Battelle
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201
Telephone (614) 424-6424
Telex 24-5454

June 13, 1984

(9.b.3)

Mr. M. Silberberg
Assistant Director for Research
and Technical Support
Accident Source Term Program Office, RES
Mail Stop 1130SS
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555

Dear Mel:

Enclosed for your information and use is the report summarizing our results for PWR Standard Problem Number Two. The results contained in this report have been previously presented and discussed at meetings of the Containment Loads Working Group (CLWG).

While it was the intent of PWR Standard Problem Number Two to focus on the issue of steam spike loadings in a subatmospheric PWR containment, our analyses indicate the possibility of significant loads due to hydrogen burning in a number of the cases specified. While this is not a new revelation, it does once again illustrate the complexities and phenomenological interdependence associated with severe accident analyses. As the "steam spike" goes away, so does its inerting effect on hydrogen burning. The pressures that would be predicted in the containment would depend on the ignition criteria assumed; the latter were not specified in the standard problem. As indicated in the enclosed report, under some of the conditions specified in the standard problem the pressure loads from hydrogen burning could be comparable or greater than those due to steam spikes.

If there are any questions on the results presented in the enclosed report, please feel free to contact me.

Sincerely,

Peter Cybulskis

PC/11d

Enclosure

[redacted]

130

REPORT

on

PWR STANDARD PROBLEM NUMBER TWO

to

U. S. NUCLEAR REGULATORY COMMISSION

June 12, 1984

by

Peter Cybulskis

BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

PWR STANDARD PROBLEM NUMBER TWO

INTRODUCTION

The objective of the Containment Loads Working Group (CLWG) is to develop an updated technical position on the relatively short term (few hours duration) containment pressure-temperature loading following reactor vessel failure. A way of developing an understanding of the problem is to have a number of experts analyze well-defined situations representative of the conditions expected during the course of severe reactor accidents. Comparison of the results of such analyses would bring into focus differences in the understanding of the phenomena and methods used to treat them as well as areas of agreement among the analysts. The analysis of a series of "standard problems" was the appraoch selected by the CLWG.

The second of the standard problems selected was the analysis of the "steam spike" in a subatmospheric containment PWR.

The particulars for the PWR Standard Problem Number Two were given in the January 11, 1984, memorandum from M. Silberberg, NRC. This report summarizes the analyses performed at Battelle's Columbus Laboratories in conjunction with this standard problem.

APPROACH

PWR Standard Problem Number Two and its variations were evaluated using the MARCH 2 computer code. However, the MARCH calculatons for these standard problem analyses differ considerably from normal MARCH calculations. Rather than starting the calculation at the beginning of the accident sequence and letting the code evaluate the parameters of interest thereafter, the MARCH input was set up to deliver to the reactor cavity the quantity and conditions of core debris as specified in the standard problem. Normal MARCH runs initiated from time zero of the accident sequence would not necessarily yield the quantity and conditions for the debris given in the standard problem. Thus, these standard problem analyses focus on the debris-water interaction (HOTDRP) and the containment response (MACE) models in MARCH 2. Additionally, for variations of the standard problem with limited water in the reactor cavity, the INTER subroutine for treating corium-concrete interactions comes into play.

A number of additional assumptions for items not specified in the standard problem definition were required in order to perform the MARCH calculations. These are described below. Since the MARCH analyses for this study were initiated at the time of reactor vessel failure, containment heat sink temperature distributions were required which took into account the heating up to that time in the accident. The heat sink temperatures used were taken from earlier analyses of the TMLB' sequence in subatmospheric containment. The MARCH calculations were started at 100 minutes after the start of the accident, with head failure taking place at 101 minutes. The time scale is needed for calculating decay heating in the core debris. Since fission product decay heat varies quite slowly at a few hours after shutdown, the results are isensitive to the actual time of head failure assumed. The interaction of the core debris with water in the reactor cavity was evaluated using the isolated particle quench model in HOTDRP; a particle diameter of 0.2 inch was assumed. The particle quench model takes into account metal-water reactions that may take place during the course of the interaction. Hydrogen burning considerations were not explicitly identified as part of this standard problem; in the MARCH analyses, however, the flammability of the containment atmosphere can be readily monitored and this was done for each of the cases considered.

RESULTS

The results of the calculations for PWR Standard Problem Number Two are summarized in Table I with graphical display of the containment response given in Figures 1 - 21. In all the cases considered the containment was at 28 psia just prior to vessel head failure. The latter was followed by the release of the high pressure steam from the primary system and then the interaction of the core derbis with water and/or concrete in the reactor cavity. Heat losses to containment structures were included in the analyses, with initial structure temperatures input to take into account the heating taking place prior to head failure.

Case 0 represents the nominal cases as defined in the standard problem. Figures 1 and 2 show the calculated pressure and temperature responses for this case. Immediately following vessel failure the containment pressure

rises from 28 to 42 psia due to the release of high pressure steam from the primary system. This is followed by the interaction of the core debris with the accumulator water, raising the containment pressure to a peak of 73 psia. In the nominal case at the time of the peak containment pressure the core debris have been quenched essentially down to the water temperature, and there is about 61,000 lb of water remaining in the reactor cavity. It takes an additional 46 minutes for this water to be boiled off by decay heating, and about a further 52 minutes for the debris to heat up to the point (~2500 F) where it is assumed to start attacking the concrete. Following debris quench, the pressure in the containment declines due to steam condensation on structures. This general trend in behavior is observed in all the high primary system pressure cases, i.e., Cases 1, 2, 5, and 6, with the magnitude of the containment loads depending on the specifics of each case. The highest containment pressure calculated is 107 psia for Case 1. This case includes the large mass of corium, high corium temperature, and high in-vessel metal-water reaction. For this combination of inputs the containment pressurization is limited by the available water, with the debris at about 1450 F at the time all the water in the cavity has been evaporated. A similar situation is found for Case 5 where all the water has been evaporated with the debris still at about 1210 F. In Cases 2 and 6, peak containment pressures are limited by the stored energy in the core debris, with significant amounts of water remaining at the time the debris has quenched.

In the high primary system pressure cases discussed above, failure of the vessel head leads to the discharge of accumulator water into the reactor cavity; this provides an ample supply of water for interaction with the core debris. In the low primary system pressure cases, the accumulators are assumed to have discharged prior to vessel failure; in these cases the amount of water in the reactor cavity may be quite limmited. This is reflected in the containment loadings for Cases 3, 4, 7, and 8. Figures 7 and 8 show the containment pressure and temperature responses, respectively, for Case 3. The release of the primary system steam raises the containment pressure from 28 to 38 psia immediately following vessel failure. This is followed by the evaporation of the available water, with the pressure rising to 46 psia. With the debris at essentially the same temperature with which it entered the cavity, and in the

absence of water, immediate attack of the concrete basemat is predicted. Since the gas generation rate from the decomposition of the basaltic concrete is relatively low, there is no further containment pressurization over the time scale illustrated. The decline of the containment pressure from the initial peak is due to condensation of steam on structures. Very similar behavior is observed for Cases 4, 7, and 8.

While hydrogen burning was not explicitly included as a consideration in this standard problem, the results of our analyses indicate that for several variations of the problem, hydrogen burning could be an issue. The high primary system pressure cases were characterized by significant steam spikes, with the high steam concentrations precluding hydrogen burning. In the low pressure cases, the quantities of water interacting with the debris were limited, as were the attendant steam spikes. As some of the steam condensed and as additional hydrogen was generated by the corium-concrete interactions, flammable conditions were predicted to be produced in all the low primary system pressure cases considered. Figures 9, 12, 18, and 21 show for Cases 3, 4, 7, and 8, respectively, the adiabatic burn pressures assuming ignition at any time after flammable conditions have been reached. The hydrogen was not actually burned in these analyses; the calculation of the adiabatic burn pressures as functions of time is just a convenient way to ascertain the magnitude of the loadings <u>if</u> burns were to occur. In these analyses, a hydrogen concentration of 10 $^{v}/_{o}$ was assumed to be required for flammability, subject to availability of oxygen and absence of inerting due to other diluents. While hydrogen ignition and burning can take place at lower hydrogen concentrations, in the absence of well defined ignition sources, there is little reason to assume early ignition. The results shown in Figures 9, 12, 18, and 21 indicate that under the assumptions utilized none of these cases would have flammable compositions immediately after head failure, but that flammable conditions would develop with time in all the cases. Case 7 was found to reach the assumed flammability limits the earliest, with the others being delayed more. For different flammability thresholds, the times to reach them would obviously be different. While actual burn calculations would produce lower pressures than the ones illustrated, they would not be dramatically lower. The results of these analyses show that in the absence of significant steam spikes and their inerting effect, hydrogen burning may be a significant threat

to containment integrity. The peak pressures due to such burns may be as high or higher than the large steam spikes previously discussed.

CONCLUSIONS

The results for PWR Standard Problem Number Two fall into two distinct categories. Those cases in which core degradation takes place at elevated pressures and the failure of the reactor vessel head is followed by the discharge of accumulator water lead to large steam spike loading of the containment. The cases in which the primary system pressures are reduced and accumulator discharge occurs prior to reactor vessel failure produce relatively small steam loadings to the containment, but have the potential of undergoing hydrogen burning.

For the specific parameters included in this standard problem, the high primary system pressure cases led to peak containment pressures of 71 - 107 psia and peak atmosphere temperatures of 300 - 424 F. In the extreme of these cases, containment pressurization was limited by the quantity of water available to interact with the core debris; in the other cases, the debris were completely quenched. The high steam partial pressures predicted in all the high primary system pressure cases would preclude hydrogen burning.

The reduced primary system pressure cases resulted in peak containment pressures of 41 - 46 psia with peak atmosphere temperatures of 336 - 417 F. In all these cases, the quantity of water in the reactor cavity available to interact with the core debris was limited. While nonflammable conditions were found to exist in all these cases immediately after vessel failure, additional hydrogen generation from corium-concrete interaction together with steam condensation led to the development of flammable conditions later in time. The containment loads that would be predicted from possible hydrogen burns would obviously depend on the ignition criteria assumed. However, from the adiabatic burn pressures evaluated as part of this analysis, it is evident that hydrogen burn pressures could be as high or higher than the steam spike loadings calculated for the high pressure cases.

Since the containment loads in PWR Standard Problem Number Two result from two distinct phenomena, only one of which was explicitly defined for consideration, it is even more difficult than usual to derive a set of low,

nominal, and high containment loads for this problem. Nevertheless, assuming that in the absence of steam inerting hydrogen burning is likely, the following containment load distribution is inferred: 70 psia represents the low containment pressure loading, 120 psia is the high load, and 100 psia would be representative of a nominal pressure load for this problem. These containment pressure loads assume that the energy available in the debris goes into generating steam and/or decomposing concrete, including appropriate chemical reactions. These loadings do not reflect the possibility of the direct heating of the containment atmosphere by the core debris, nor the possible air oxidation of the metallic components of the debris. Such considerations may increase the containment pressure and temperature loadings above those calculated in the present analyses.

The most significant parameters with regard to the predicted containment pressure loads were found to be mass and temperature of the debris, and the quantity of water available for interaction. In cases with appreciable water available, containment pressure loads were found to increase with increasing mass and temperature of debris until all the available water was evaporated. In cases with limited water available, steam pressurization was also limited, but the occurrence of large hydrogen burns became possible.

PWR STANDARD PROBLEM NUMBER TWO

Summary of Results

Case	Corium Composition	Corium Temp, F (C)	Primary Pressure (psi)	Water Depth(in)	Peak Pressure (psi)	Peak Temp(^{o}F.)
1	H	4940 (2727)	2280.	13.	107	424
2	L	2780 (1527)	2280.	13.	71	300
3	L	4940 (2727)	940.	13.	46*	349*
4	H	2780 (1527)	940.	13.	46*	336*
5	L	4940 (2727)	2280.	2.	101	421
6	H	2780 (1527)	2280.	2.	81	318
7	H	4940 (2727)	940.	2.	46*	417*
8	L	2780 (1527)	940.	2.	41*	341*
0		4100 (2260)	2280.	4.	73	334

* Flammable conditions predicted, but hydrogen burning not included in these values.

TABLE 1.

Battelle
Columbus Laboratories

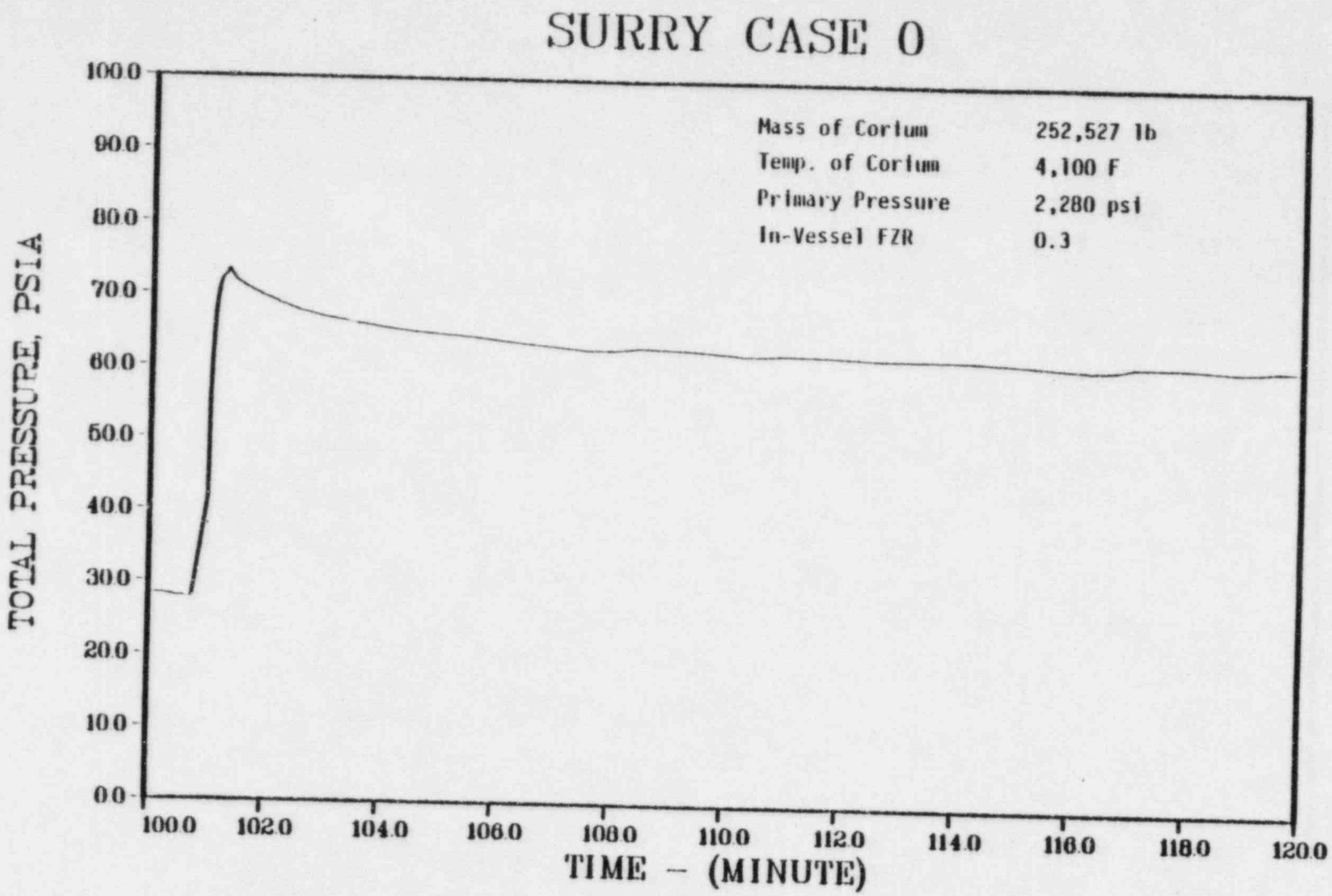

SURRY CASE 0
Mass of Corium 252,527 lb
Temp. of Corium 4,100 F
Primary Pressure 2,280 psi
In-Vessel FZR 0.3
TOTAL PRESSURE, PSIA
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0
TIME – (MINUTE)

FIGURE 1.

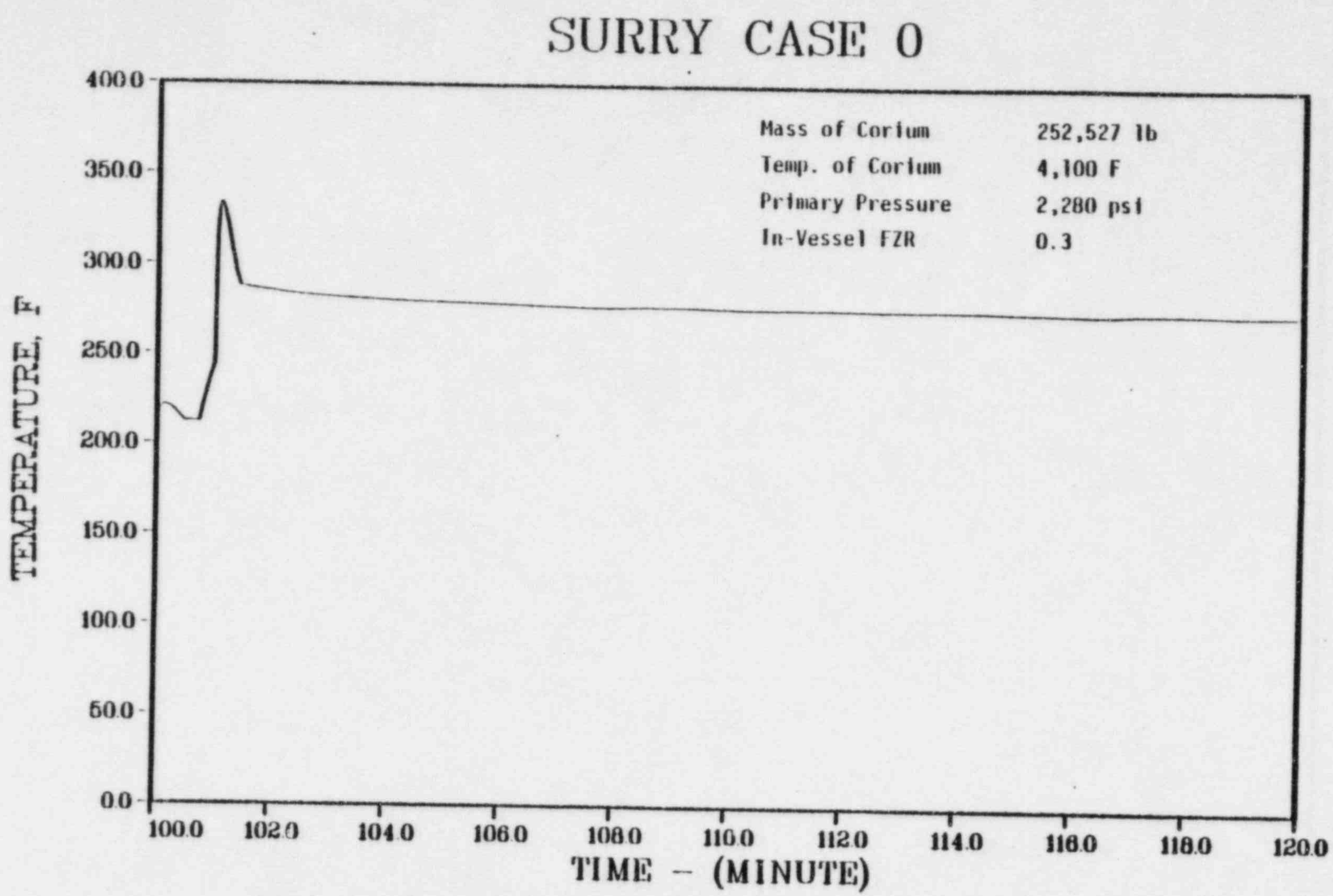
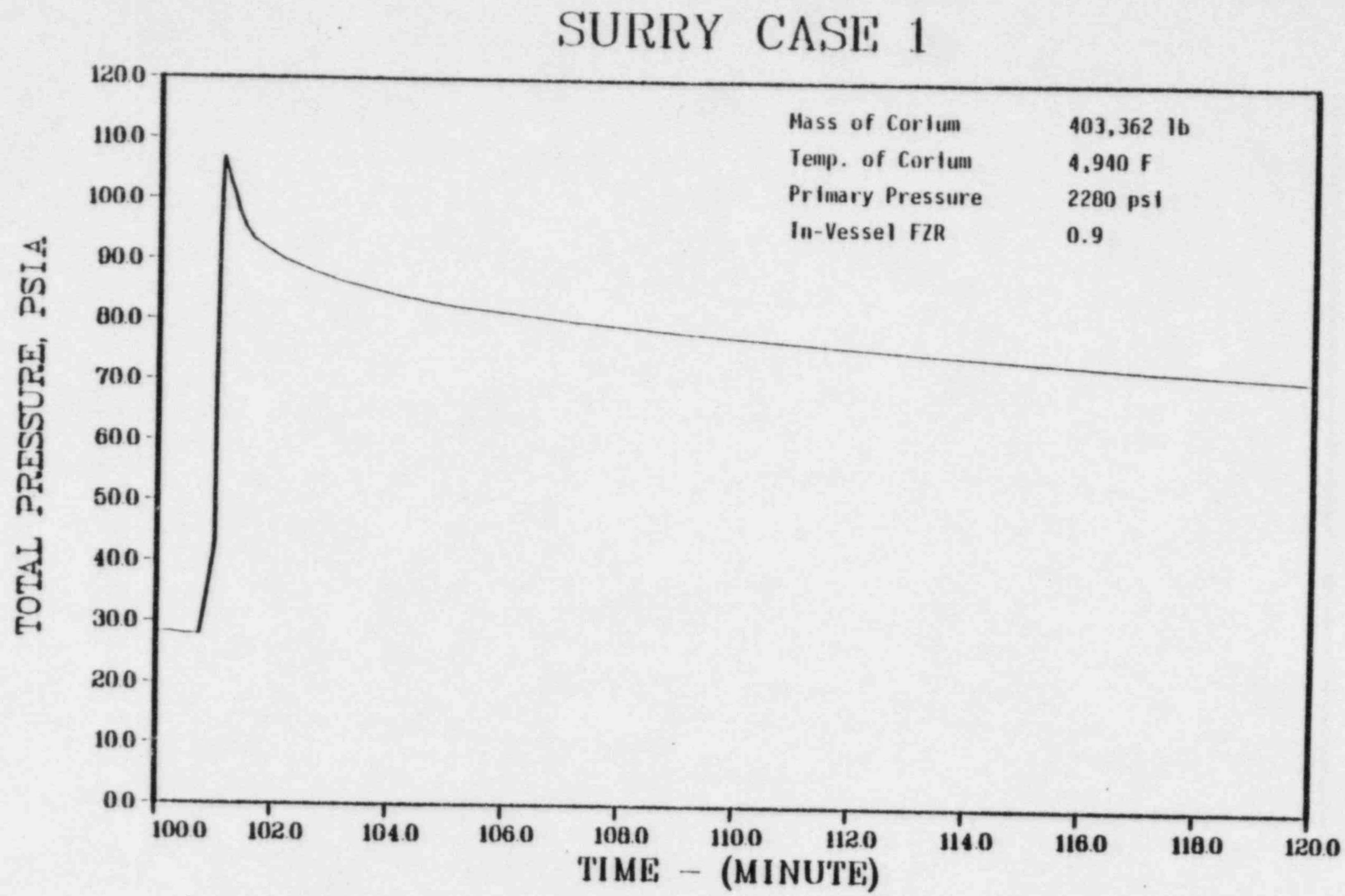
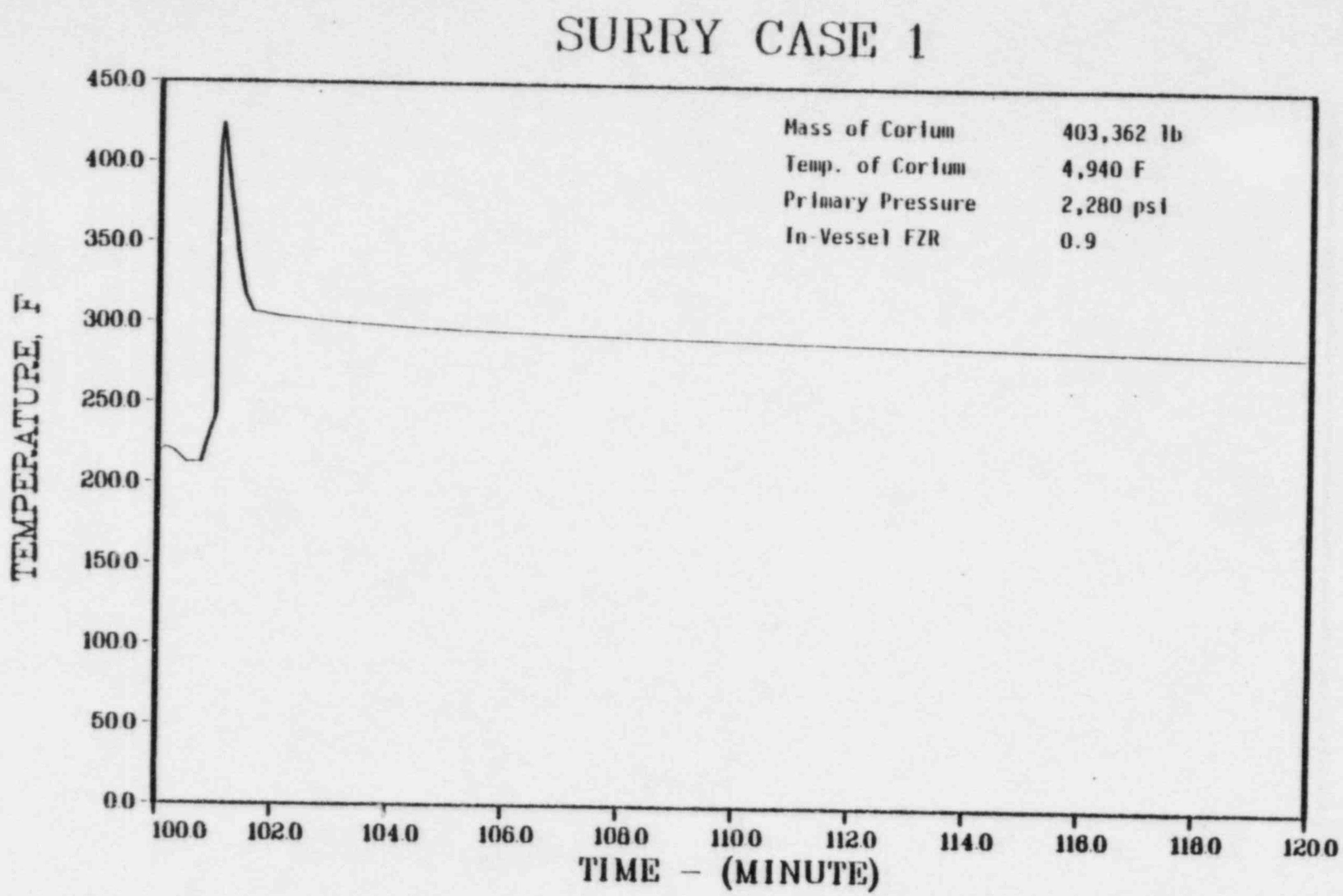

SURRY CASE 0
Mass of Corium 252,527 lb
Temp. of Corium 4,100 F
Primary Pressure 2,280 psi
In-Vessel FZR 0.3
TEMPERATURE, F
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0
TIME – (MINUTE)

FIGURE 2.



SURRY CASE 1
Mass of Corium 403,362 lb
Temp. of Corium 4,940 F
Primary Pressure 2280 psi
In-Vessel FZR 0.9
TOTAL PRESSURE, PSIA
TIME – (MINUTE)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0

FIGURE 3.



SURRY CASE 1
Mass of Corium 403,362 lb
Temp. of Corium 4,940 F
Primary Pressure 2,280 psi
In-Vessel FZR 0.9
TEMPERATURE, F
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0
TIME – (MINUTE)

FIGURE 4.

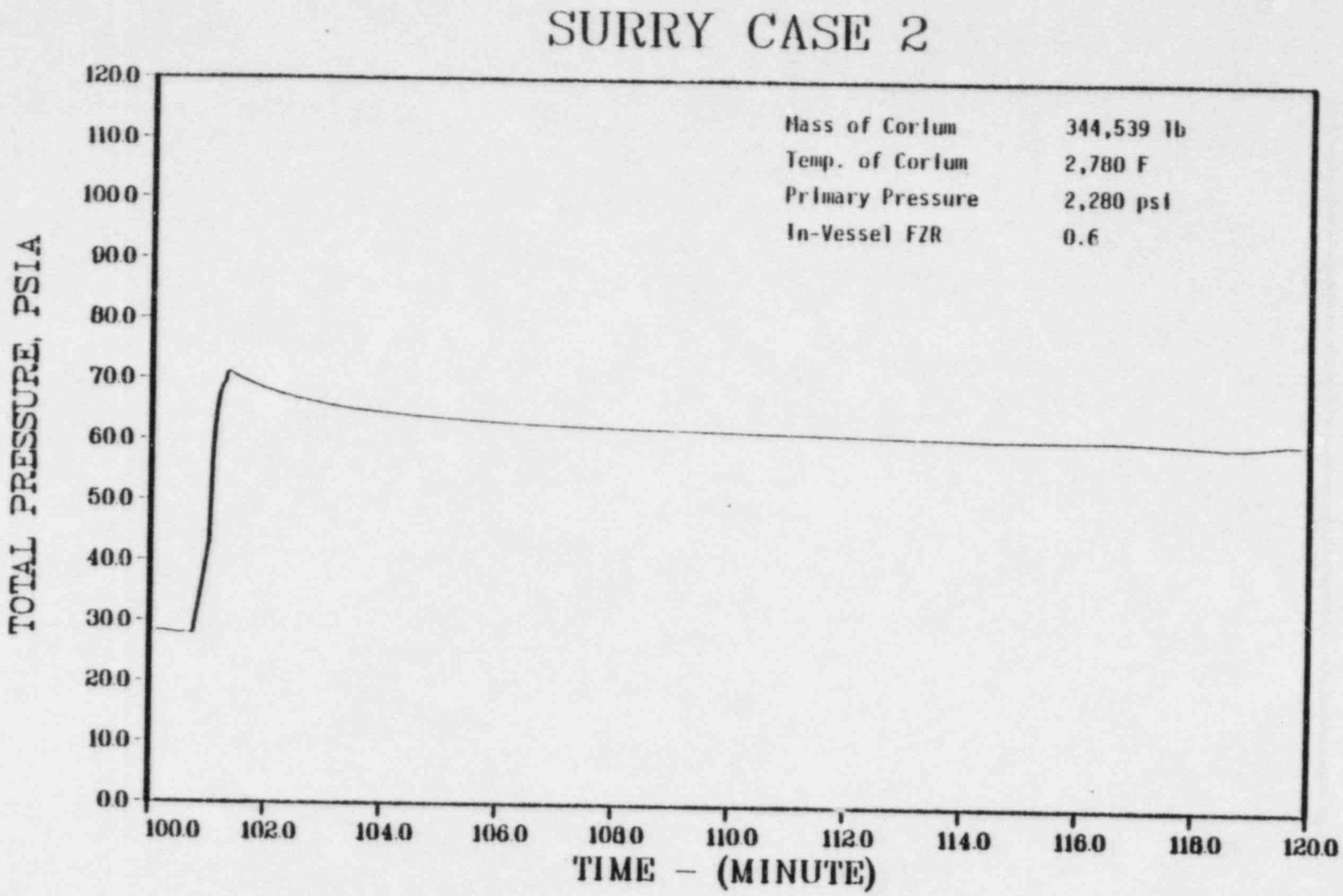

SURRY CASE 2
Mass of Corium 344,539 lb
Temp. of Corium 2,780 F
Primary Pressure 2,280 psi
In-Vessel FZR 0.6
TOTAL PRESSURE, PSIA
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0
TIME – (MINUTE)

FIGURE 5.

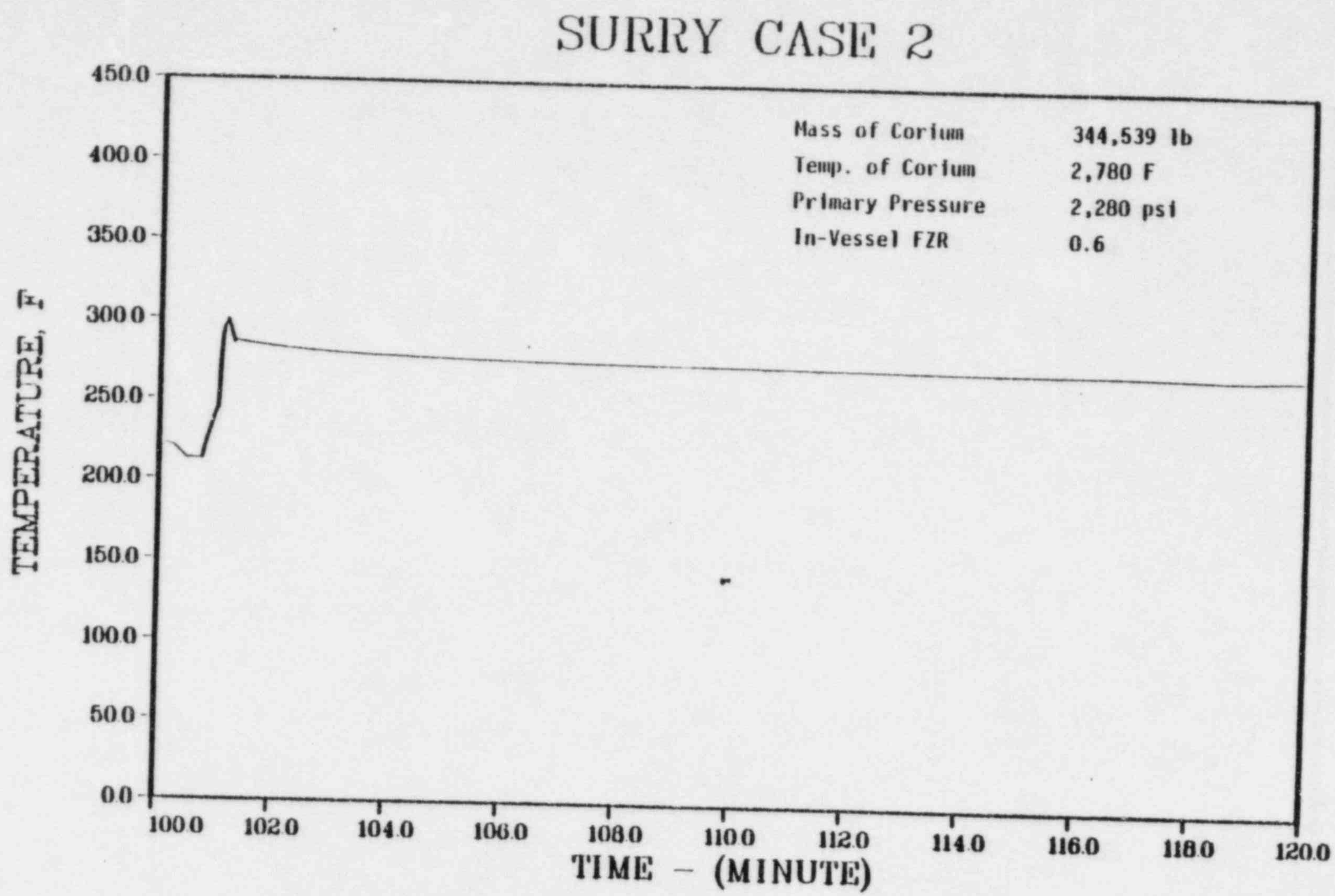
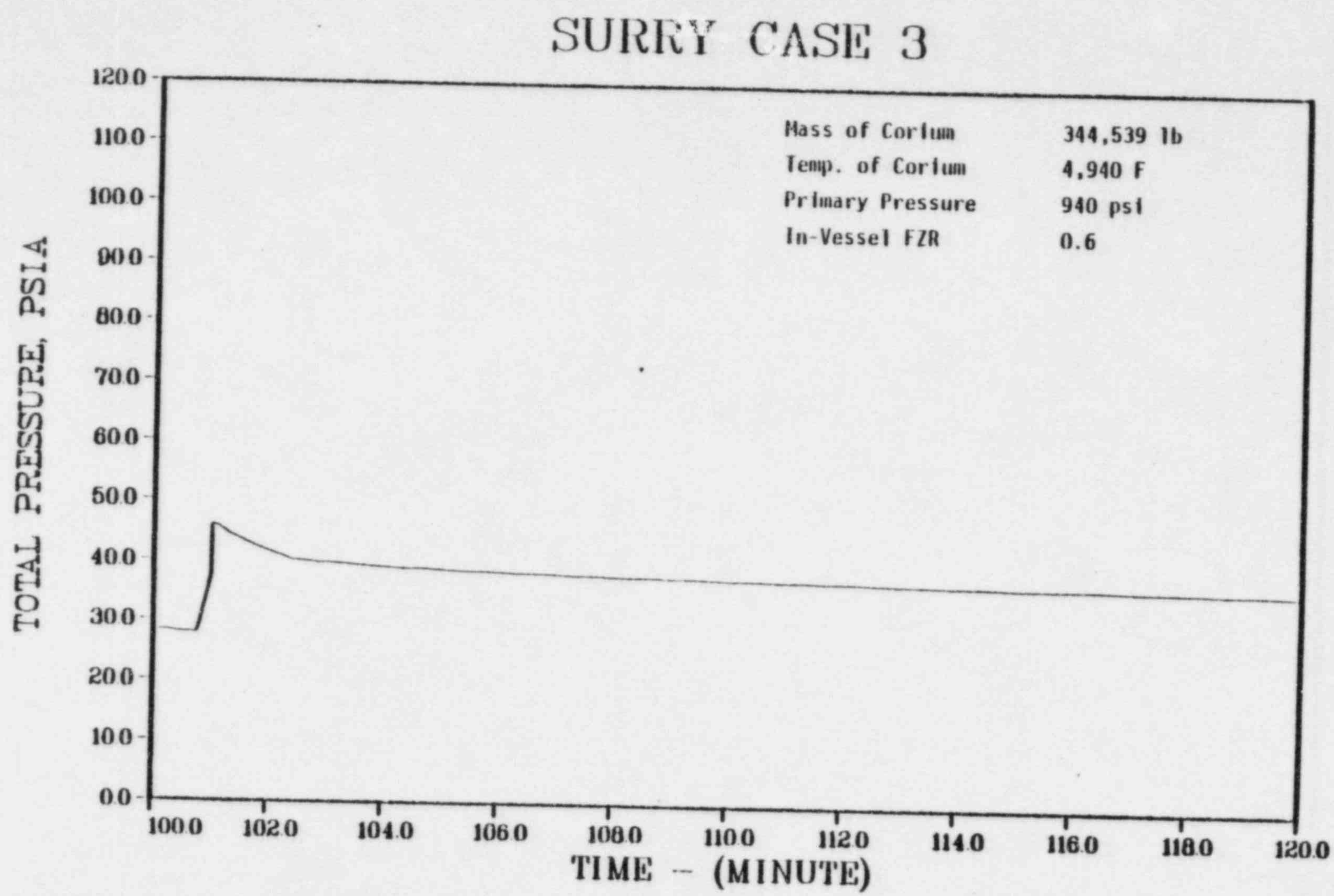

SURRY CASE 2
Mass of Corium 344,539 lb
Temp. of Corium 2,780 F
Primary Pressure 2,280 psi
In-Vessel FZR 0.6
TEMPERATURE, F
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0
TIME – (MINUTE)

FIGURE 6.



SURRY CASE 3
Mass of Corium 344,539 lb
Temp. of Corium 4,940 F
Primary Pressure 940 psi
In-Vessel FZR 0.6
TOTAL PRESSURE, PSIA
TIME – (MINUTE)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0

FIGURE 7.

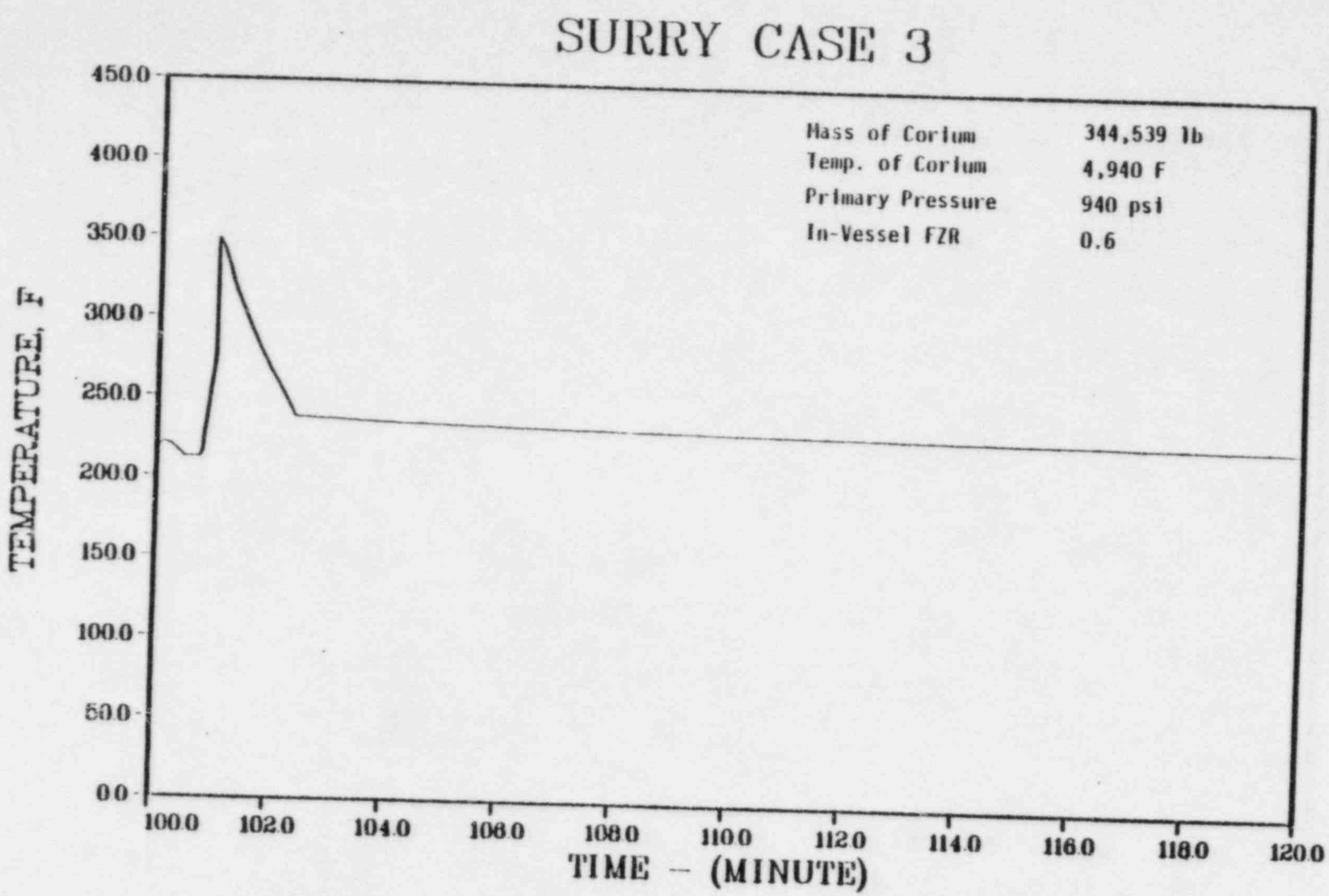

SURRY CASE 3
Mass of Corium 344,539 lb
Temp. of Corium 4,940 F
Primary Pressure 940 psi
In-Vessel FZR 0.6
TEMPERATURE, F
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0
TIME – (MINUTE)

FIGURE 8.

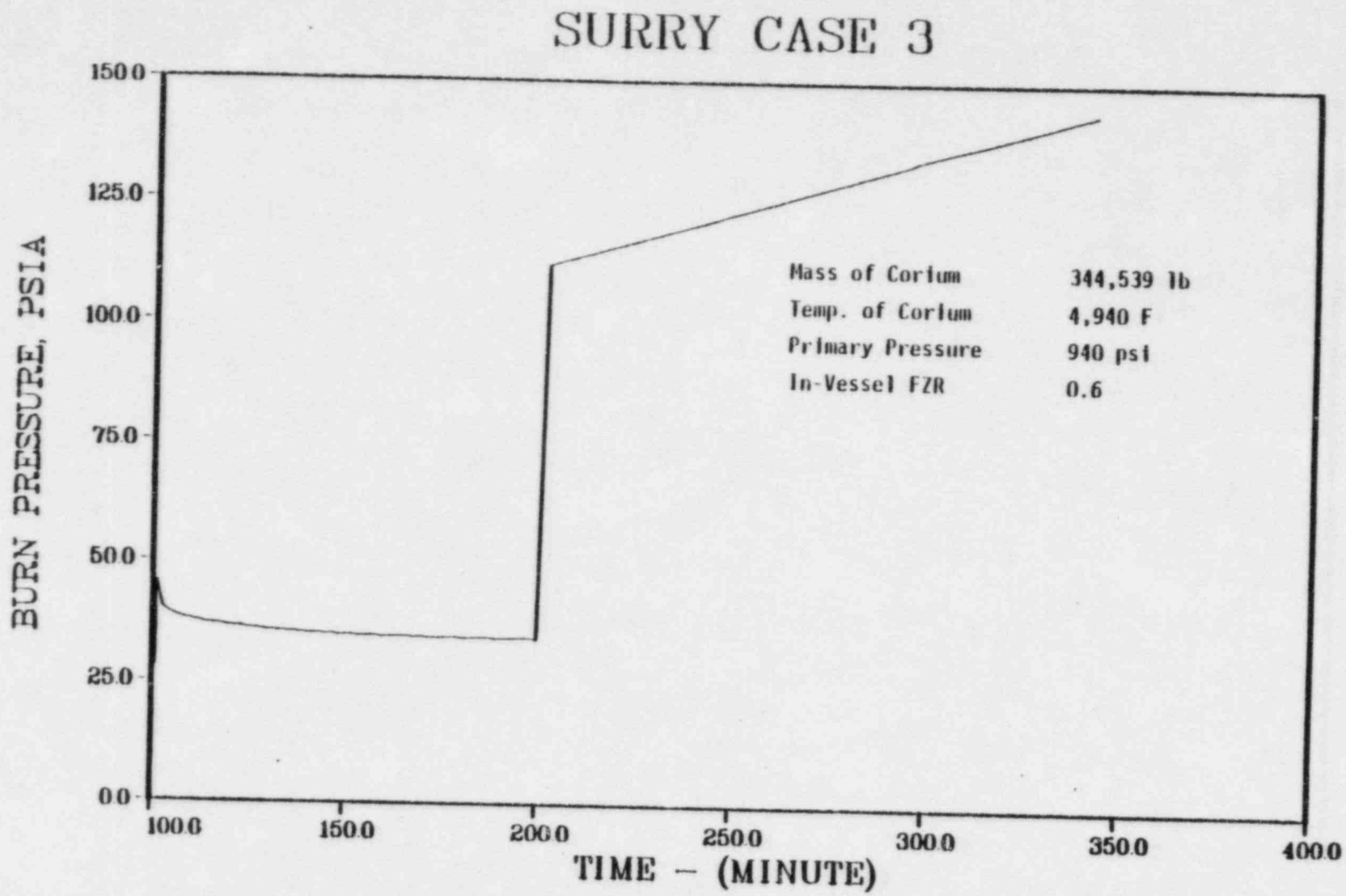

SURRY CASE 3
BURN PRESSURE, PSIA
150.0
125.0
100.0
75.0
50.0
25.0
0.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
TIME – (MINUTE)
Mass of Corium 344,539 lb
Temp. of Corium 4,940 F
Primary Pressure 940 psi
In-Vessel FZR 0.6

FIGURE 9.

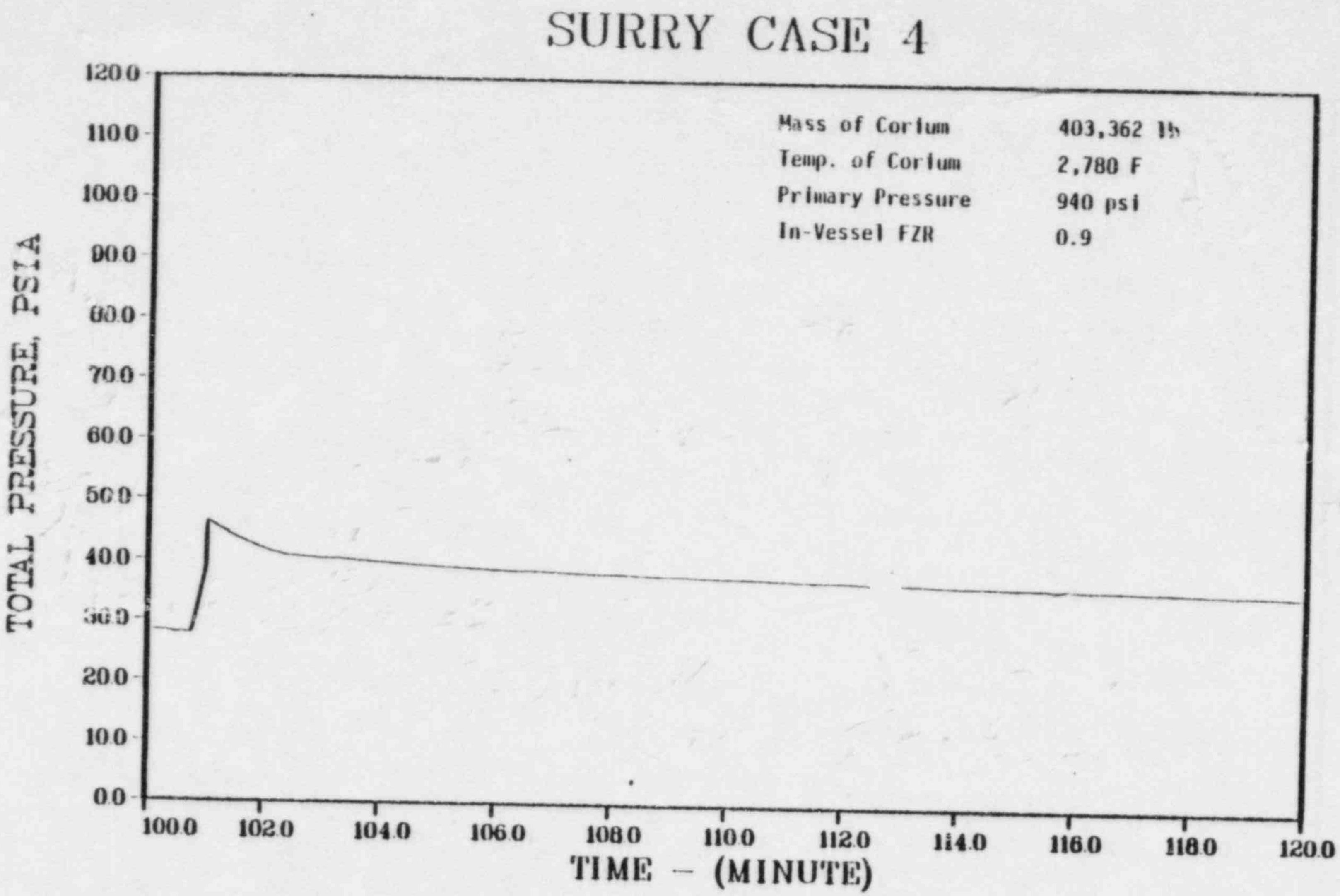
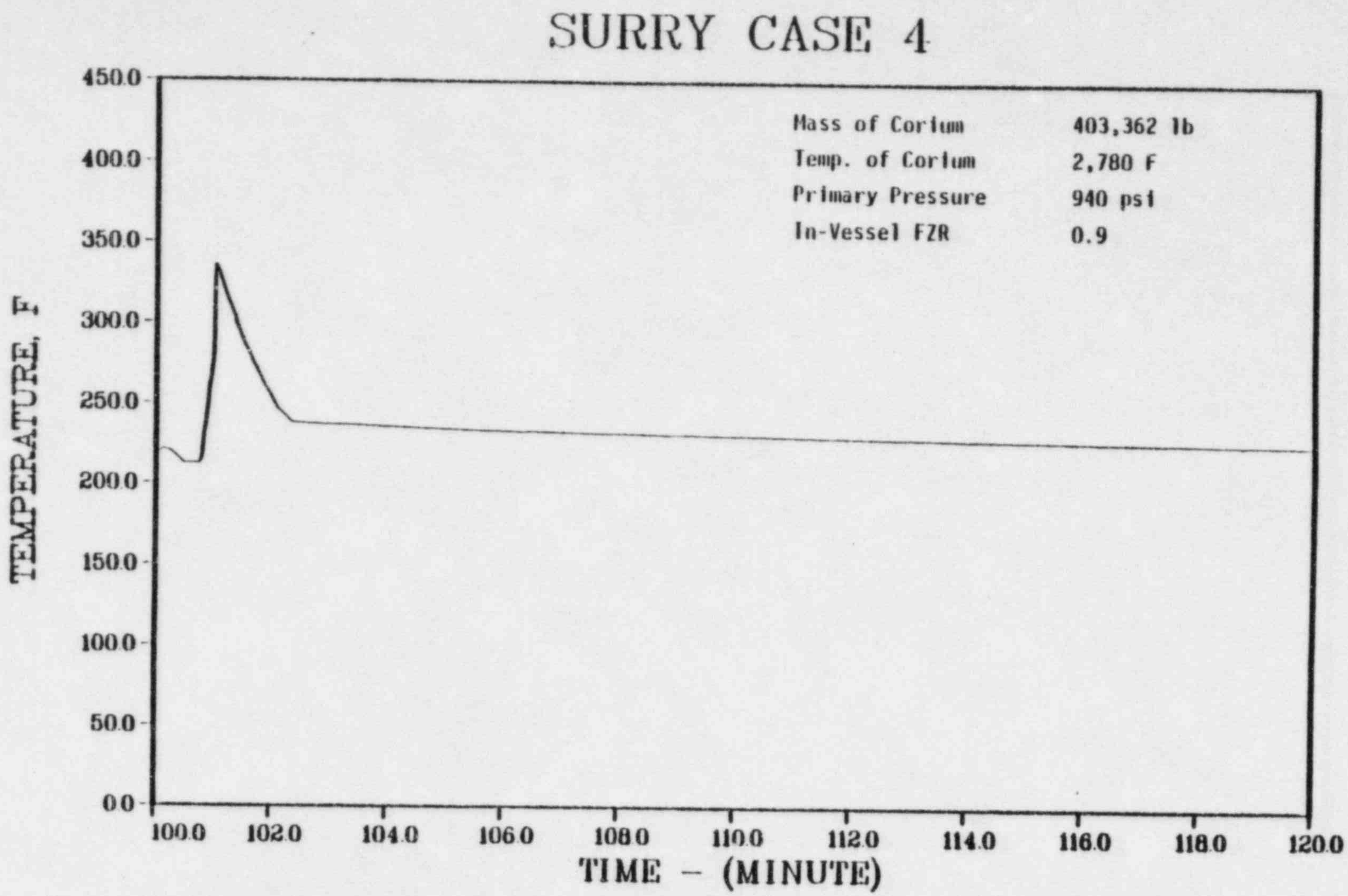

SURRY CASE 4
Mass of Corium 403,362 lb
Temp. of Corium 2,780 F
Primary Pressure 940 psi
In-Vessel FZR 0.9
TOTAL PRESSURE, PSIA
TIME – (MINUTE)

FIGURE 10.



SURRY CASE 4
Mass of Corium 403,362 lb
Temp. of Corium 2,780 F
Primary Pressure 940 psi
In-Vessel FZR 0.9
TEMPERATURE, F
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0
TIME – (MINUTE)

FIGURE 11.

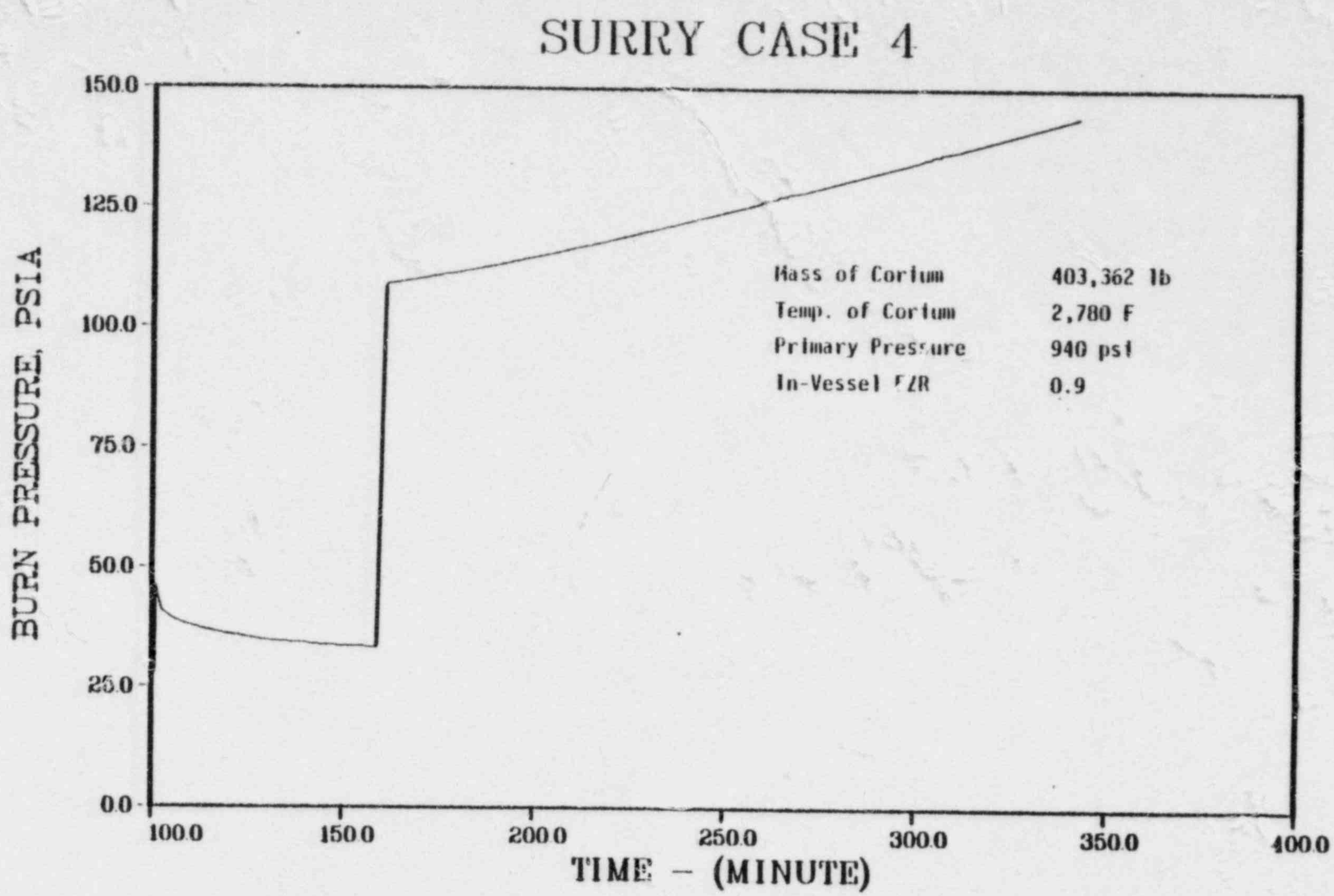

SURRY CASE 4
BURN PRESSURE, PSIA
150.0
125.0
100.0
75.0
50.0
25.0
0.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
TIME – (MINUTE)
Mass of Corium 403,362 lb
Temp. of Corium 2,780 F
Primary Pressure 940 psi
In-Vessel FZR 0.9

FIGURE 12.

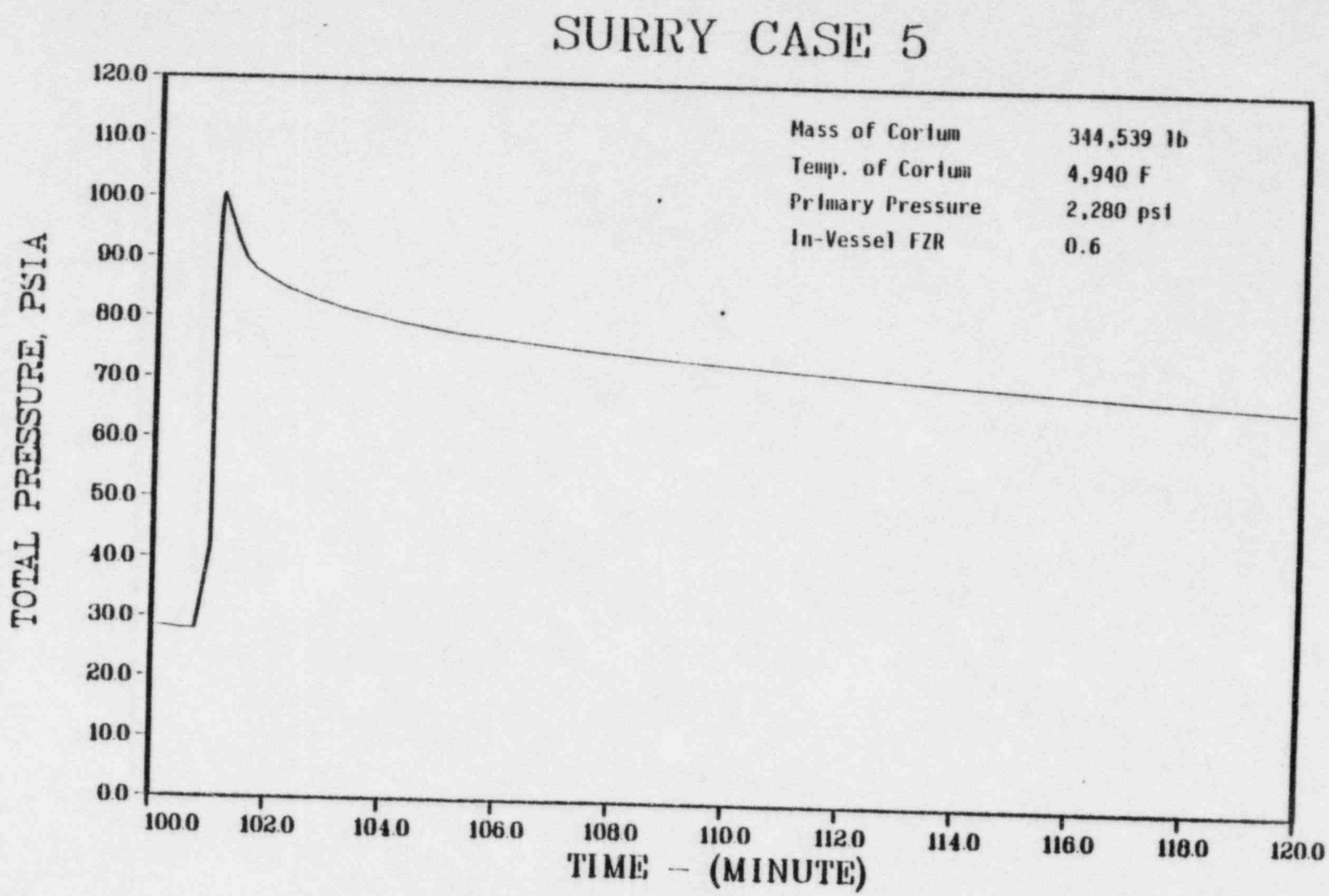

SURRY CASE 5
Mass of Corium 344,539 lb
Temp. of Corium 4,940 F
Primary Pressure 2,280 psi
In-Vessel FZR 0.6
TOTAL PRESSURE, PSIA
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0
TIME – (MINUTE)

FIGURE 13.

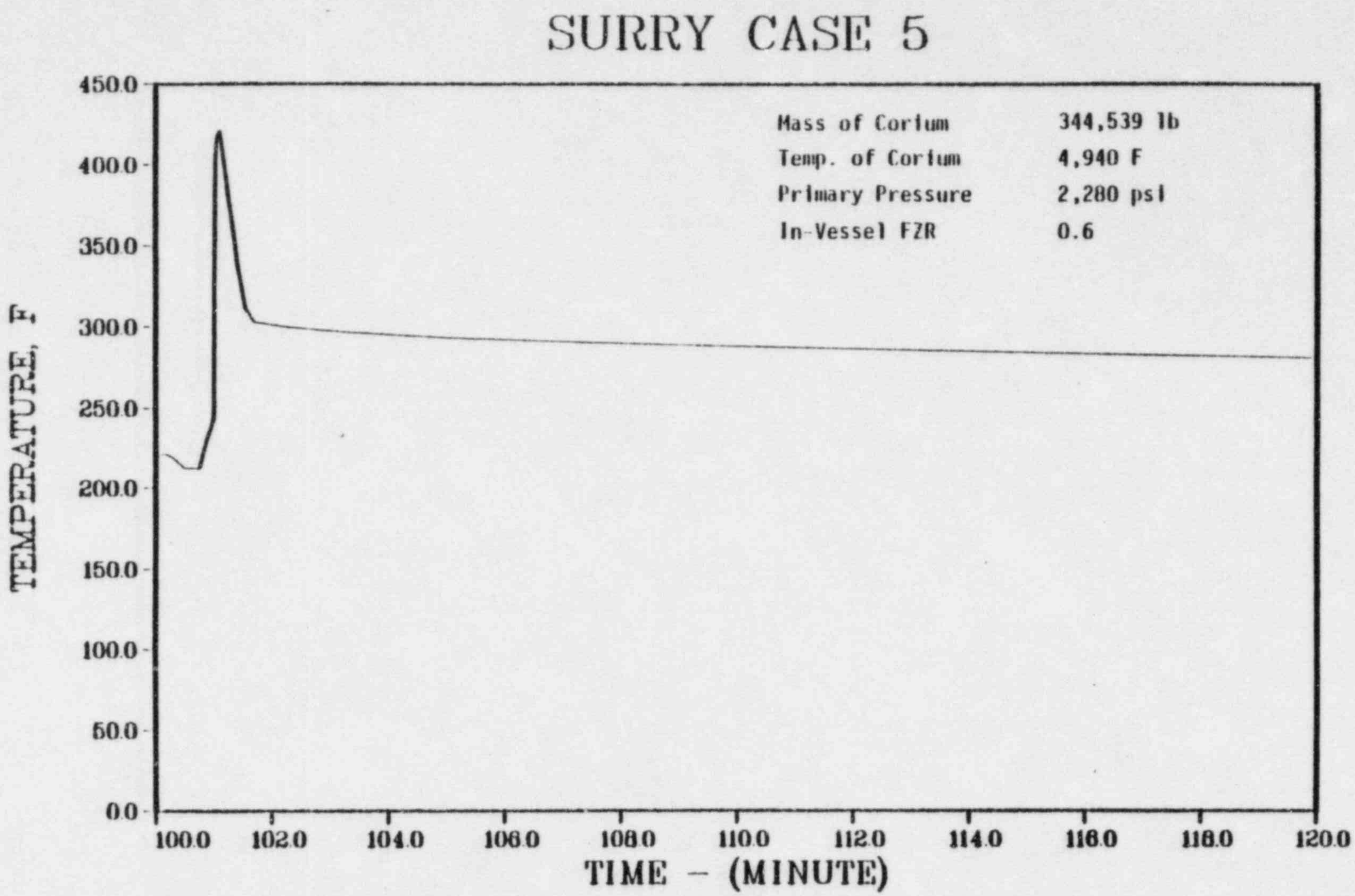
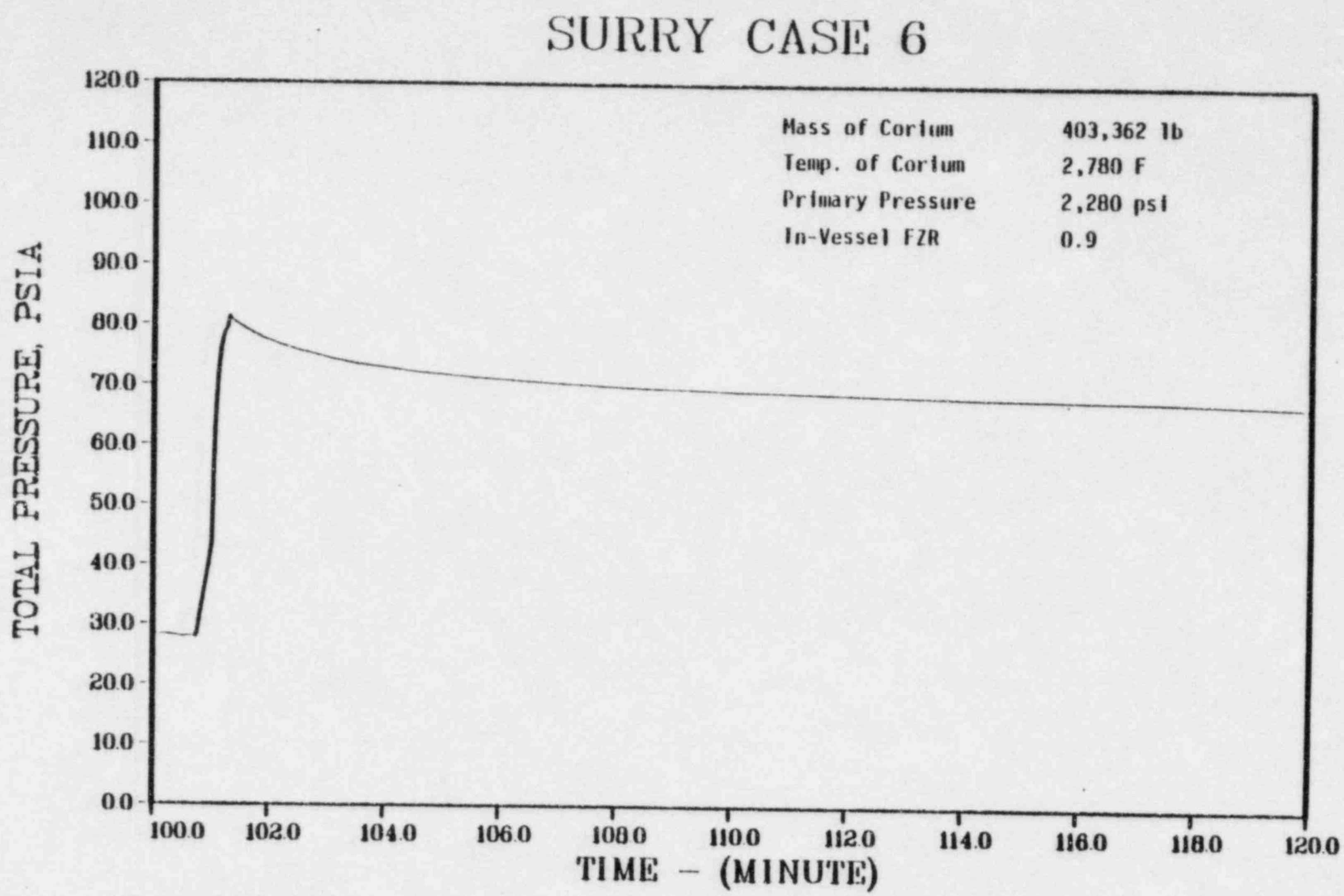
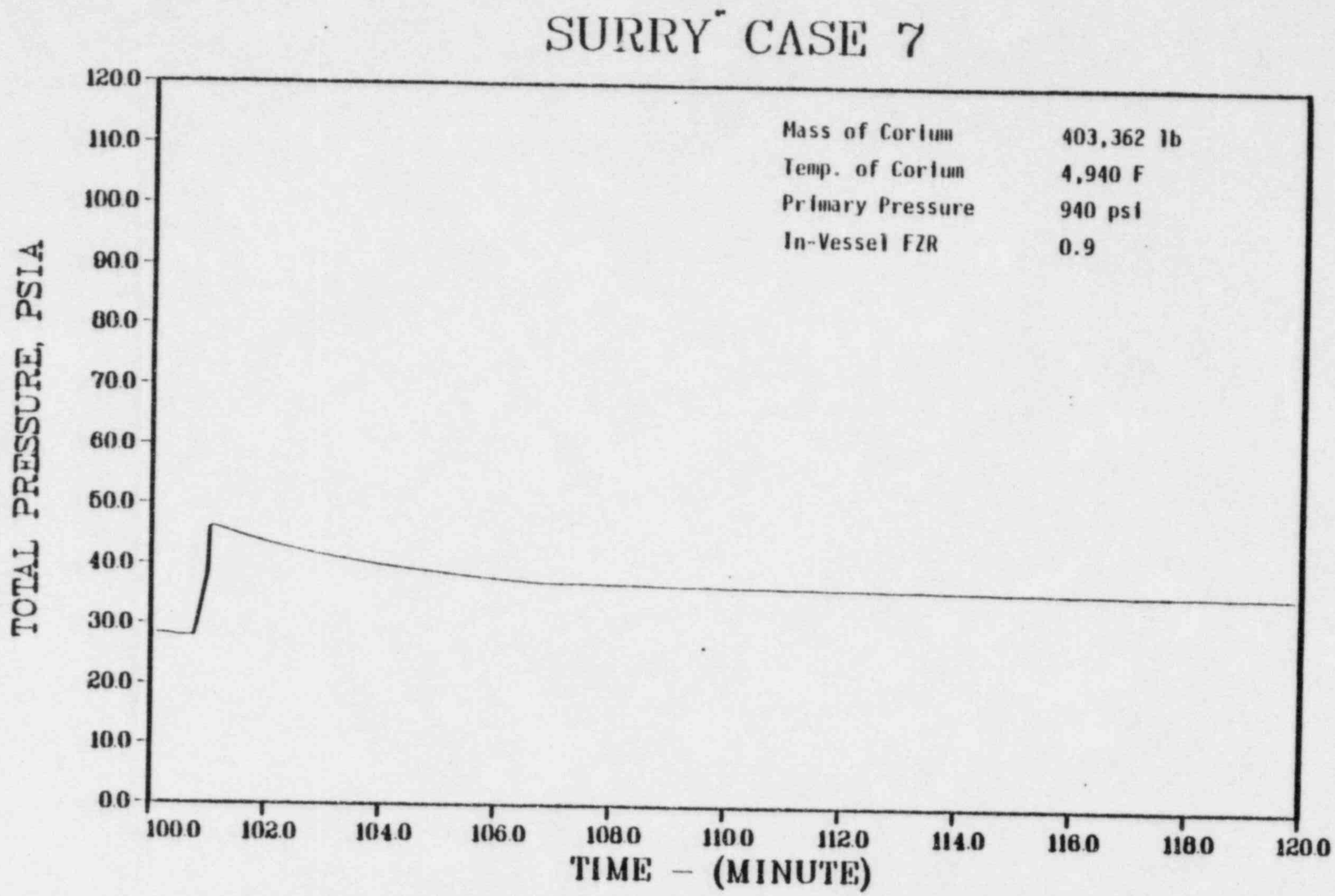

SURRY CASE 5
Mass of Corium 344,539 lb
Temp. of Corium 4,940 F
Primary Pressure 2,280 psi
In-Vessel FZR 0.6
TEMPERATURE, F
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0
TIME – (MINUTE)

FIGURE 14.



SURRY CASE 6
Mass of Corium 403,362 lb
Temp. of Corium 2,780 F
Primary Pressure 2,280 psi
In-Vessel FZR 0.9
TOTAL PRESSURE, PSIA
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0
TIME – (MINUTE)

FIGURE 15.



SURRY CASE 7
Mass of Corium 403,362 lb
Temp. of Corium 4,940 F
Primary Pressure 940 psi
In-Vessel FZR 0.9
TOTAL PRESSURE, PSIA
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0
TIME – (MINUTE)

FIGURE 16.

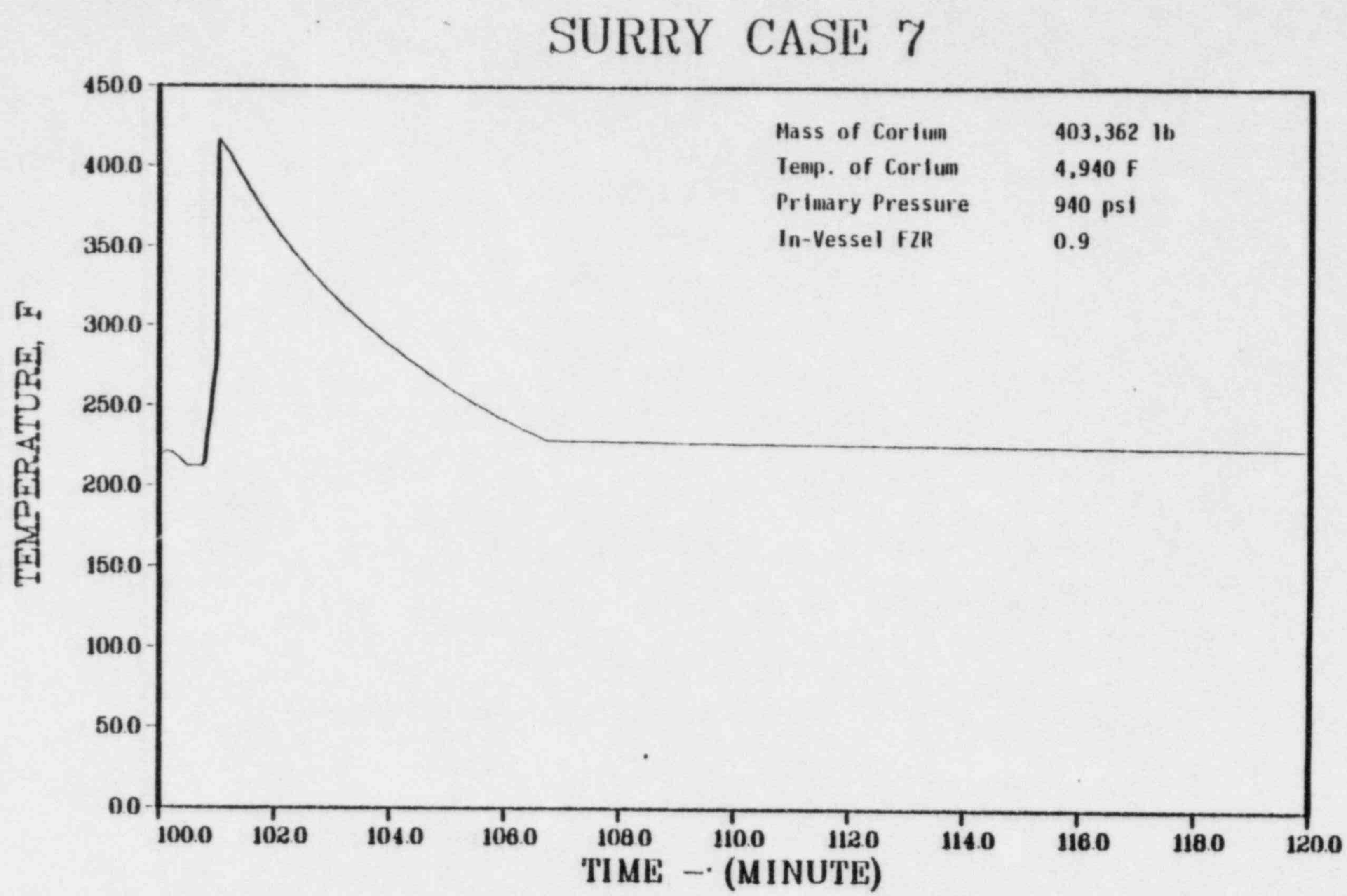

SURRY CASE 7
Mass of Corium 403,362 lb
Temp. of Corium 4,940 F
Primary Pressure 940 psi
In-Vessel FZR 0.9
TEMPERATURE, F
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0
TIME — (MINUTE)

FIGURE 17.

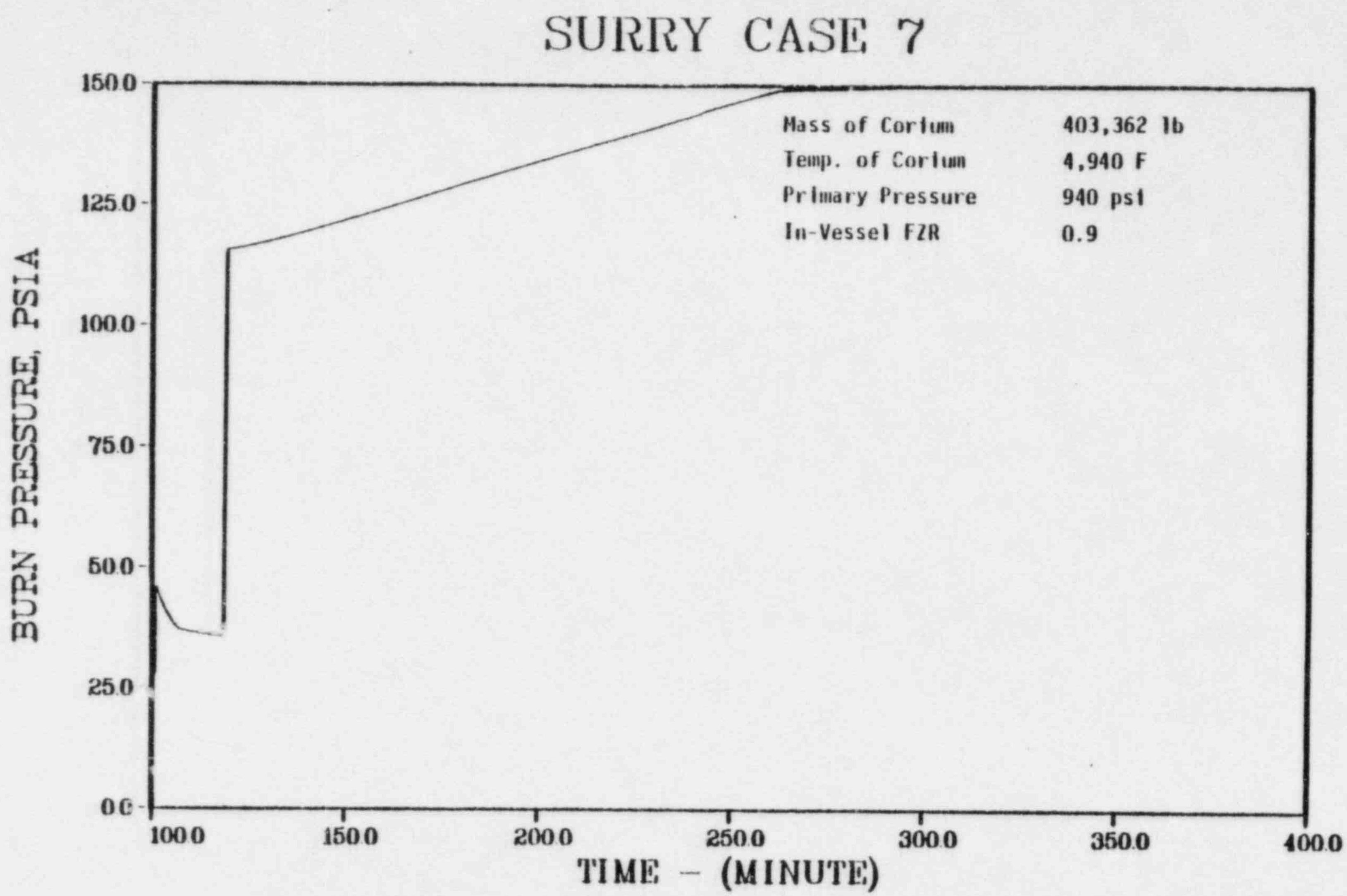

SURRY CASE 7
Mass of Corium 403,362 lb
Temp. of Corium 4,940 F
Primary Pressure 940 psi
In-Vessel FZR 0.9
BURN PRESSURE, PSIA
150.0
125.0
100.0
75.0
50.0
25.0
0.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
TIME – (MINUTE)

FIGURE 18.

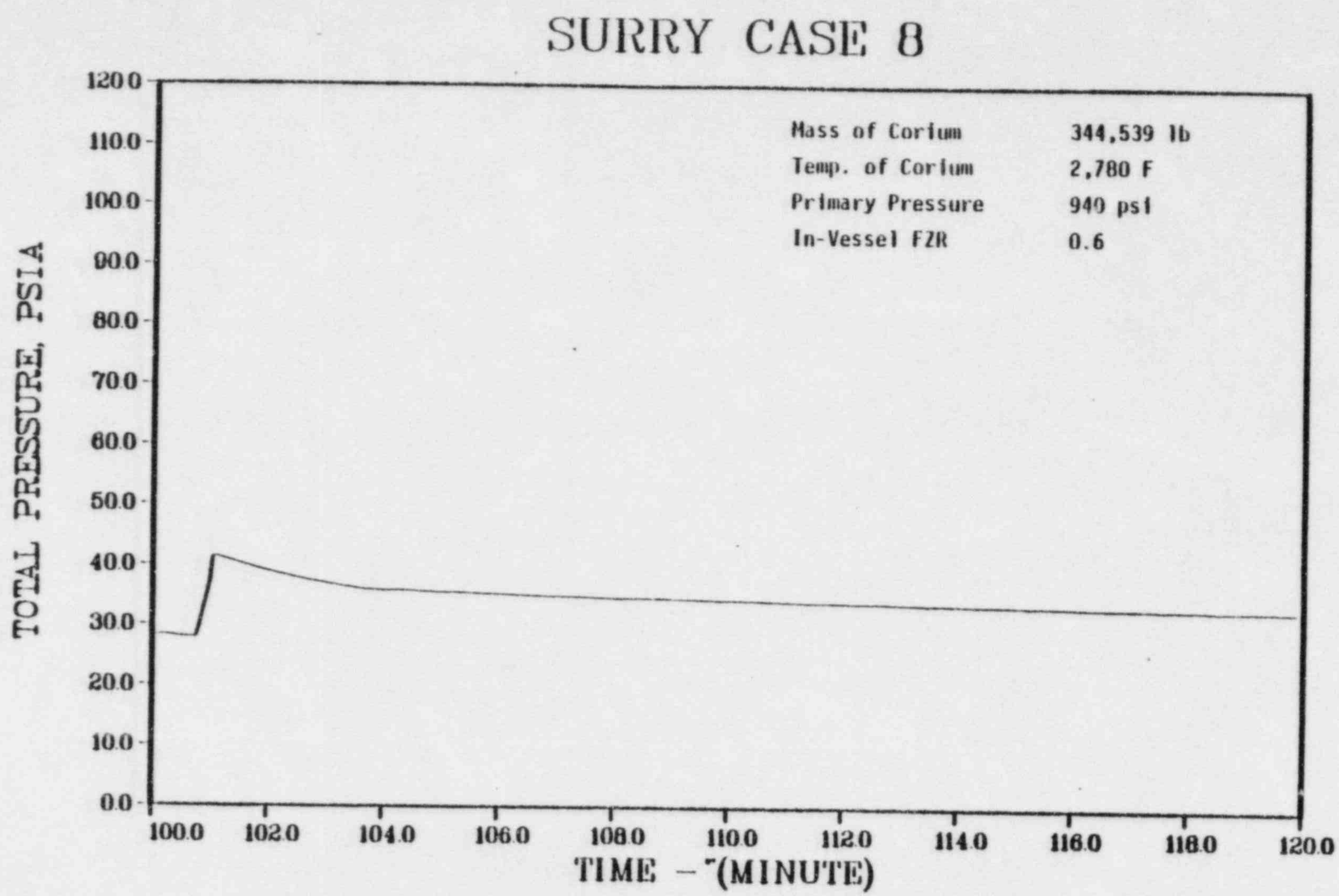

SURRY CASE 8
Mass of Corium 344,539 lb
Temp. of Corium 2,780 F
Primary Pressure 940 psi
In-Vessel FZR 0.6
TOTAL PRESSURE, PSIA
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0
TIME -(MINUTE)

FIGURE 19.

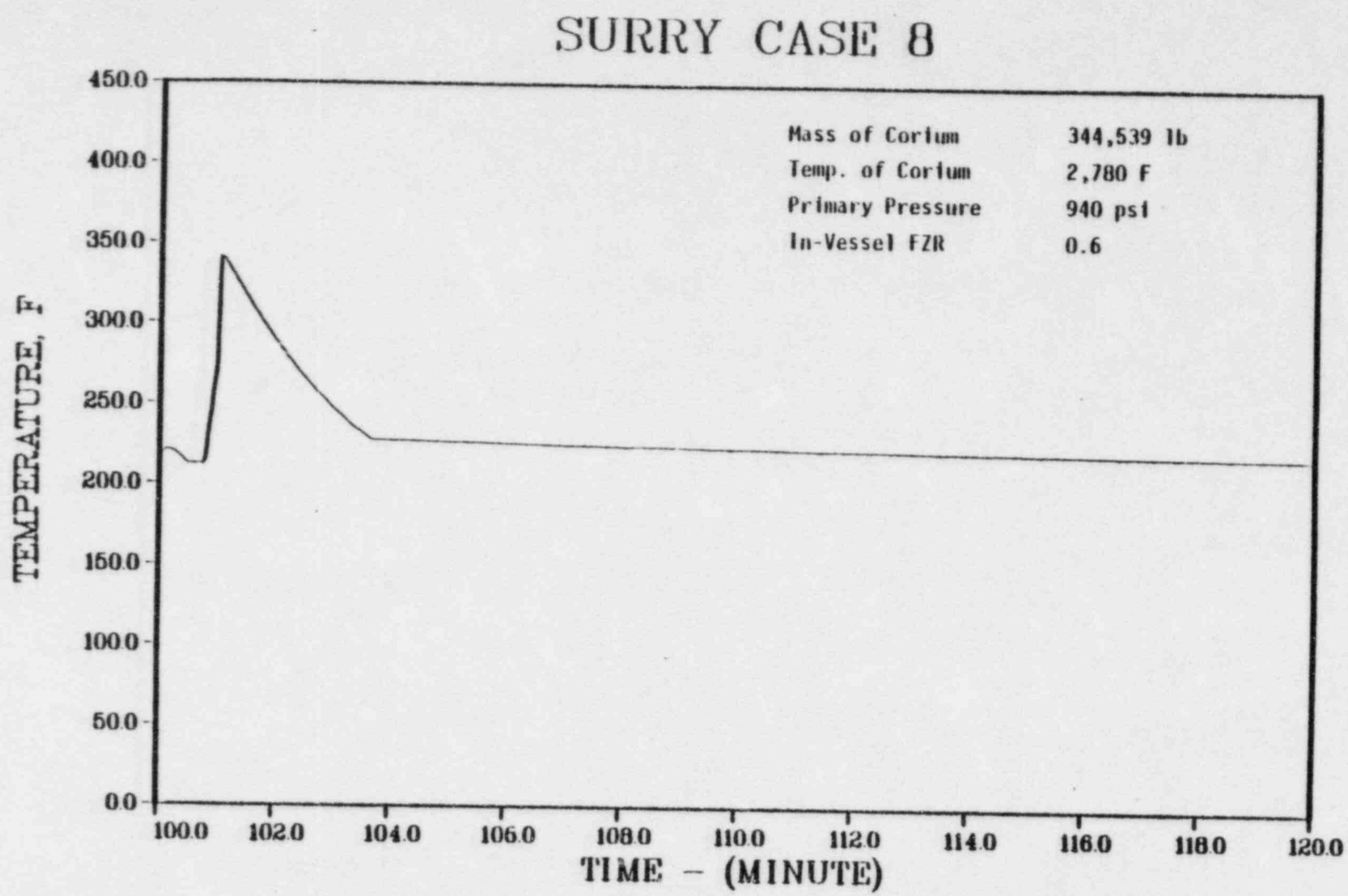

SURRY CASE 8
Mass of Corium 344,539 lb
Temp. of Corium 2,780 F
Primary Pressure 940 psi
In-Vessel FZR 0.6
TEMPERATURE, F
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
100.0
102.0
104.0
106.0
108.0
110.0
112.0
114.0
116.0
118.0
120.0
TIME – (MINUTE)

FIGURE 20.

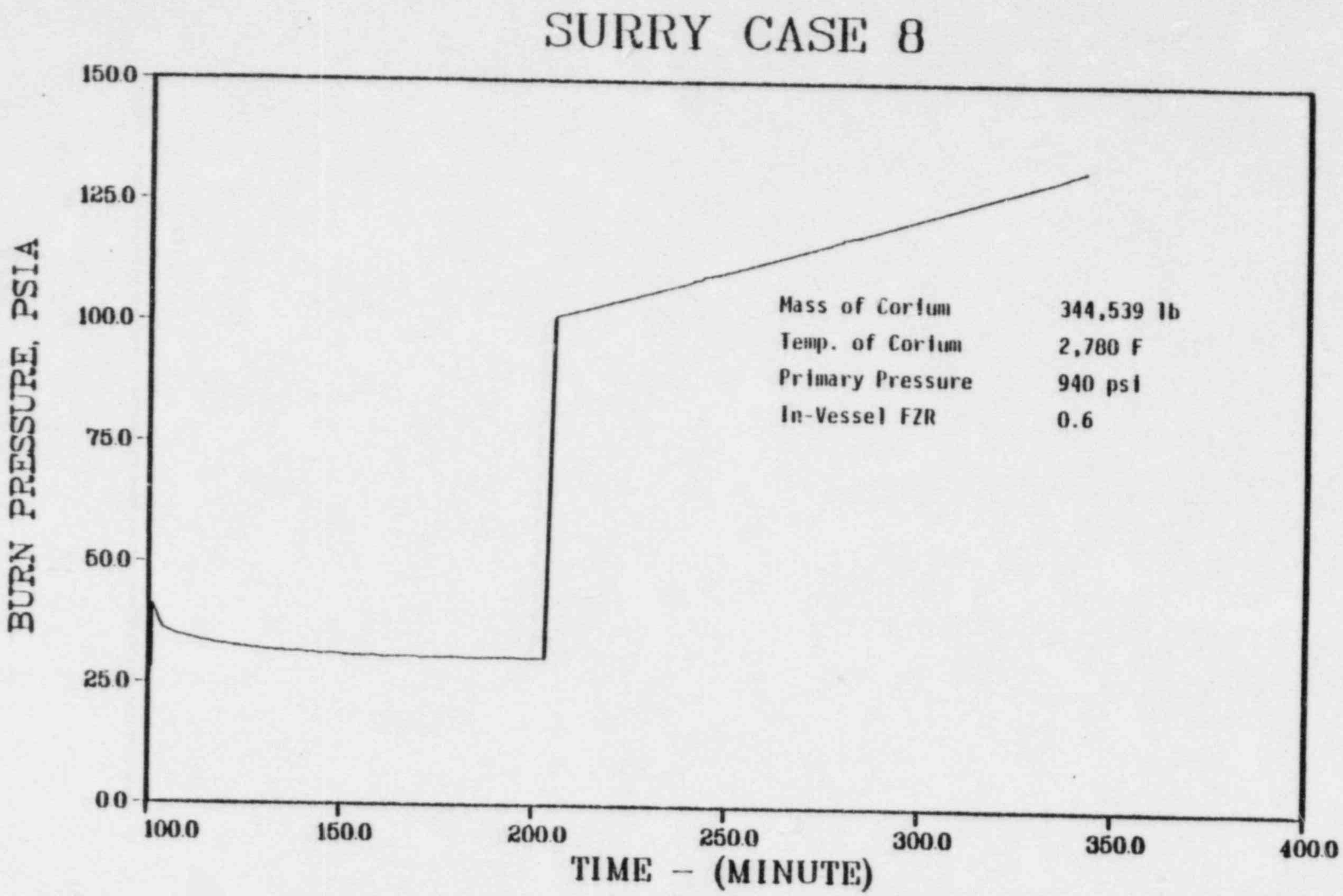

SURRY CASE 8
150.0
125.0
100.0
75.0
50.0
25.0
0.0
BURN PRESSURE, PSIA
100.0
150.0
200.0
250.0
300.0
350.0
400.0
TIME – (MINUTE)
Mass of Corium 344,539 lb
Temp. of Corium 2,780 F
Primary Pressure 940 psi
In-Vessel FZR 0.6

FIGURE 21.

Sandia National Laboratories

Albuquerque, New Mexico 87185

June 12, 1984

Summary (9.b.1)

TO: CLWG SP-2 ANALYSTS

Dear Colleagues:

I am enclosing a rough draft of the summary we have prepared describing the work CLWG members did on Standard Problem Number Two. In some cases, our only available record of the work performed consisted of vugraph packets distributed at the meetings and information exchanged by telephone. Hence, omissions and errors are possible. Please review this draft and forward comments and corrections to Ken Bergeron or myself by July 1.

Sincerely,

David C. Williams

David C. Williams
Containment Modelling
Division 6449

DCW:6449:bkd

Enc.

Distribution:
See next page

APPENDIX B

SUMMARY OF RESULTS FOR STANDARD PROBLEM NO. 2

-------DRAFT-------

D. C. Williams and K. D. Bergeron
Containment Modeling Division 6449
Sandia National Laboratories
Albuquerque, N. M. 87112

B.1. Introduction

The CLWG Standard Problem No. 2 (SP-2) involves analysis of a subatmospheric PWR large dry containment. Although many of the parameters are taken from an actual plant of this general type, no effort was made to be completely faithful to any particular existing containment in defining SP-2 and there is consensus among the analysts that some of the specified problem parameters are not realistic. Hence, the results obtained should not be taken as actual predictions of the containment loads to be expected for a specific sequence at a specific plant. Instead, the results should be taken as providing a common basis for discussion by specifying initial and boundary conditions for detailed calculations, with the purpose of revealing current expert thinking about severe accident containment phenomena.

Independent calculations were performed and submitted to the CLWG by analysts at Battelle Columbus Laboratories (BCL), Brookhaven National Laboratories (BNL), the University of Wisconsin (UW), and Sandia National Laboratories (SNL). The major features of the results will be summarized, with important similarities and differences among the calculations identified. Some of the key reasons for for the main features of the results will be noted; however, no attempt will be made to explain all aspects of the calculations or identify all reasons for the differences among them, in part because adequate detail on the calculations is not available.

Section 2 of this summary will discuss the principal features of SP-2, including the sensitivity study specified as part of the problem. Section 3 will present results for the base case, while Section 4 includes the results for the sensitivity studies. Section 5 includes conclusions and recommendations to the CLWG.

B.2. Definition of SP-2

SP-2 represents a TMLB' sequence leading to core melt and vessel failure at high pressure. The principal features of the standard problem specifications are the initial containment conditions prior to vessel failure, the mass of molten debris released to the cavity, the temperature and composition of the released debris, the water level in the reactor cavity, and various geometric features of the containment building. Table B-1 provides the most important of the standard problem parameter specifications as given in Ref. 2 for the base case, while Table B-2 gives the parameter variations specified for the sensitivity studies.

It should be noted that although the specification of initial conditions was helpful in focusing attention on specific containment phenomenological issues, it was also a source of some difficulties. The most important of these include the following:

1. In code analyses taking into account heat transfer to structures, it proved necessary to run the problem from the beginning of the accident (i.e., the initial blowdown) in order to condition the heat sinks. However, it was sometimes found to be difficult or impossible to reproduce the specified containment pressure at vessel failure if realistic blowdown histories were used. Different analysts coped with this problem in different ways, and it is estimated that differences in final containment pressures of up to 0.05 MPa can result from this cause.

2. Some of the specified initial conditions appear to be inconsistent: in particular, the accumulator pressure specified (4.69 MPa) is lower than the RCS pressure specified (6.48 MPa) for Cases 3, 4, 7, and 8 in Table B-2, yet it is also specified that the accumulators have dumped prior to vessel failure for these cases. Again, different approaches to coping with this inconsistency can introduce differences into the results.

3. The containment atmosphere was specified as being steam inerted, and none of the analysts included any release of hydrogen oxidation energy in their calculations. However, some of the analysts noted that, for the conditions calculated, such energy might be released, and the more important of these cases will be noted in the following sections.

4. The SP-2 specifications include 100% of the corium being molten and ejected coherently at vessel failure time. There was a consensus among the analysts that this assumption is not realistic. (Some

Table B-1

SP-2 Base Case

<u>Containment before vessel failure:</u>

Volume	50,971 m^3
Pressure	0.19 MPa (absolute)
	(0.10 MPa steam; 0.09 MPa noncondensable)
Temperature	275 K
Water level in cavity	10 cm

Atmosphere was specified as being steam inerted

<u>Reactor Coolant System (RCS) conditions:</u>

Pressure	15.7 MPa (absolute)
Volume (including pressurizer)	275.3 m^3
Accumulators	
Pressure	4.6 MPa (gage)
Temperature	322 K
Water volume	78.58 m^3

<u>Corium specifications:</u>

Total mass	114,556 kg
UO_2	79,820 kg
Zirconium (total)	16,500 kg
Zirconium (unoxidized)	11,550 kg
Steel	16,500 kg
Fraction of core released	100%

Table B-2

SP-2 Sensitivity Study

Case	Corium Composition	Corium Temperature (K)	Primary Pressure (MPa)	Water Depth (cm)
1	Corium H	3000	15.7	33
2	Corium L	1800	15.7	33
3	Corium L	3000	6.5 (Low)	33
4	Corium H	1800	6.5 (Low)	33
5	Corium L	3000	15.7	5
6	Corium H	1800	15.7	5
7	Corium H	3000	6.5 (Low)	5
8	Corium L	1800	6.5 (Low)	5

Notes:

1. Corium H is 79,820 kg UO_2; 81,500 kg steel (45.8 weight percent); 16,500 kg zirconium (assume 90% of the zirconium will oxidize in-vessel); total mass of 177,820 kg.
2. Corium L is 79,820 kg UO_2; 56,500 kg steel (37.0 weight percent); 16,500 kg zirconium (assume 60% of the zirconium will oxidize in-vessel); total mass of 152,820 kg.
3. For the primary system pressure of 15.7 MPa, the accumulators will dump onto the corium. The vessel hole equivalent radius is 0.145 m.
4. For the primary system pressure of 6.48 MPa, the accumulator water has already boiled off. The vessel hole equivalent radius is 0.46 m.
5. All other initial conditions are as specified in the base case.

analysts also believed that the entire question of high pressure ejection should be dropped because of their belief that such sequences can not arise; however, there was no consensus to this effect and addressing this issue was defined as lying outside the scope of SP-2.)

The above difficulties include some, though not all, of the reasons that there was a consensus that the results obtained should not be viewed as providing actual predictions of containment loads to be expected for a specific accident sequence in any specific plant.

For the base case, the analysts were requested to provide "high" and "low" estimates that were to bound the range within which the actual containment loads (i.e., pressures and temperatures) might reasonably be expected to fall, and they were also requested to provide "central" estimates. For the "high" case, results were to include the quantities of steam, H_2, CO, and CO_2 added to the atmosphere, as well as the extent of basemat attack after one and three hours. For the sensitivity study, it was requested that the combination of governing phenomena assumed for the "high" case be used throughout, and that peak pressures and temperatures during the first hour after vessel failure be reported. All analysts were encouraged to include the contribution of direct heating to the total peak pressure and temperature in containment.

3.3. Base Case Results

The CLWG spent considerable amounts of time evaluating consistency of different calculations of steam spike loads (i.e., without direct heating) and evaluating the importance of non-adiabatic effects for steam spike calculations. Most of this work was performed in connection with Standard Problem 1 (SP-1) and will not be discussed extensively here; Ref. 1 may be consulted for details. Salient conclusions that are relevant to the SP-2 results include the following:

1. Adiabatic steam spike calculations can conveniently be characterized in terms of a single parameter, e.g., the mass of steam added to the containment. For equivalent assumptions concerning this parameter, there was good agreement among the results obtained by different analysts

2. With some qualifications, non-adiabatic calculations can be characterized in terms of two parameters, with the second parameter being a time parameter. Again, with equivalent assumptions different analysts obtained equivalent results.

3. For steam addition times of 1 minute or less, nonadiabatic effects reduced the pressure increase only slightly, i.e., by ≤ 7% with respect to the adiabatic case.

4. A consensus was reached that "high" steam spike calculations should be performed assuming rapid quench of 100% of the core, with 30% of the metallic zirconium present reacting with water. The heat of reaction of the zirconium is assumed to be available for steam generation.

For the SP-2 analyses, BCL employed MARCH 2 and BNL employed MARCH 1.1. The UW results (reported for the base case only) were performed using adiabatic calculations. SNL results were based upon calculations performed with the CONTAIN code, although many of the actual numerical results cited were obtained using a much simpler adiabatic code, DHEAT, which had been validated by performing detailed comparisons with CONTAIN calculations over the full range of parameter values of interest(1). Sources of gases due to core-concrete interactions were calculated by MARCH/INTER (BCL), MARCH/INTER or CORCON (BNL), and CORCON (SNL). Differences between INTER and CORCON, as well as differing input assumptions, led to substantial variations in the amounts of these gases that were calculated to be produced. However, in no cases did the core-concrete interactions drive the peak pressures and temperatures during the periods of interest and the SNL calculations typically omitted core-concrete interactions once this fact had been established.

Peak pressures and temperatures that were reported for the base case are summarized in Table B-3. Not all analysts reported results for all cases. The BCL and the BNL results included no direct heating, the UW results included 10% direct heating in the "high" case, and the SNL results included significant direct heating for the "central" and, especially, the "high" cases. The MARCH assumptions used by BCL and BNL for the "high" case appear to correspond reasonably well to the CLWG consensus position for maximum steam spike calculations that was noted above.

The tabulated results indicate that there are differences between the BCL and BNL "high" results that appear significant (almost 0.1 MPa), even though the problems analyzed are nominally quite similar, in terms of the data given. The difference between these two results is very much less than the difference with respect to the SNL "high" results. From other SNL calculations of steam spikes (see Section IV), it is apparent that this difference in results has little to do with the difference in calculational tools; rather, it is almost entirely due to the inclusion of substantial direct heating in the SNL calculations. The UW "high" results are significantly increased by even the small amount of direct heating assumed. The UW "central" results are based

upon steam generation only and are thus more nearly comparable to the BCL and BNL "high" results.

Table B-3

SP-2 Base Case Pressure and Temperatures

	BCL	BNL	UW	SNL
"High" P (MPa)	0.50	0.41	0.64	1.13
T (K)	425	408	---	915
"Central" P (MPa)	---	---	0.54	0.72
T (K)	---	---	---	545
"Low" P (MPa)	---	0.38	(0.26*)	0.48
T (K)	---	404	---	415

*Performed for a low pressure sequence, and thus not directly comparable to other results.

The potential importance of direct heating effects was further illustrated by parametric calculations presented by SNL for both SP-1 and SP-2(1). The SP-2 results are reproduced in Fig. B-1, in which the peak pressures and temperatures are plotted against the fraction of the core which participates in direct heating. For that fraction of the core debris which participates in direct heating, 100% of the metal (but none of the UO_2) was assumed to oxidize and the associated corium was assumed to come into thermal equilibrium with the containment atmosphere. The remainder of the corium was assumed to steam quench without chemical reaction. From these results, it is clear that even moderate amounts of direct heating can have very important effects upon containment loads. Based upon results given in Ref. 1, both the core thermal energy and the chemical energy release make important contributions to the total direct heating effect in Fig. B-1, with the effect of the chemical energy release being somewhat larger than that of the core thermal energy.

Since direct heating is potentially such a dominant effect, it is appropriate to review the findings of the CLWG Direct Heating Subcommittee, as summarized by T. Ginsberg in Appendix G(3). A consensus of the subcommittee

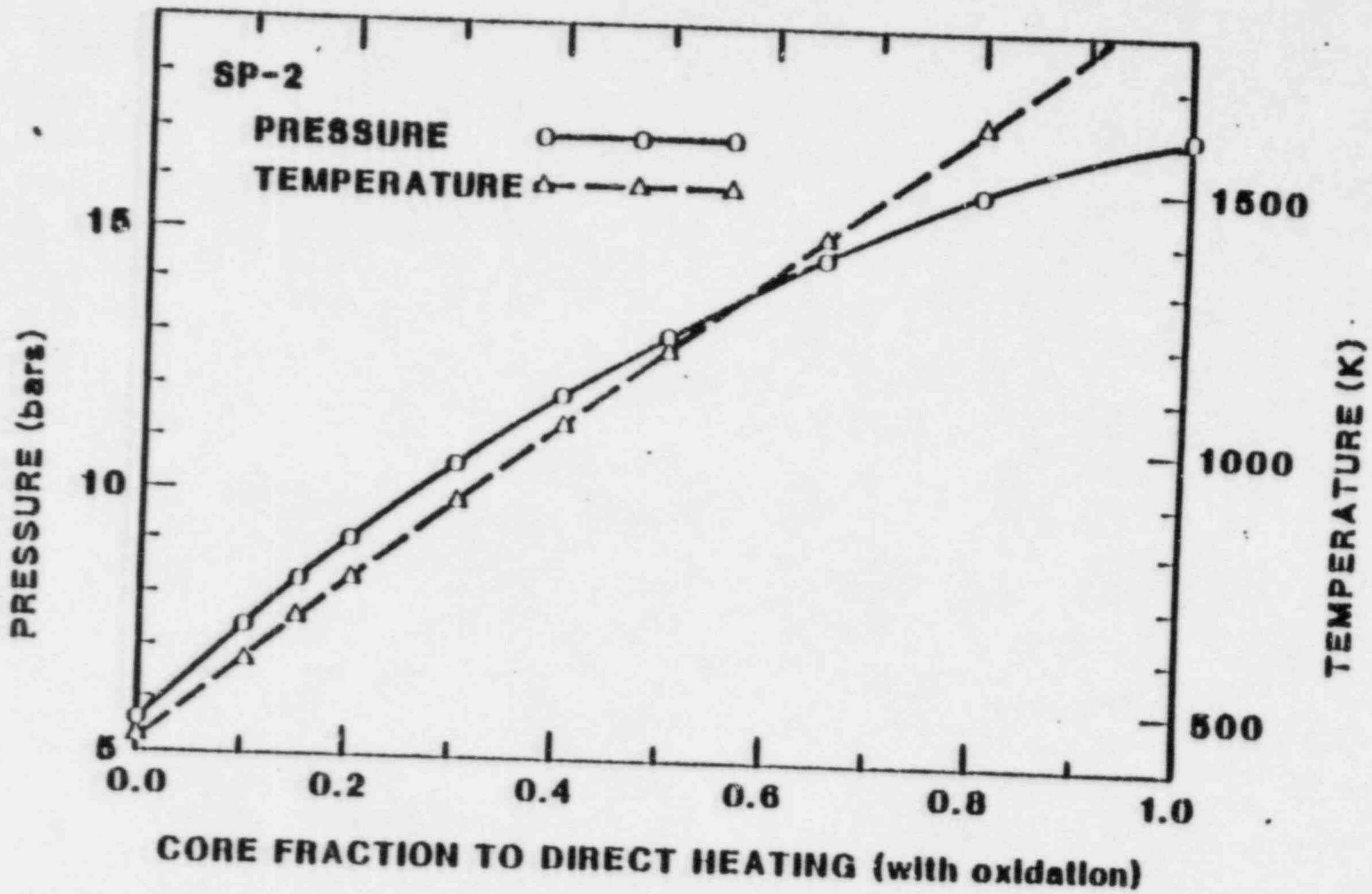


Figure B-1. SP-2 pressure and temperature as a function of core fraction involved in direct heating (with metal oxidation)

was reached that direct heating effects would not be large if the vessel failed while under low pressure, at least in the case of SP-2. However, no consensus could be reached as to the potential importance of direct heating in high pressure ejection scenarios. Some analysts (designated "Group A" in Ref. 3) believed that significant direct heating effects could be ruled out. However, a number of other analysts ("Group B") believed that, at present, "...it is not possible to rule out occurrence of sufficient direct heating to present a severe challenge to PWR large dry containments."

Participants in the direct heating evaluation were asked to provide "high", "low", and "best estimate" values as to the fractions of the core thermal energy and the metal oxidation energy that might be transferred to the containment atmosphere in the direct heating process. Group A, believing the process to be negligible, provided only a single estimate. The estimates of the Group B analysts themselves spanned a considerable range, but there was consensus among the group that the uncertainties are large and that the differences among the various Group B estimates should not be viewed as being particularly significant. There was also consensus that the "high" estimates, at least, would fall within the range for which Fig. B-1 implies that severe challenges to the containment will arise.

Although no consensus position could be formed that incorporated both groups, it was possible to offer values reasonably reflective of a consensus within each group individually. As a result, the Subcommittee on Direct Heating presented two sets of recommendations on direct heating parameters. Because the direct heating uncertainties dominate any others considered quantitatively by the SP-2 analysts, it was judged that, for the present SP-2 Summary, the best single representation of the state of knowledge of the CLWG as a whole would be a set of calculations performed using the various sets of parameters for SP-2 that were presented by the Direct Heating Subcommittee. Hence, a set of calculations, not reported previously by any of the laboratories, was carried out specifically for the SP-2 Summary. The calculational approach employed was that of SNL, i.e., use of the DHEAT code backed by CONTAIN. However, it should be emphasized that there is every reason to believe that differences in analytical techniques introduce uncertainties that are quite small in comparison with the variations due to differences in the assumed direct heating parameters.

In Table B-4, the best-judgment recommendations for SP-2 direct heating parameters are reproduced from Ref. 3. Also given are the pressures and temperatures calculated for the present Summary by applying these parameters to the SP-2 base case. In each case, the numbers in the columns headed "thermal" indicate the fraction of the core thermal energy that goes to the indicated process (direct heating or steam quench). For that portion of the core, the fraction of the unoxidized metal therein that releases its chemical

oxidation energy to the indicated process is given in the column headed "chemical". The labels "O_2" and "STM" mean that the metal reaction is with O_2 or steam, respectively; this distinction is important because the reactions of the metals with steam release considerably less energy than the reactions of the same amounts of metal with oxygen. (Hydrogen produced by metal-water reaction is assumed not to react with oxygen in these calculations.) Note that the fractions given under "Chemical" apply only to the fraction of the core material specified under "Thermal", not to the total core inventory. Thus, for the Group B "high" case, the fraction of the total core metallic inventory which reacts with oxygen and contributes to direct heating is 25%, not 50%.

Table B-4

SP-2 Pressures and Temperatures with Direct Heating

Group and Case	Direct Heating Thermal	Direct Heating Chemical	Water Quench Thermal	Water Quench Chemical	Pressure (MPa)	Temp. (K)
A: All	2%	--	80%	--	0.53	431
B: "High"	50%	50% O_2	50%	30% STM	1.08	944
B: "Central"	25%	50% STM	75%	25% STM	0.78	611
B: "Low"	15%	50% STM	85%	0	0.68	539

The pressures and temperatures given in the last two columns of Table B-4 were calculated assuming containment conditions at vessel failure taken from the CONTAIN calculations, rather than those specified in the definition of SP-2. Use of the latter would reduce pressures by about 0.04 MPa (but increase temperatures somewhat, except when direct heating is negligible). Even allowing for this effect of the initial conditions, it is obvious that only the results for the Group A parameters are comparable to those results in Table B-3 that included no direct heating. For Group B, even the "low" parameters yield significant enhancement of containment pressures and temperatures by direct heating, and the "high" case presents a very severe challenge. Even this case does not represent a consensus as to an absolute

upper limit: one analyst estimated "high" parameters which would imply pressures and temperatures of the order of 1.3 MPa and 1500 K, respectively.

Both the SP-2 analysts and the members of the Direct Heating Subcommittee have cautioned that there are many factors not taken into account in the results discussed here. Both conservative and non-conservative factors are involved. Two of the most important factors are:

1. The assumption that 100% of the corium is molten and is released coherently when the vessel fails.

2. Neglect of possible hydrogen-oxygen recombination in direct heating scenarios. Even when the criteria for self-propagating hydrogen burns, in the usual sense, are not met, high containment temperatures and large surface areas of suspended hot particulate might promote recombination in direct heating scenarios. This effect could increase containment pressures by up to 0.1 - 0.3 MPa in typical cases.

Some analysts believed that the net effect of the various factors not treated was to render the "high" calculations, at least, excessively conservative. There was no consensus to this effect, however.

3.4. Sensitivity Studies

The sensitivity studies presented by BCL, BNL, and SNL were performed using calculational techniques and input parameters similar to those employed for the "high" base case results summarized in Table 3-3. Thus, the BCL and BNL results did not include direct heating while the SNL results did. Results given above for the base case show that it is necessary to include an examination of the impact of direct heating upon the sensitivity study. As in the case of the base case analyses, it is probably more representative of the CLWG state of understanding to employ direct heating parameters based upon the recommendations of the Direct Heating Subcommittee than to employ the results of any one analytical team. Calculations of this kind will be presented later in this section. However, it is also of interest to summarize the results obtained when the problem is restricted by specifying no direct heating, and these results will be considered first.

In addition to the sensitivity study with direct heating, SNL performed the study with direct heating eliminated. These calculations were run for the limiting cases of 0% and 100% zirconium-water reaction as part of a parameter study, and thus none of the calculations were exactly comparable to those

performed by BCL and BNL which included metal-water reactions as calculated by the HOTDROP module of MARCH. However, the SNL results showed that including 30% zirconium-water reaction would increase the base case pressures by about 0.04 MPa, and the pressures in the sensitivity study cases would be increased by only 0.01-0.02 MPa in two instances and there would be no effect in the other six cases. Hence, the zirconium-water reactions are not a major factor in the steam spike sensitivity study calculations and the SNL results without zirconium-water reactions will be presented here along with the BCL and BNL results.

In Figs. B-2 and B-3 the pressures and temperatures, respectively, obtained in the three sets of analyses are presented graphically. In each figure, the first bar on the left represents the base case while the remaining eight bars represent the results for the sensitivity study cases specified in Table B-2. As might be expected, the four cases where the vessel fails at low primary system pressure (cases 3, 4, 7, and 8) give substantially lower pressures than do the high-pressure cases. In large part, this result follows from the fact that only the (very limited) amount of water in the cavity is available for steam generation in the low-pressure cases, since the accumulator water is assumed to have dumped and boiled off before vessel failure. It also reflects the smaller release of steam and gas upon vessel failure.

There is one major qualification that must be made to the conclusion that the low-pressure cases are much less severe. BCL noted that, for all four low-pressure cases, flammable conditions were calculated to exist within the containment, but hydrogen burning was not included in the results given. If the hydrogen is assumed to burn efficiently, the BCL calculations indicate that pressures could be at least as high as any shown in Fig. B-2, and temperatures would be much higher than any of those in Fig. B-3. On the otherhand, the occurrence of flammable conditions for these scenarios can not be taken to be rigorously established, because of limitations in the definition of SP-2 and limitations in the analyses. For example, none of the analysts took into account outgasing of unlined concrete within the containment, which might reduce or eliminate flammability of the atmosphere.

Among the high-pressure cases, the high-temperature corium releases yielded more severe results than did the lower-temperature releases, which is hardly surprising. In at least one set of calculations (SNL's), the difference would have been considerably greater were it not for the fact that steam generation was water limited; that is, the total water available (cavity plus accumulator water) was inadequate to completely quench the large mass of hot corium.

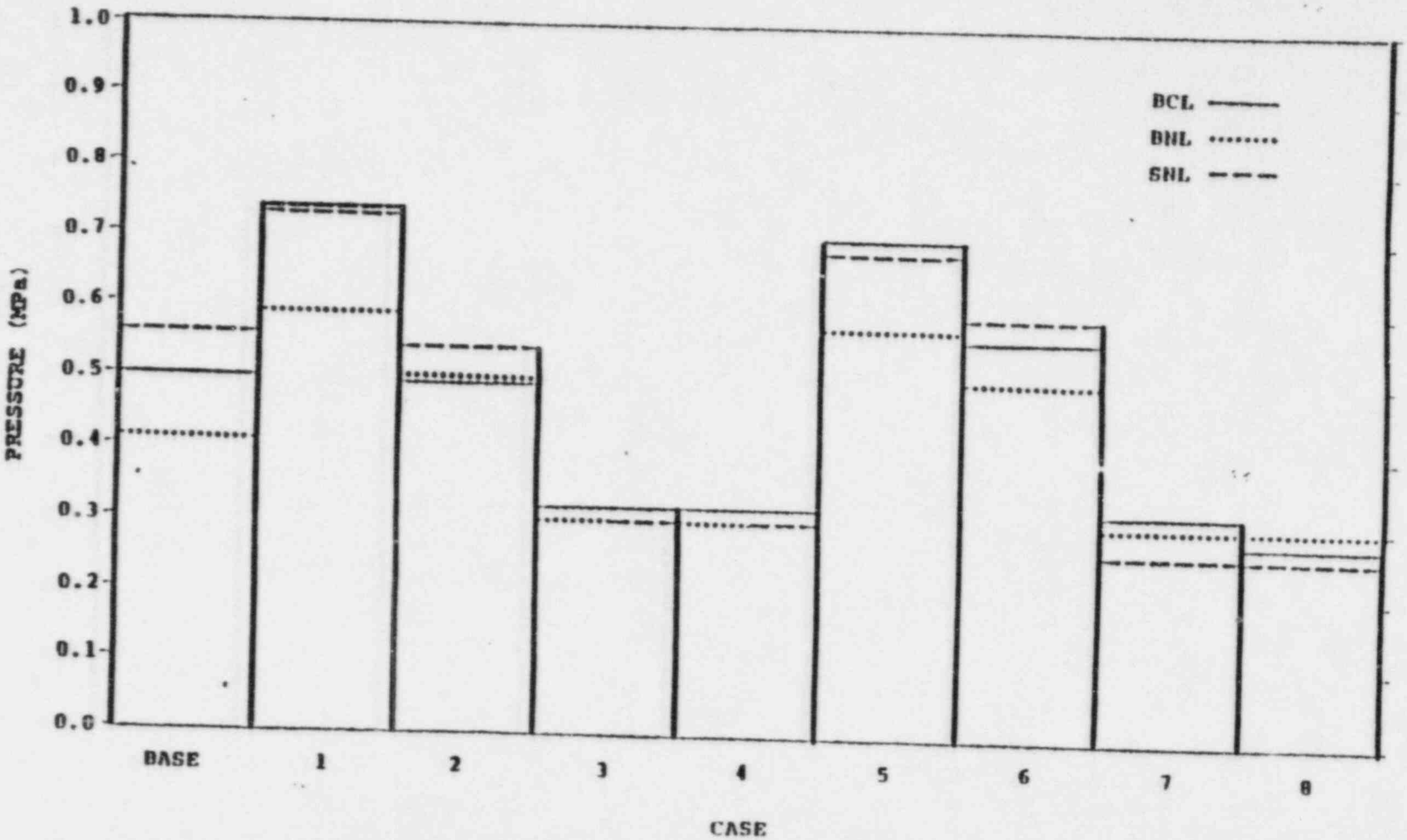


Figure B-2. SP-2 pressures for the "high" steam spike sensitivity study (no direct heating)

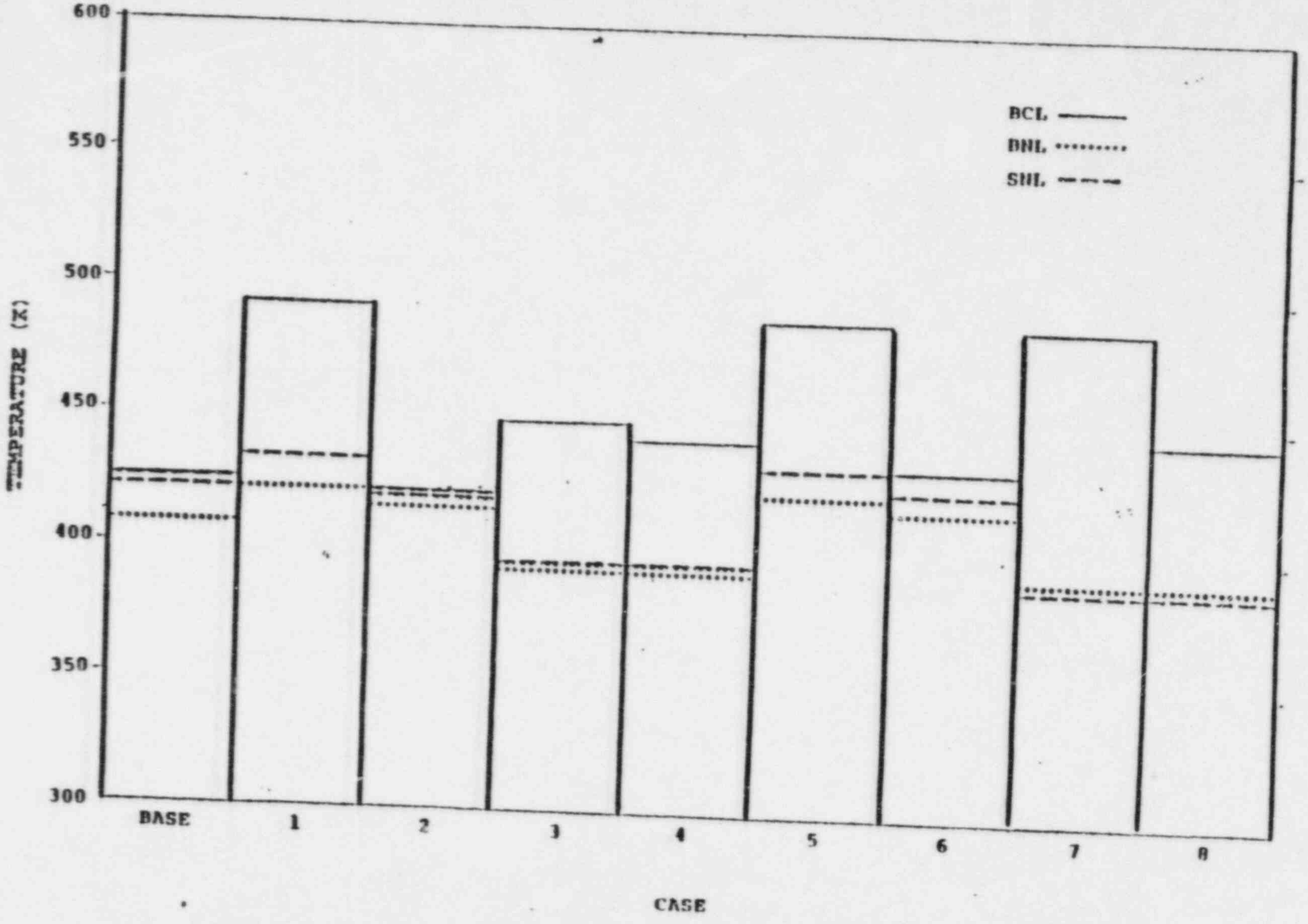


Figure B-3. SP-2 temperatures for the "high" steam spike sensitivity study (no direct heating)

In comparing the results obtained by different analysts, it is seen that the qualitative trend of the pressures from case to case shows good agreement between the three sets of results. Quantitatively, there is good agreement for several of the cases but significant differences (up to 0.15 MPa) arise in some instances, notably the most severe cases. In calculating the temperatures shown in Fig. B-3, the SNL results were obtained using the adiabatic DHEAT code, which assumes the containment atmosphere is saturated unless direct heating is involved. The MARCH calculations assumed superheating in some cases, presumably due to superheated gases released from the RCS. Hence, it is not surprising that the SNL temperatures tend to be the lowest. Actually, however, the SNL and BNL temperatures are very similar. The BCL temperatures are significantly higher in some instances.

No effort has been made to identify in detail the reasons for the differences in the results obtained by the different analysts. It is worth noting that the differences between the BCL and BNL results, which were obtained using similar calculational tools, are comparable in magnitude to the differences between these results and the SNL results, which were obtained using quite different calculational tools. This fact suggests that the differences reflect different input assumptions at least as much as they reflect differences in calculational approach. Such a conclusion, if valid, is all the more striking in view of the fact that the range of input assumptions was heavily restricted by the definition of the problem, which corresponds closely to the CLWG consensus "high" steam spike case with direct heating postulated to be absent. (It should be noted that the present problem is dominated by sources of steam and energy released to containment over a short time, which minimizes the dependence upon calculational approach.)

A very much wider range in calculated results becomes possible when the restrictions upon input assumptions are relaxed to reflect more realistically the range of parameters deemed credible within the CLWG community as a whole. This enhanced range is illustrated in Figs. B-4 and B-5 which present, respectively, the pressures and temperatures obtained in the following sets of calculations for the sensitivity study:

1. The results labeled "BNL Low" in Figs. B-4 and B-5, which were obtained by BNL for the complete sensitivity study using the same assumptions they used for their base case "low" steam spike calculations. These assumptions included incomplete corium-water mixing, followed by CORCON calculations with film boiling on the top surface.

2. The shaded zone, labeled "High Steam Spike Range", represents the range of results spanned by the calculations summarized in Figs. B-2 and B-3.

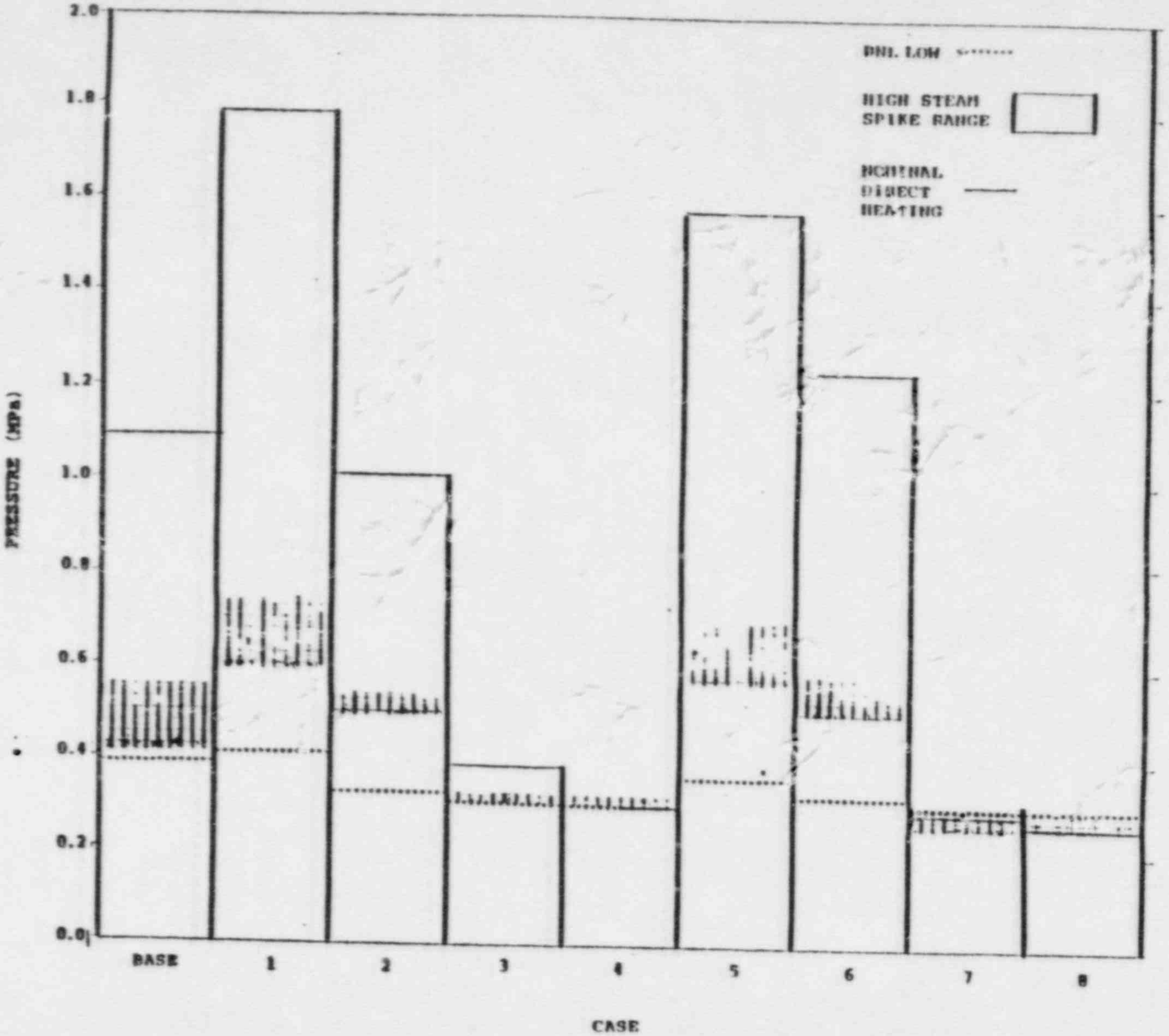


Figure B-4. Calculated SP-2 pressures for the "low" and "high" steam spikes and for the nominal direct heating scenario

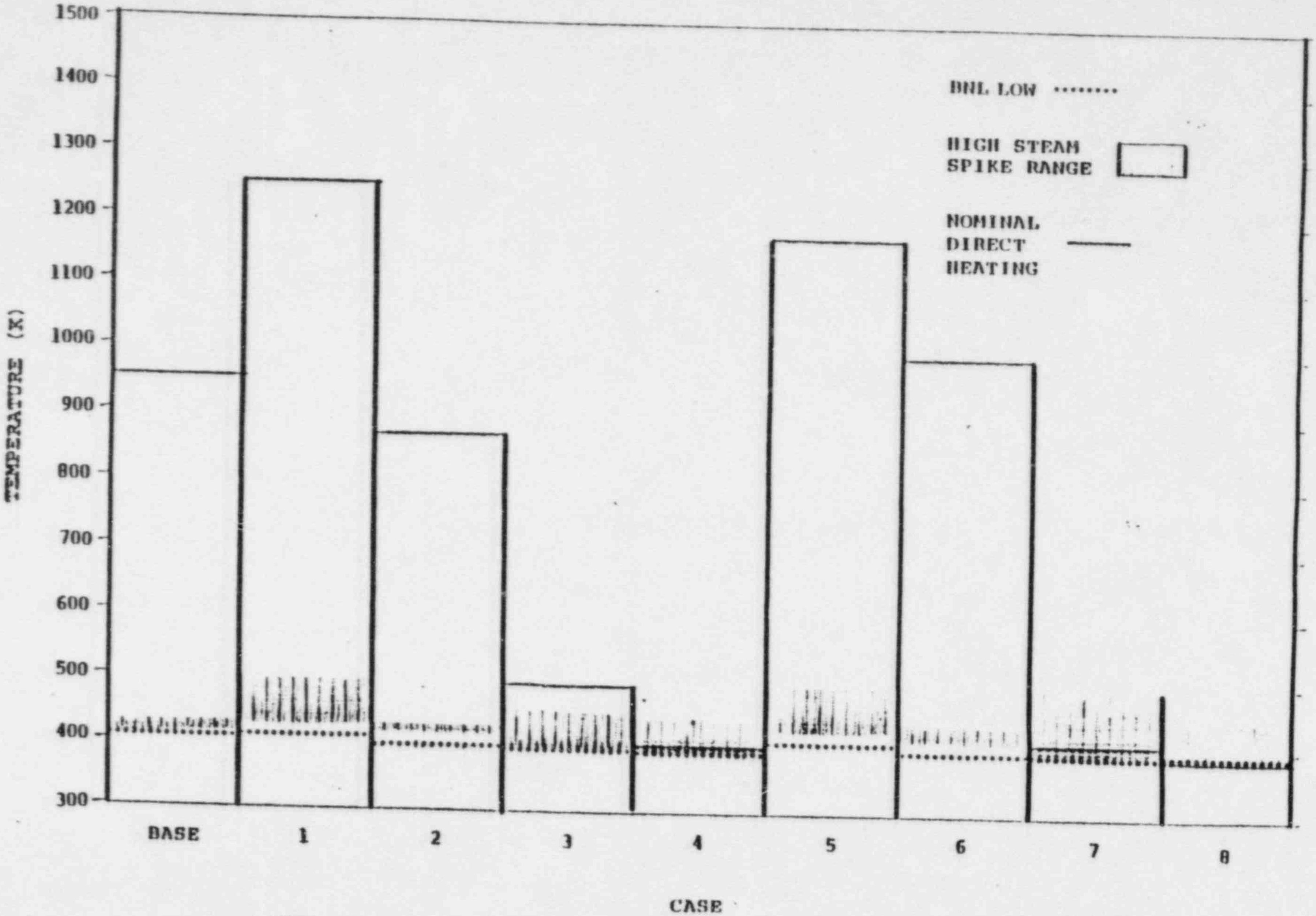


Figure B-5. Calculated SP-2 temperatures for the "low" and "high" steam spikes and for the nominal direct heating scenario

3. The results labeled "Nominal Direct Heating" were calculated for the present Summary using the consensus recommendations of the Direct Heating Subcommittee Group B for SP-2 "high" base case direct heating parameters (Table B-4) as a starting point. Since these recommendations were clearly not intended to be applicable for all the parameter combinations of the sensitivity study, the direct heating parameters were varied as a function of these parameters in a manner similar, but not identical, to that employed by SNL in Ref. 1. Some details are given in the Addendum to this Appendix. For the Cases 3, 4, 7, and 8, it was assumed that the primary system was fully depressurized, since the pressure specified in Table B-2 was incompatible with the specification that accumulator discharge occurred prior to vessel failure.

Obviously, the range spanned by the results given in Figs. B-4 and B-5 greatly exceeds the range spanned by the results for the more restricted steam spike sensitivity study. The dominant effect is that of direct heating, though the difference between the "BNL Low" results and the other steam spike results is also significant in some cases. The extremely large direct heating effects calculated for some of the high pressure ejection cases arise from the very large corium masses with very high steel content specified in Table B-2. For the high pressure cases, the thermal energy contributes slightly over 60% of the total direct heating for the higher-temperature coriums (cases 1 and 5), while chemical energy contributes about two thirds of the total for the lower-temperature coriums (cases 2 and 6).

It is noteworthy that the wide spread in the results applies only to the high pressure ejection cases. For the low pressure cases, there was little difference between the "low" and the "high" steam spike calculations of BNL, and the direct heating prescription described in the Addendum also largely or entirely eliminates direct heating in the low pressure cases. It should be emphasized that this elimination of direct heating is based upon assumptions, not mechanistic calculations. These assumptions are believed to be reasonably consistent with the consensus of the Direct Heating Subcommittee, although the Subcommittee did not explicitly consider the question in detail.

Limitations in the base case calculations noted at the close of Section B-3 also apply here. These include the highly conservative assumption of coherent release of 100% of the molten corium and the nonconservative neglect of hydrogen-oxygen recombination which may occur under severe direct heating conditions.

8.5. Conclusions and Recommendations to the CLWG.

1. Results obtained by different analysts for SP-2 peak pressures and temperatures agree reasonably well when equivalent input assumptions are used even if different calculational techniques are employed. However, the limited sensitivity to calculational approach should not be overgeneralized; other containment loading problems can show a much greater dependence upon the sophistication of the calculation.

2. Results obtained by different analysts differ widely for high pressure ejection scenarios, but do not differ greatly for the low pressure ejection scenarios. The large differences among the high pressure results primarily reflect the different beliefs about the appropriate input assumptions, especially with respect to direct heating. Even with direct heating defined out of the problem, the steam spike results showed significant (about 0.15 MPa) differences in some cases. Obtaining closer agreement will require more care in identifying and defining significant parameters in addition to direct heating.

3. There is at least an implied consensus that neither steam spike nor direct heating effects will present a severe threat of massive structural failure in low pressure ejection scenarios for SP-2. (Significant leakage induced by pressure and/or temperature transients are not ruled out, however.)

4. There is a consensus that steam spike effects alone will not present a severe threat of massive structural failure in high pressure ejection scenarios, although some of the pressures calculated for certain (rather extreme) parameter choices specified in the sensitivity study do present quite substantial challenges, of the order of 0.7 MPa.

5. If direct heating parameters are assumed similar to the "high" values of the Direct Heating Subcommittee Group B consensus, a very severe threat to containment integrity results. No consensus could be reached among SP-2 analysts as to whether these parameter values are credible.

6. Of the parameters treated quantitatively and in detail by the SP-2 analysts, the direct heating question is the dominant uncertainty. Other important issues, not analyzed in detail, appear to include the fraction of the core that might actually undergo coherent ejection and the extent of hydrogen-oxygen recombination, especially under strong direct heating conditions.

7. It is recommended that the results calculated for SP-2 using the various Group A and Group B consensus parameters of the Direct Heating Subcommittee be taken as providing the best representation of the CLWG position on SP-2. There is a consensus among the SP-2 analysts that results for this Standard Problem should not be interpreted as actual predictions of the containment loads to be expected for any specific accident sequence in any specific plant. Some analysts believe that at least the "high" SP-2 results are unrealistically conservative, but there is no consensus to this effect.

REFERENCES

1. D. C. Williams and K. D. Bergeron, "Calculations for PWR Standard Problems 1 and 2 with Direct Heating", Letter Report dated 4/30/1984, Sandia National Laboratories.

2. M. Silberberg, "Assignments for the PWR Standard Problem Number Two", Memorandum to CLWG Distribution, January, 1984.

3. T, Ginsberg, "Appendix G: Consensus Summary on Direct Heating" (Draft), Brookhaven National Laboratory, May, 1984.

ADDENDUM

Sensitivity Study with Direct Heating for Figs. B-4 and B-5

The starting point for this analysis is adaptation of the consensus parameters for the "High" SP-2 base case reported for Group B of the Direct Heating Subcommittee. These parameters include 50% of the total corium thermal energy and 25% of the total corium potential energy from metal oxidation going to direct heating. However, the cases defined for the sensitivity study differ from the base case in up to three important ways that could significantly affect direct heating:

1. In all cases, the coriums contain much more steel, but less unoxidized zirconium, than does the base case.

2. In four of the sensitivity study cases, the primary system pressure is specified to be much lower than for the base case (for present purposes, it was redefined as being fully depressurized in these four cases.)

3. In four of the sensitivity study cases, the corium temperatures were defined as being much lower than in the base case, so low that it is likely that steel would be the only corium component actually molten to a large degree.

The SNL analysts were the only team to explicitly confront these differences since only they performed the sensitivity study with direct heating included. In Ref. 1, they described the prescriptions which they developed for modifying the direct heating parameters to take into account these factors. Though qualitatively reasonable, these prescriptions are rather arbitrary in terms of the actual numbers assumed; nonetheless, better prescriptions are not available. Hence, they will be employed here except for the prescription used for the first of the above items, the difference in composition. The Group B base case parameters are rather different from those of Ref. 1, and applying the prescription in Ref. 1 to the present case would almost totally eliminate the chemical contribution to direct heating, something that is judged contrary to the spirit of the recommendations of Group B of the Direct Heating Subcommittee. Therefore, no allowance for the difference in composition has been made in the present work.

Major assumptions used for the sensitivity study calculations with direct heating are as follows:

1. In the high pressure cases involving the higher temperature (3000 K) coriums, the parameters were as in the "high" base case: 50% of the core thermal energy and 25% of the total available metal oxidation energy goes to direct heating; 50% of the corium steam quenches with 30% of the associated zirconium undergoing reaction with water, with the heat produced going to steam generation.

2. In the high pressure cases involving the lower temperature (1800 K) coriums, only the steel (analyzed as consisting of iron) was assumed to participate in direct heating, with the percentages being as above. The rationale is that sufficient fragmentation for efficient direct heating is judged improbable for constituents that are solid. The remainder of the iron, and all of the other constituents, were assumed to steam quench.

3. In the low pressure sequences, the only direct heating allowed for in the higher temperature corium cases was reaction of 25% of the zirconium with steam, with the energy going to direct heating. (The resulting direct heating effects are not large because the amounts of unoxidized zirconium are relatively small in these coriums.) In the low temperature, low pressure cases, no direct heating was allowed for.

4. Steam spike calculations for the high temperature coriums included reaction of 30% of the available zirconium with water, but no chemical energy release was assumed for the low temperature corium steam spike calculations. Water available for steam generation was assumed to include both cavity water and accumulator water in high pressure sequences and only cavity water was included in the low pressure sequences. If water was exhausted, energy remaining in unquenched corium was ignored.

5. For all sequences, the containment conditions at vessel failure time were assumed to be the same. (This is not realistic; different RCS pressures imply sequences that differ in ways that would affect containment conditions.)

It must be stressed that the Direct Heating Subcommittee has not considered in detail how the direct heating parameters might vary as a function of the accident sequence parameters considered here, and no endorsement by the Subcommittee of the above prescriptions is implied. No

clear conflicts between these prescriptions and the recommendations of the Subcommittee are known, however.