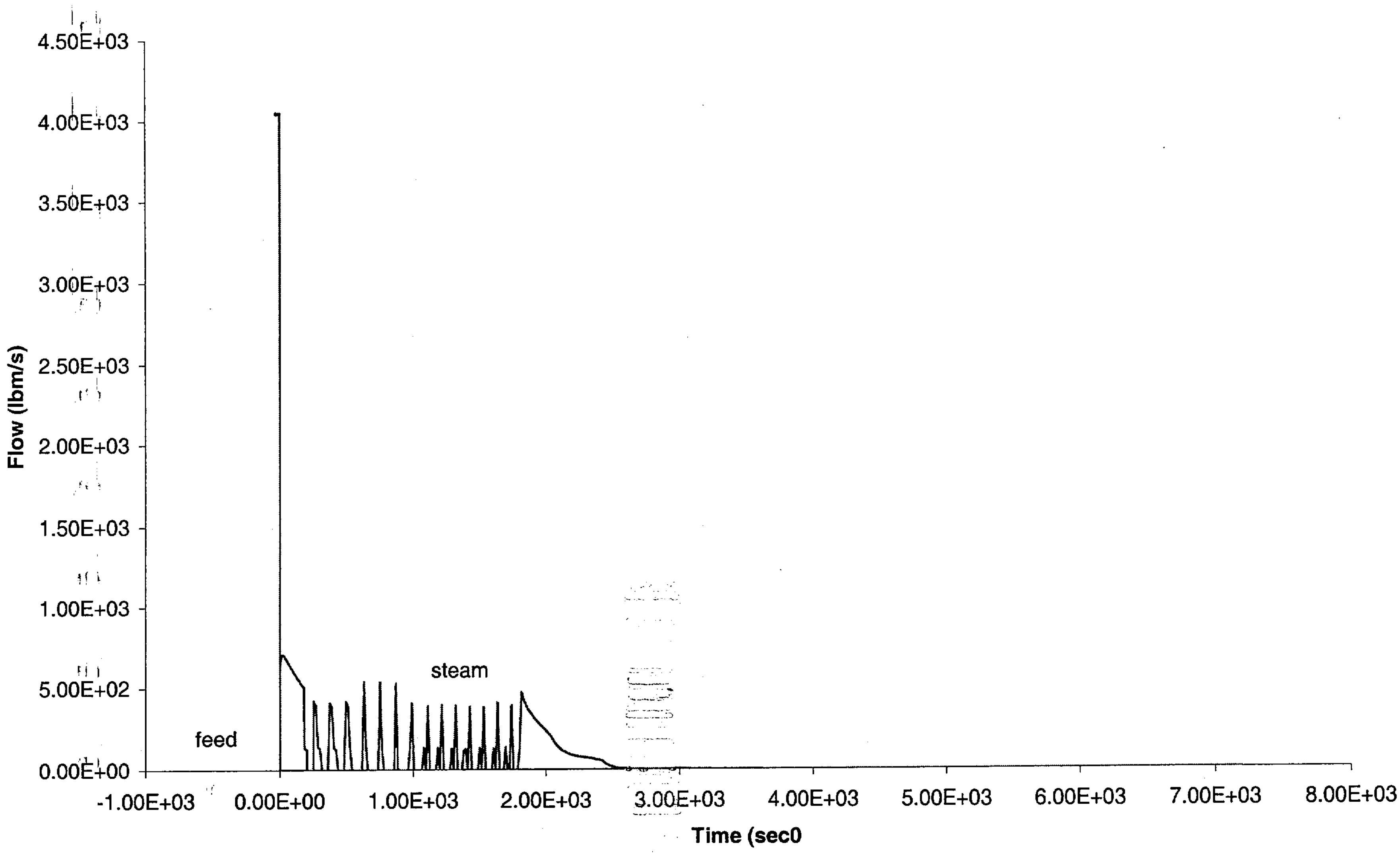

Fig. A.6b-4: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - <u>Charging and SI Flows</u>

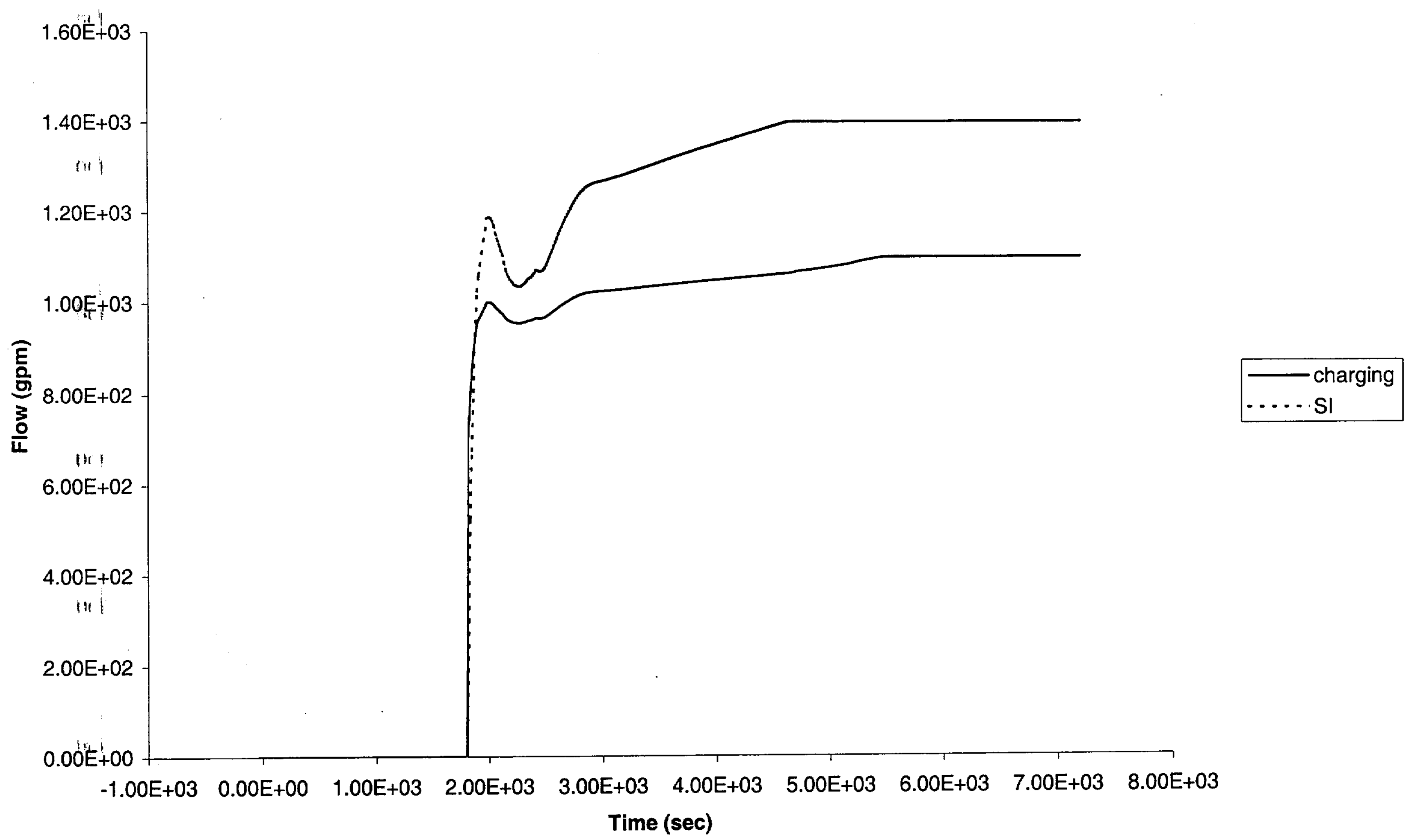

Fig. A.6b-5: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - <u>RCS Temperatures</u>

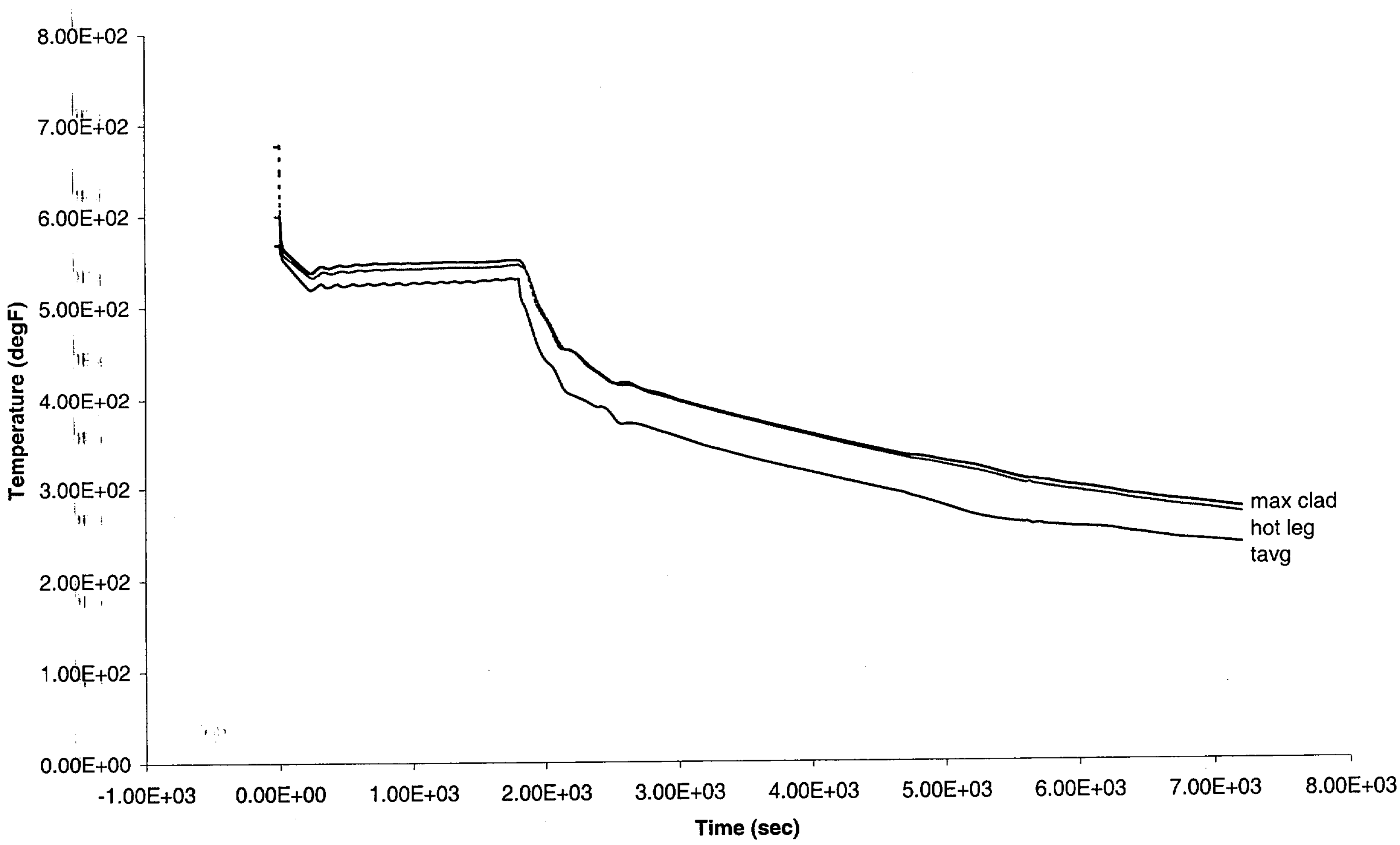

Fig. A.6b-6: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - PRZR Level

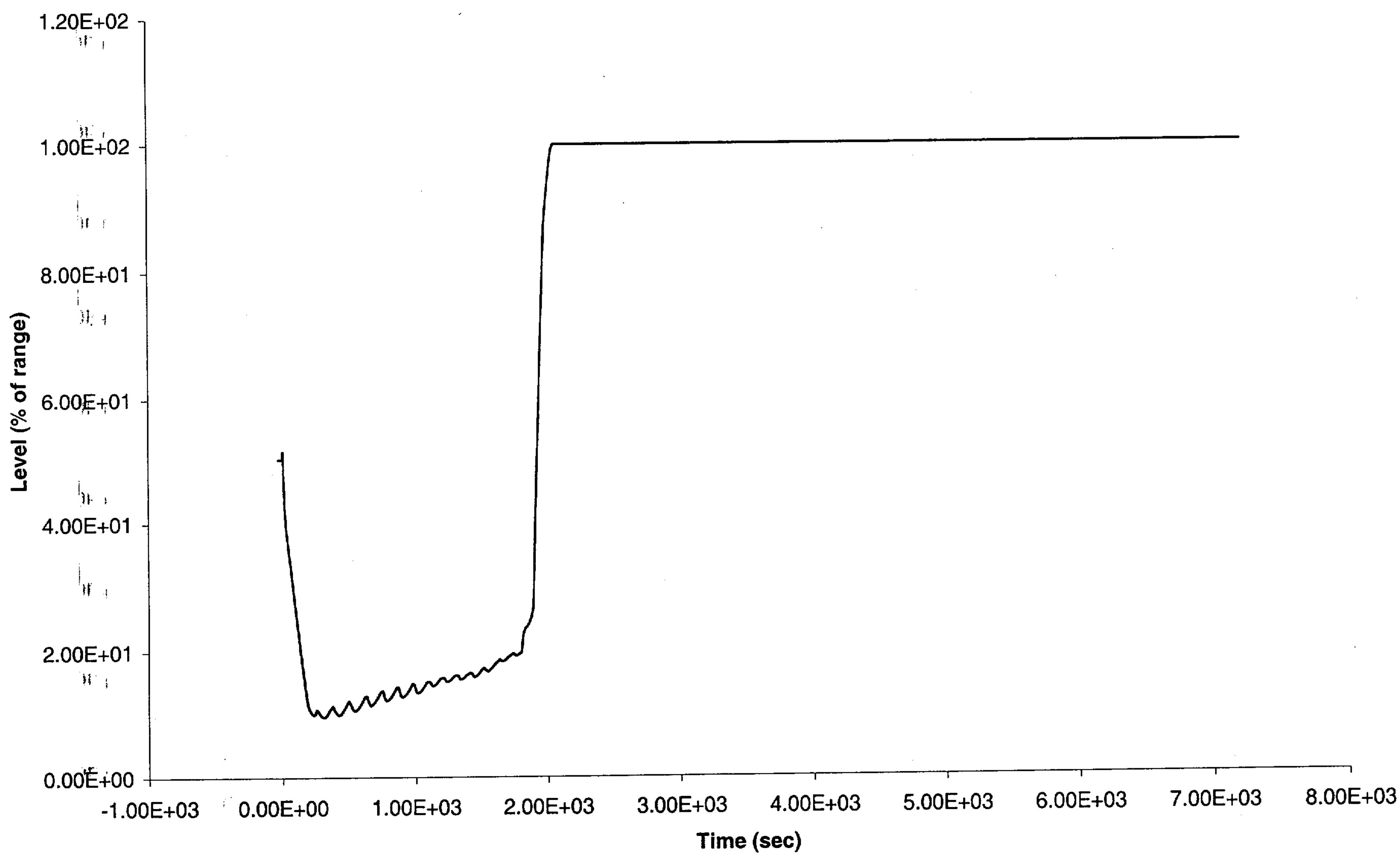

Fig. A.6b-7: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - PORV Flow

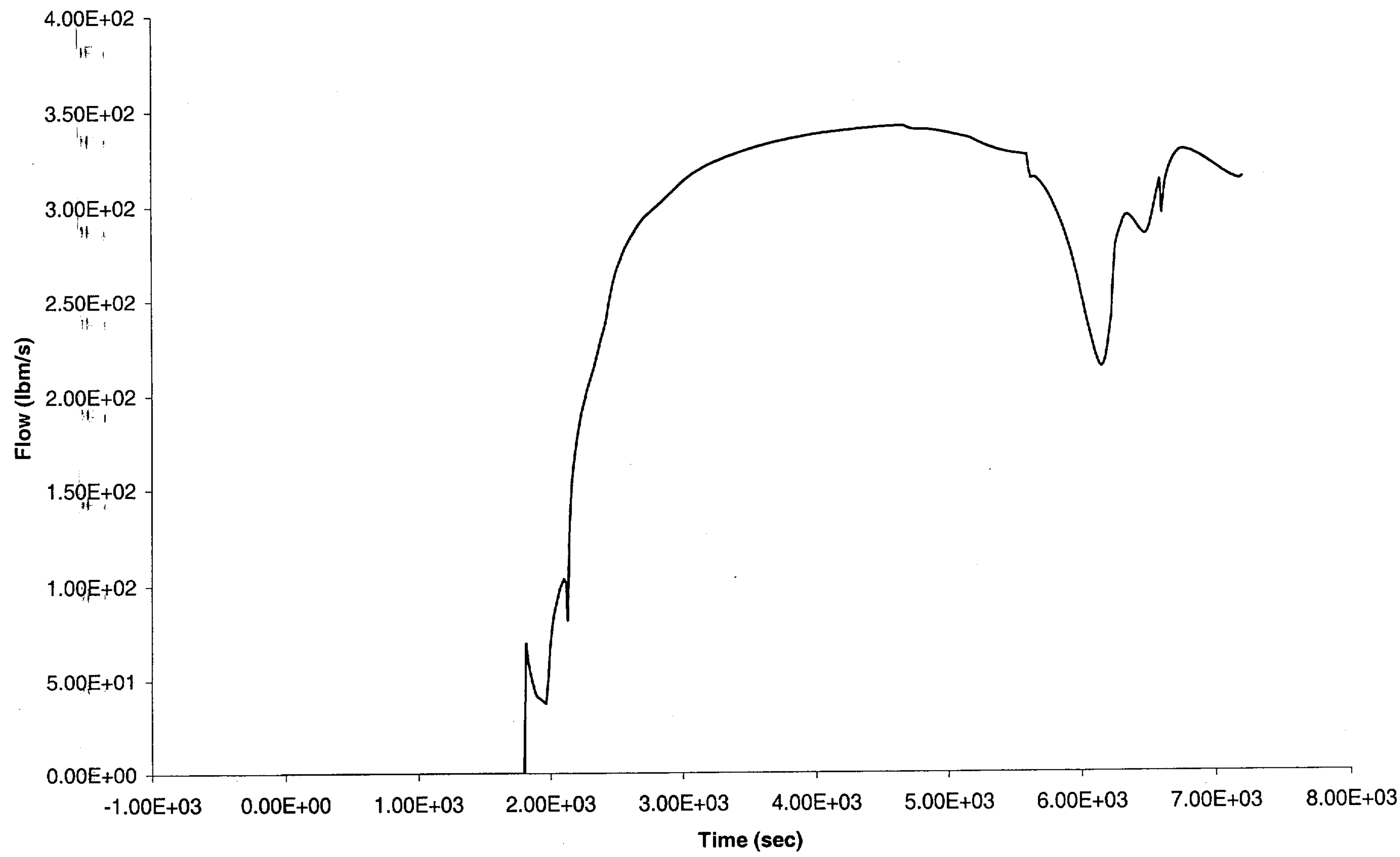

Fig. A.6b-8: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - SG 1 WR Level

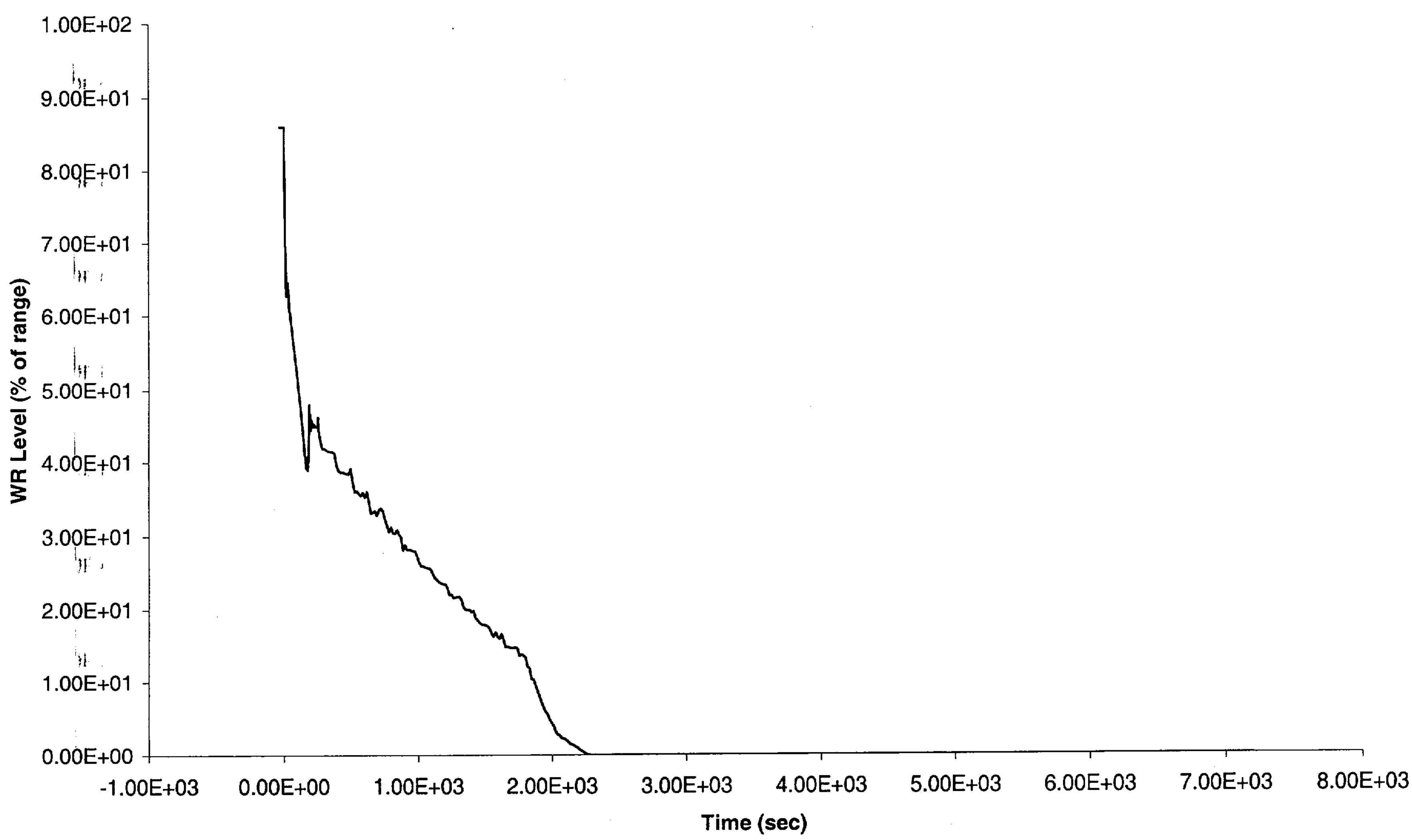

Fig. A.6b-9: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - SG 1 Pressure

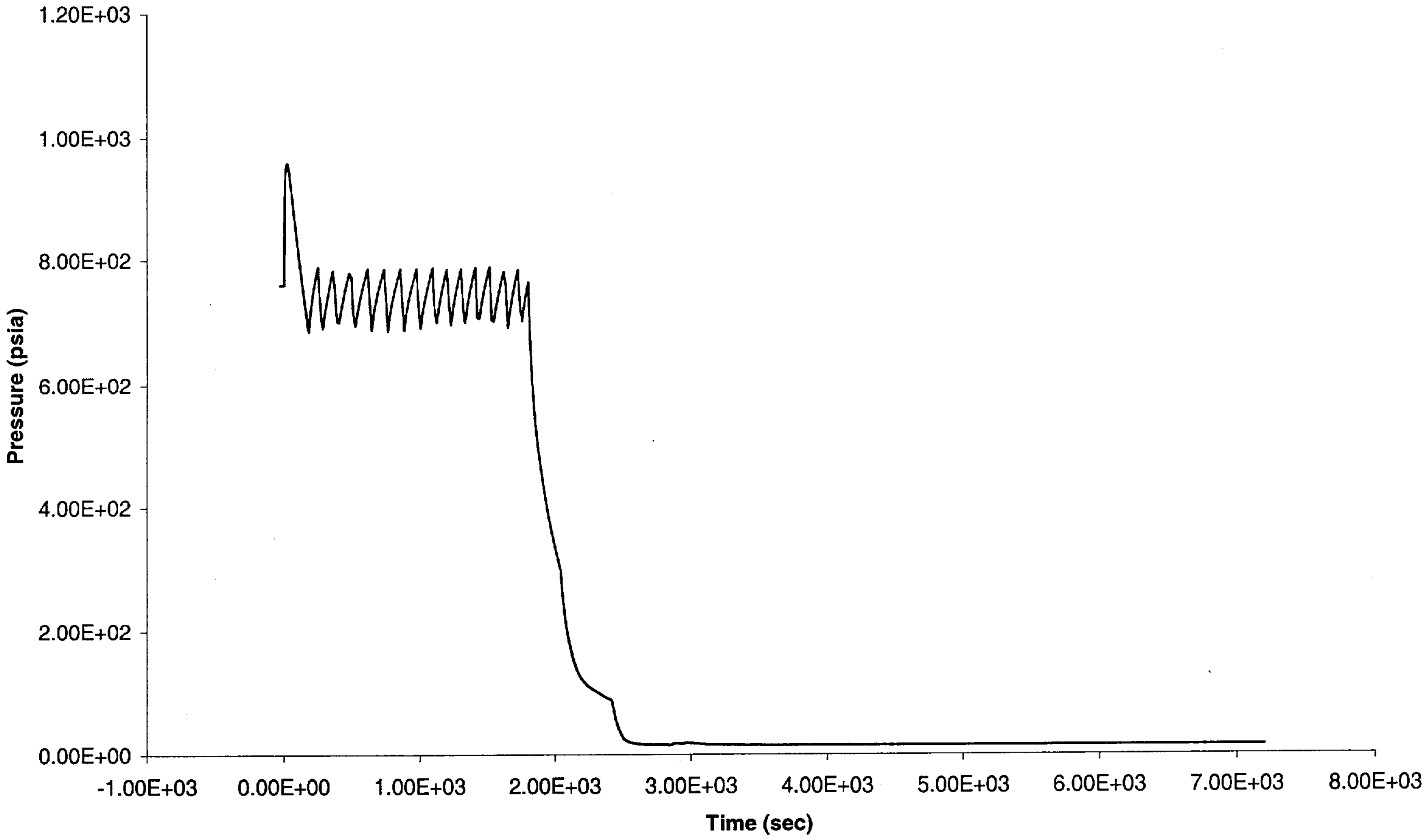

Fig. A.6b-10: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - SG 1 Temperature

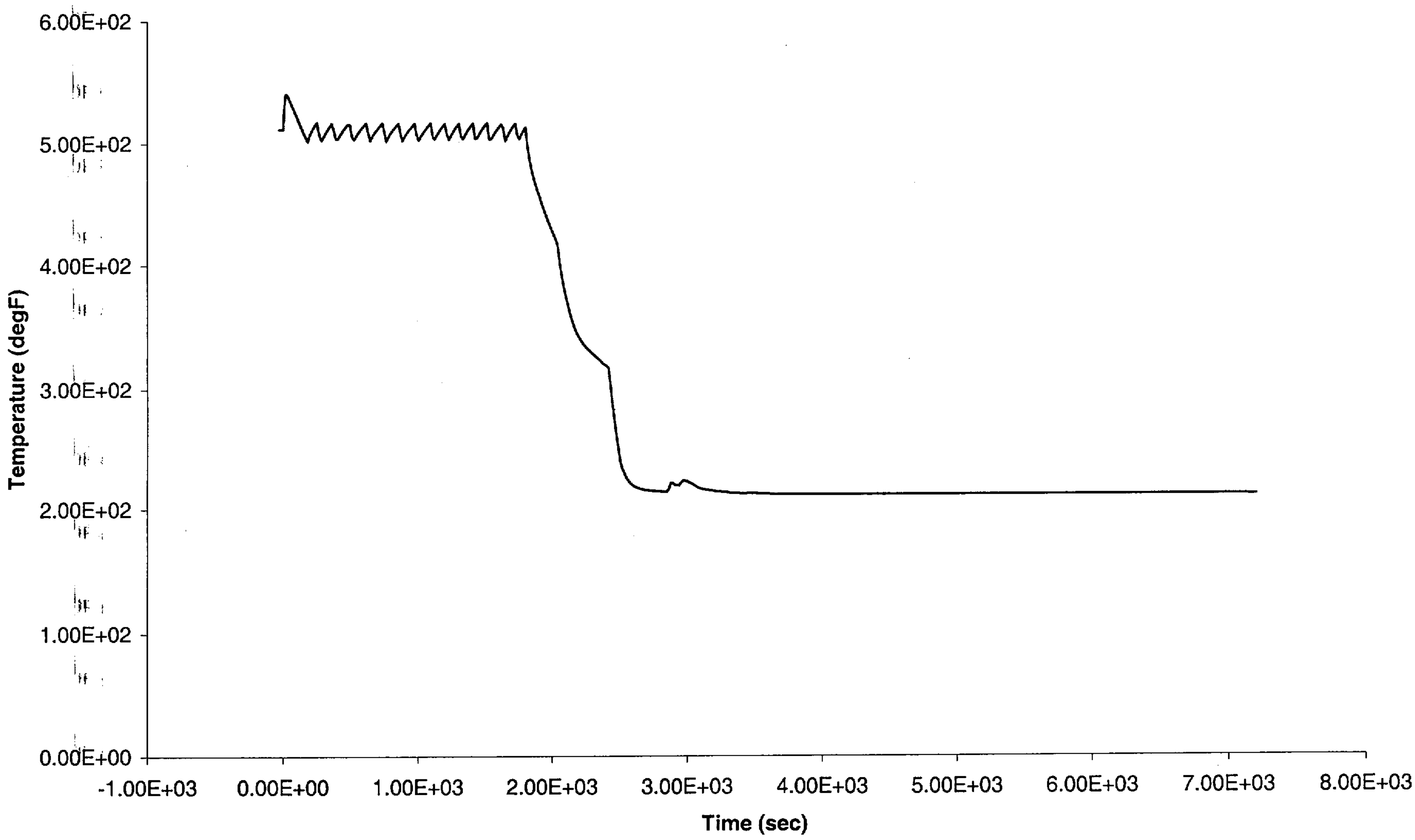

Fig. A.6b-11: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - RCP 1 Speed

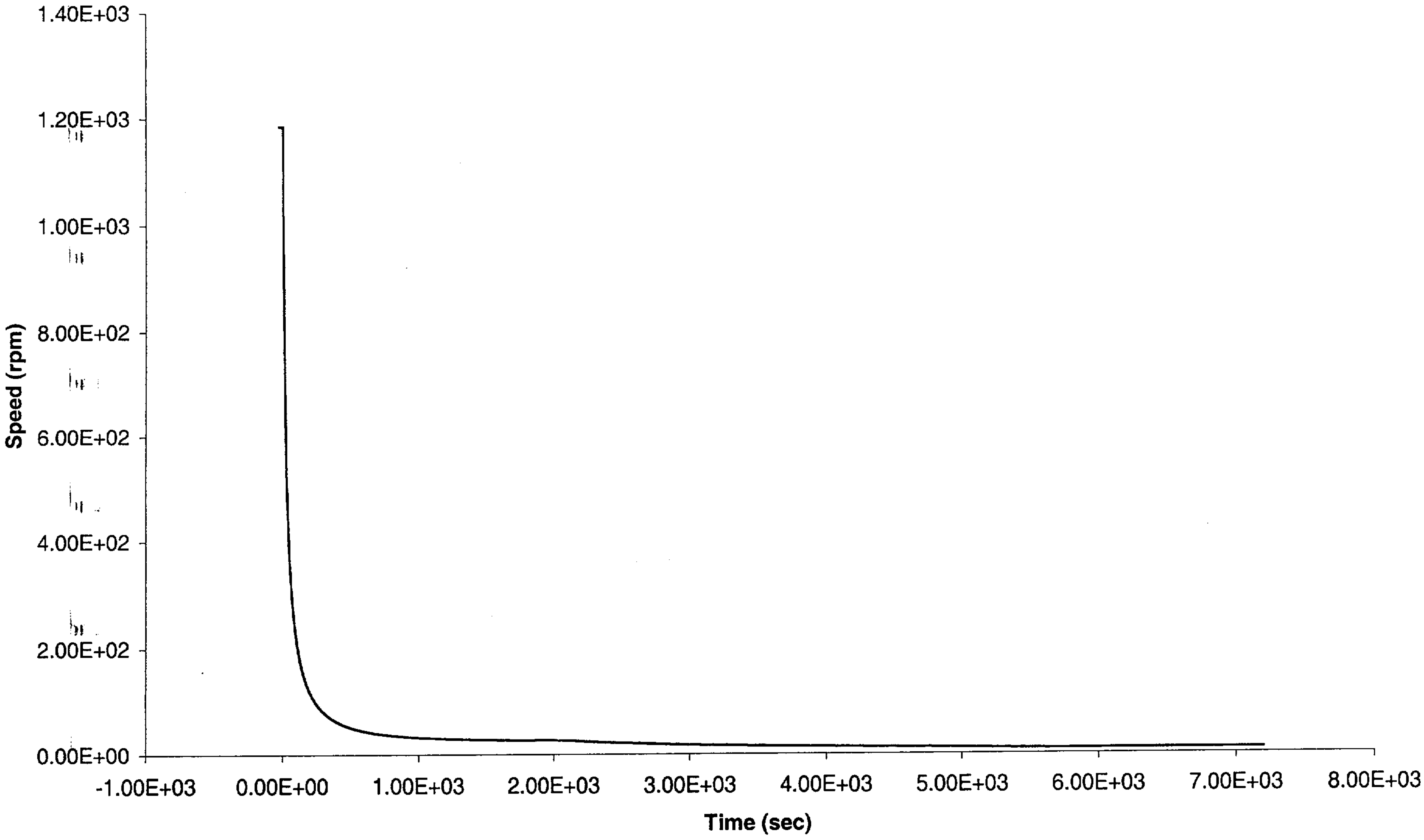

Fig. A.6b-12: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - <u>Core Exit Subcooling</u>

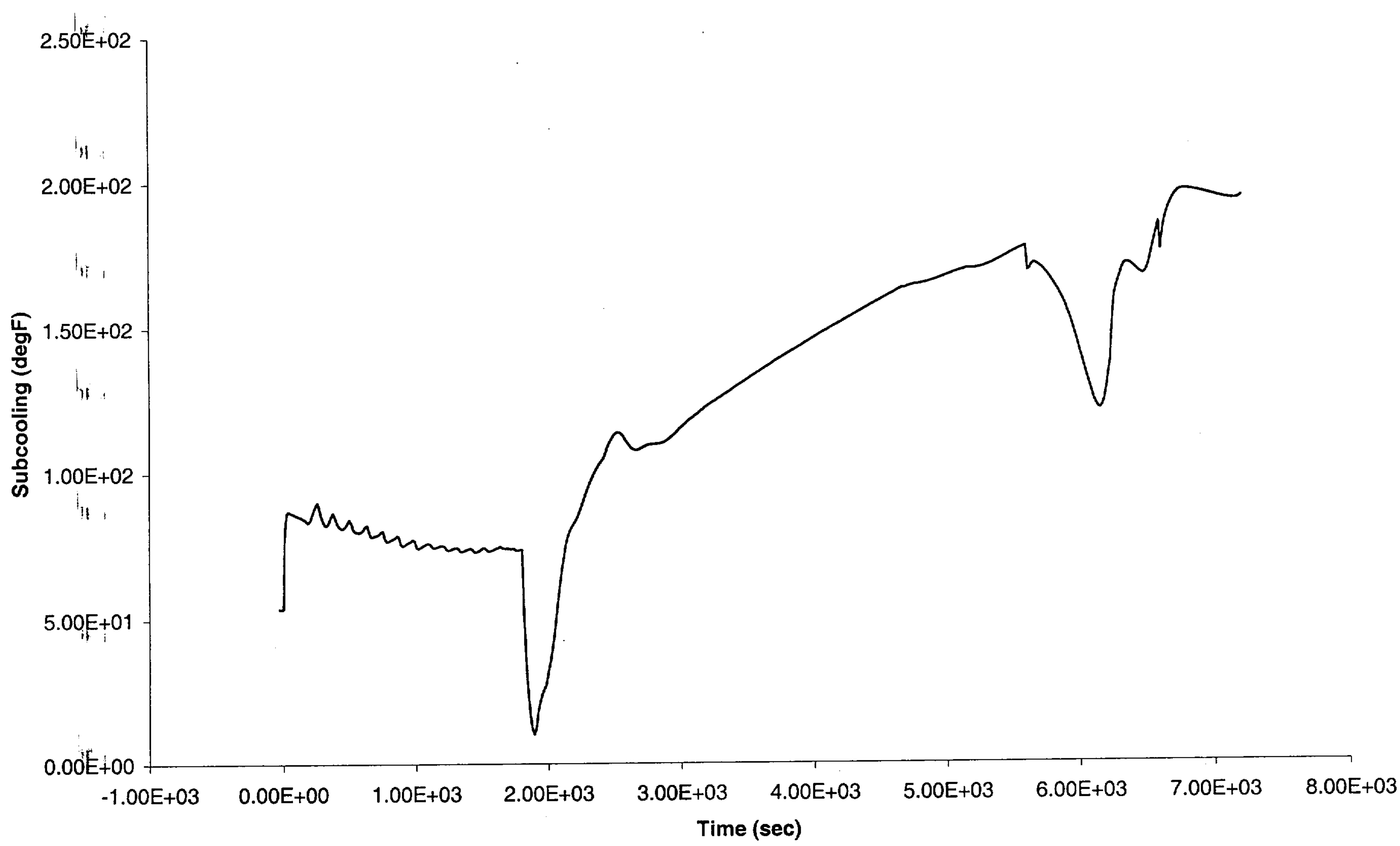

Fig. A.6b-13: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - <u>RCS Cooling Rate</u>

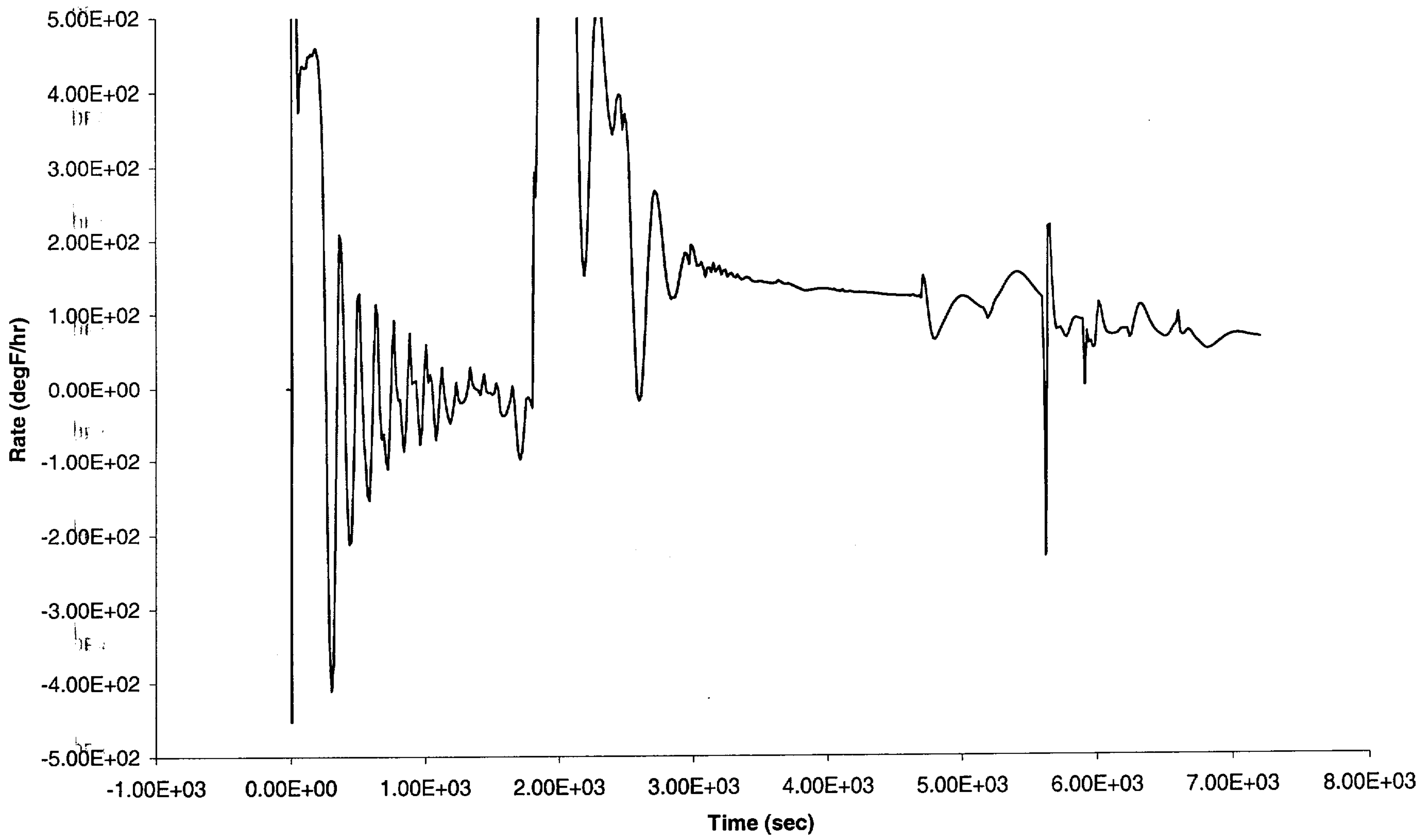

Fig. A.6b-14: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - Cummulative Charging + SI Flow

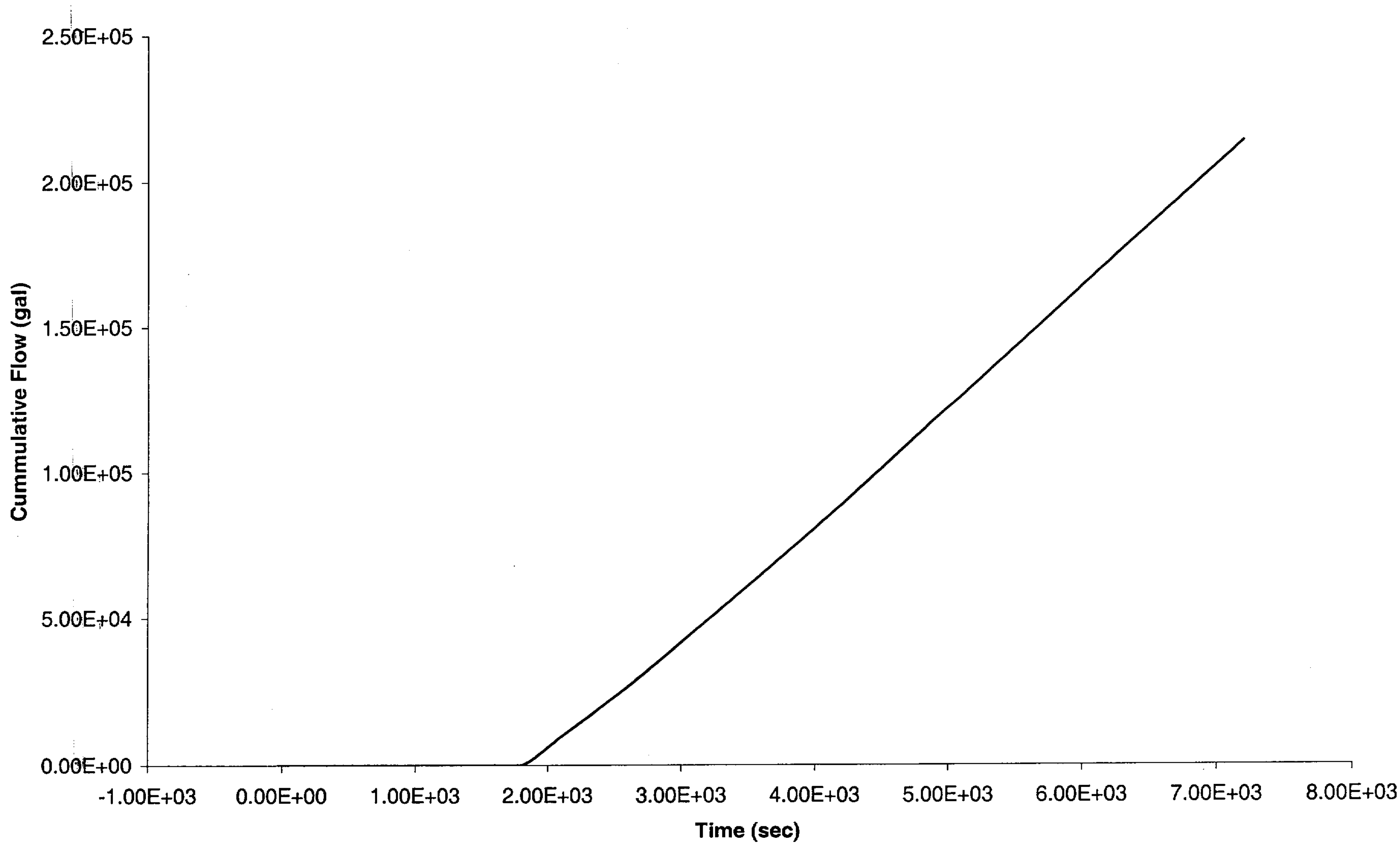

Fig. A.6b-15: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - PRT Pressure

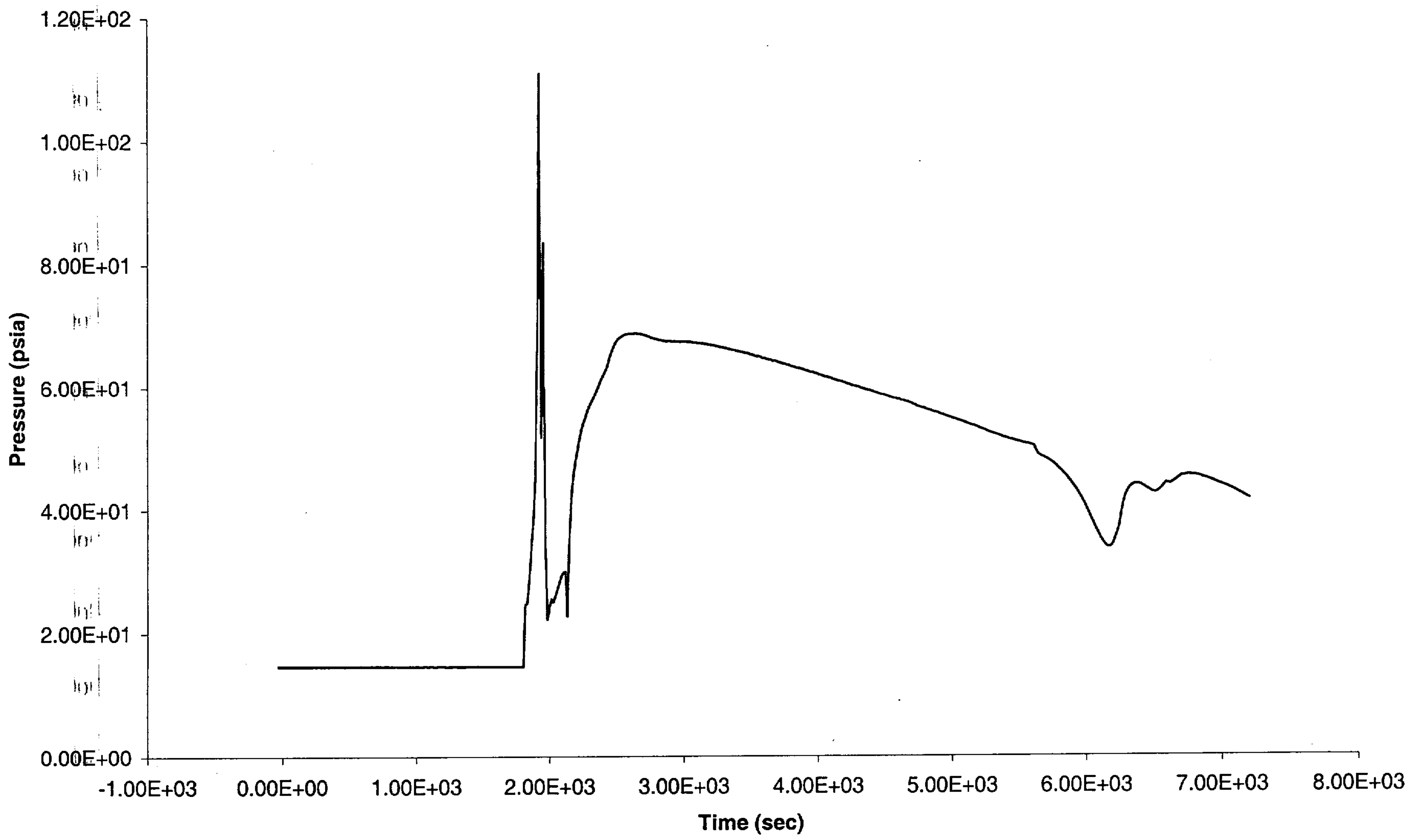

Fig. A.6b-16: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - PRT Burst Disk Flow

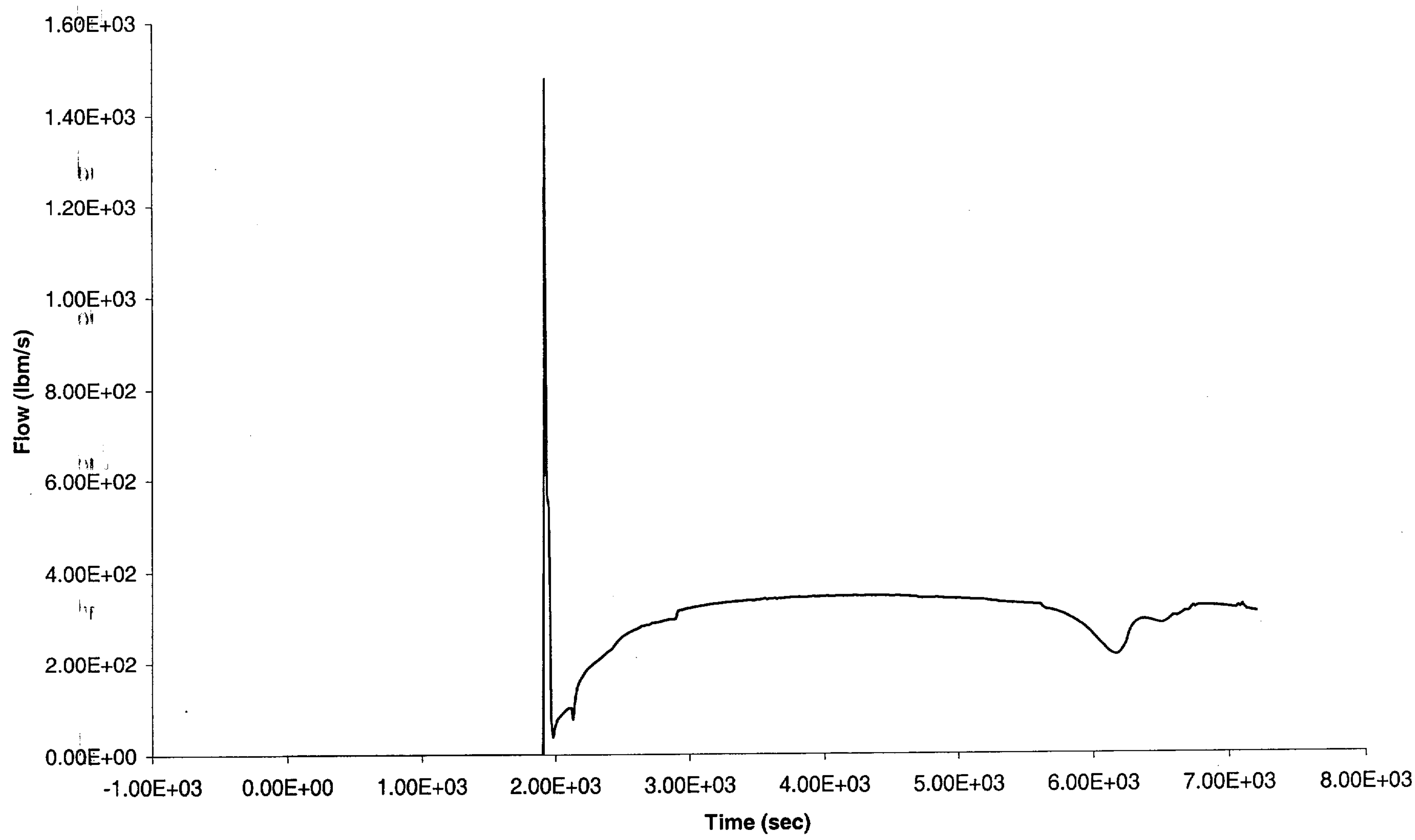

Fig. A.6b-17: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - Burst Disk Flow Quality

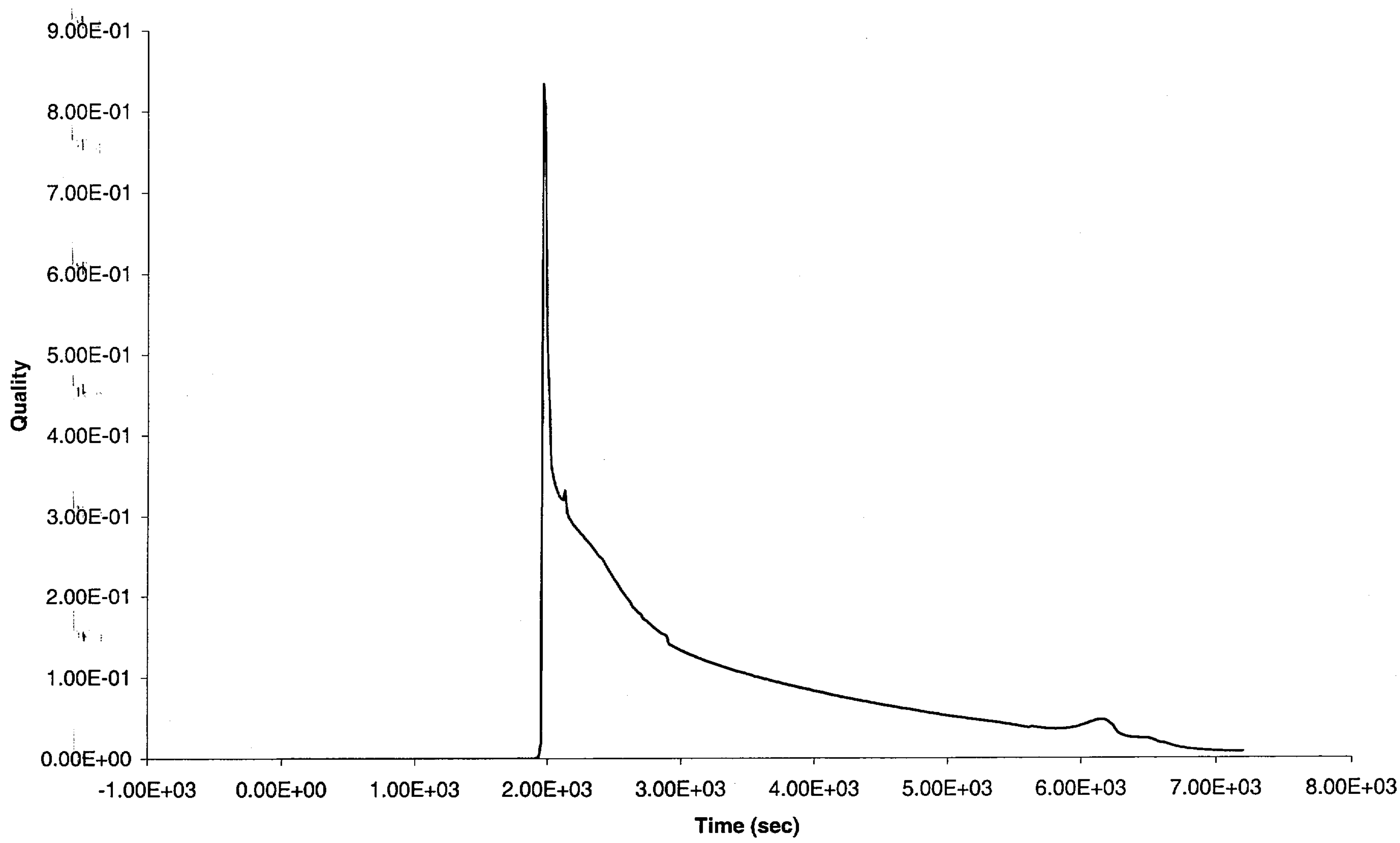

Fig. A.6b-18: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - <u>Burst Disk Phasic Velocities</u>

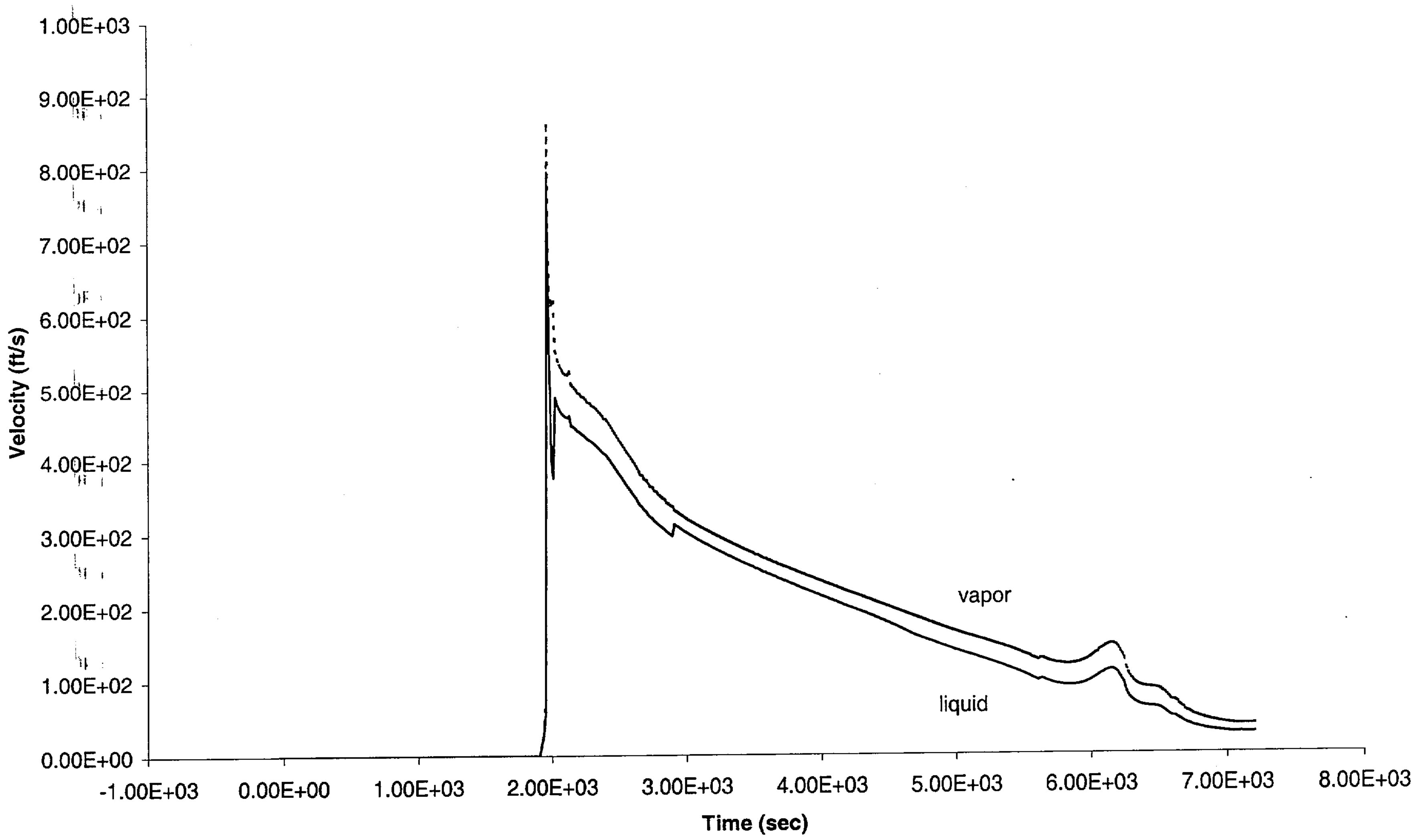

Fig. A.6b-19: LOSP with Subsequent AFW Failure, Aggressive Cooling at 30 min - PRT Liquid Temperature

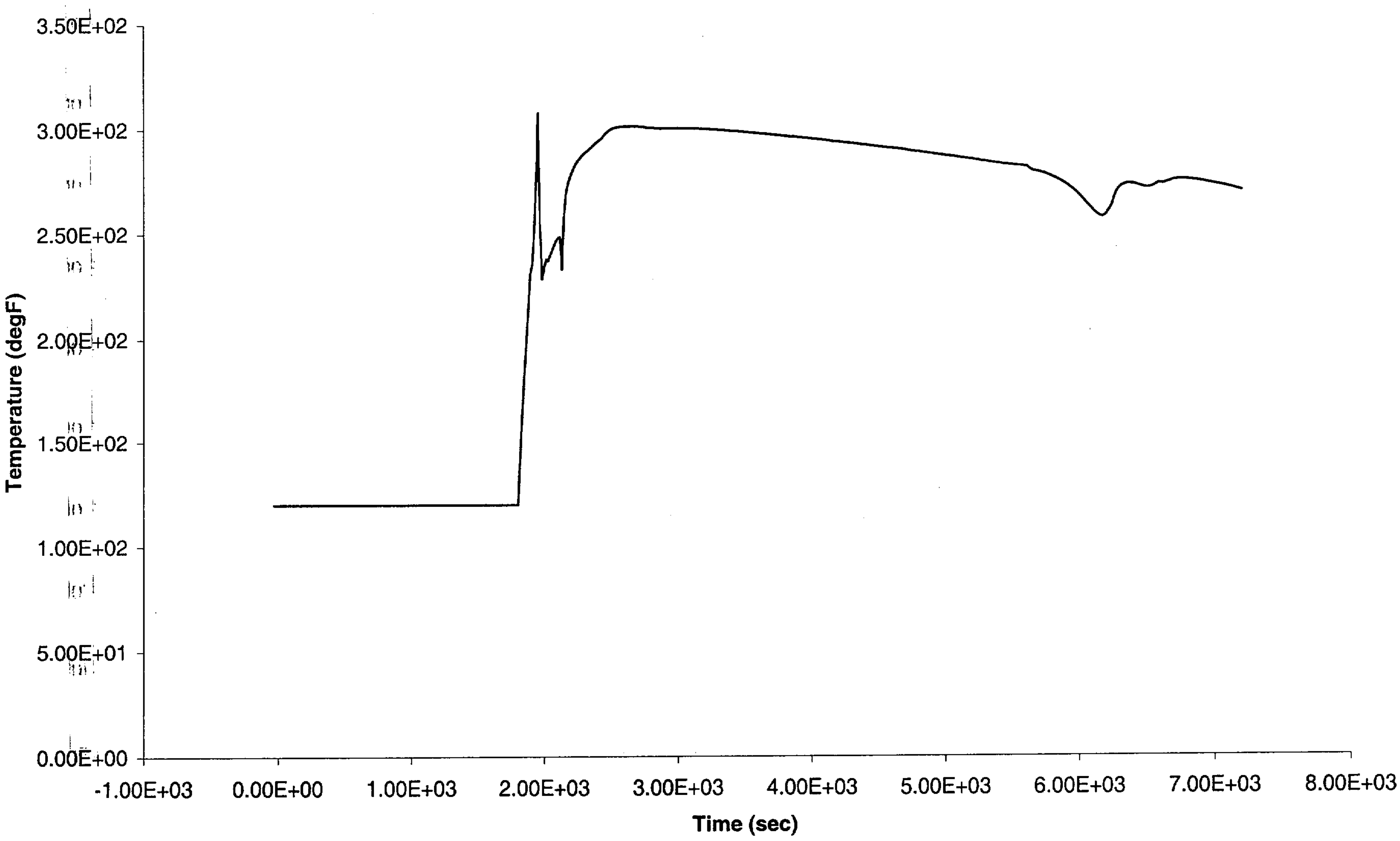

Fig. A.6c-1: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - Core Power

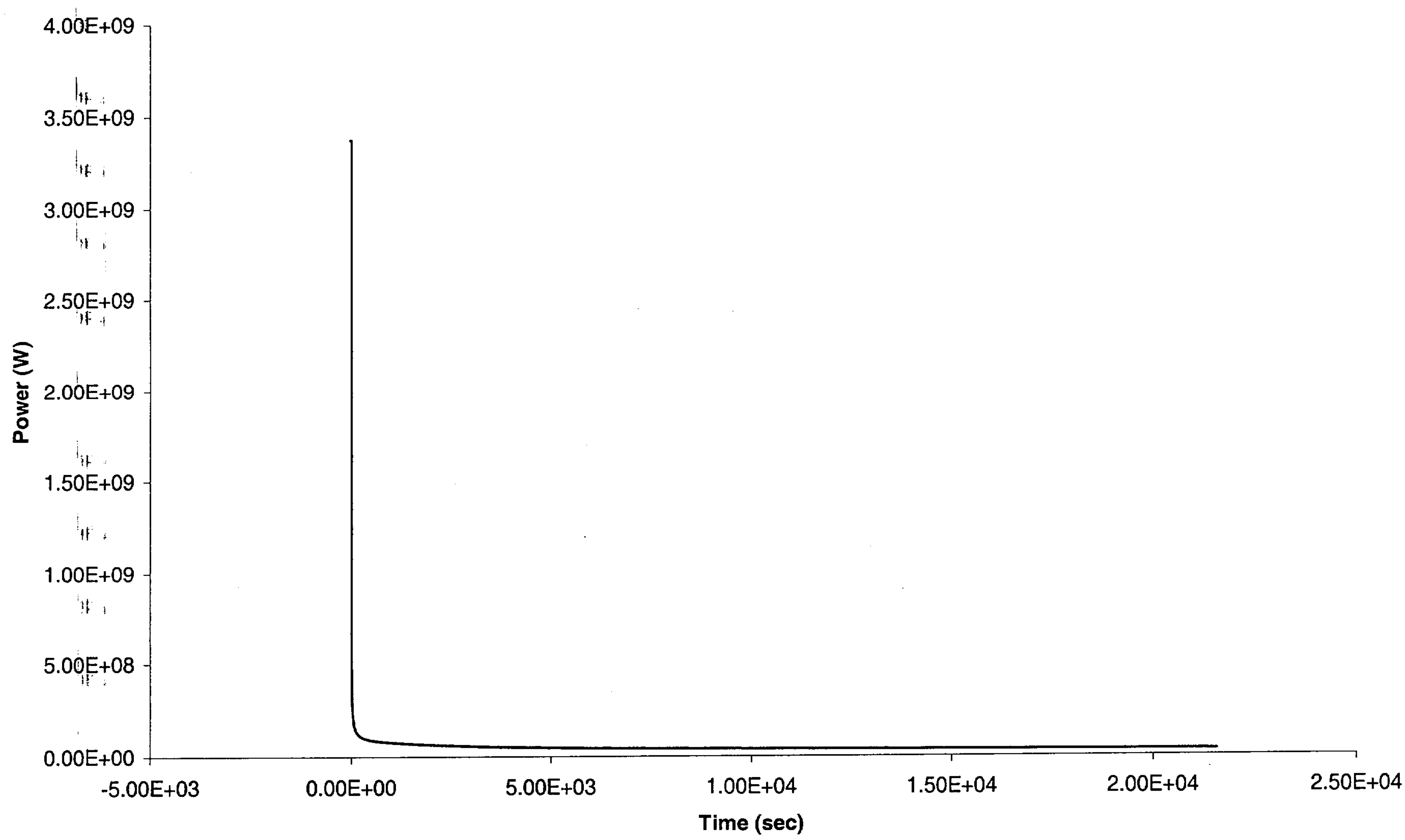

Fig. A.6c-2: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - <u>RCS Pressure</u>

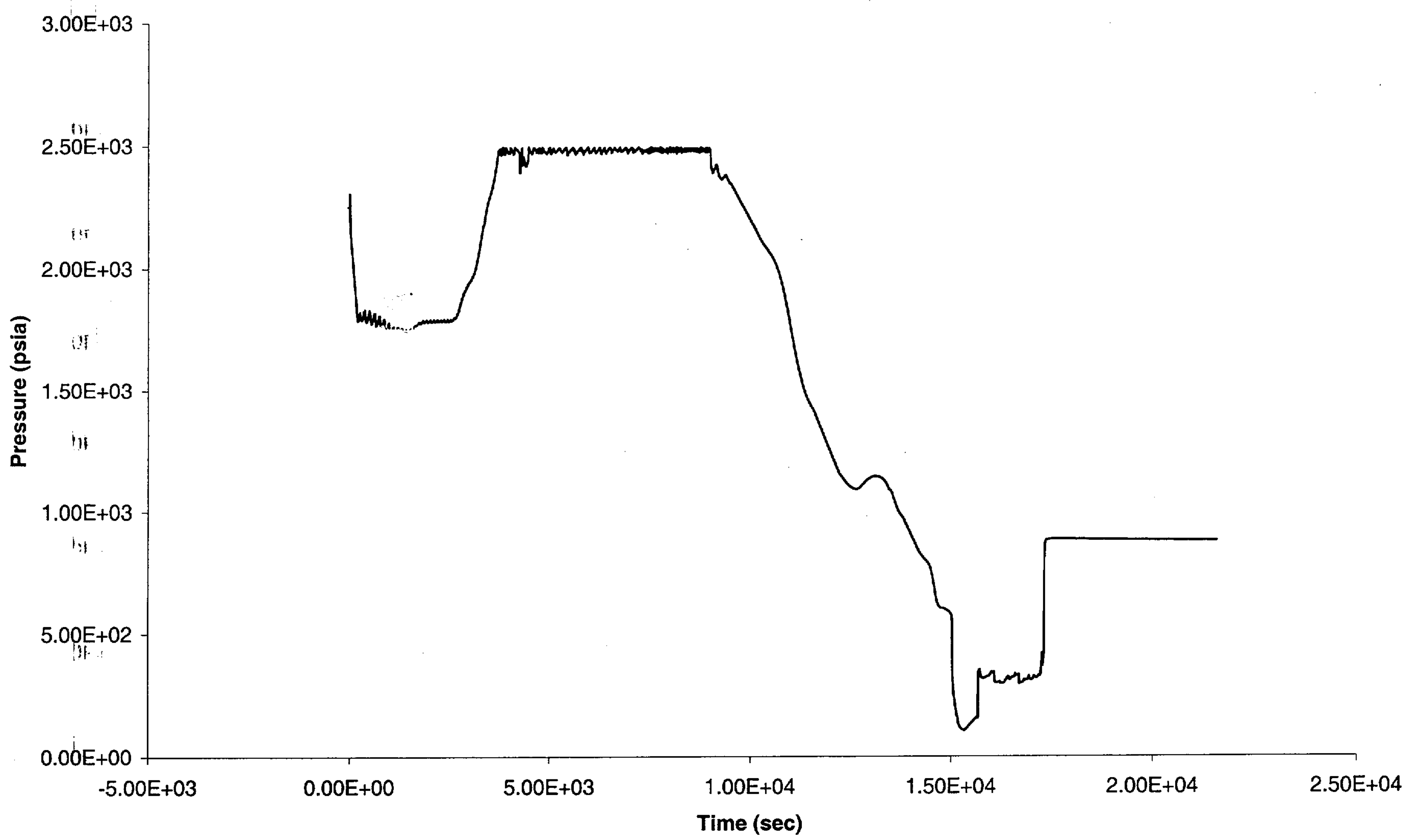

Fig. A.6c-3: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min -
<u>Feed/Steam Flows</u>

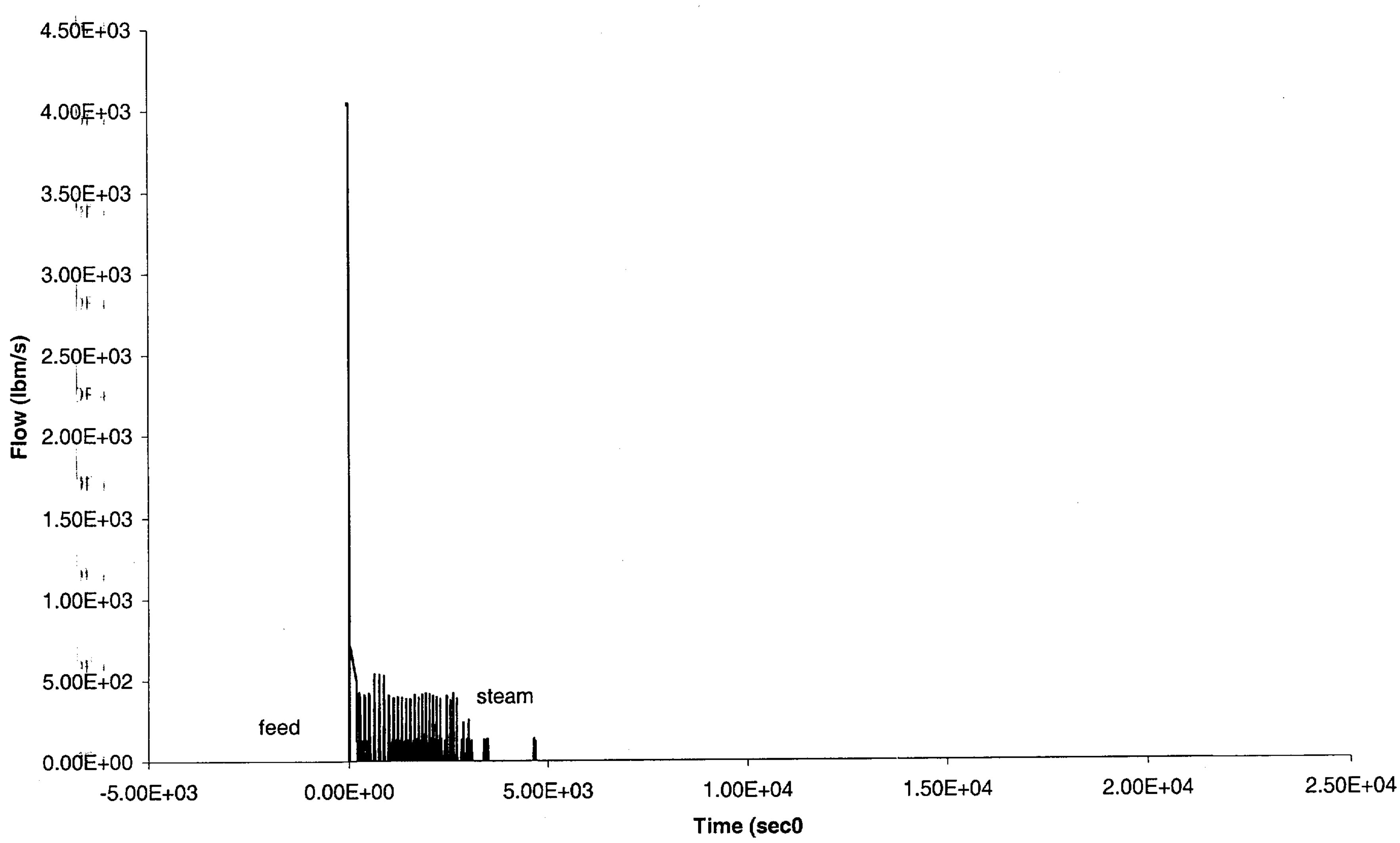

Fig. A.6c-4: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - Charging and SI Flows

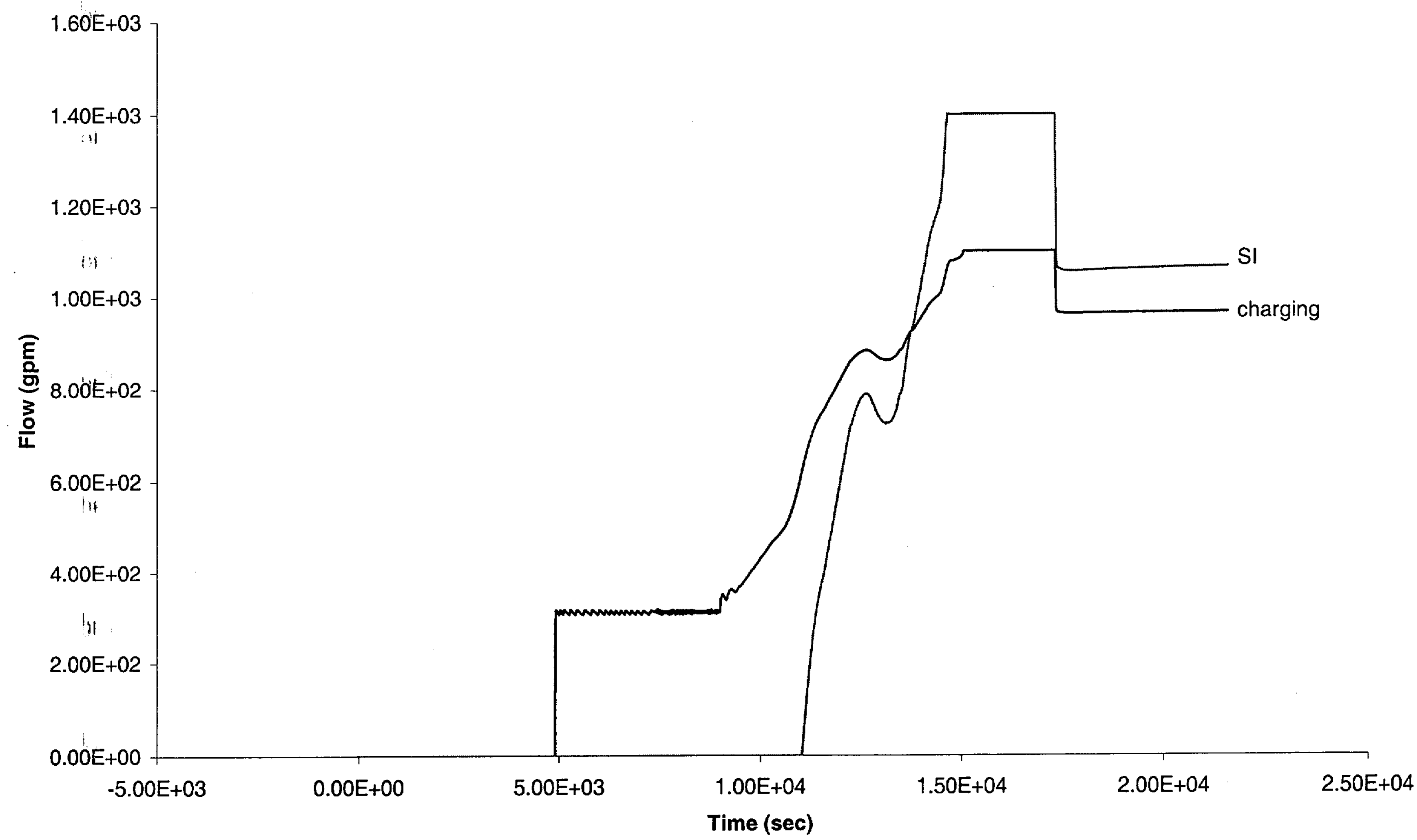

Fig. A.6c-5: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - RCS Temperatures

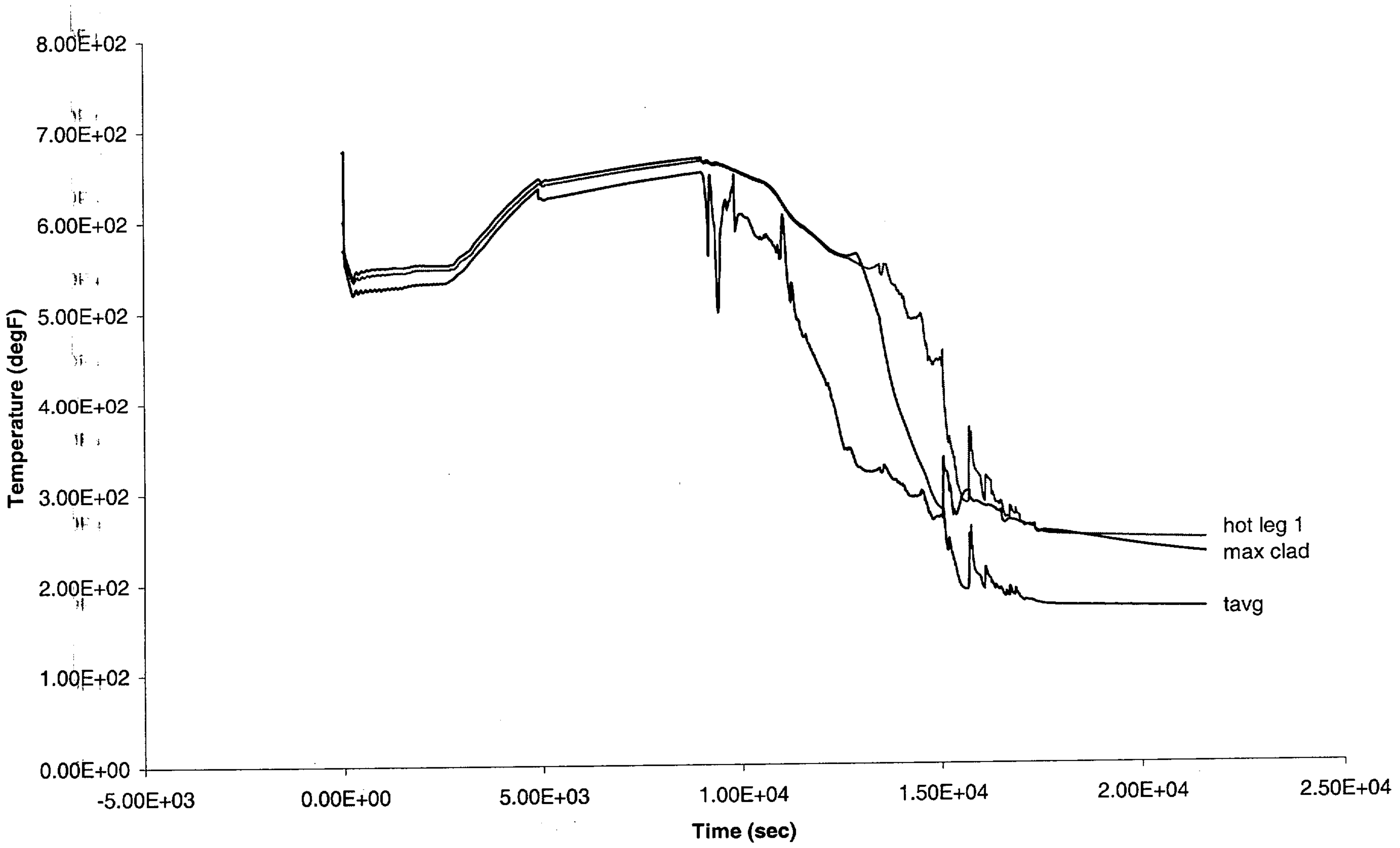

Fig. A.6c-6: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - <u>PRZR Level</u>

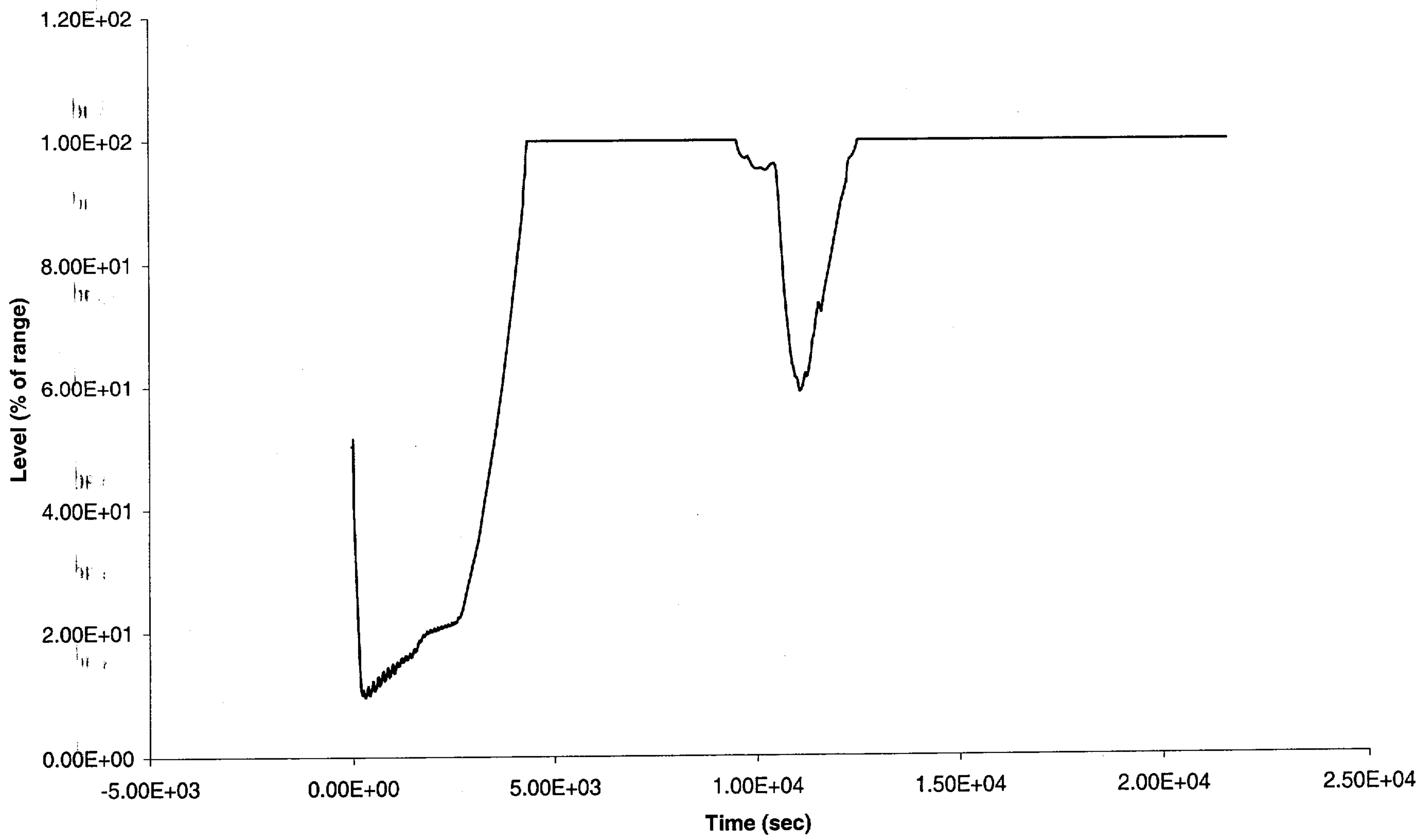

Fig. A.6c-7: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - <u>PORV Flow</u>

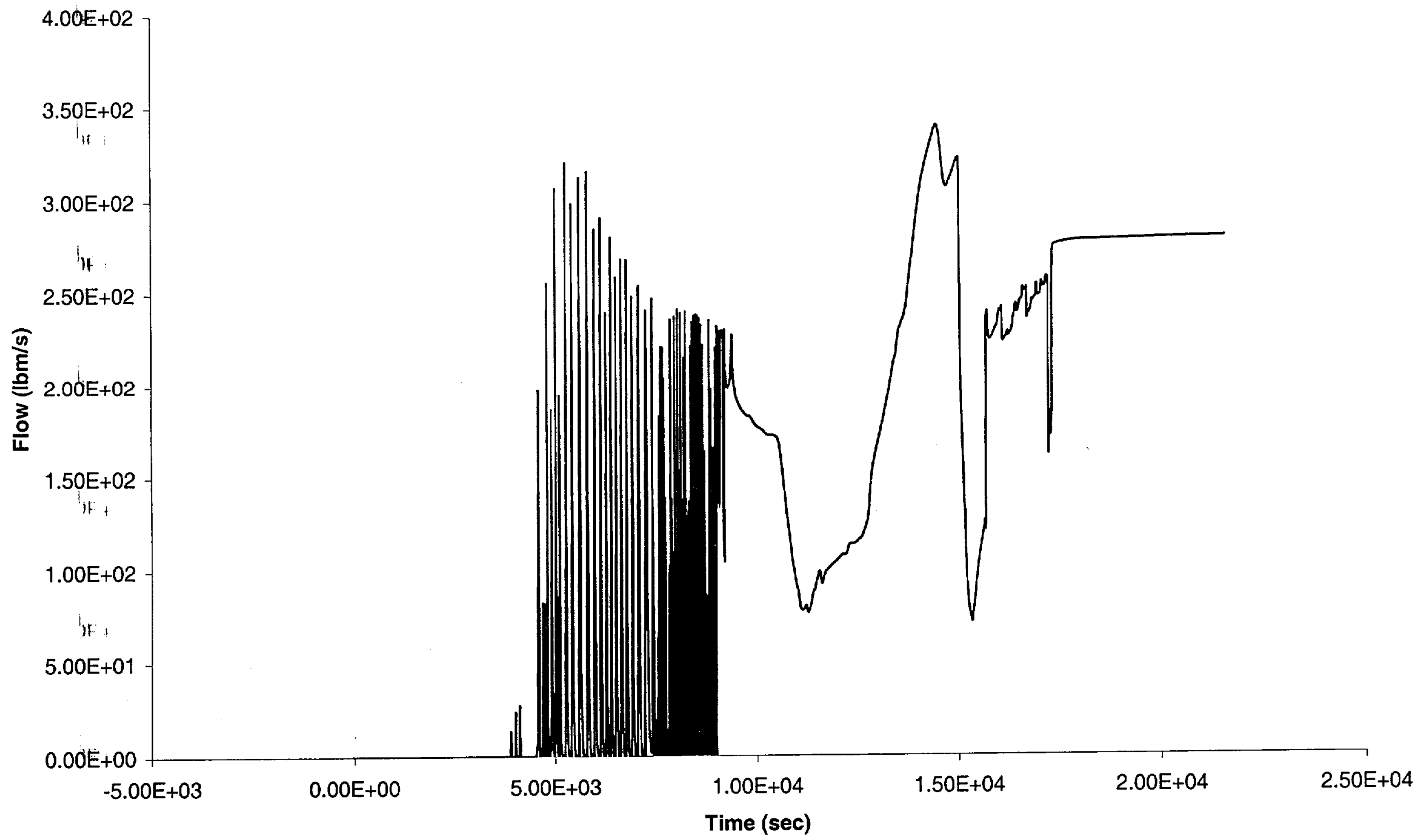

Fig. A.6c-8: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - SG 1 WR Level

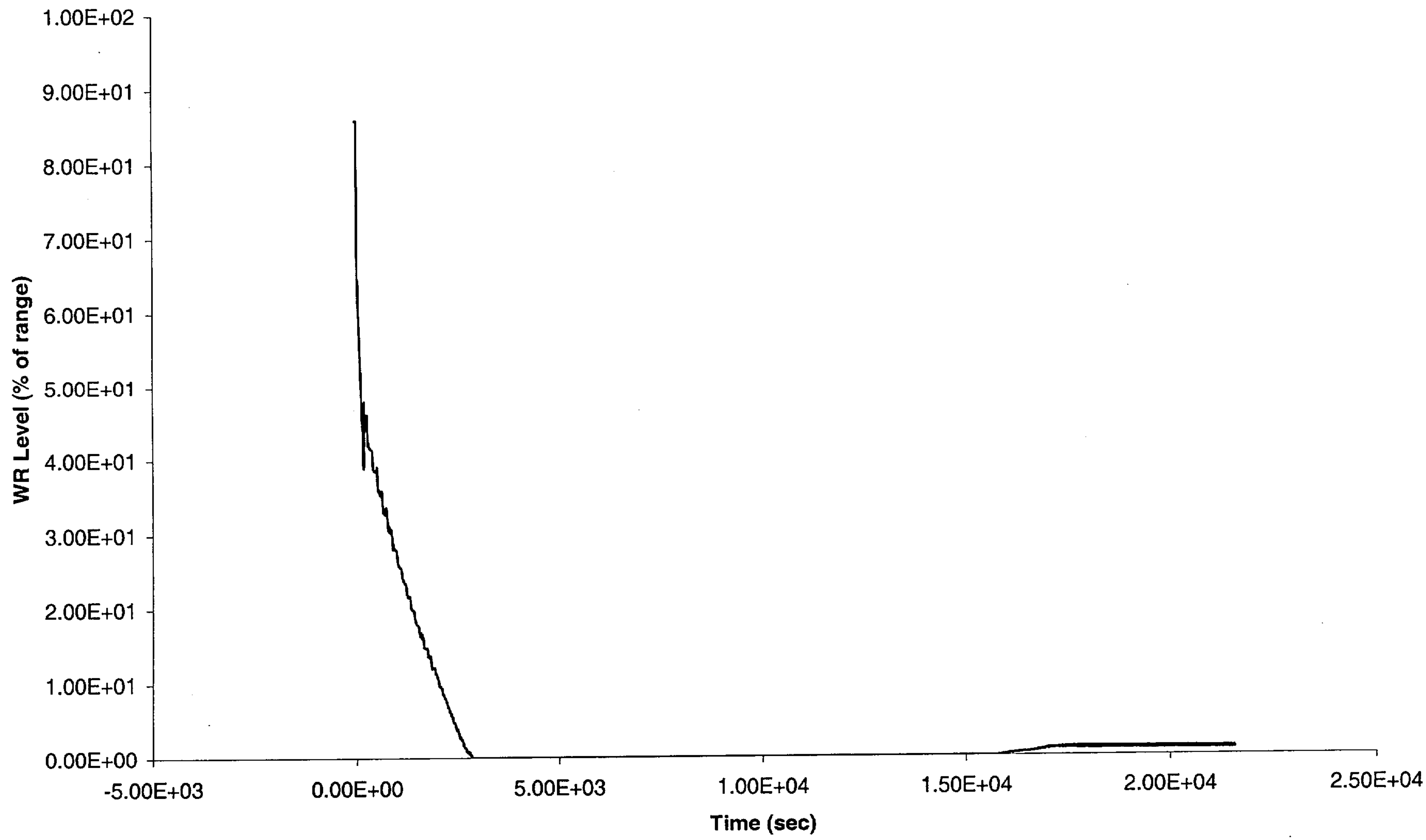

Fig. A.6c-9: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - SG 1 Pressure

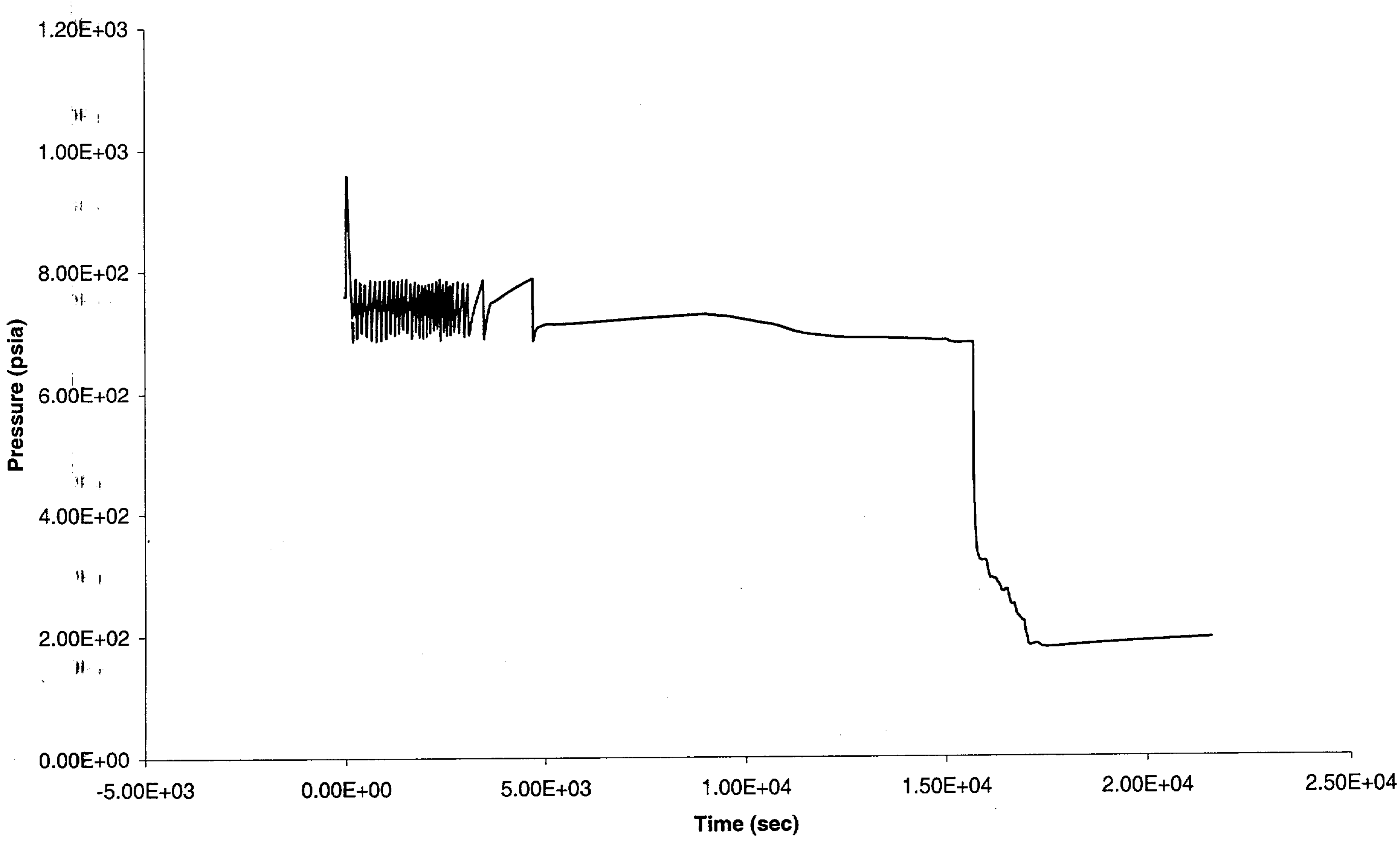

Fig. A.6c-10: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - SG 1 Temperature

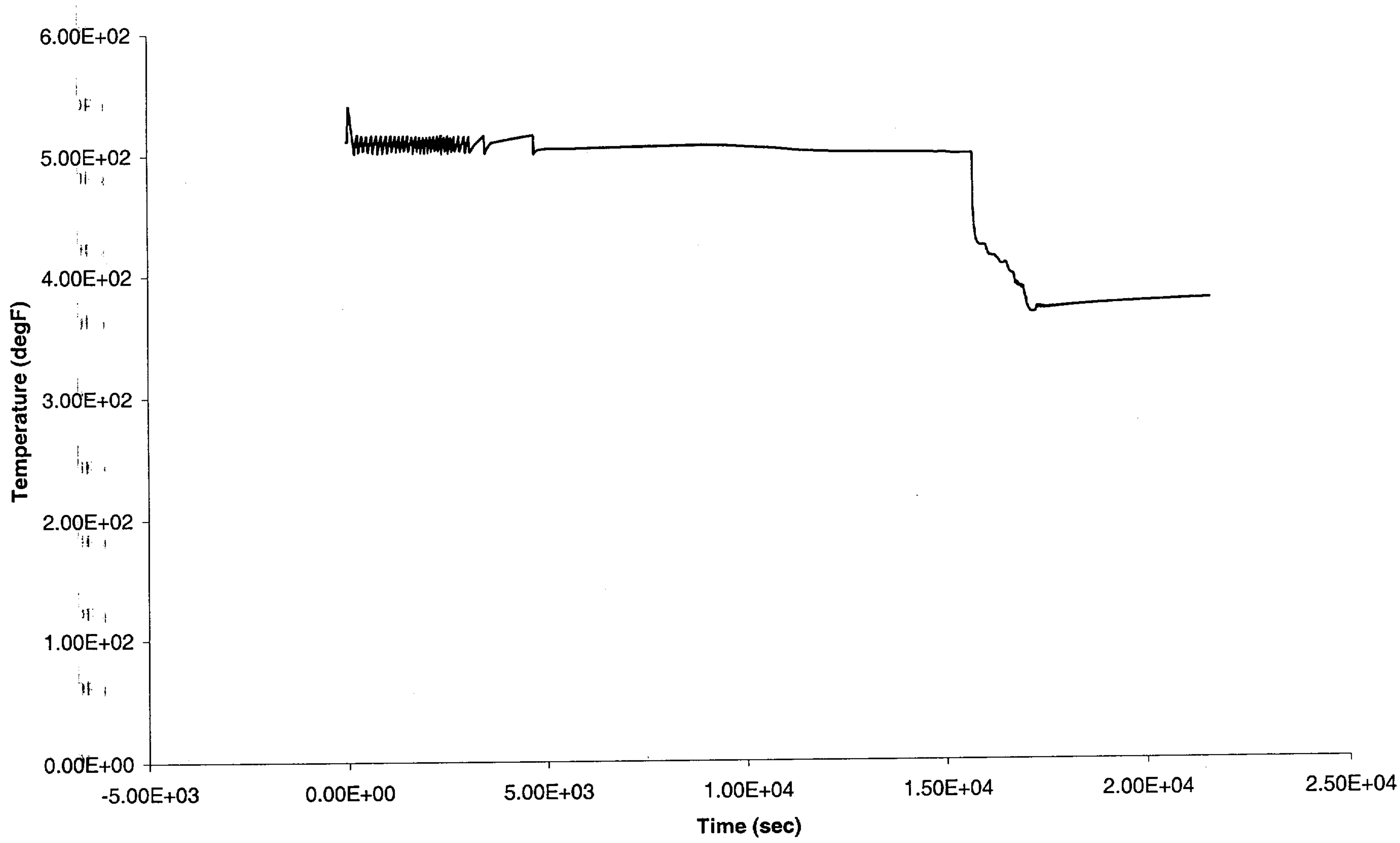

Fig. A.6c-11: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - <u>RCP 1 Speed</u>

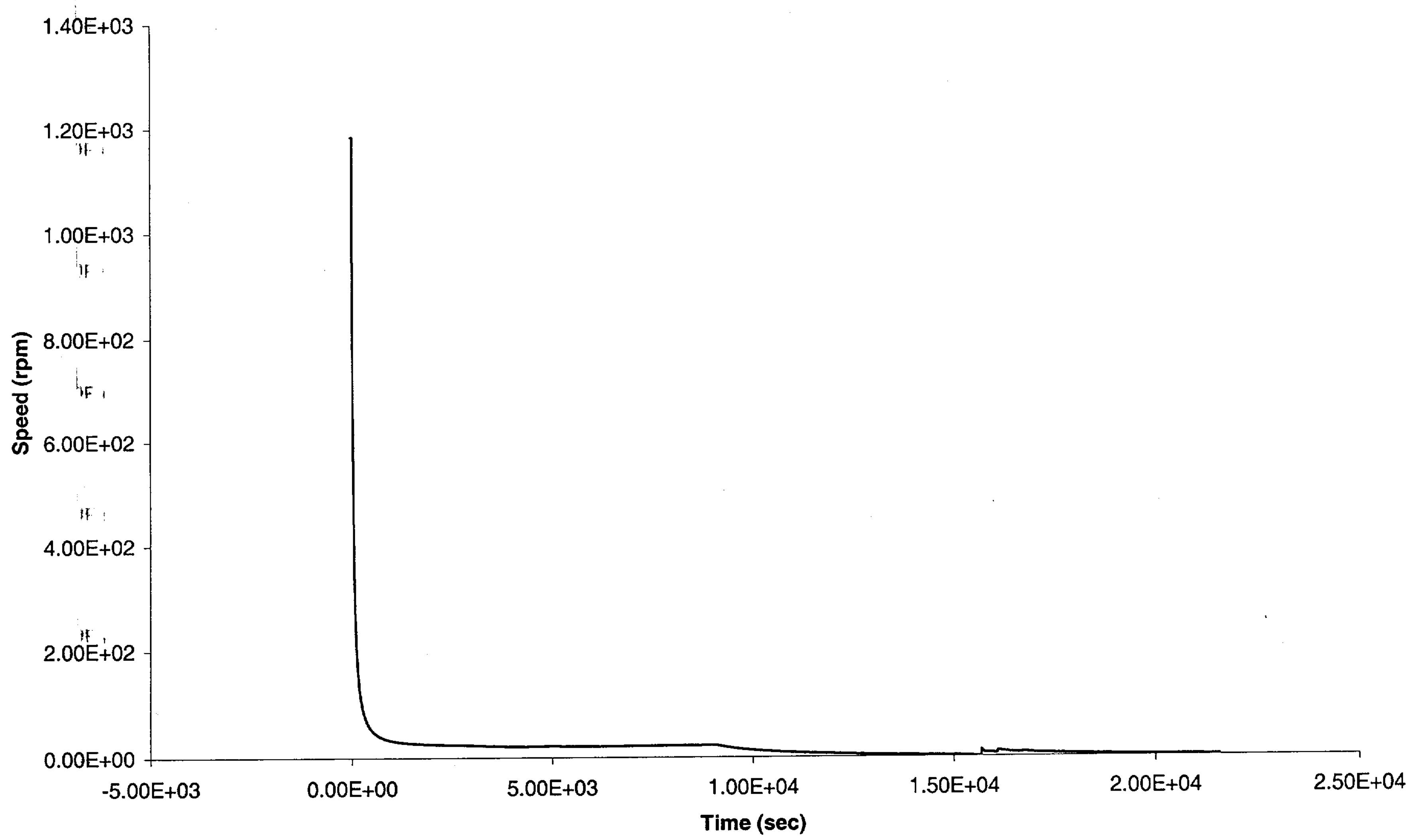

Fig. A.6c-12: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - Core Exit Subcooling

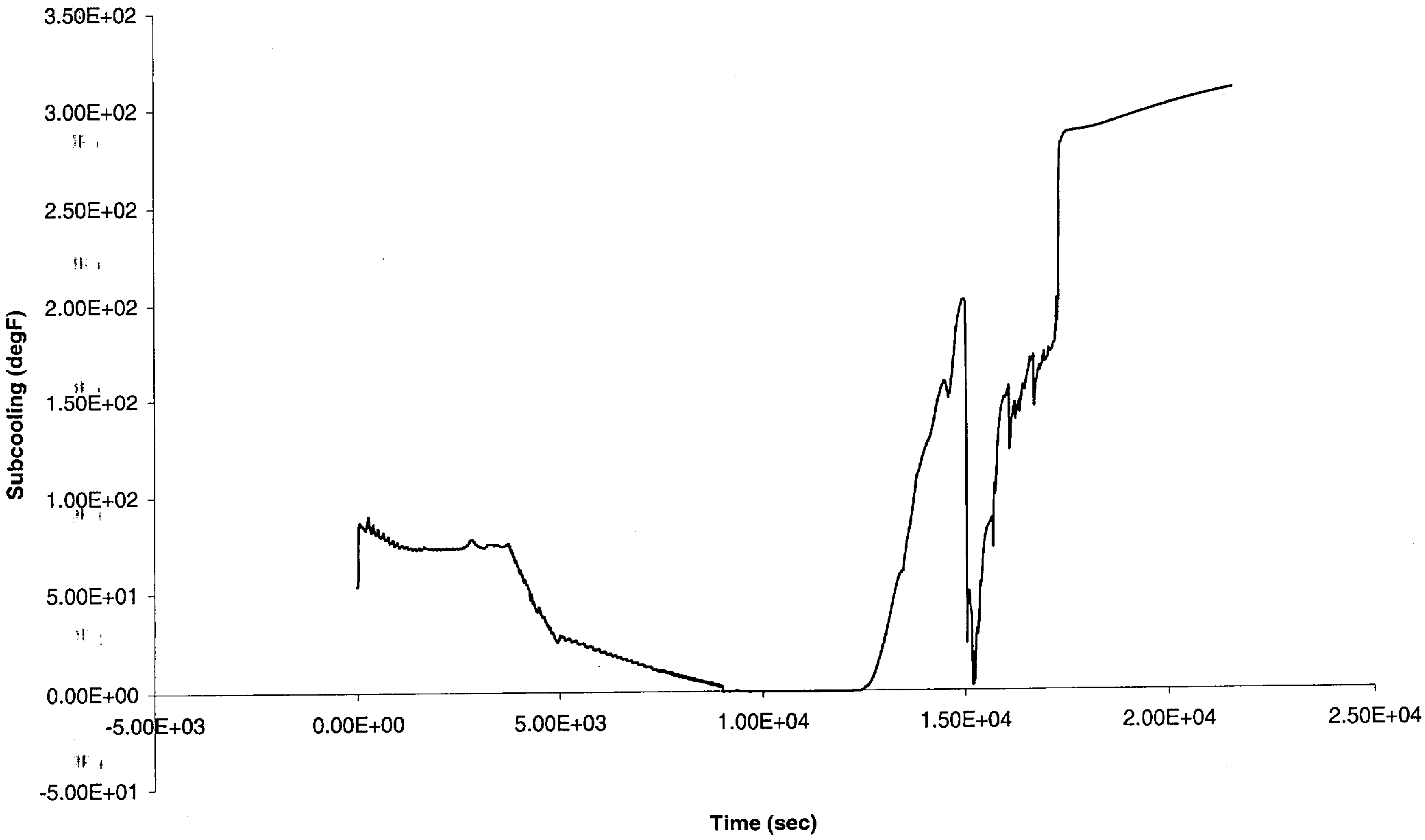

Fig. A.6c-13: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - <u>RCS Cooling Rate</u>

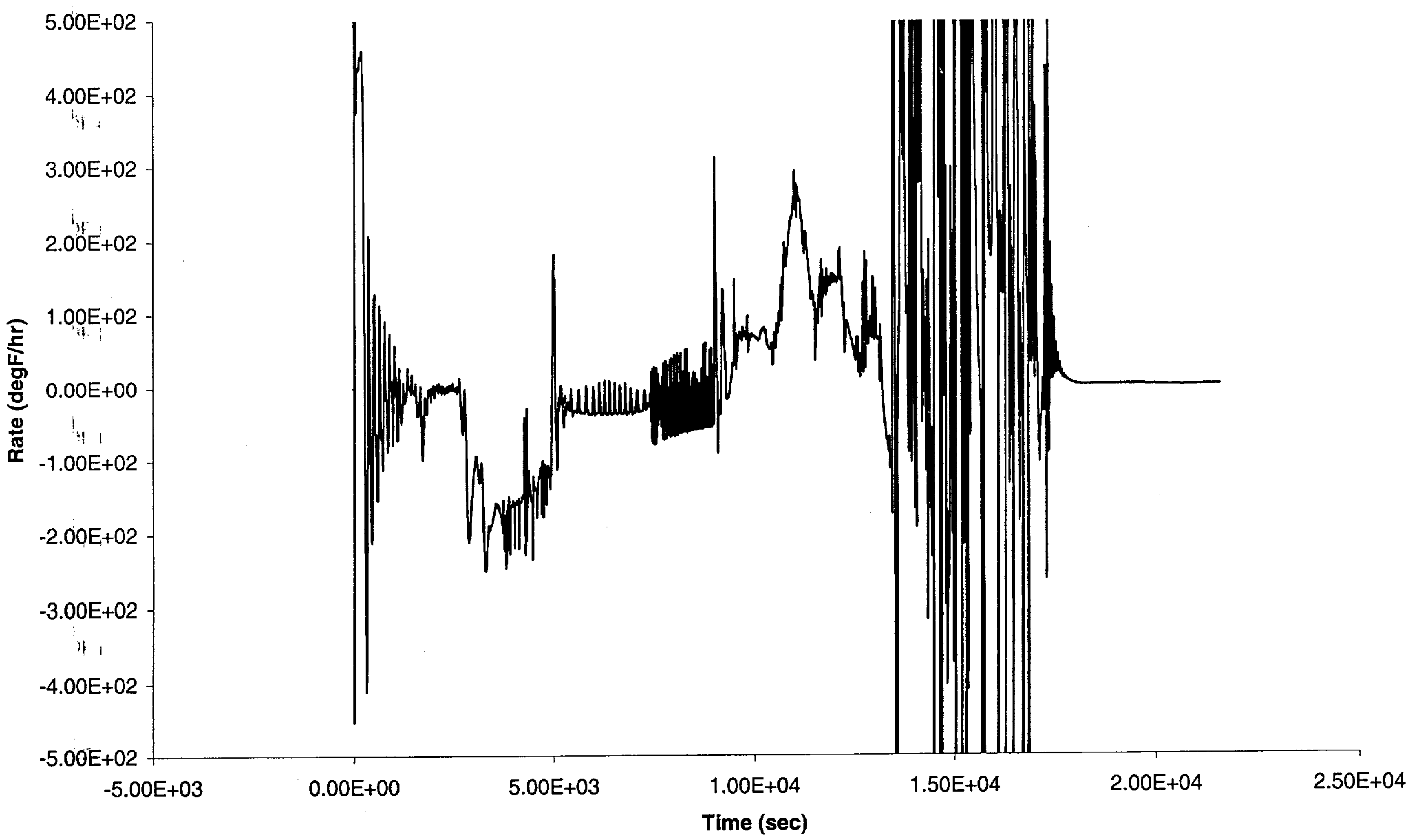

Fig. A.6c-14: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - Cummulative Charging + SI Flow

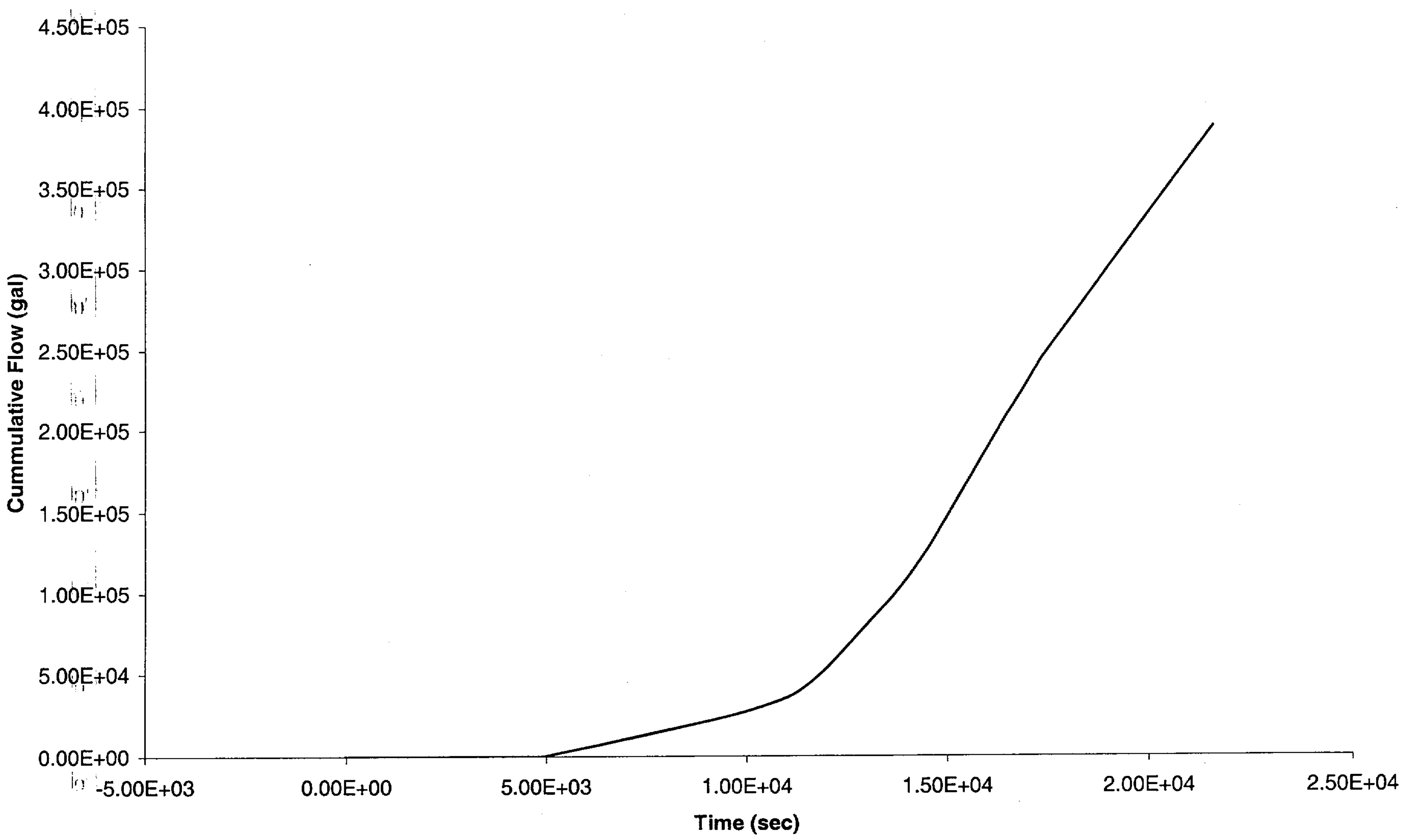

Fig. A.6c-15: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - <u>PRT Pressure</u>

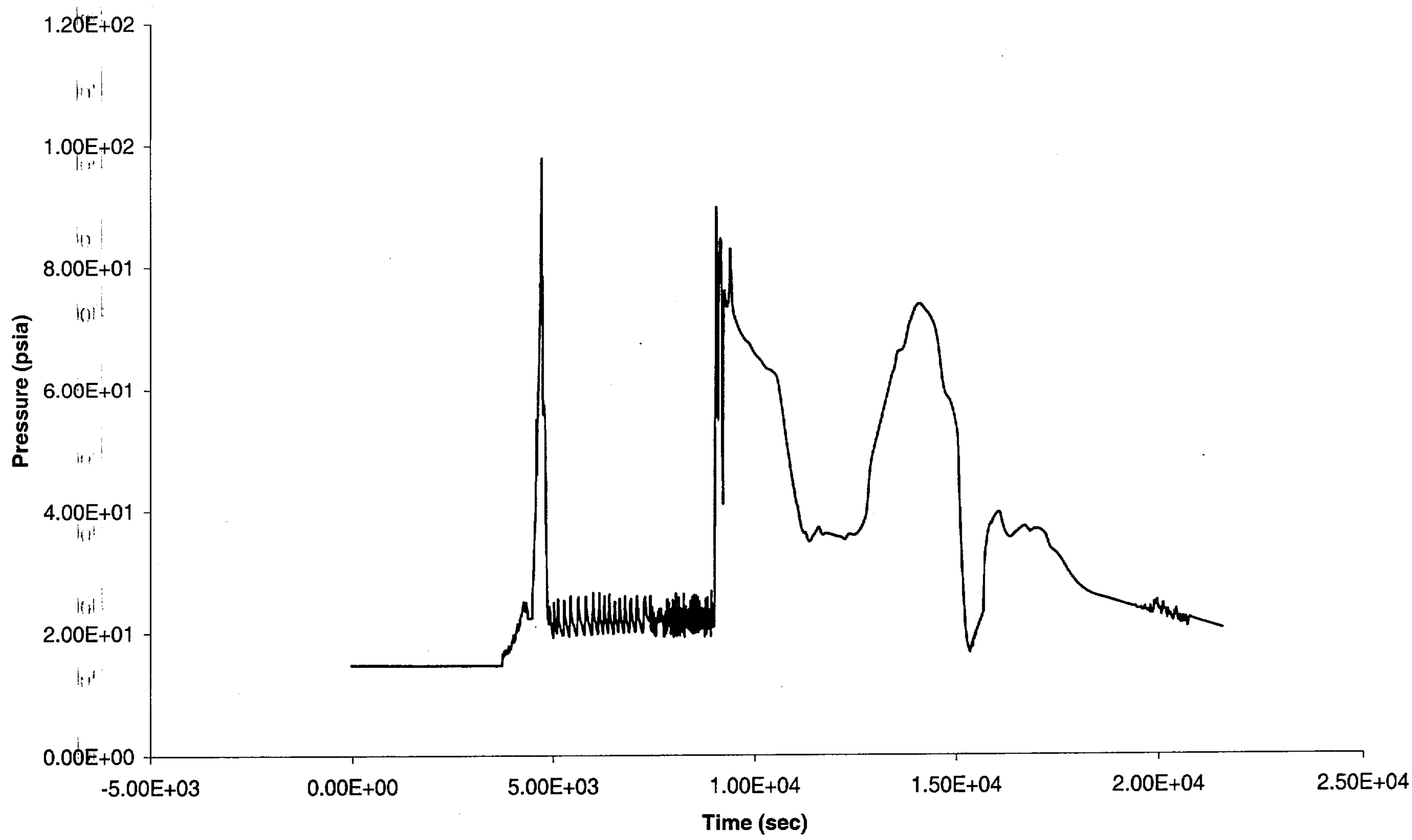

Fig. A.6c-16: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - <u>PRT Burst Disk Flow</u>

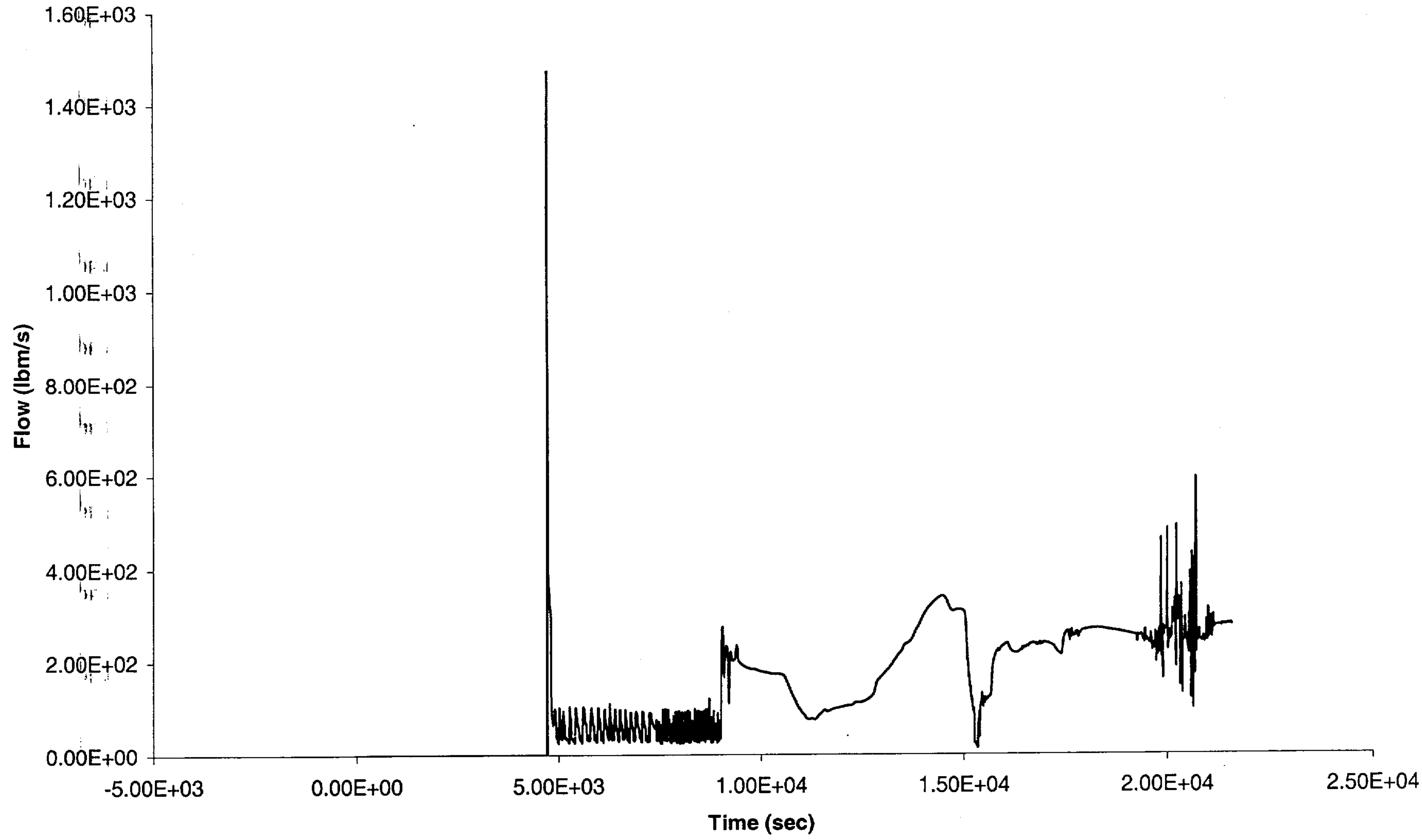

Fig. A.6c-17: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - <u>Burst Disk Flow Quality</u>

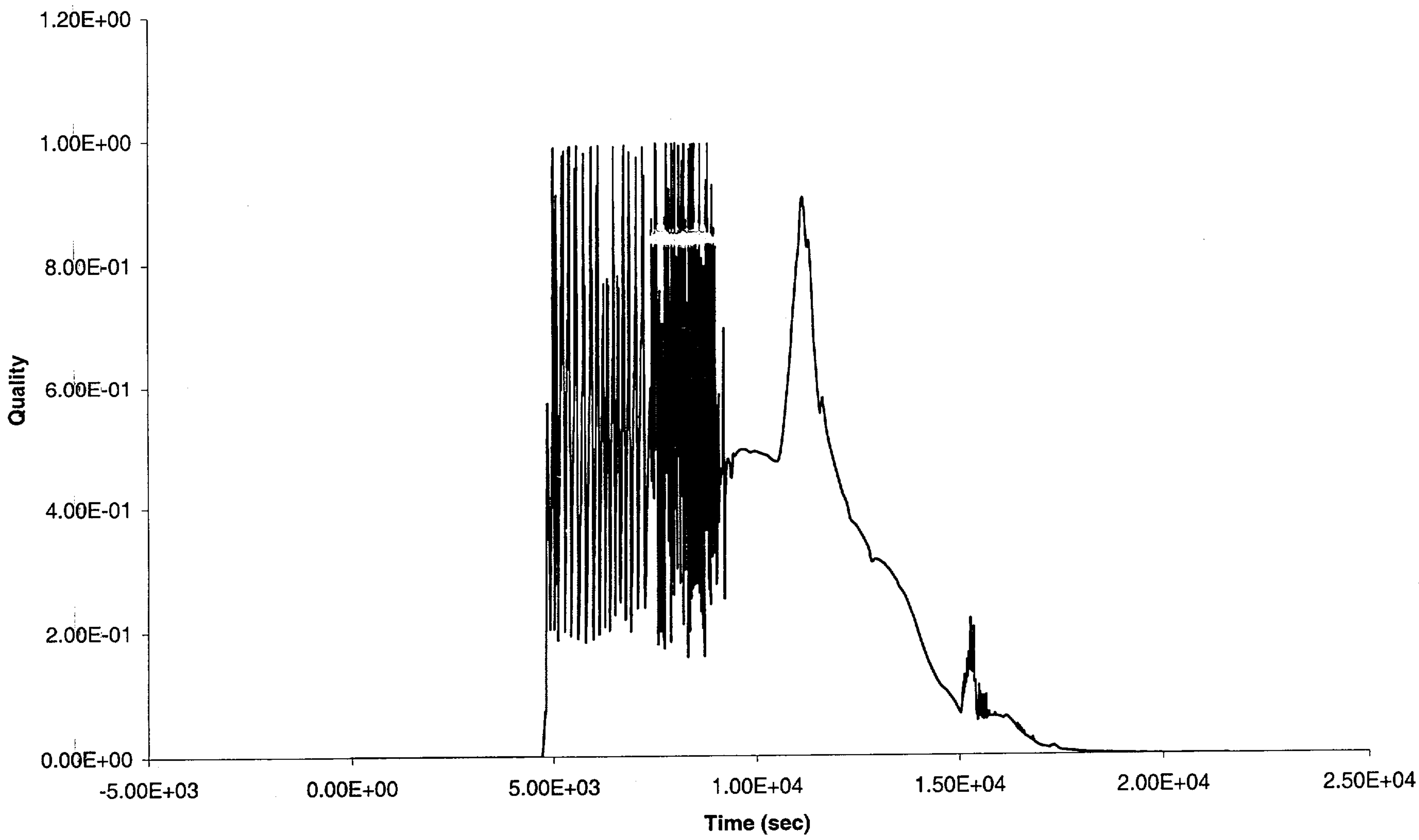

Fig. A.6c-18: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - <u>Burst Disk Phasic Velocities</u>

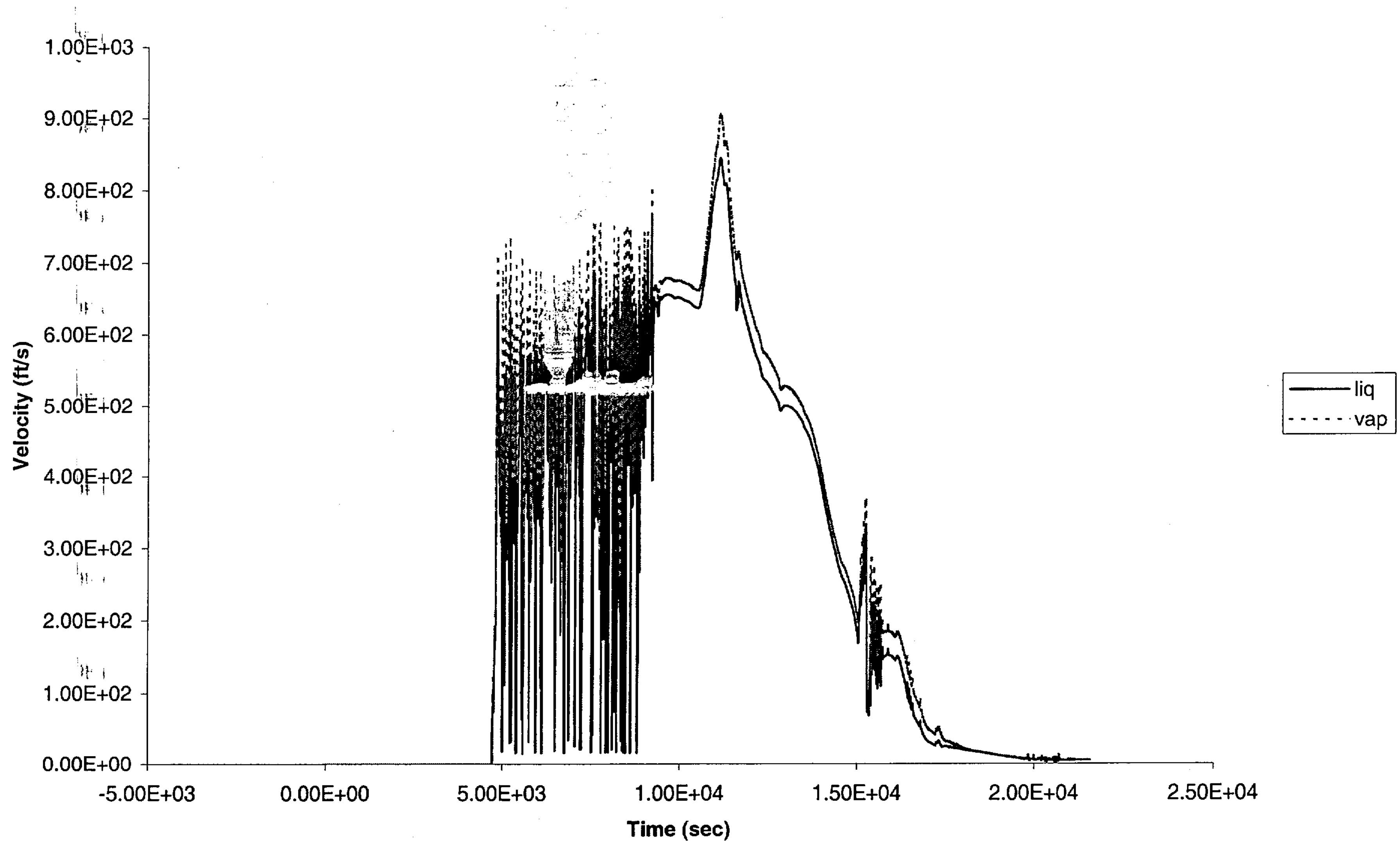

Fig. A.6c-19: LOSP with Subsequent AFW Failure, No Operator Action for 2 hrs 30 min - PRT Liquid Temperature

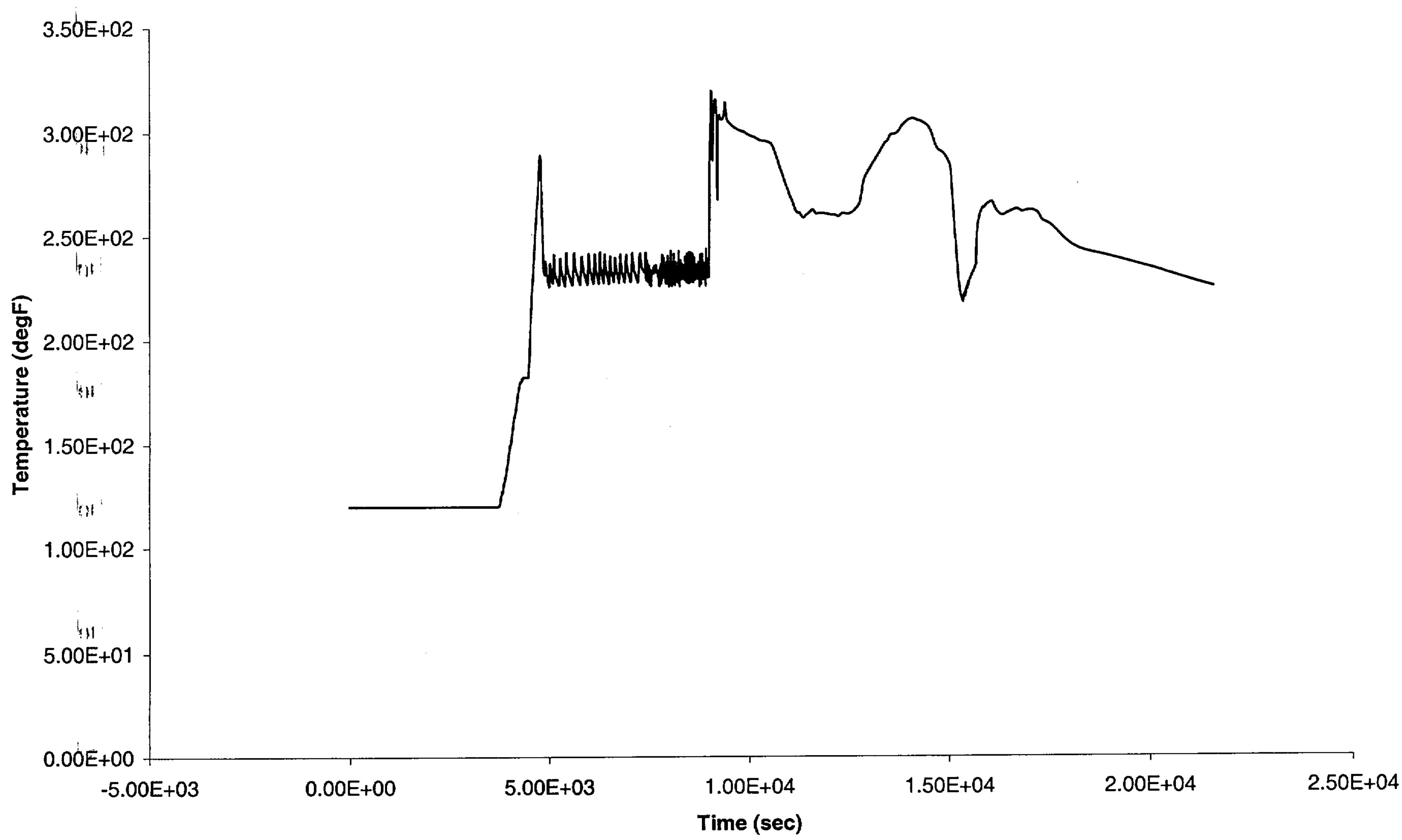

Fig. A.7-1: PORV Falsely Lifts and Sticks Open - Core Power

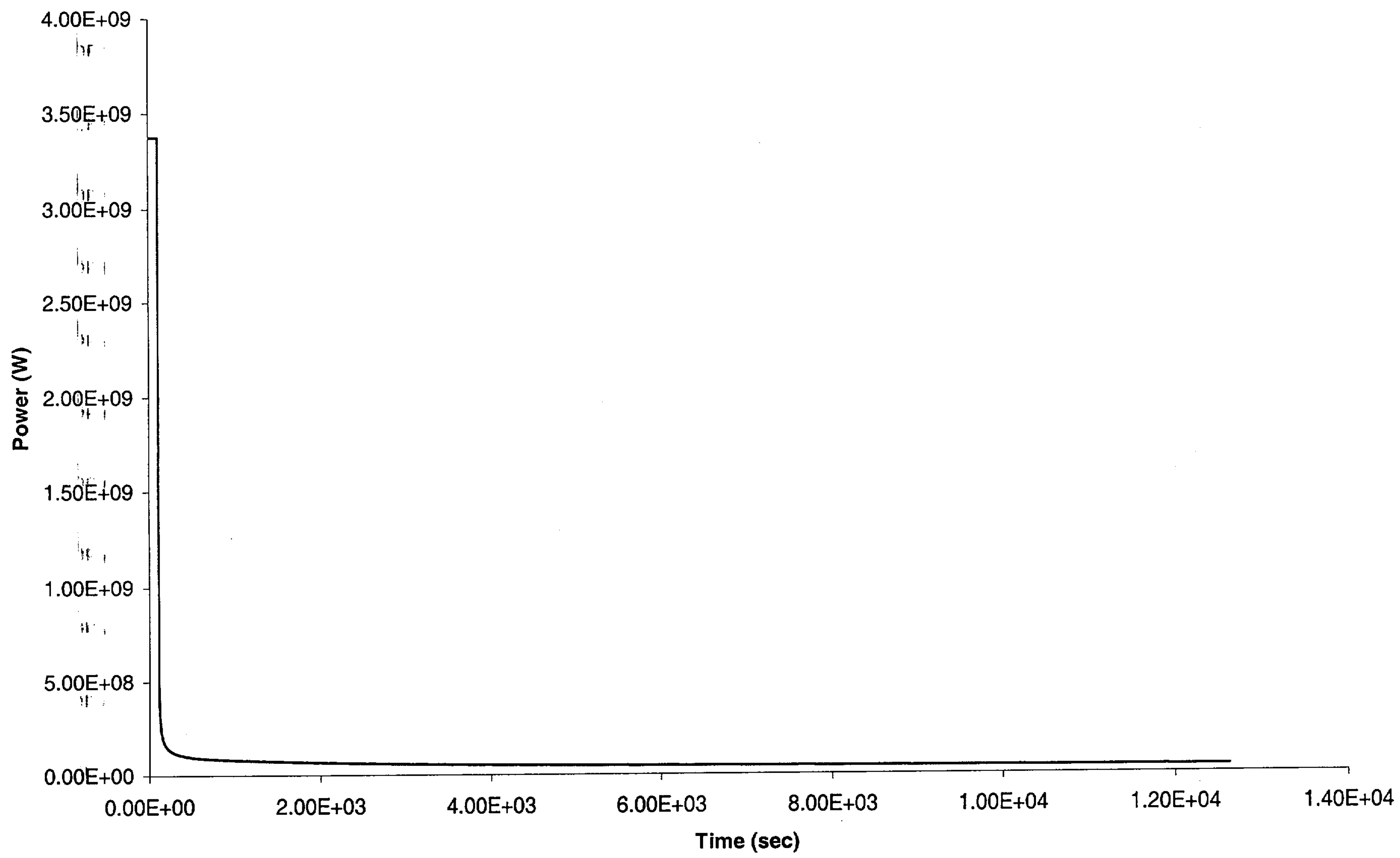

Fig. A.7-2: PORV Falsely Lifts and Sticks Open - RCS Pressure

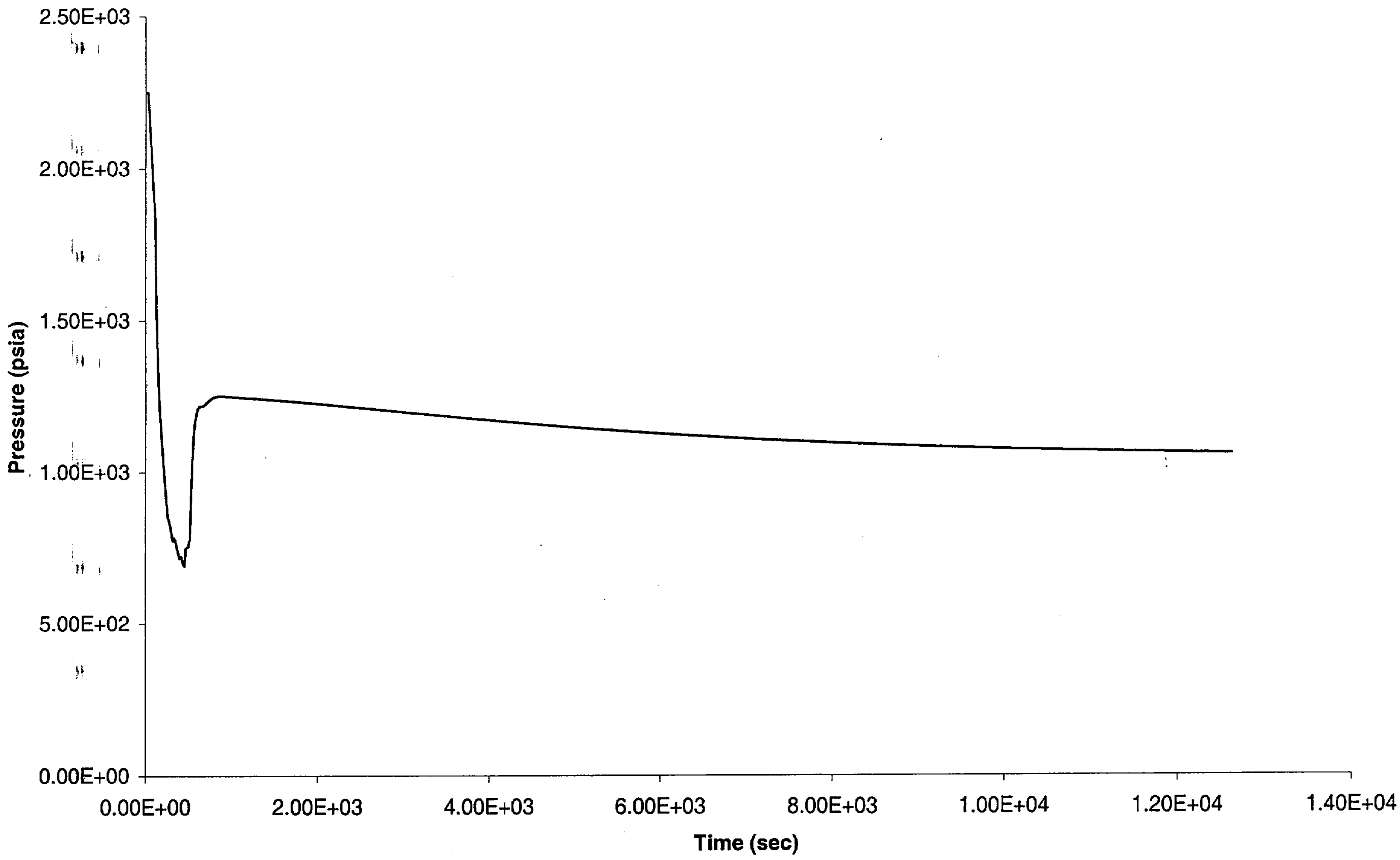

Fig. A.7-3: PORV Falsely Lifts and Sticks Open - Feed/Steam Flows

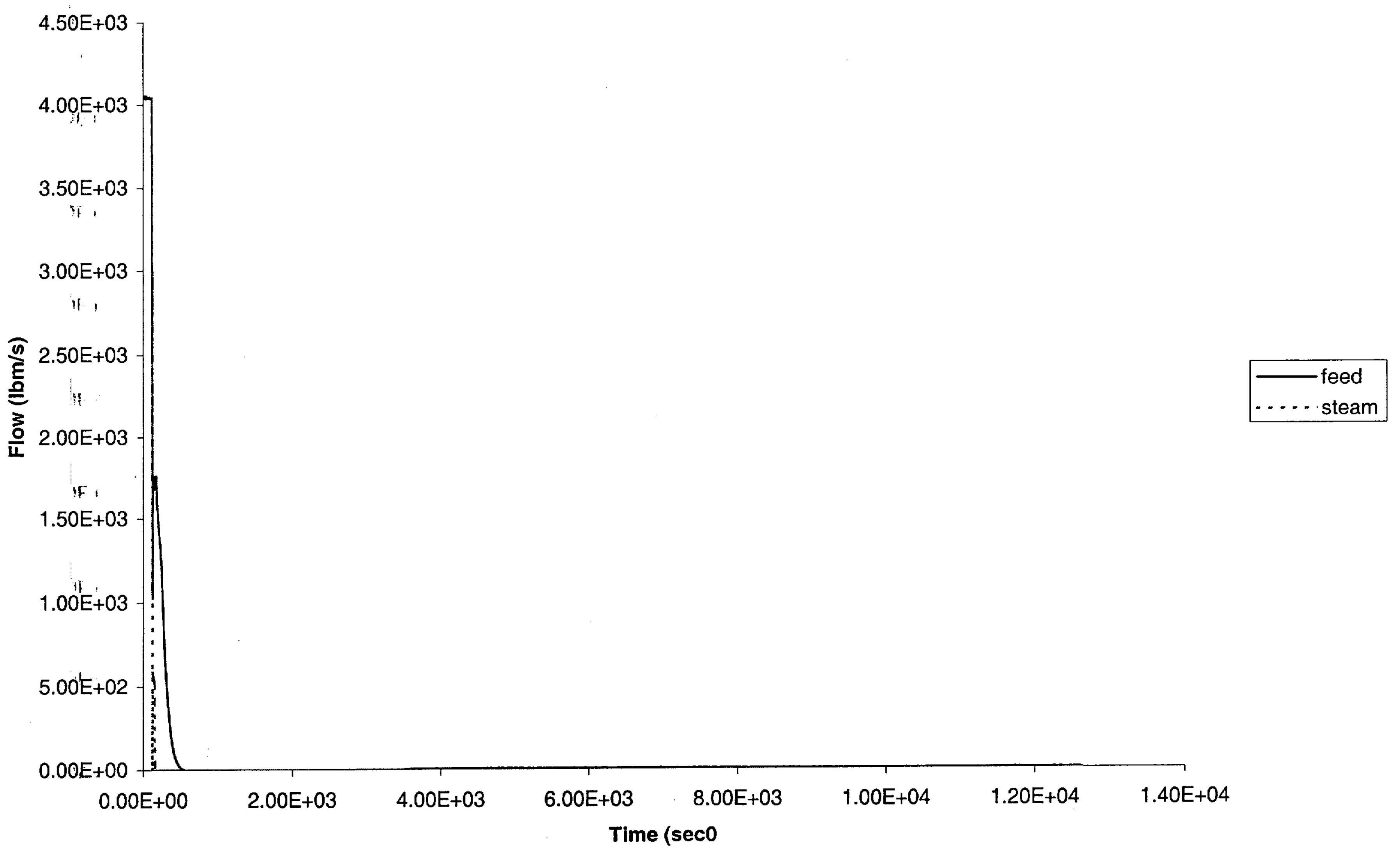

Fig. A.7-4: PORV Falsely Lifts and Sticks Open - Charging and SI Flows

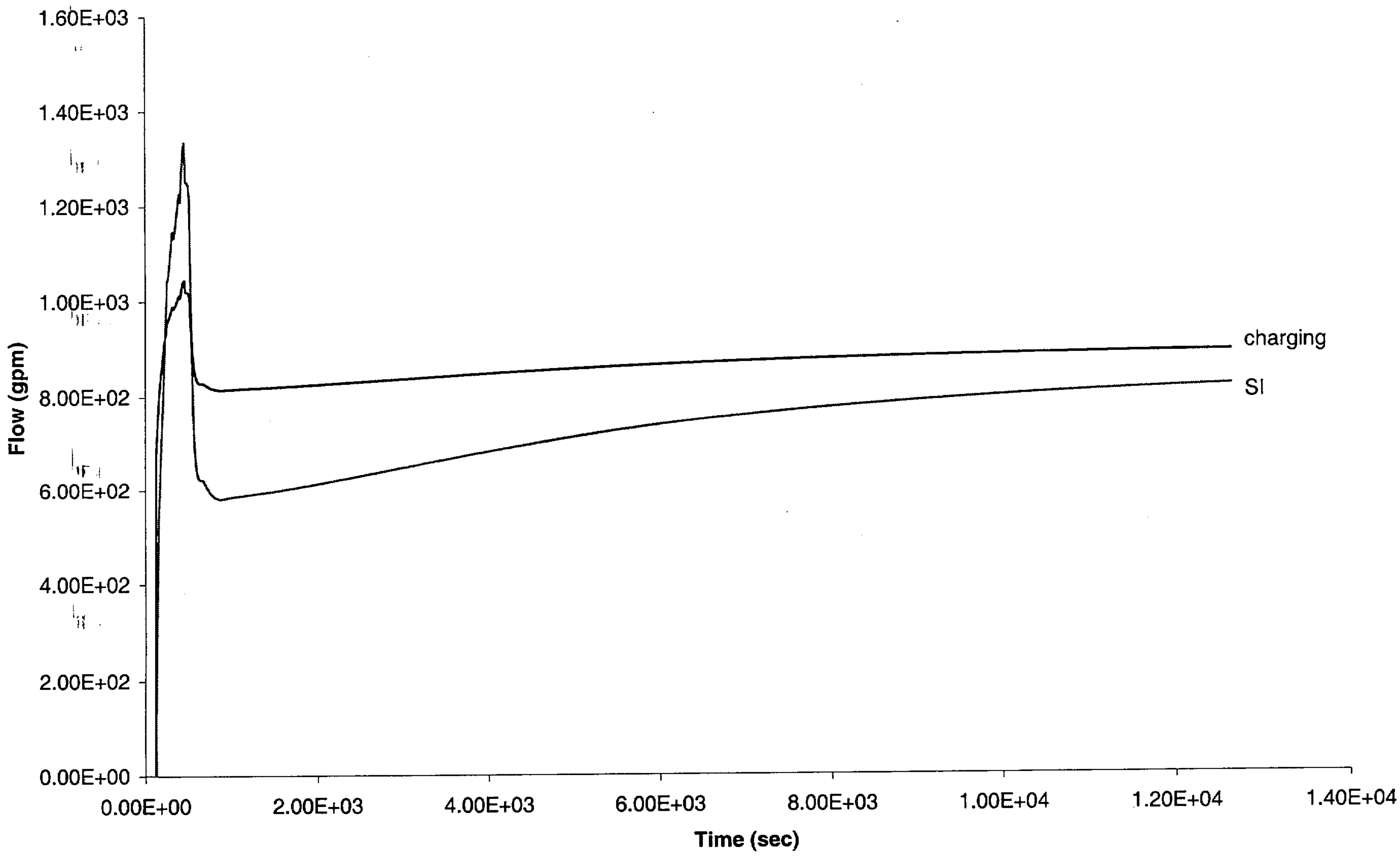

Fig. A.7-5: PORV Falsely Lifts and Sticks Open - RCS Temperatures

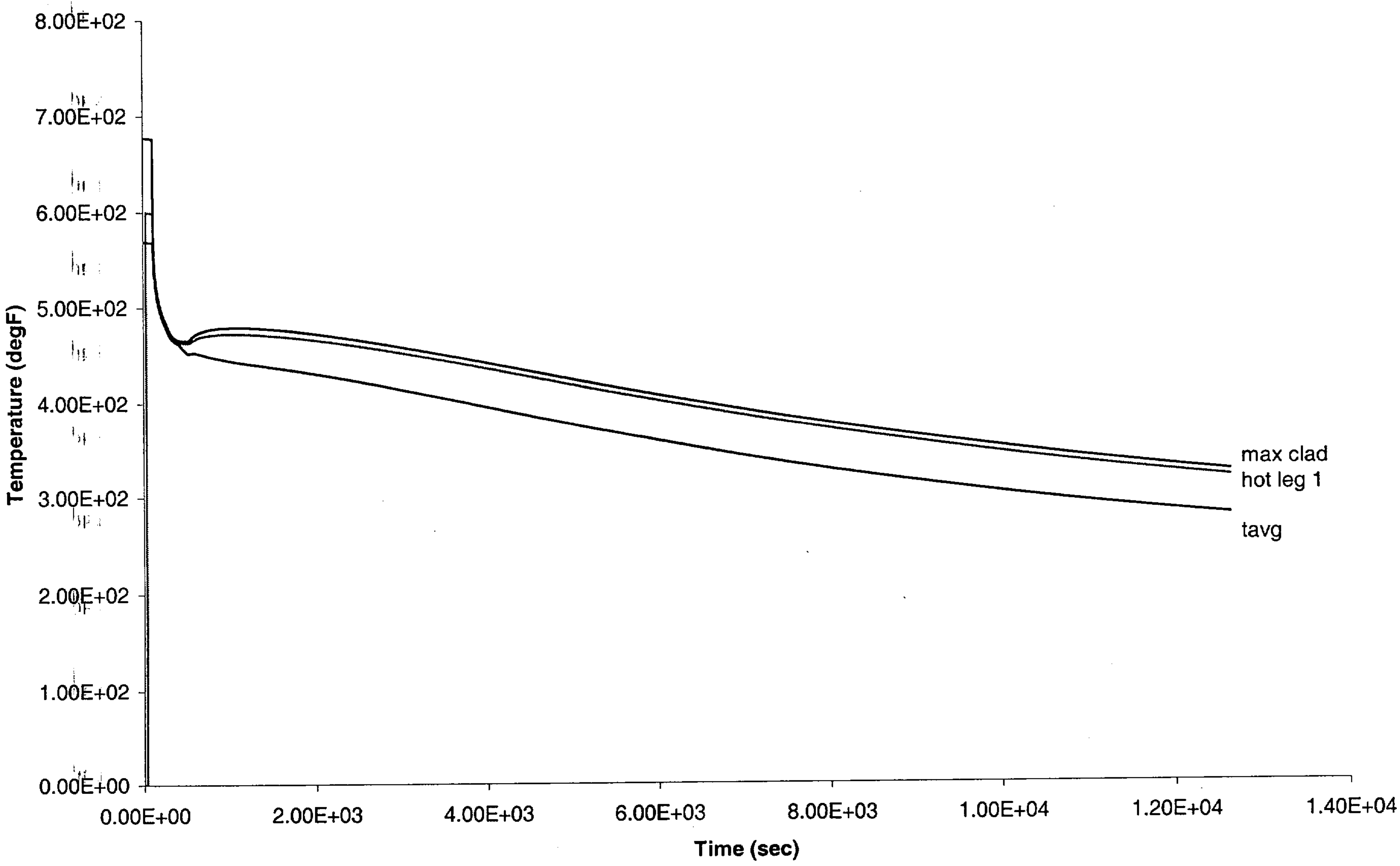

Fig. A.7-6: PORV Falsely Lifts and Sticks Open - PRZR Level

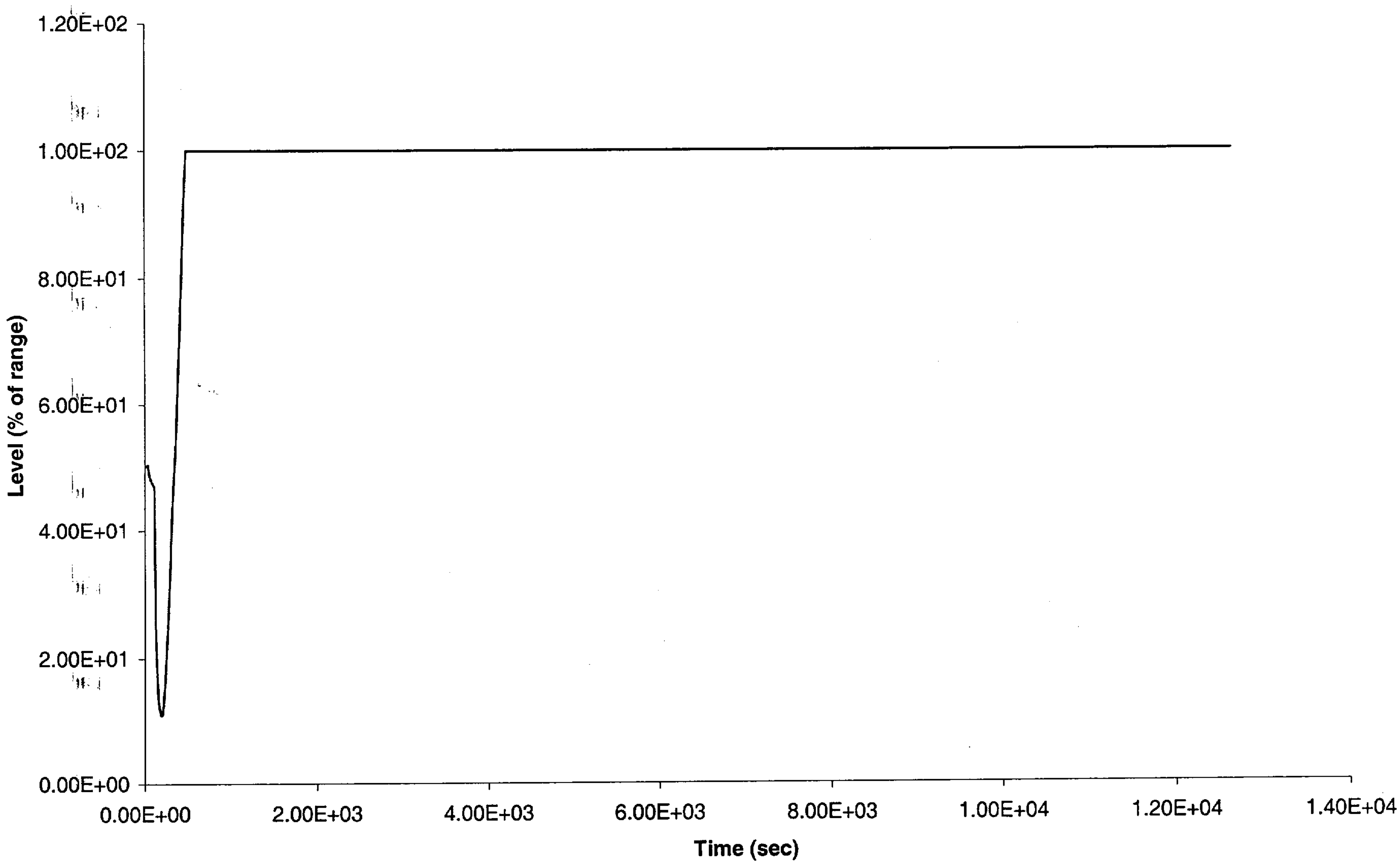

Fig. A.7-7: PORV Falsely Lifts and Sticks Open - PORV Flow

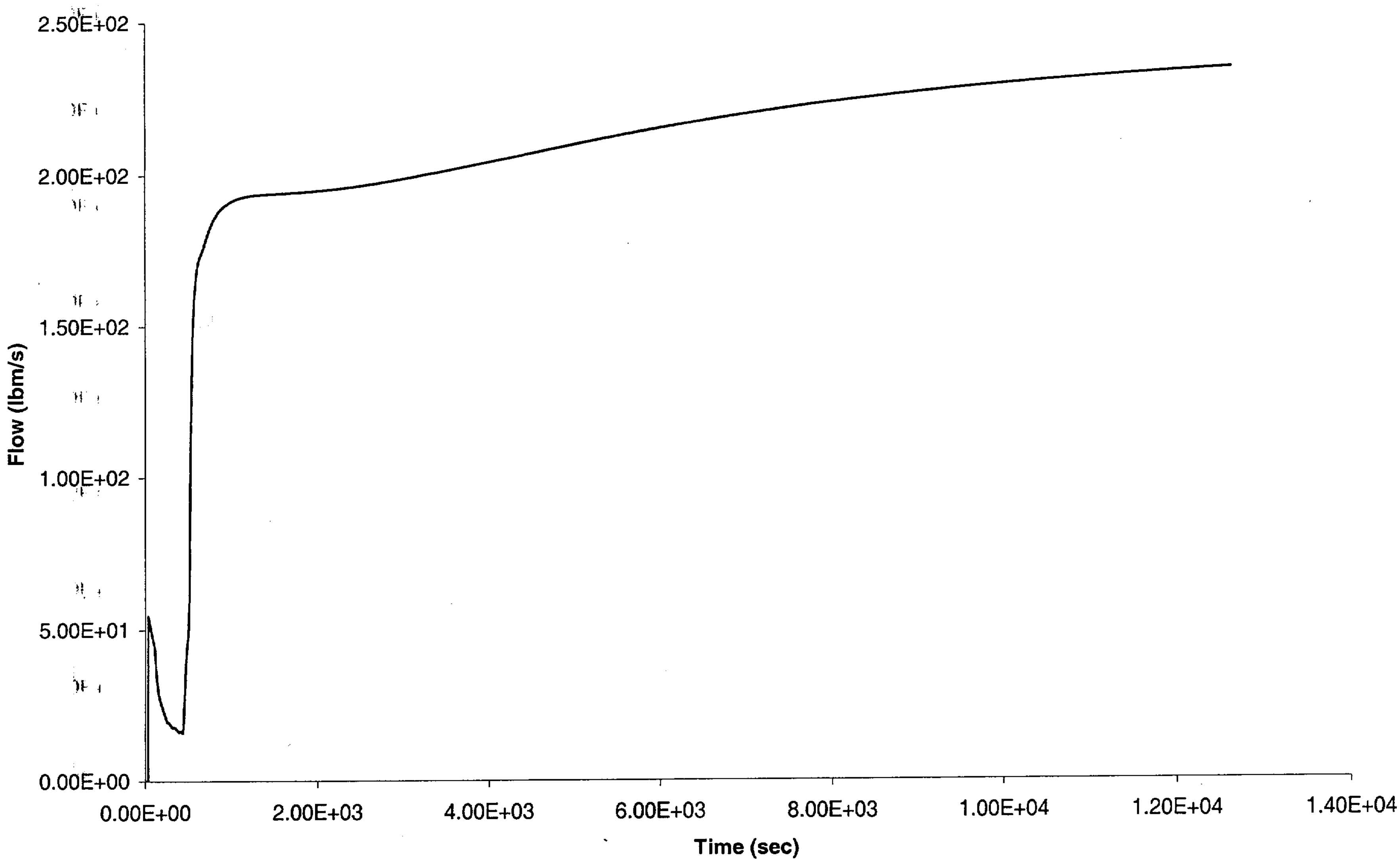

Fig. A.7-8: PORV Falsely Lifts and Sticks Open - SG 1 WR Level

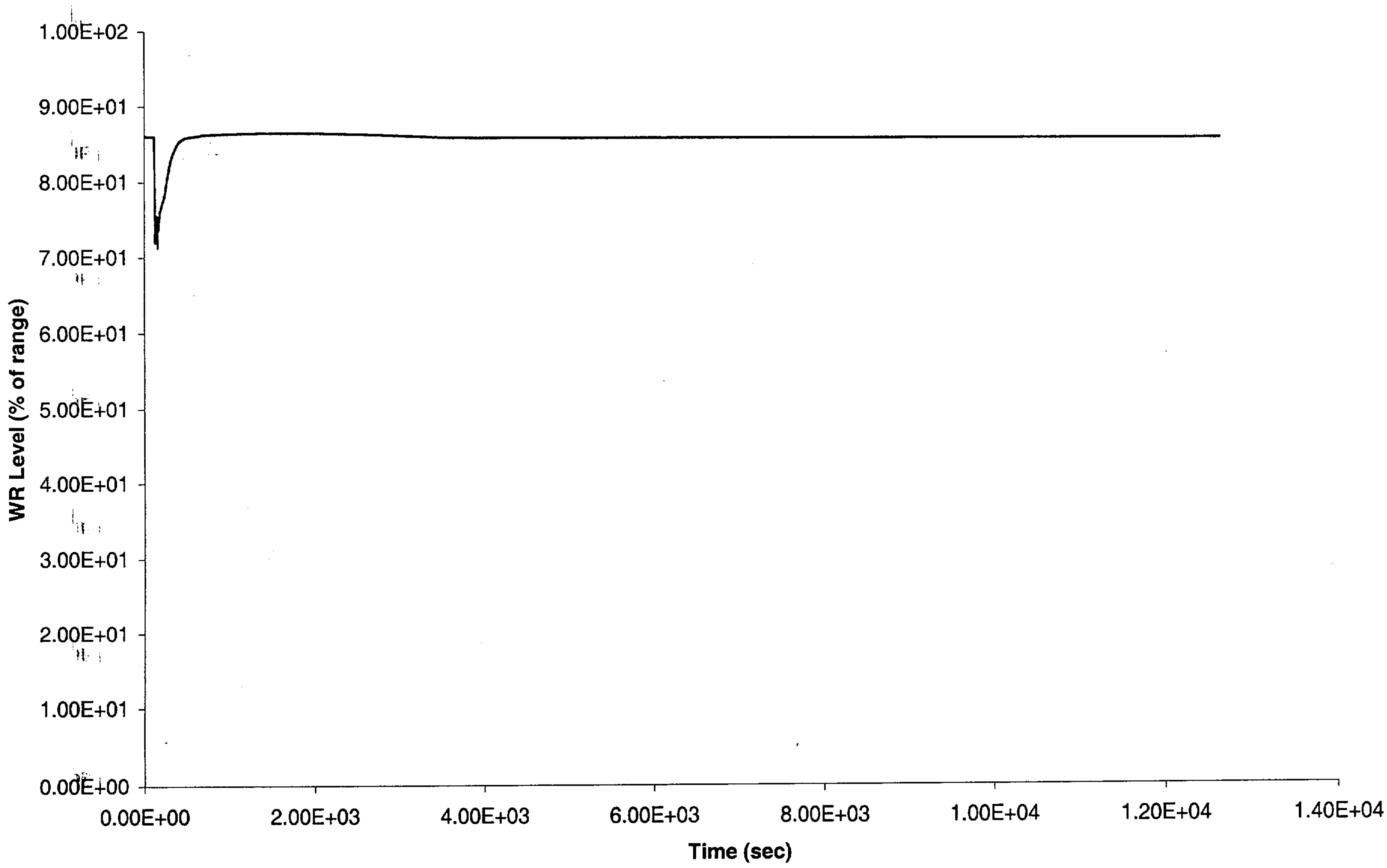

Fig. A.7-9: PORV Falsely Lifts and Sticks Open - SG 1 Pressure

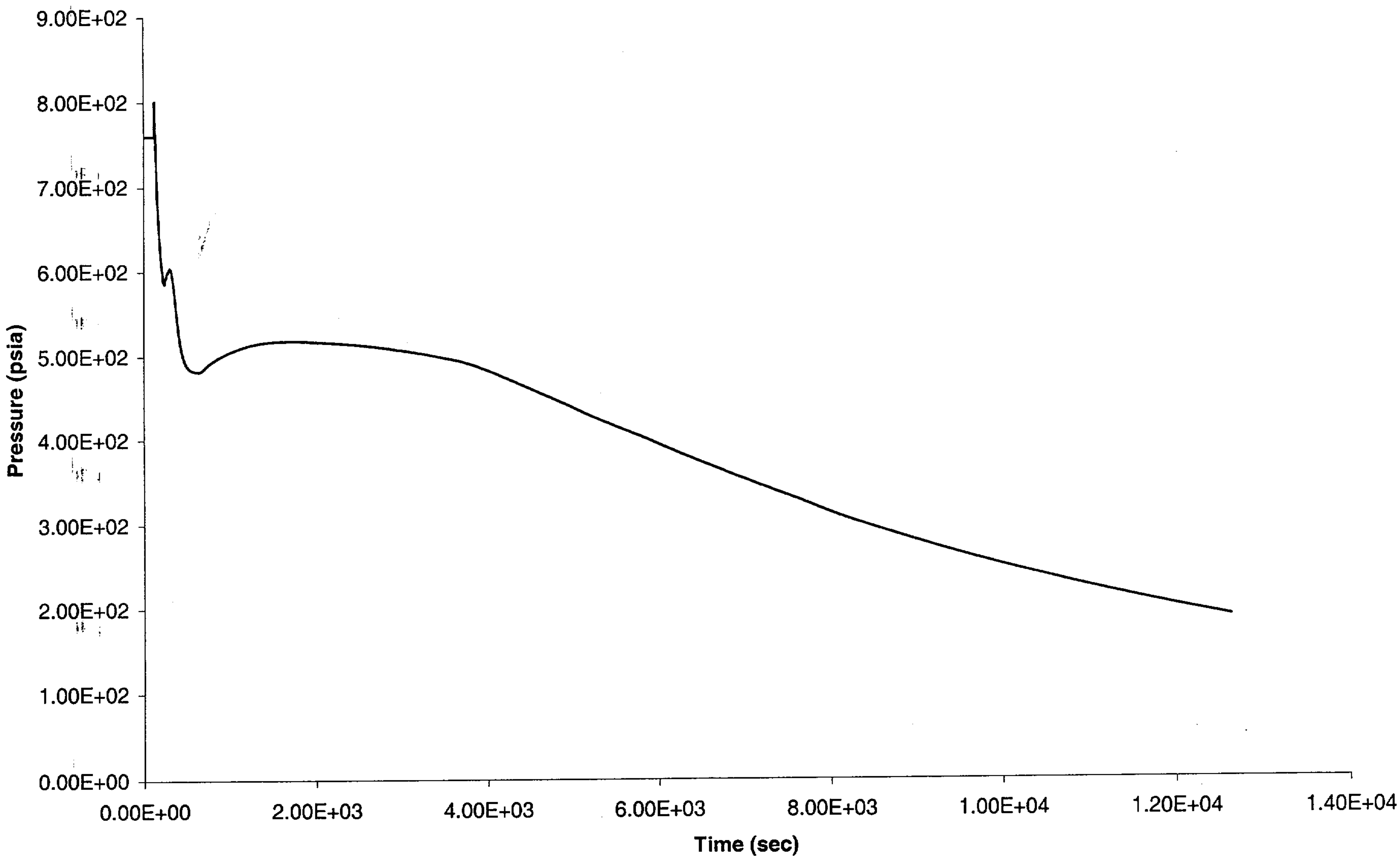

Fig. A.7-10: PORV Falsely Lifts and Sticks Open - SG 1 Temperature

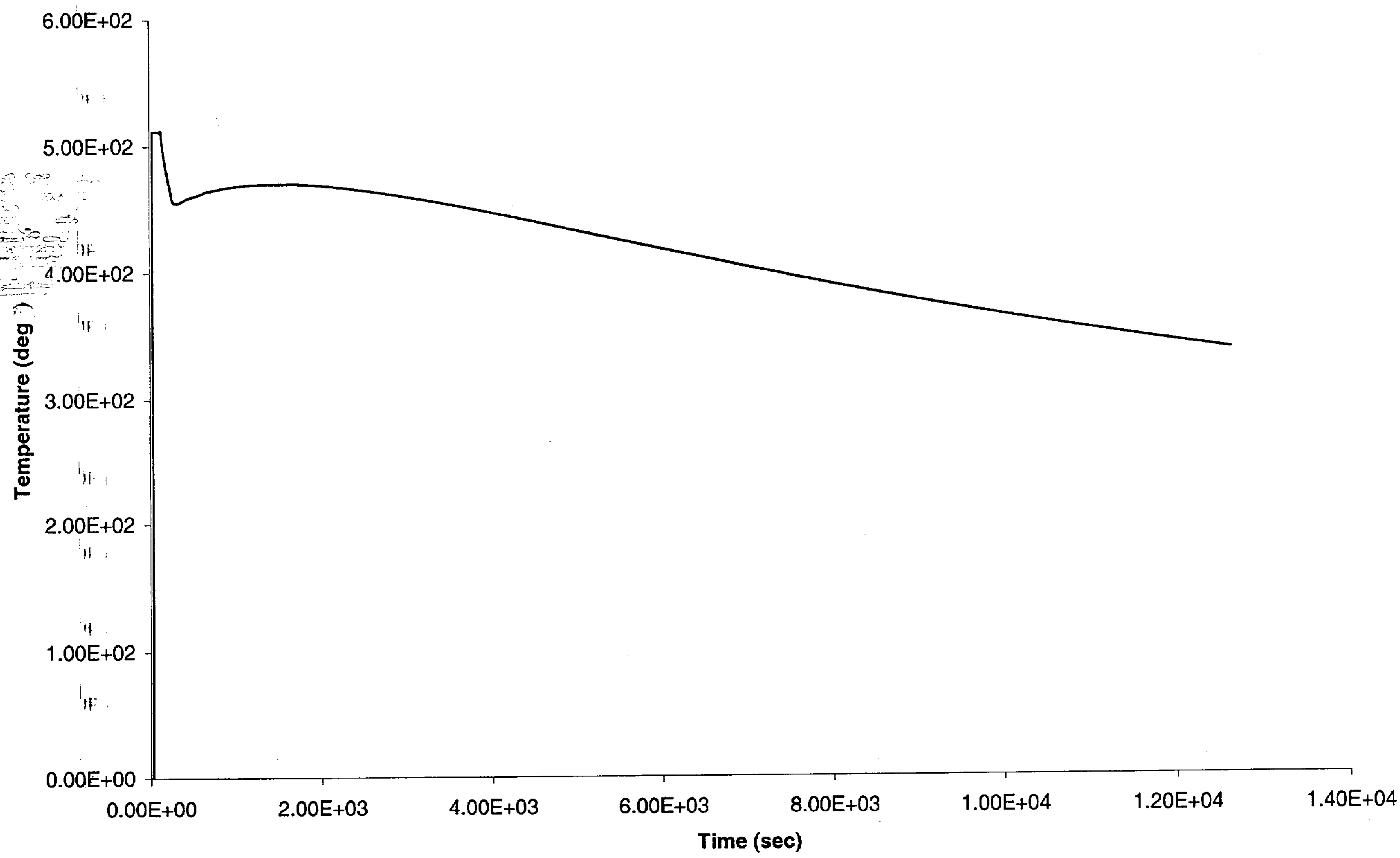

Fig. A.7-11: PORV Falsely Lifts and Sticks Open - RCP Speed

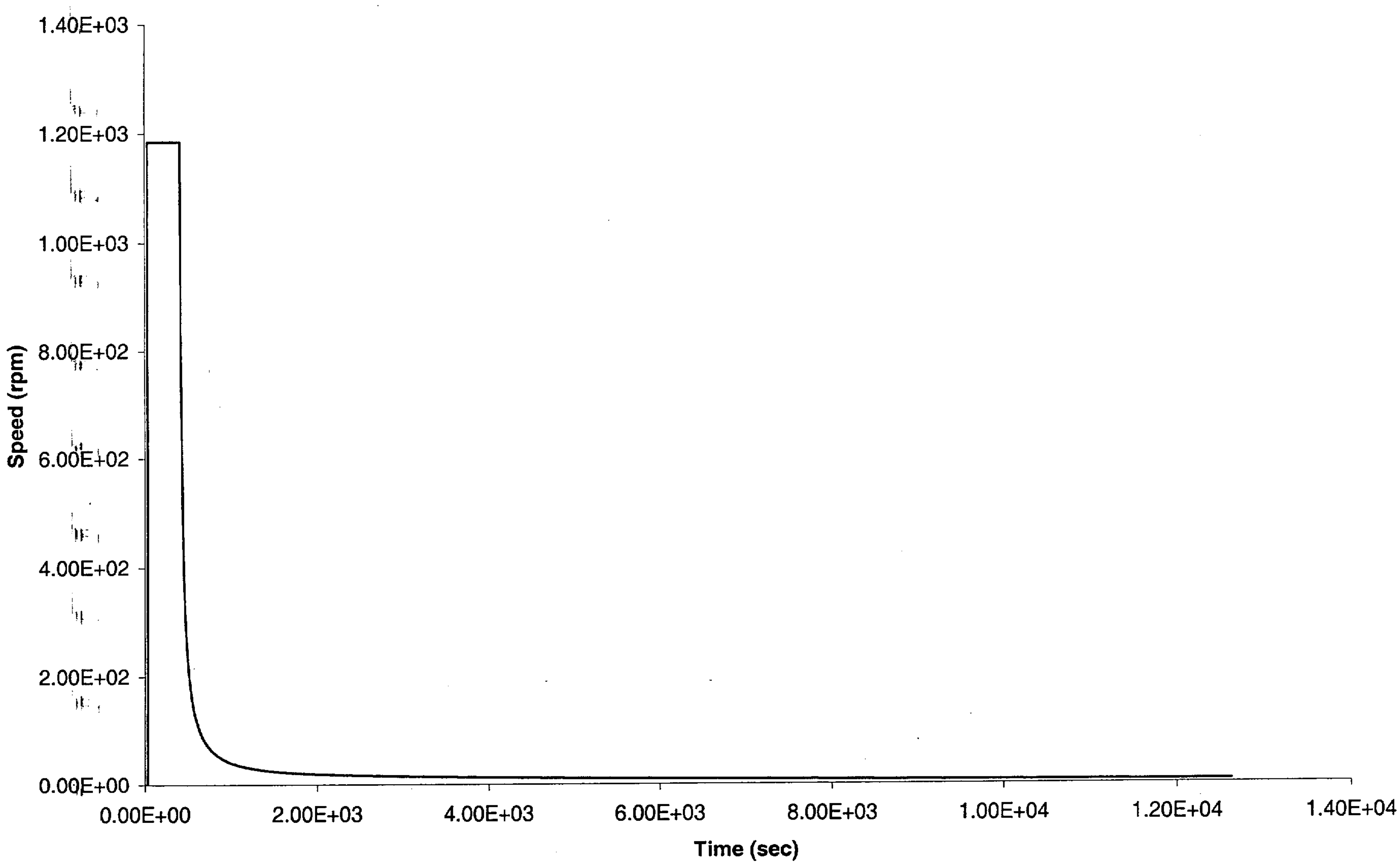

Fig. A.7-12: PORV Falsely Lifts and Sticks Open - Core Exit Subcooling

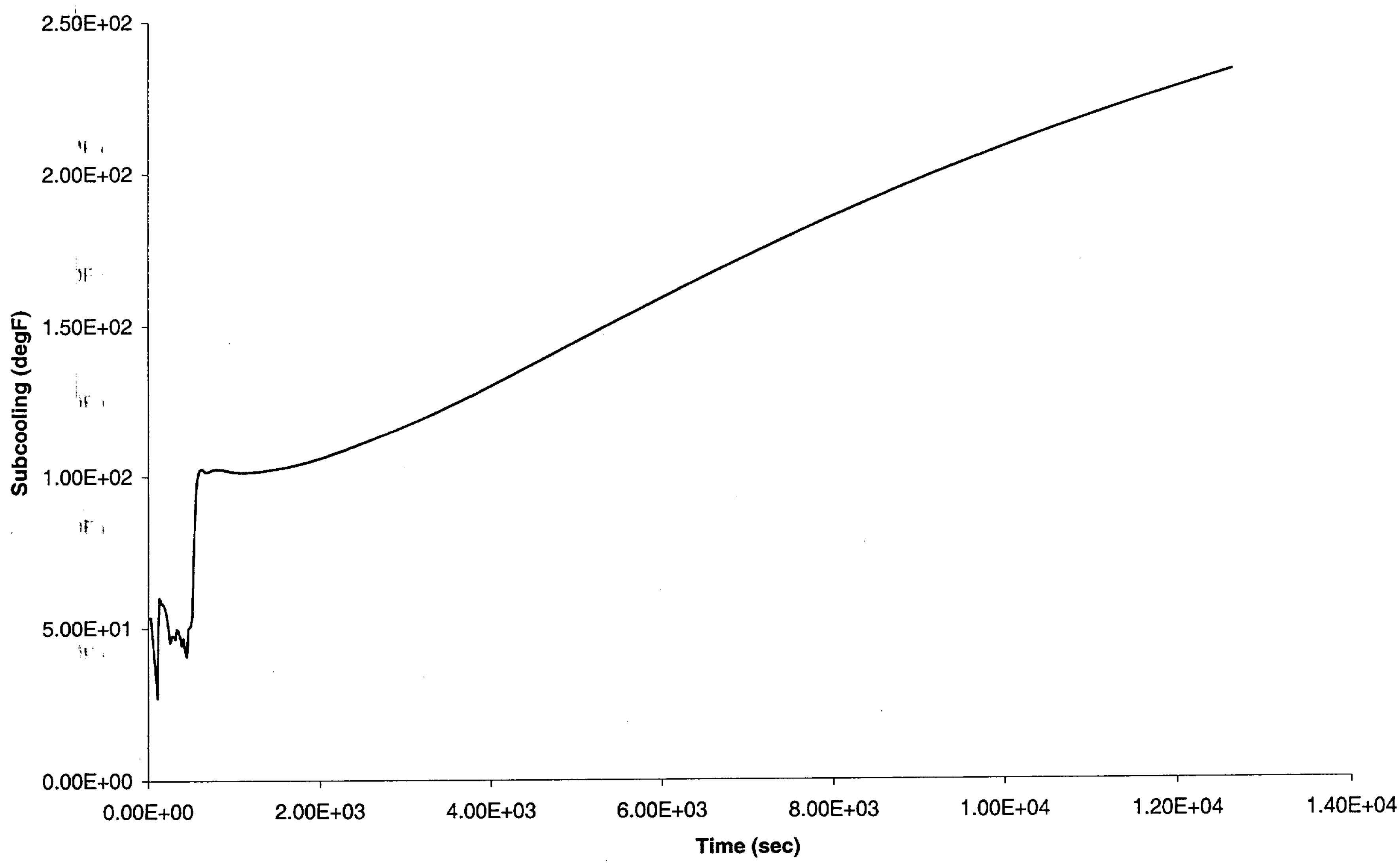

Fig. A.7-13: PORV Falsely Lifts and Sticks Open - RCS Cooling Rate

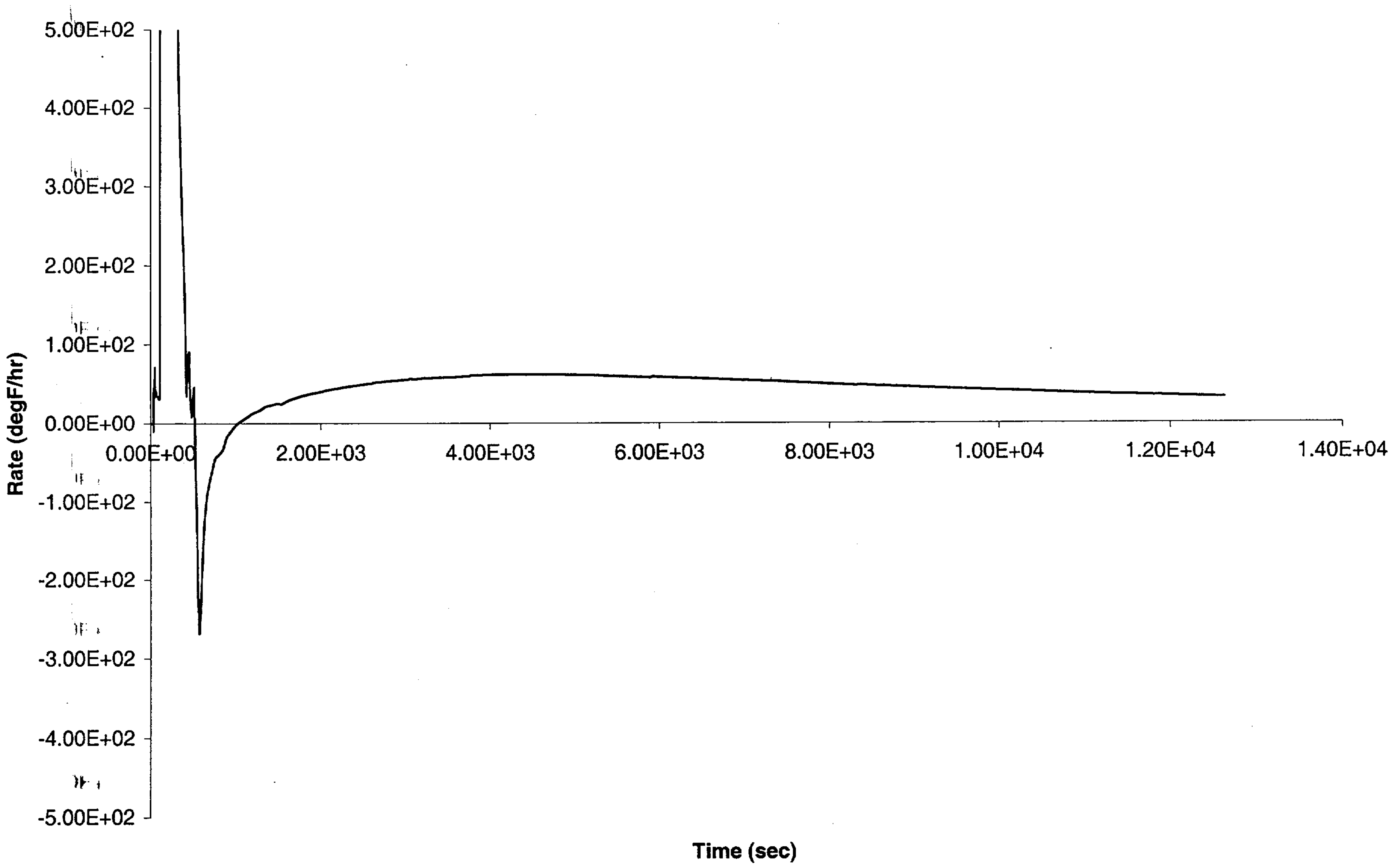

Fig. A.7-14: PORV Falsely Lifts and Sticks Open - Cummulative Charging + SI Flow

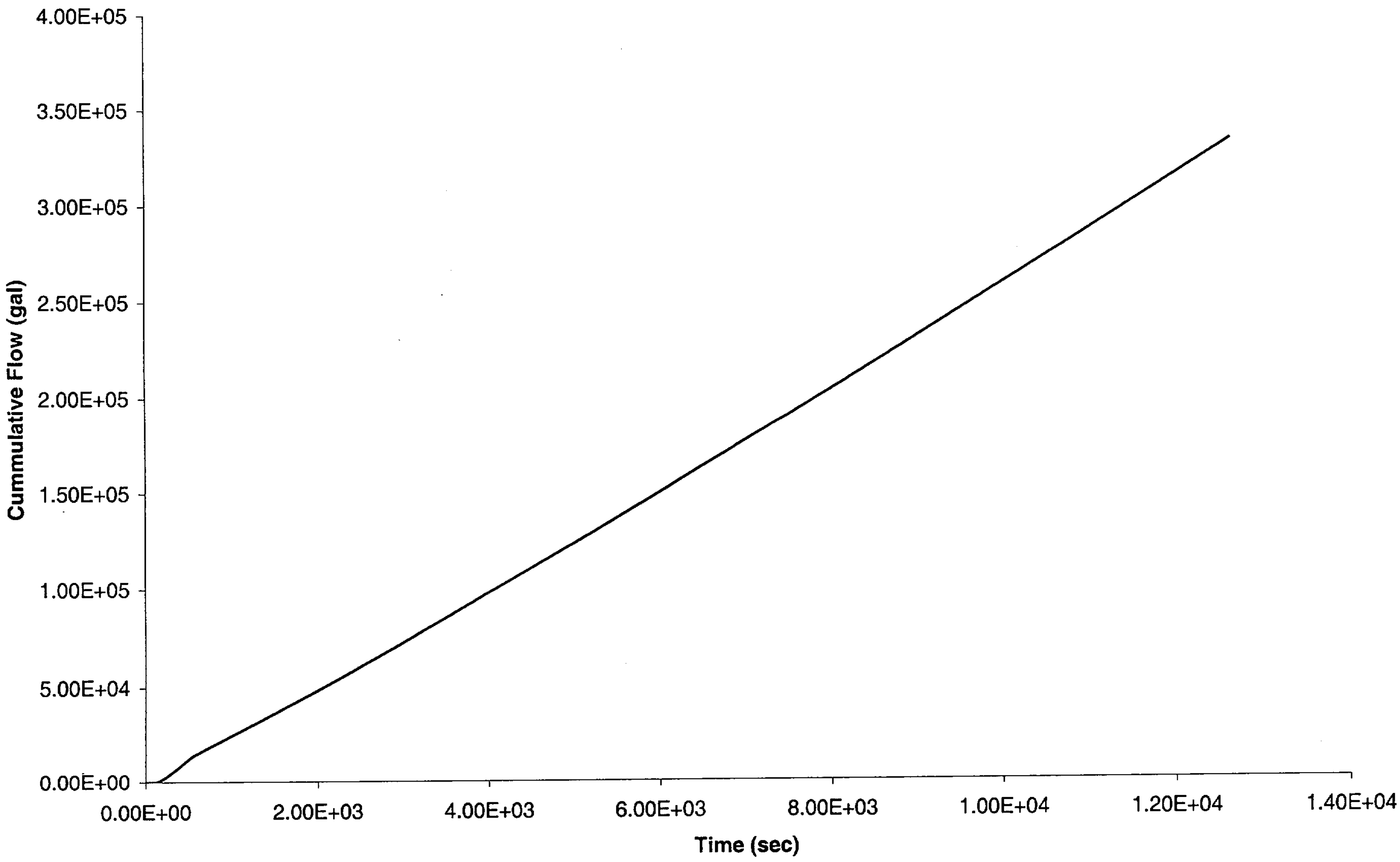

Fig. A.7-15: PORV Falsely Lifts and Sticks Open - PRT Pressure

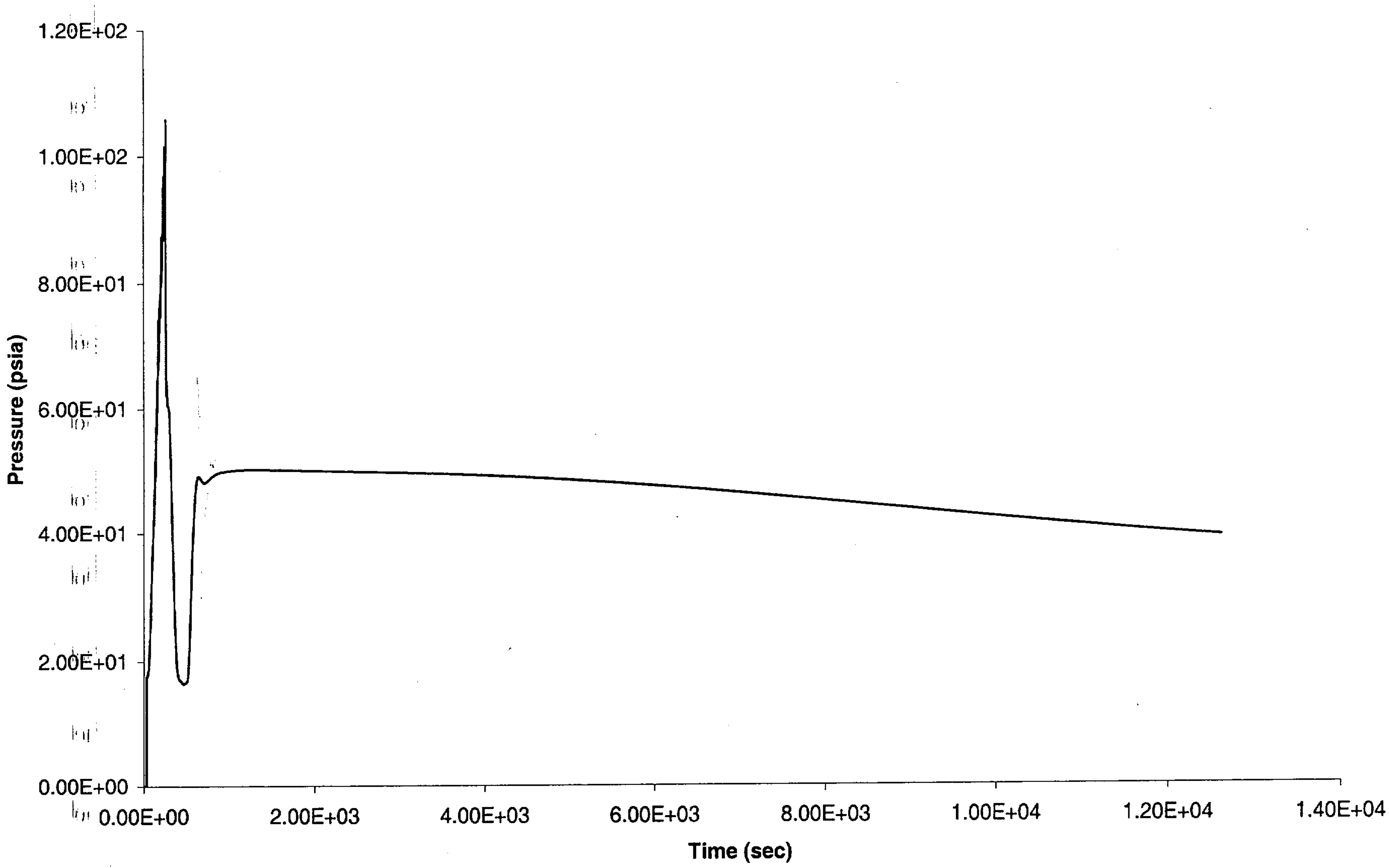

Fig. A.7-16: PORV Falsely Lifts and Sticks Open - PRT Burst Disk Flow

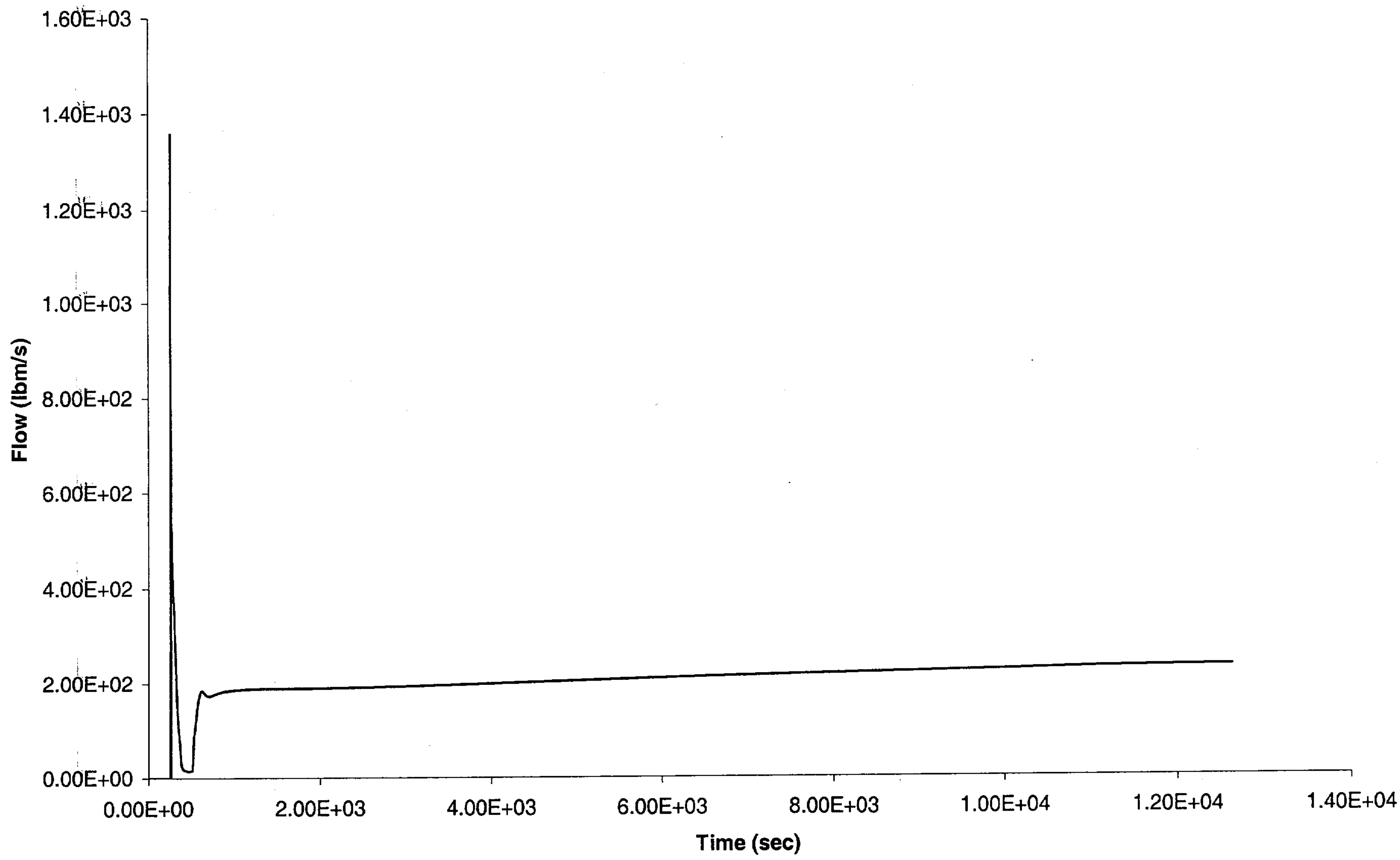

Fig. A.7-17: PORV Falsely Lifts and Sticks Open - Burst Disk Flow Quality

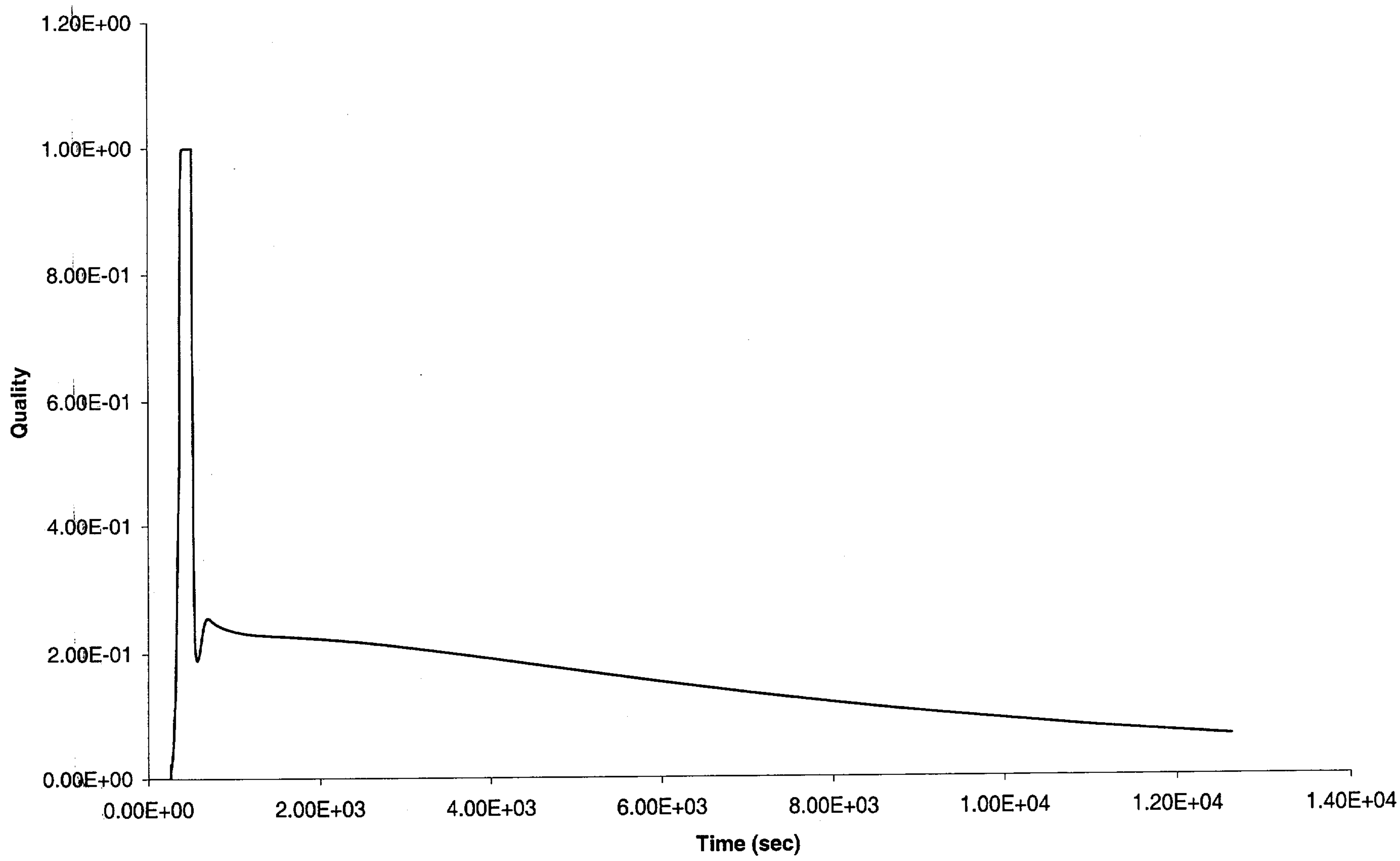

Fig. A.7-18: PORV Falsely Lifts and Sticks Open - Burst Disk Phasic Velocities

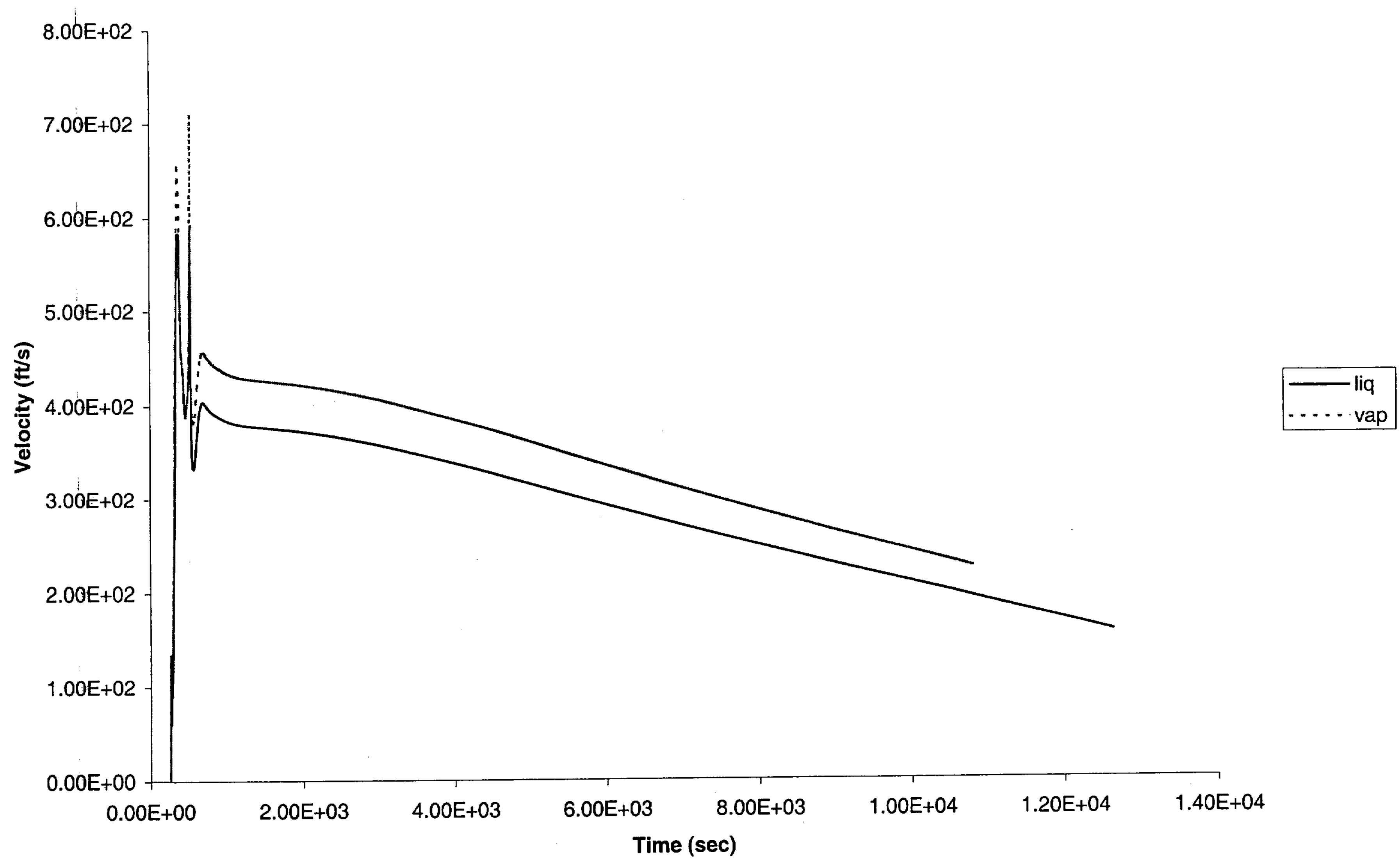

Fig. A.7-19: PORV Falsely Lifts and Sticks Open - PRT Liquid Temperature