REPORT

on

PWR STANDARD PROBLEM NUMBER ONE

to

U. S. NUCLEAR REGULATORY COMMISSION

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by

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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 approach selected by the CLWG.

The first of the standard problems selected was the analysis of the "steam spike" in a large dry containment PWR (Zion).

The particulars for the PWR Standard Problem Number One were given in the July 29, 1983, memorandum from M. Silberberg, NRC. This report summarizes the analyses performed at Battelle's Columbus Laboratories in conjunction wiht this standard problem.

APPROACH

Two types of analyses were performed at Battelle-Columbus on PWR Standard Problem Number One. The first type consisted of a series of hand calculations to consider a number of simple quenching cases; the second type consisted of a number of MARCH 2 calculations to investigate the effects of various debris-water interaction assumptions on the predicted results. Each of these sets of analyses is discussed below. Both the simple quenching analyses as well as the MARCH 2 calculations assumed adiabatic conditions in the containment, i.e., heat losses to structures were not considered. The latter condition was imposed on the standard problem to simplify the analyses and to assist in putting the several analyses on a common footing.

RESULTS

Simple Quench Analyses

A series of "hand" calculations were performed to scope the analyses, define the controlling parameters, and indicate the range of containment pressures to be expected for the conditions as defined in the standard problem. The first consideration was given to the amount of water available in relation to the mass and heat capacity of the debris. Table I summarizes the water available as given in the problem definition or inferred from other parameters. As will be shown later, if the accumulators are assumed to discharge onto the debris in the reactor cavity, there will be more than sufficient water to fully quench the core debris. For the case of the 3.2 m depth of water initially in the cavity, there will be an excess of water available. Heating of the excess water by the core debris was not considered in the simple quenching calculations.

Table II summarizes the results of the simple quenching analyses. All the results in this table are based on the quenching of 138,400 kg of debris, with the available energy going into the production of steam. The debris temperatures considered are given in the table, with the (S) and (L) denoting solid and fully liquid debris at the given temperature. The table entries for the weight of steam (WSTM) in the atmosphere correspond to the incremental steam addition for each of the individual cases considered. The first entry corresponds to the steam present in the containment prior to reactor vessel failure; the second entry gives the steam addition from the blowdown of the primary system, without any debris quenching. The last four entries in the WSTM column give the steam produced from quenching of the debris for each of the assumed debris initial conditions. Note that the maximum steam from debris quench corresponds approximately to the accumulator water inventory. The total pressure column, PTOT, gives the total pressure in the containment for each of the conditions considered, including non-condensable gases as well as steam addition. The initial pressure of 0.40 MPa was given in the problem definition; the pressure was calculated to rise to 0.48 MPa due to the release of the primary system steam inventory. The other entries

correspond to pressures resulting from the quenching of the debris for each of the conditions considered.

As noted above, the containment pressures given in Table II are based on the quenching of 138,400 kg of debris. Figure 1 presents the results of containment pressure as a function of the mass of debris quenched. As would be expected, the relationship is essentially linear. It may be noted that the latent heat of fusion assumed in these analyses corresponds roughly to 500 K of debris temperature; thus, the pressures for conditions not explicitly shown on the figure, e.g., 2033 K (L), can be easily inferred.

MARCH 2 Calculations

Following the simple quenching calculations discussed above, a number of MARCH 2 calculations were performed; the MARCH analyses duplicated some of the hand calculations as well as considering other assumptions of the debris interaction with water, as well as concrete. In the MARCH analyses, no heat losses to structures were considered, per standard problem definition, even though it could easily be accommodated. Thus, the relatively short term pressure peaks as derived from these analyses would be of principal interest, with those taking long times to develop being suspect due to the neglect of heat losses.

The MARCH calculations performed for the purpose of these standard problem analyses differ considerably from normal MARCH calculations. Rather than starting the analyses at the beginning of the accident sequence and letting the code evaluate all parameters of interest thereafter, the MARCH input was set up to deliver to the reactor cavity the quantities and conditions of core debris as specified in the standard problem. Normal MARCH runs initiated from time zero would not necessarily yield the quantities and temperatures of debris defined by the standard problem. Thus, the present set of MARCH calculations focused on the debris-water interaction model (HOTDRP) and the containment response model (MACE) in MARCH.

Table III summarizes the results of the MARCH analyses and Figures 2 - 10 give graphical presentations of selected results. The first three cases of Table III consider rapid quenching of the core debris for an assumed particle size of 5 mm and the debris temperatures indicated. These are analogous

to the simple quenching hand calculations except that the HOTDRP analyses include the effect of metal-water reactions during the quenching process. It is seen that appreciable additional clad oxidation was predicted only for the highest temperature considered, i.e., FZR goes from 0.49 at the start of quench to 0.61 when quenching is complete. The corresponding containment pressure and temperature responses for the three rapid quenching cases as shown in Figures 2 - 6. The continued increases in containment temperature following the spike due to debris quenching in Figures 3 and 5 are due to the fission product heating model in MARCH; the effect is particularly noticeable since heat losses to structures are not considered in these analyses.

Cases 4 and 5 of Table III give the results for slow debris quenching from particle beds, for two assumed particle sizes. Heat transfer from the particle bed to the overlying water is evaluated by the debris bed models in HOTDRP. In these analyses, the accumulator water was assumed to be injected on top of the particle bed and there was no further, continuing water addition. The results indicate that steam generation by the debris beds for the assumed conditions is much slower than quenching of isolated particles, as would be expected. It is interesting to note that in the case of the small particle size, substantial oxidation of the metals in the debris is predicted, indicating poor coolability and thus high particle temperatures during bed dryout. For the larger particle size considered, the quenching of the bed appears to be fast enough to preclude extensive additional reactions. Figures 7 and 8 show the containment pressure histories for these two cases.

Cases 6 and 7 of Table III consider minimal interaction between the core debris and water, but address the direct attack of the concrete; limestone and basalt concrete types are considered. The containment pressure histories for the two cases are illustrated in Figures 9 and 10. Containment pressurization due to concrete decomposition is seen to be much slower than that due to water quenching of debris. The penetration of the basalt concrete is seen to be greater than that of the limestone type. Since heat losses to structures are not included in these calculations, containment pressurization as presented here is expected to be overestimated.

DISCUSSION OF RESULTS

The hand calculations and the HOTDRP analyses of rapid debris quenching yield very similar results. This is to be expected for the simplified conditions assumed for both sets of calculations. The neglect of heat losses to structures is not expected to be a serious limitation for the short quench times predicted. Except for extremes in particle sizes, the containment pressure from debris quench would be expected to be proportional to the stored energy in the debris. For extremely small particle sizes, the reaction of the metals in the debris may be significant; for extremely large debris particle sizes, quench times may be long enough that heat losses to structures should be considered.

For the cases of slow debris quenching via particle bed, the two cases considered show a dependence on the assumed size of the particles in the bed. It will be recalled that for the cases considered, the particle beds had initial overlying water layers with no further addition of water; thus, whether the beds were intrinsically coolable or not, they would eventually heat up due to the evaporation of the coolant. For the case of the larger particle size considered, the bed quenched fast enough to preclude substantial additional metal-water reaction; the peak containment pressure in this case is largely due to steam generation from the debris quench. The rate of bed quenching is, of course, much slower than quenching of isolated particles. In the case of the small particle size considered, the bed did not quench rapidly, staying at an elevated temperature, and led to substanital additional reaction of the meals with steam. For the particular set of parameters considered, all the Zircaloy cladding, as well as a substantial portion of the steel in the debris, was predicted to have reacted with steam to generate hydrogen. While these calculations are by no means definitive, they do indicate that for marginally coolable debris beds, or beds that are subjected to dryout, considerable hydrogen production beyond that occurring in-vessel can be encountered. While this additional hydrogen does not pose a threat to large dry containments by overpressurization due to the buildup of non-condensables, its role in the event of hydrogen burning

may need further consideration. Also, the significance of such additional hydrogen could be substantially different in other containment designs.

For limited interaction of the core debris with water in the reactor cavity, early concrete attack would be encountered. The cases considered under these assumptions show that the pressurization of large dry containments due to concrete decomposition is much slower than that from water quenching of the debris. This is, of course, an expected result. The erosion of the basalt concrete was faster than that of the limestone concrete. This, again, is an known result.

While the standard problem specified both low pressure and high pressure meltdowns, only the high pressure cases were explicitly considered in these analyses. For the same debris-water interaction assumptions, the difference between the high and low pressure cases would be expected to be the pressurization due to the release of high pressure steam, or about 0.08 MPa for the present case. However, for high pressure meltdowns, there may be a significant likelihood that the core debris would be ejected from the reactor cavity following vessel failure. In the latter case, the debris escaping the cavity would in all likelihood be quenched by the water on the containment floor. For the low pressure meltdowns, there would be less likelihood of debris ejection from the cavity. Further, in the low pressure cases, the rate of debris quenching may be limited by the ability of the steam to leave the cavity and/or the ability of water to enter the cavity. The above questions of debris ejection and countercurrent flow limitations on the rate of debris quenching were not explicitly addressed in the present study.

CONCLUSIONS

The analyses discussed above have addressed the question of the steam spike loading due to debris-water interactions in a large dry containment design. The analyses show that the process of rapid debris quenching can be adequately approximated by a simple thermodynamic analysis. Slower debris quenching, such as may take place in a particle bed, may involve significant chemical reactions in addition to the heat transfer processes

and may thus require more elaborate consideration. For the range of conditions and modeling assumptions considered, peak containment pressures following vessel breach were found to range from 0.48 to 0.81 MPa, starting from the given initial pressure of 0.40 MPa. The 0.48 MPa pressure corresponds to just the release of high pressure steam from the primary system to the containment with no contribution from debris quenching. The 0.81 MPa pressure was calculated for a bed of 5 mm particles and included substantial hydrogen generation during the bed dryout process. Based on the analyses performed, and assuming that all of the core debris as defined in the problem interact with water, it is inferred that 0.5 MPa would represent a low containment pressure loading, 0.8 MPa the high loading, and 0.7 MPa the nominal loading. If less than the entire debris is assumed to participate, the loadings would be correspondingly lower. These pressure loadings assume that the energy in the debris goes into generating steam and/or decomposing concrete, including appropriate chemical reactions. These containment loadings do not include consideration of the direct heating of the containment atmosphere by the debris, nor the air oxidation of the metallic components of the debris. Such considerations may increase the containment pressures above those calculated in the present analyses. The most significant parameters with regard to the predicted containment pressure loads were found to be the mass and temperature of the debris that undergo interaction with water.

PWR Standard Problem Number One was posed to examine the so-called "steam spike" loadings in a representative large dry containment. The problem did not include consideration of hydrogen burning. It is not clear that questions of containment loads due to hydrogen burning should be excluded from consideration for these types of containments. In the cases involving rapid steam generation, hydrogen burning would be precluded by high partial pressures of steam. In the absence of large steam spikes, or in cases where the steam generation takes place over extended periods of time, hydrogen burning may not be precluded. Since the standard problem as posed did not include heat losses (steam condensation) to structures, it is not possible to draw conclusions regarding the likelihood and magnitude of possible hydrogen burns under the conditions considered.

WATER AVAILABLE

Accumulator	90,000 kg
0.5 m Depth	17,812 kg
3.2 m Depth	113,979 kg

TABLE I.

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TDBR, K	WSTM, KG	PTOT, MPa
---	133,357	0.40
---	40,560	0.48
2533(S)	60,770	0.67
2533(L)	76,630	0.71
2033(S)	46,464	0.63
3033(L)	90,904	0.74

WDBR = 138,400 KG

TABLE II.

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CASE	TDBR, K	WSTM, kg	PRESSURES, MPa PNCD	PSTM	PTOT	DT, sec	REMARKS
			RAPID QUENCH				
2	2533(S)	58,469	0.12	0.54	0.66	17	FZR = 0.49
1	2533(L)	75,615	0.13	0.60	0.73	16	FZR = 0.53
3	3033(L)	89,994	0.13	0.65	0.79	12	FZR = 0.61
			SLOW (DEBRIS BED) QUENCH				
4	2533(S)	88,543	0.17	0.64	0.81	1060	DP = 5 mm, FZR = 1.0, FFE = 0.86
5	2533(S)	79,606	0.13	0.59	0.72	770	DP = 25 mm, FZR = 0.63, FFE = C.09
			DIRECT CONCRETE ATTACK				
6	2533(S)	36,252	0.13	0.49	0.61	3600	FZR = 0.47, DZ = 12 cm, DR = 10 cm Limestone Concrete
7	2533(S)	57,250	0.14	0.56	0.70	3600	FZR = 0.96, DZ = 44 cm, DR = 23 cm Basalt Concrete

WDBR = 137,644 kg

TABLE III.

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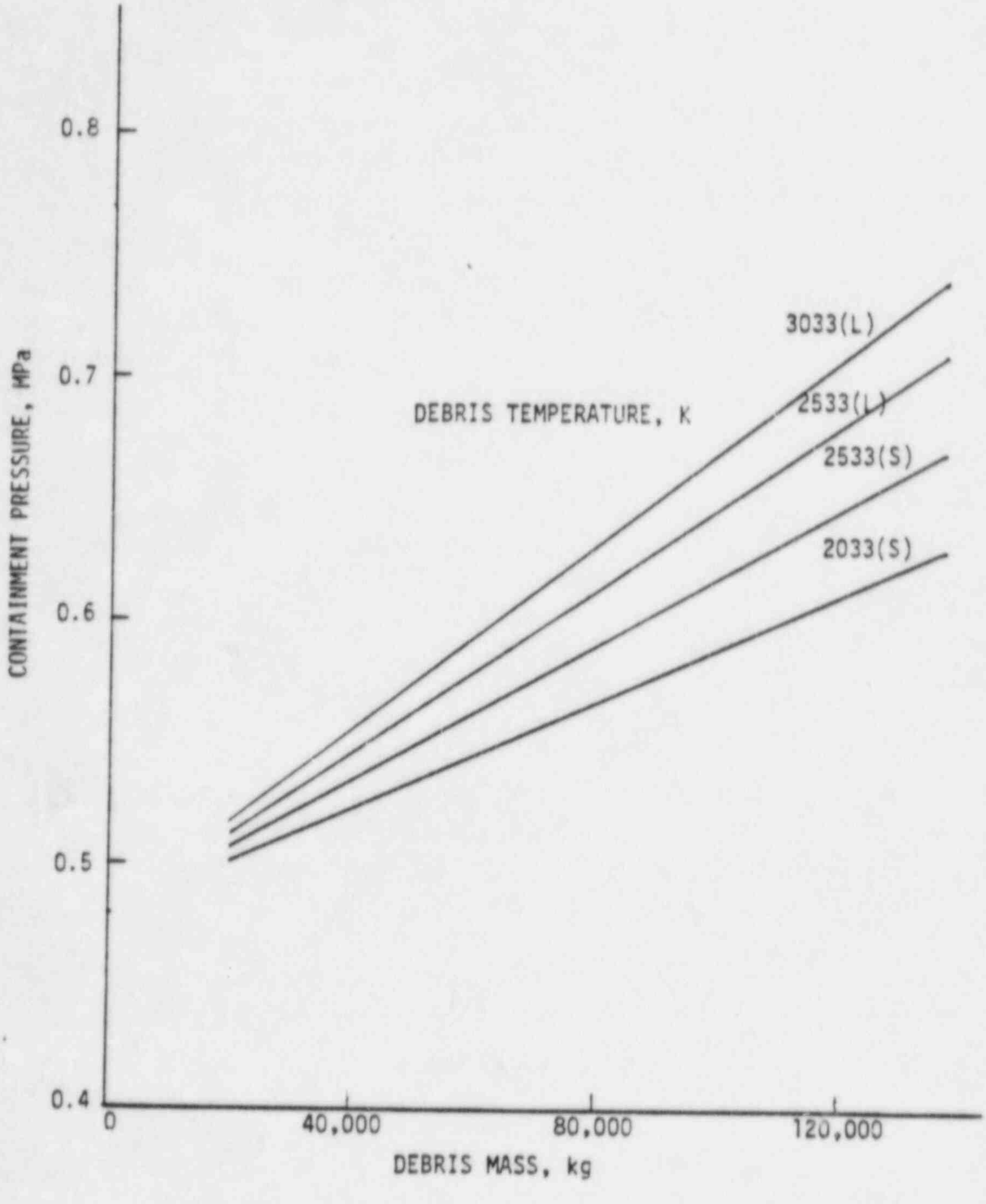

FIGURE 1.

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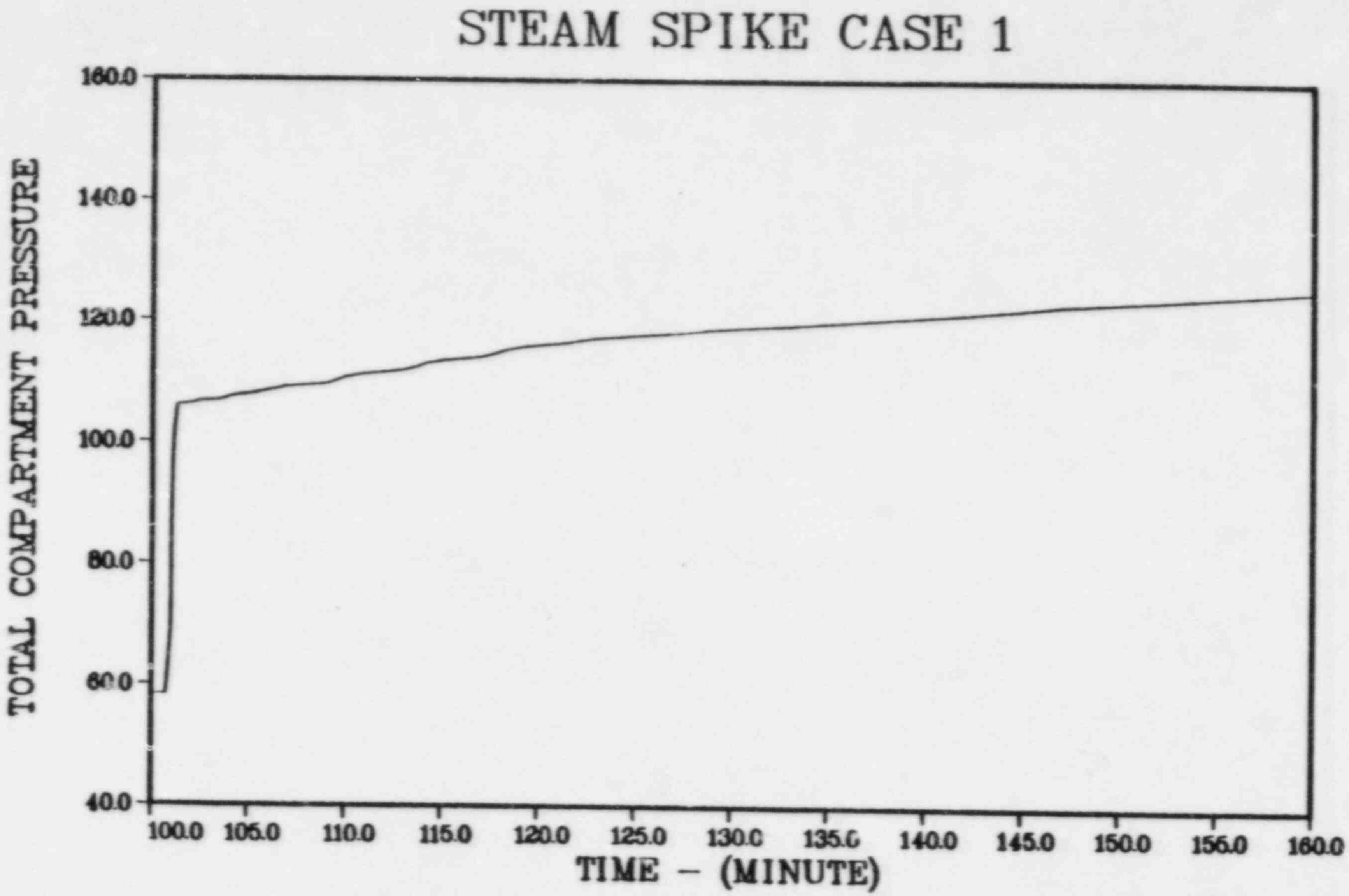

FIGURE 2.

VOLUME NO. 1

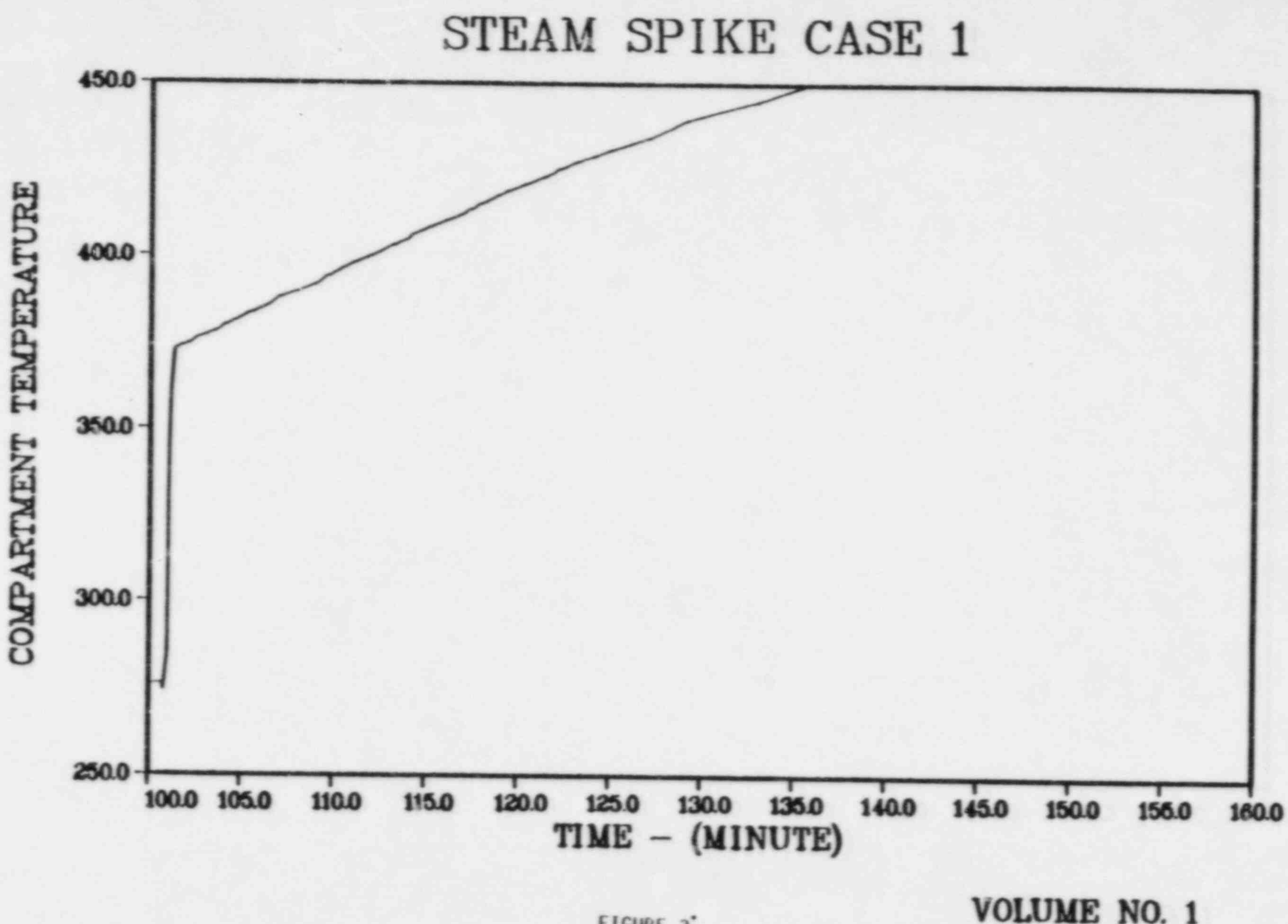
STEAM SPIKE CASE 1
450.0
400.0
350.0
300.0
250.0
COMPARTMENT TEMPERATURE
100.0
105.0
110.0
115.0
120.0
125.0
130.0
135.0
140.0
145.0
150.0
155.0
160.0
TIME – (MINUTE)
VOLUME NO. 1

FIGURE 3

STEAM SPIKE CASE 2

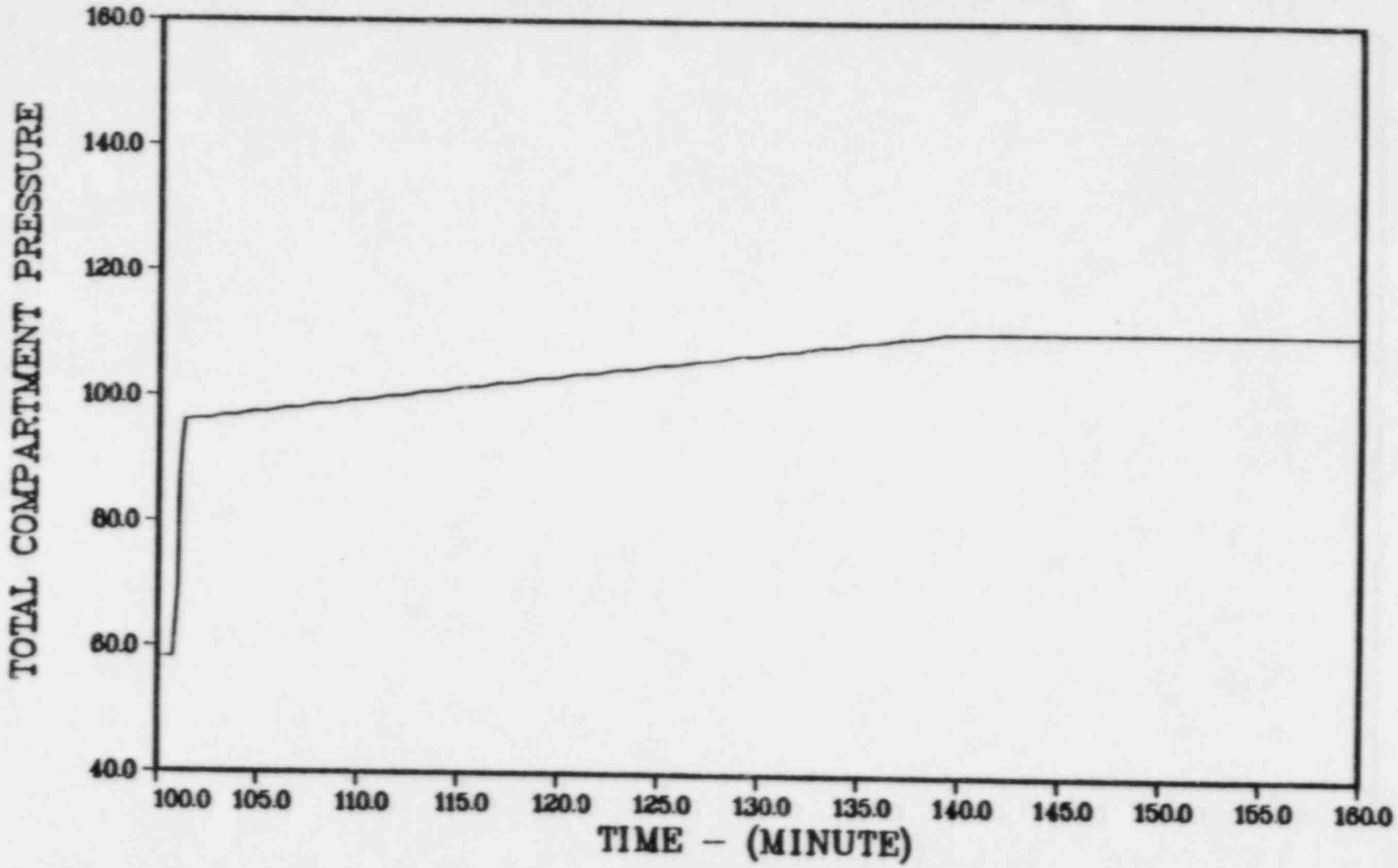

FIGURE 4.

VOLUME NO. 1

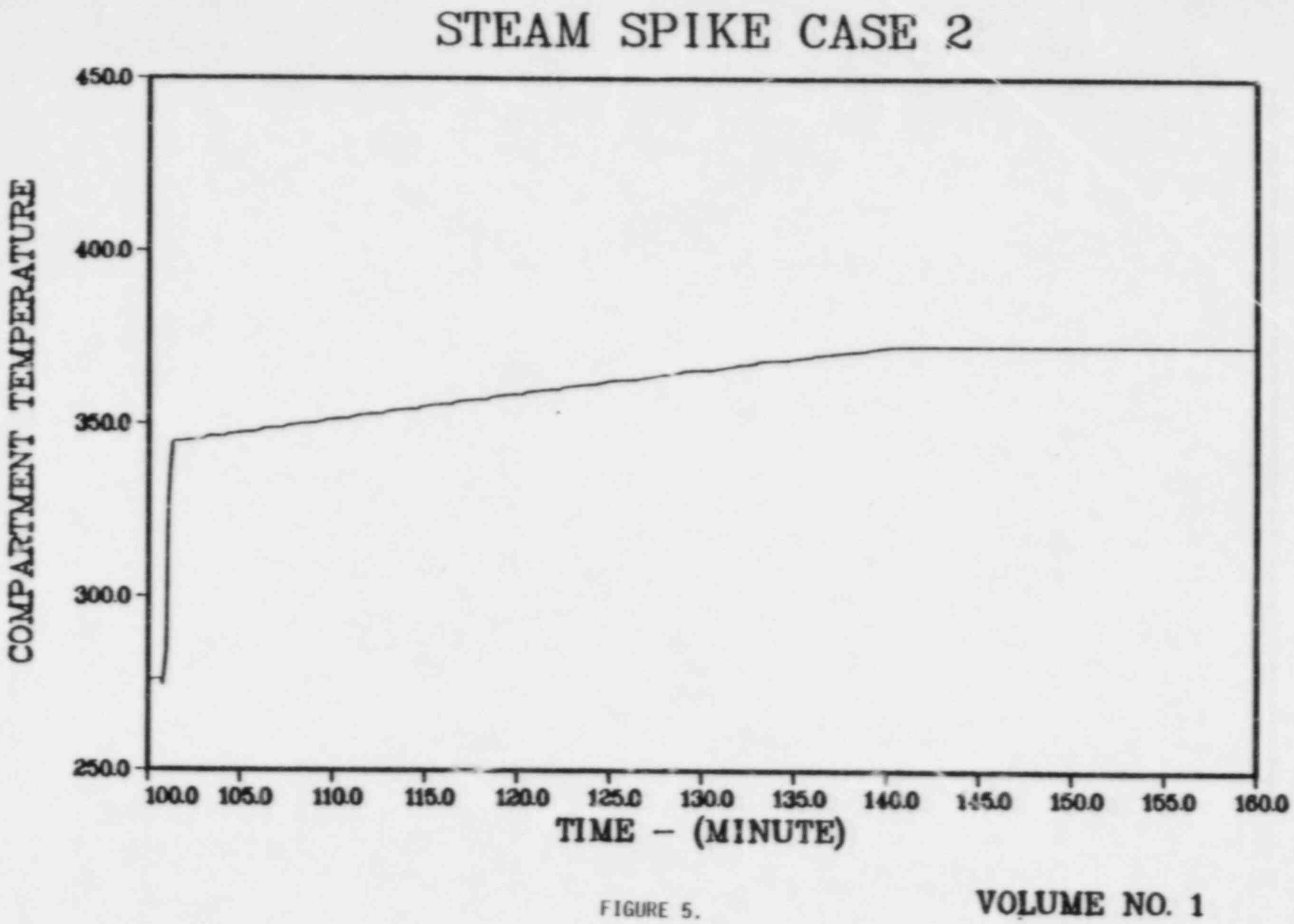
STEAM SPIKE CASE 2
450.0
400.0
350.0
300.0
250.0
COMPARTMENT TEMPERATURE
100.0
105.0
110.0
115.0
120.0
125.0
130.0
135.0
140.0
145.0
150.0
155.0
160.0
TIME – (MINUTE)
VOLUME NO. 1

FIGURE 5.

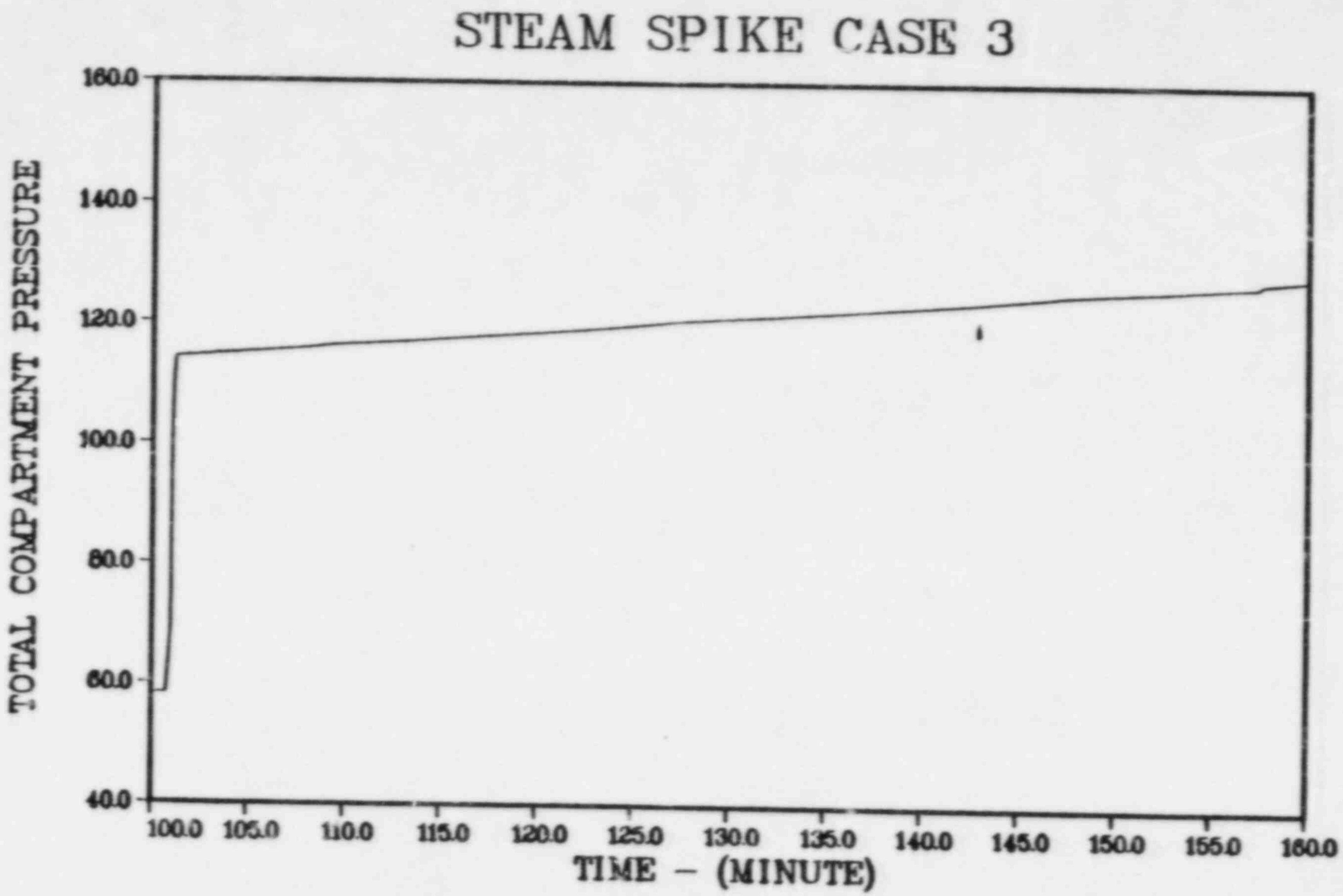

FIGURE 6.

VOLUME NO. 1

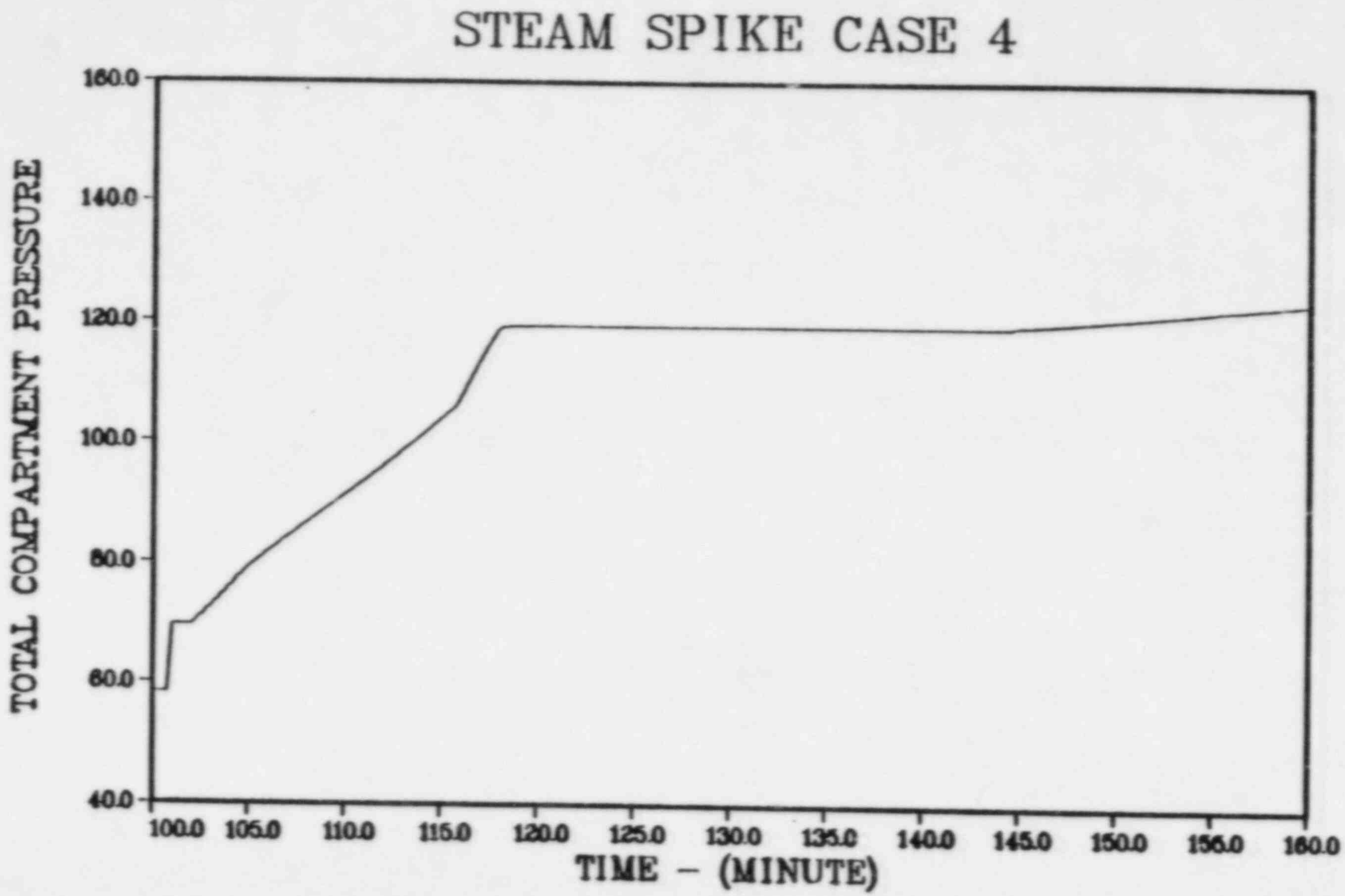

FIGURE 7.

VOLUME NO. 1

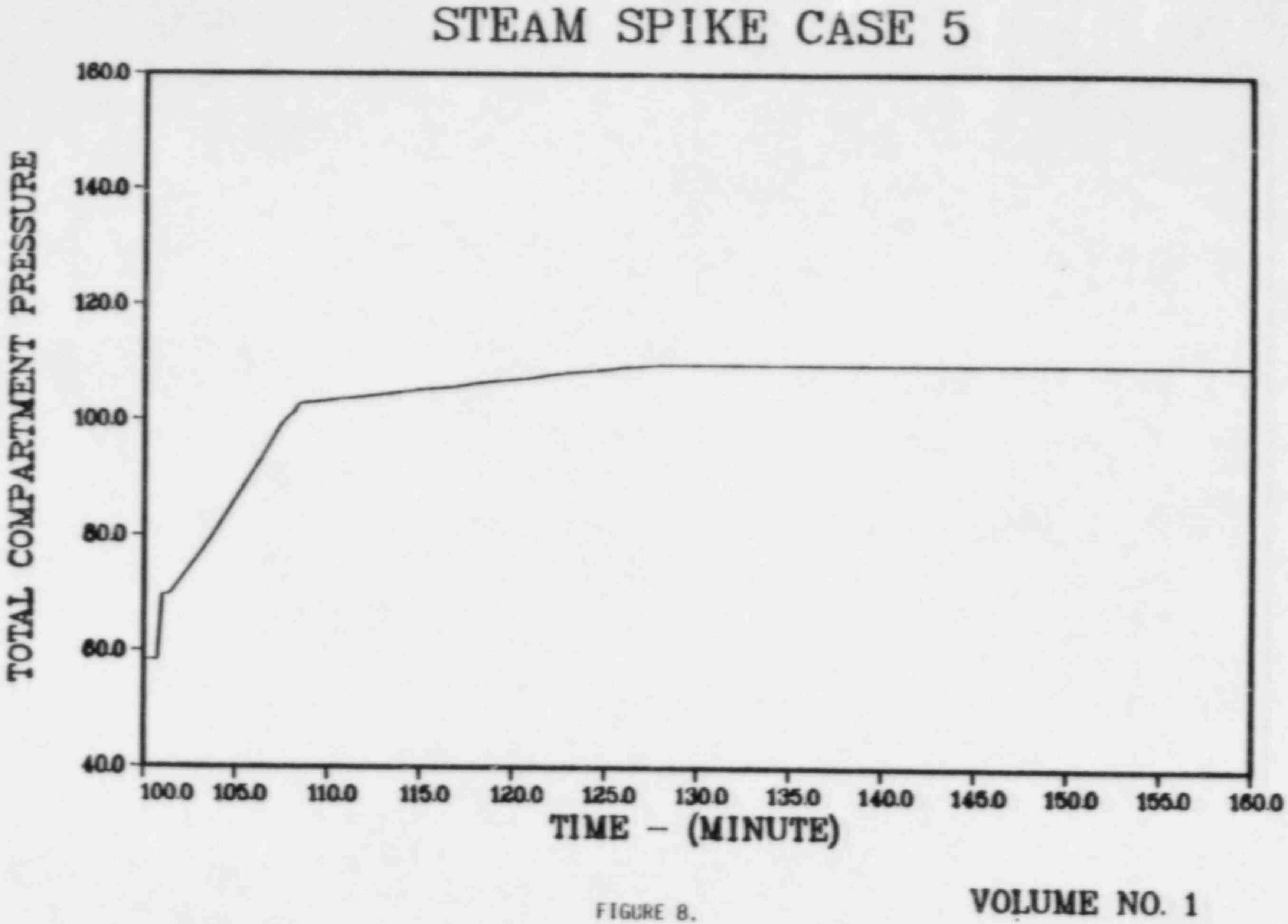
STEAM SPIKE CASE 5
TOTAL COMPARTMENT PRESSURE
160.0
140.0
120.0
100.0
80.0
60.0
40.0
100.0
105.0
110.0
115.0
120.0
125.0
130.0
135.0
140.0
145.0
150.0
155.0
160.0
TIME – (MINUTE)
VOLUME NO. 1

FIGURE 8.

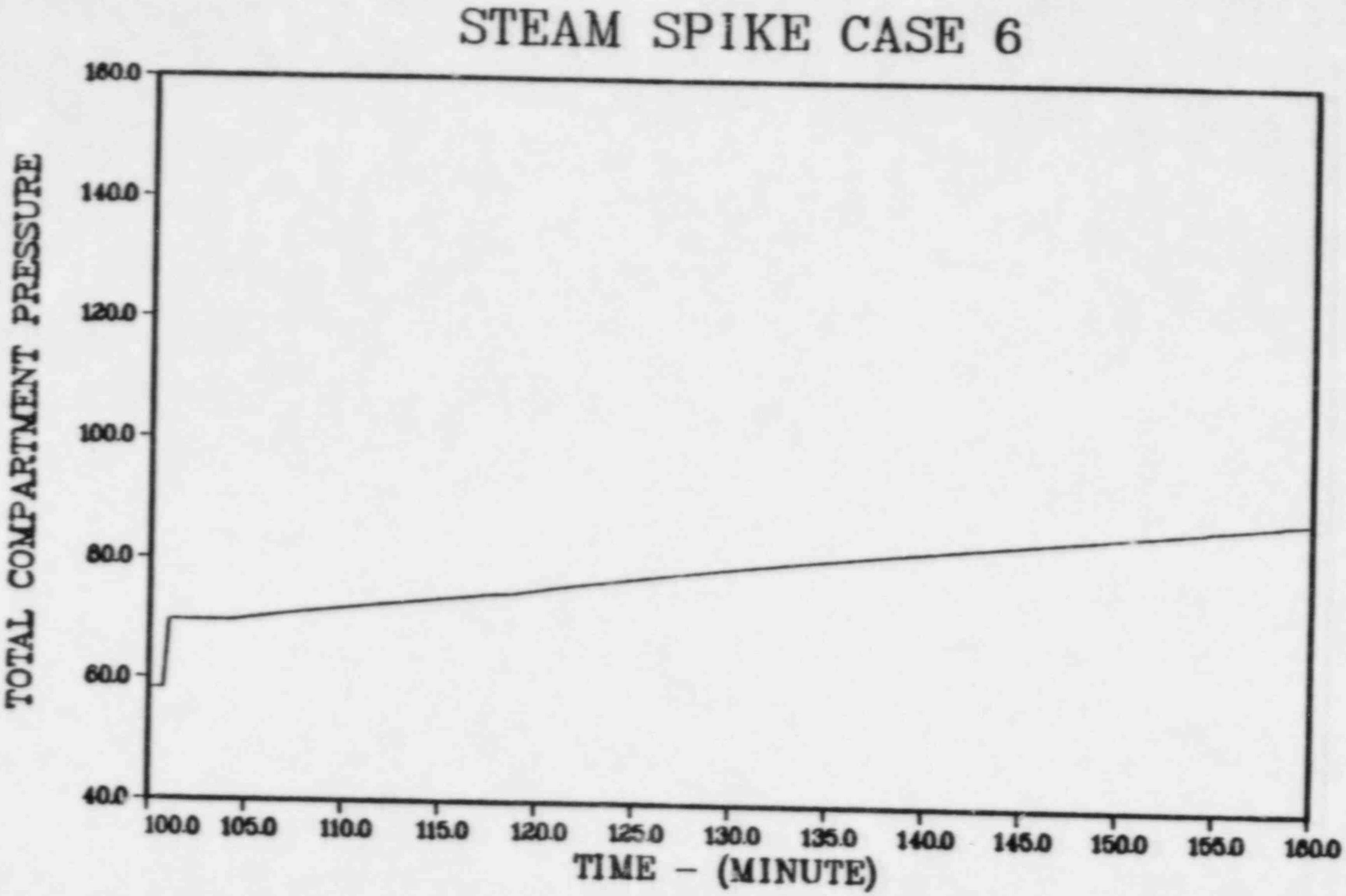

FIGURE 9.

VOLUME NO. 1

STEAM SPIKE CASE 7

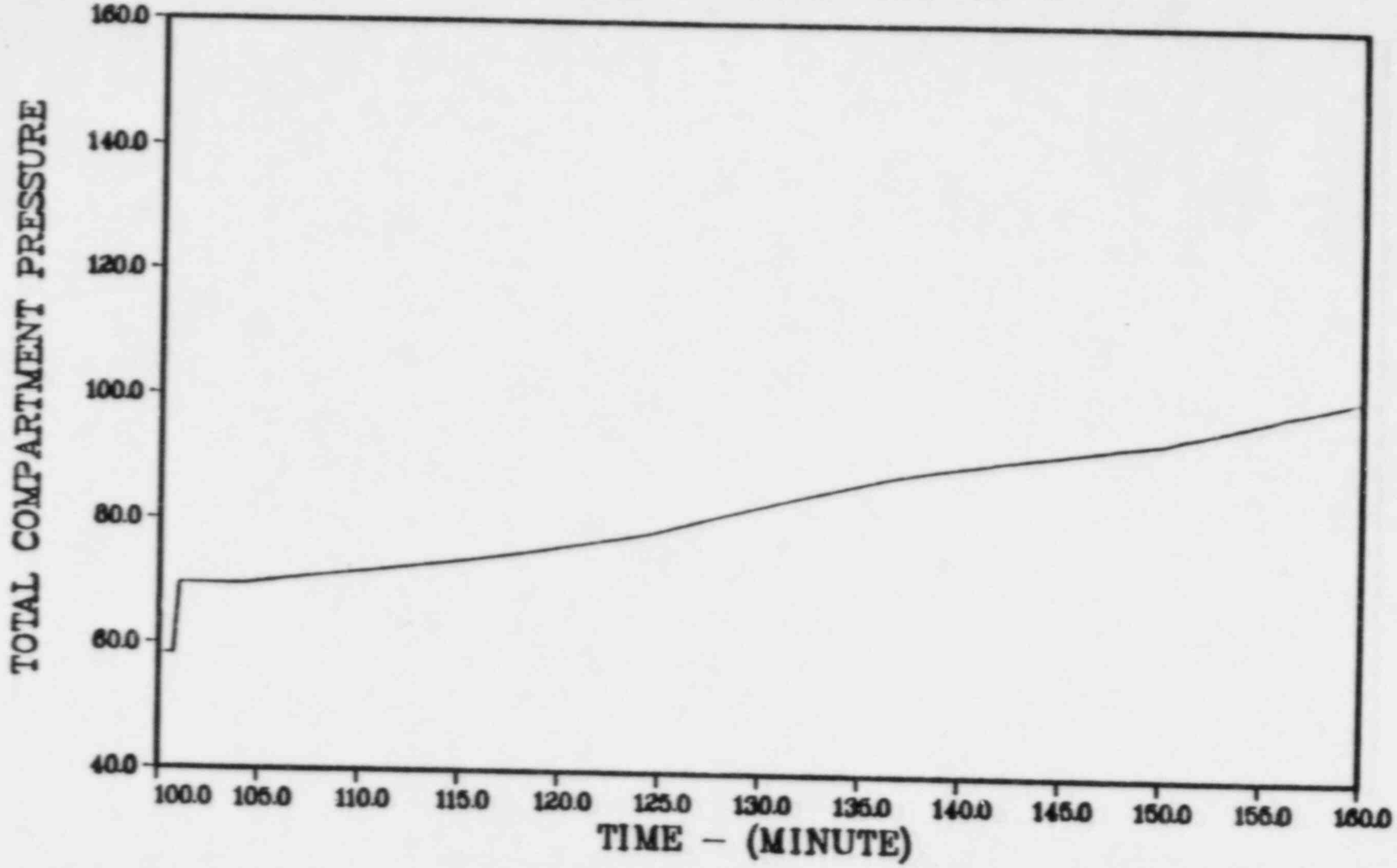

FIGURE 10.

VOLUME NO. 1