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TECHNICAL MEMORANDUM

ANL-CT-79-17

PLENUM-2A: A PROGRAM FOR TRANSIENT ANALYSIS OF LMFBR OUTLET PLENUMS

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Components Technology Division

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~~APPLIED TECHNOLOGY~~

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LMFBR Reactor Core
Systems (UC-79e)

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NOMENCLATURE

Variable Name	Description	Dimensions
a,b	constants from Ref. 8	
BFRAC	fraction of the outlet nozzle covered by volume 1	
Cp	specific heat capacity of water	cal/(gm * °C)
D1, D2, D3, D4	different diameters of the outlet plenum - see Fig. 1	cm
DJ	effective jet diameter at impingement - see Ref. 1	cm
DTIME	time step in the calculations	s
E	energy of the total outlet plenum volume	cal
E1	energy of volume 1	cal
Frj	modified Froude number, as in Ref. 7	
g	gravitational acceleration	cm/s^2
FLOW	flow rate	cm^3/s
H	height of the jet, as in Ref. 6	cm
M	total mass of the water in the outlet plenum	gm
M1	mass of volume 1	gm
Ri	Richardson number	
TIME	time	s
TINLET	temperature of inlet water	°C
TOUT	temperature of outgoing water	°C
TH	temperature of the hot water	°C

TC	temperature of the cold water	°C
T1	temperature of volume 1	°C
T2	temperature of volume 2	°C
VELOC	velocity of incoming water	cm/s
VT	total volume of the plenum	cm^3
V1	volume 1	cm^3
V2	volume 2	cm^3
VJ	average jet velocity at impingement, as in Ref. 7	cm/s
Z1, Z2, Z3	dimensions of the outlet plenum, Fig. 2	cm
ZB	height of the boundary separating volume 1 and 2	cm
ρ	density	gm/cm^3

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ABSTRACT

An improved version of the PLENUM-2 code, PLENUM-2A, has been developed to predict the thermal conditions in an LMFBR outlet plenum after a reactor scram. Both the old and the improved versions divide the transient into three consecutive stages and consider only two mixing regions within the outlet plenum. Modifications of the code as reported here include elimination of the three second delay between Stage 1 and Stage 2, a simplification of the transition stage which occurs between complete mixing and the stratification phase, and an improved hot-cold interface rise-rate correlation. In most cases, PLENUM-2A has better agreement with available data than does PLENUM-2.

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ACKNOWLEDGMENTS

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1.0 INTRODUCTION

The thermal-hydraulic phenomena occurring in the outlet plenum of a Liquid Metal Fast Breeder Reactor (LMFBR) after a normal scram have been addressed (with different levels of sophistication) by several people, ranging from one region complete mixing models to three-dimensional transient thermal-hydraulic models [1-4]. The primary purpose of the outlet plenum is to mitigate any rapid temperature changes that occur due to changes in reactor power. If, due to poor mixing within the outlet plenum, a rapid temperature change should propagate through the outlet plenum, temperature sensitive components could be damaged. Temperature changes of 30-40°C/s would occur at the core outlet due to a reactor scram, while most components downstream of the outlet plenum are designed to withstand temperature changes only in the neighborhood of 1-2°C/s. A proven computer code that would predict thermal conditions in an LMFBR outlet plenum after a reactor scram would be a valuable aid for designers who are considering several reactor geometries. PLENUM-2A is a code which has been verified by simulation experiments that incorporate the basic physics of the mixing processes into a simple Fortran code with a minimum amount of mathematical sophistication.

The PLENUM-2 code [5], developed earlier at Argonne National Laboratory, is a two region outlet plenum model. Although good agreement with experimental data was obtained using this code, there were some discrepancies between the code and the data which have been removed with the new version. Specifically, when the height of the plenum inlet was less than the height of the plenum outlet nozzles, the predicted outlet temperature was significantly lower than the experimental values. Furthermore, during Stage 3, the predicted rise-rate of the interface disagreed with experimental results.

The new version of PLENUM-2 is simpler than the previous one; the differences are as follows:

a. All plenum geometries are treated in a similar manner, independent of the relative position of the inlet plenum and the outlet nozzles. Therefore, the two different configurations of the previous version of PLENUM-2 are no longer considered.
b. New correlations are used for the hot-cold interface.
c. The transition phase, Stage 2, has been simplified.

Most of the calculations performed by the program are identical to the ones described in a previous report for PLENUM-2 [5]. However, for completeness, all of the calculations at each step are again described in detail. Some of the variables used in the program are represented in Fig. 1, a Generalized Outlet Plenum.

2.0 COMPUTER CALCULATIONS

The complete transient has been divided into three consecutive stages. Another stage, called Stage 0, is defined prior to the initiation of the transient, and no calculations are done during this stage. The program assumes that the plenum is isothermal, with only one region (completely mixed) before the transient starts (Stage 0), and during Stage 1 of the transient. Two different regions exist during Stages 2 and 3, and, hence, the name of the code, PLENUM-2.

2.1 Stage 0

A steady-state isothermal plenum exists where V1 is equal to the total plenum volume. Although no calculations are done, the presence of this stage simplifies the comparison of predictions and data because a short period of time is required during each experiment to insure isothermal conditions throughout the plenum.

2.2 Stage 1

Stage 1 corresponds to the start of the transient, where the high flow rate gradually diminishes to a lower steady-state value, and the high inlet temperature changes to a lower steady-state value. There is no space dependence for the temperature, but there is a time dependence for temperature and/or flow rate. Only one region exists in the outlet plenum, and perfect mixing occurs. This stage ends when the jet height drops below the top of the plenum. The calculations performed during this state are as follows:

Energy Balance:

$$E\Big|_{TIME + DTIME} = E\Big|_{TIME} + Cp * FLOW * DTIME * (\rho(TINLET) * TINLET - \rho(T1) * T1)$$

Temperature:

$$T1\Big|_{TIME + DTIME} = \frac{E\Big|_{TIME + DTIME}}{Cp * M\Big|_{TIME + DTIME}}$$

$$\text{where } M\Big|_{TIME + DTIME} = VT * \rho(T1)$$

TOUT = T2 = T1

The height of the jet is calculated by the formula [Ref. 6]

$$H = 1.0484 * Ri^{-.785} * \frac{D4}{2}, \text{ with}$$

$$Ri = \text{Richardson number} = \frac{(\rho(TINLET) - \rho(T1)) * g * \frac{D4}{2}}{VELOC^2 * \rho(TINLET)} \qquad [1]$$

2.3 Stage 2

This stage starts when the jet height drops below the top of the plenum and the entering fluid mixes with the water below the plenum inlet. The initial volume of region 1 is assumed to be the volume below the plenum inlet. The boundary separating the cold (below) from the hot (above) regions is initially formed at the plenum inlet, Z2 (see Fig. 1).

Stage 2 is a transition stage where the flow pattern changes from perfect mixing, Stage 1, to stratified flow, Stage 3. During Stage 2, the fluid below the plenum inlet is cooled, and a hot-cold interface is formed. It has been determined experimentally that the duration of Stage 2 is between 1/4 and 1/6 of the time needed to fill the volume below the plenum inlet with the incoming fluid. [5]

The temperature of region 2 is assumed constant and equal to the final temperature of region 1 at the end of Stage 1. No heat transfer between region 1 and region 2 is assumed during this stage. The calculations during Stage 2 are performed as follows:
The initial volume of region 1 is

$$V1 = \frac{\pi}{4} * Z2 * (D1^2 - D2^2)$$

When Stage 2 starts, the incoming flow is multiplied by four (the choice of this constant is discussed in Section 4.0) and integrated in time. When this integrated flow is equal to the volume of region 1, Stage 3 starts. Perfect mixing is assumed between the incoming fluid and the fluid in volume 1.

Energy balance:

$$E1 \Big|_{TIME + DTIME} = E1 \Big|_{TIME} + Cp * FLOW * DTIME * (\rho(TINLET) * TINLET - \rho(T1) * T1)$$

Temperature:

$$T1\Big|_{TIME + DTIME} = \frac{E1\Big|_{TIME + DTIME}}{Cp * M1\Big|_{TIME + DTIME}}$$

where $M1\Big|_{TIME + DTIME} = V1 * \rho(T1)$

T2 = constant

TOUT = T1 * BFRAC + T2 * (1 - BFRAC)

$$\text{with BFRAC} = \frac{ZB\Big|_{TIME} - (Z3 - D3/2)}{D3}$$

with the conditions: if BFRAC < 0 BFRAC = 0
if BFRAC > 1 BFRAC = 1

During the development of PLENUM-2A, an alternate approach was used to terminate Stage 1 and begin Stage 2. The technique that was used utilized a minimum value for the Richardson number, above which stratification was assumed to occur. A value of 0.15 was chosen as that minimum Richardson number above which perfect mixing did not occur. Both approaches yielded nearly identical results, and they will be discussed in detail in Section 4.0.

2.4 Stage 3

The hot-cold boundary rises according to the formula [7]

$$\frac{dZB}{DTIME} = a*(Frj)^{-b} * \frac{(D1)^2}{(DJ)^2} * Vj$$

where Frj, DJ, and Vj are respectively the modified Froude number, modified or effective jet diameter, and the modified or effective jet impinging velocity at the hot-cold interface. They are defined in Ref. 7 as a function of the distance between the hot-cold interface and the plenum inlet. For most outlet plenums, the flow regime for the hot-cold interface is referred to as the region of flow establishment, and the values of the constants a and b are taken from Ref. 8:

$a = 1.1 \quad b = 1.45$ for velocities higher than 6 cm/s

$a = 1.0 \quad b = 1.1$ for velocities lower than 6 cm/s

The velocity of the hot-cold interface is integrated, and its position is calculated as follows:

$$ZB\Big|_{TIME + DTIME} = ZB\Big|_{TIME} + \frac{dZB}{DTIME} * DTIME + \frac{FLOW * DTIME * (1 - BFRAC)}{\frac{\pi}{4} * (D1)^2}$$

The second term in this expression is the height of the hot-cold interface at the previous time step. The third term represents the change in height due to the entrainment of the cold impinging jet. The fourth term takes into consideration the fact that when the outlet nozzles are above the plenum inlet, the interface separating the cold and hot regions also rises because the incoming liquid is pumped into the lower region and, therefore, the volume of this region grows. When the boundary is above the outlet nozzles, BFRAC = 1, and the fourth term will be zero.

Volume and mass balances for Stage 3 are

$$V1\Big|_{TIME + DTIME} = V1\Big|_{TIME} + \frac{dZB}{DTIME} * DTIME * \frac{\pi}{4} * D1^2 + FLOW * DTIME * (1 - BFRAC)$$

$$V2 = VT - V1$$

$$M1\Big|_{TIME + DTIME} = V1\Big|_{TIME + DTIME} * \rho(T1)$$

The energy balance as calculated during Stage 3 is as follows:

$$E1\Big|_{TIME + DTIME} = E1\Big|_{TIME} + Cp * FLOW * DTIME * \rho(TINLET) * TINLET$$

$$+ Cp * \frac{dZB}{DTIME} * DTIME * \frac{\pi}{4} * D1^2 * \rho(T2) * T2$$

$$- Cp * FLOW * DTIME * \rho(T1) * T1 * BFRAC$$

Temperature:

$$T1\Big|_{TIME + DTIME} = \frac{E1\Big|_{TIME + DTIME}}{Cp * M1\Big|_{TIME + DTIME}}$$

TOUT = T1 * BFRAC + T2 * (1 - BFRAC)

T2 = constant

When the hot-cold boundary reaches the top of the plenum, complete mixing occurs, and, therefore, the conditions of Stage 1 apply again. The difference between the plenum temperature and the inlet temperature would decrease exponentially in time.

3.0 COMPUTER PROGRAM

A flow chart of computer program PLENUM-2A is given in Fig. 2. Versions of the program for Hewlett Packard, IBM, and CDC computers are available. The Hewlett Packard version is listed in the Appendix. All the versions have plotting capability, so the output can be a table and/or a plot. The input to the program is the flow rate and temperature of the inlet fluid and the geometric dimensions of the plenum. Density as a function of temperature must also be input in the Hewlett Packard version. The calculated results are the outlet temperature, the upper region temperature, the lower region temperature, and the position of the hot-cold interface.

The Hewlett Packard version has been run extensively because the graphic output can be compared directly with experimental results that were taken with the same computer system.

4.0 MODEL VERIFICATION

All experimental data available from the Base Technology (BT) tests have been compared with the calculated results from the PLENUM-2 and PLENUM-2A codes. Figs. 3 to 21 show comparisons of experimental data and predictions. Table 1 lists all the BT tests, where data and calculations are compared. All the tests in this table were compared with the output of PLENUM-2 except tests BT29 and BT30.

Several different combinations of inlets and exits have been compared to the calculations. These geometric combinations included high and low inlets used in conjunction with high or low exits. The height of exit nozzles relative to the inlet was used in PLENUM-2 to influence the duration of Stage 2. Calculations were conducted with two different integration constants in PLENUM-2A. Because the results were so close, PLENUM-2A was simplified to eliminate the geometry dependent integration constant. A schematic drawing of the cross-section of the plenum is included in each figure to allow visualization of the plenum geometry used with each run.

The outlet temperature is considered the most important calculated output of the code because it influences the thermal conditions to which components downstream of the outlet plenum are subjected (e.g. pumps and intermediate heat exchangers).

The conditions of the BT tests have been described in detail in an earlier report [5]. Only the aspects of those tests that were not treated in that report are described here, together with the different predictions of the PLENUM-2A code.

4.1 Exit Nozzle Temperature

Agreement between the experimental and calculated results is significantly better with PLENUM-2A when the outlet nozzles are above the plenum inlet. Specifically, the predictions of TOUT for tests BT10, 11, 13, 14, 32, and 33 are better with the new version early in the transient. For the other tests, the predictions with the new version are almost identical to those with the previous version. However, because of the improved correlation for the rise-rate of the hot-cold interface of Stage 3, slightly better agreement has been obtained in all the tests for this part of the transient.

4.2 Effect of the Stage 1 to Stage 2 Switching Condition

Calculations were performed to determine the best criterion to use for switching from Stage 1 to Stage 2. Two different conditions tested were

a. Height of the plume less than the top of the plenum

b. Ri greater than 0.15.

For tests BT10, 11, 13, 14, and 32 (Figs. 3, 4, 5, 6, and 20), Stage 2 occurred earlier with condition (a) than with condition (b). This improves the results for tests BT11, 13, 14, and 32, and gives worse results for test BT10.

Two other tests behaved very differently: BT24 and BT25 (Figs. 16 and 17). The data show that using condition (a), stratification occurs; while using condition (b), perfect mixing is predicted. In both cases, the agreement with the outlet temperature is very good. Since there were no thermocouples located at high positions in the plenum, there is no way to check experimentally if stratification occurred. The only way to solve this uncertainty is to repeat the tests with a thermocouple at a high position in the plenum. Condition (a) has been chosen for PLENUM-2A because the outlet plenum height is included in the switching criterion. One would expect stratification to occur sooner in a plenum where the incoming fluid must rise higher. Reference 6 indicates that when the modified Froude number is greater than 5, no entrainment occurs in the plenum. That reference uses a modified Froude number that is the inverse of the Richardson number used in this report. Thus, the value of 5 in Ref. 6 corresponds to a value of .20 in this work. Using this value, two tests, BT32 and BT27, did not switch to Stage 2 because their Richardson numbers were .156 and .19, respectively. Hence, the value Ri = .15 was chosen as that value above which perfect mixing does not occur.

Reducing the value of the Richardson number still more will allow stratification for tests BT24 and BT25. However, it is not clear if stratification occurred in these two tests, and, therefore, choosing a smaller value for the Richardson number is not justified.

A three second delay between Stage 1 and Stage 2 exists in PLENUM-2. This delay artificially models the collapse of the plume and the mixing of the incoming jet with the fluid within the plenum. This feature has been eliminated from PLENUM-2A because its effect was small and the duration was arbitrary. Although the flow pattern does not change from perfect mixing (Stage 1) to a collapsing

plume (Stage 2) instantaneously, there was little physical justification for the three second delay other than experimental observations.

4.3 Effect of the Correlation Used for Stage 3

Calculations were performed for two different hot-cold interface rise-rate correlations for tests BT19, 20, 26, and 27: one with a = 1.1 and b = 1.45 valid for flow rates with velocities higher than 6 cm/s; and the other with a = 1.0 and b = 1.1 valid for flow rates with velocities lower than 6 cm/s. Test BT20 had a velocity lower than 6 cm/s, and better agreement with the data was obtained when the latter correlation was used (Fig. 12).

This additional feature is incorporated into the code for completeness. Although there is little outlet plenum data that shows its effect, hot-cold interface data, however, does show this trend.

5.0 CONCLUSIONS

The computer code PLENUM-2A has been compared with the experimental data, and the following conclusions can be made:

a. This two-region outlet plenum model predicts transients in a simplified outlet plenum after a reactor scram reasonably well.

b. The Richardson number as defined in Formula [1] is an important parameter in outlet plenum mixing. If the Richardson number is less than .15, complete mixing occurs. Richardson numbers larger than .15 indicate stratification in the plenum.

c. Another important parameter used to determine outlet plenum mixing is the height of the plume. When this value is greater than the top of the plenum, complete mixing occurs.

d. The code is essentially self-documented and can be used for sodium simply by specifying the density of sodium as a function of temperature.

REFERENCES

1. Lorenz, J. J., "MIX, A Computer Code for Transient Thermal-Hydraulic Analysis of LMFBR Outlet Plenums", ANL-CT-75-41, May 1975.
2. Cook, J. L. and P. I. Nakyama, "Varr II - A Computer Program for Calculating Time Dependent Flows and Slight Density Variations", SAI, August 1974.
3. Howard, P. A., "PLENUM-3: A Lumped Parameter LMFBR Outlet Plenum Mixing Code", ANL-CT-76-32, March 1976.
4. Sha, W. T., A. M. Domanus, R. C. Schmitt, J. J. Oras and E. I. H. Lin, "COMMIX-1: A Three Dimensional Transient Single-Phase Component Computer Program for Thermal-Hydraulic Analysis", ANL-77-96, NUREG-0415.
5. Howard, P. A. and J. J. Carbajo, "PLENUM-2: A Two Region Outlet Plenum Model", ANL-CT-78-16, March 1976.
6. Yang, J. W., "Penetration of a Turbulent Jet with Negative Buoyancy into the Upper Plenum of an LMFBR", NED-40, 1977, pp. 207-301.
7. Lorenz, J. J. and P. A. Howard, "A Study of the Density Interface in a Stratified LMFBR Outlet Plenum", Paper 77-HT-23 AICHE-ASME, Heat Transfer Conference, Salt Lake City, Utah, August 1977.
8. Harrell, Jefferson A., "Correlations for the Rise Rate of the Hot-Cold Interface in a Liquid Metal Fast Breeder Reactor", M.S. Thesis, University of Illinois at Urbana-Champaign, May 1978.

Table 1. Summary of the Tests

Test No.	Z1 (cm)	Z2 (cm)	Z3 (cm)	Area 4 / Area 1	TH (°C)	TC (°C)	Flow * 10^{-3} (cm^3/s) Max.	Min.
BT10	59.3	11.4	15.4	1.0	78	42	8.95	.883
BT11	59.3	11.4	15.4	1.0	77	17	8.70	.820
BT13	59.3	11.4	15.4	.6	79	19	8.83	.883
BT14*	59.3	11.4	15.4	.6	78	17	8.83	.946
BT15	59.3	21.6	15.4	1.0	80	18	8.70	.946
BT16	59.3	21.6	15.4	1.0	75	18	.851	NT
BT17	60.4	1.3	53.3	1.0	77	17	.870	NT
BT18	60.4	37.0	53.3	1.0	83	18	.851	NT
BT19	60.4	37.0	53.3	1.0	82	19	.466	NT
BT20	59.3	37.0	15.4	1.0	85	20	2.52	.440
BT21	59.3	37.0	15.4	1.0	83	18	5.42	.776
BT22	59.3	37.0	15.4	1.0	79	18	8.83	.883
BT23	59.3	21.6	15.4	1.0	82	21	2.52	NT
BT24	59.3	21.6	15.4	1.0	81	19	3.47	NT
BT25	59.3	21.6	15.4	.2	80	21	.630	NT
BT26	59.3	21.6	15.4	.2	79	18	.309	NT
BT27	59.3	21.6	15.4	.2	78	18	.353	NT
BT29	59.3	1.3	15.4	.2	74	18	.694	.063
BT30	59.3	1.3	15.4	.2	78	21	.694	.315
BT32	59.3	1.3	15.4	.6	76	19	1.51	NT
BT33	59.3	1.3	15.4	.6	73	24	1.00	NT

*Salt was added to the cold fluid to increase its density to 1.040 kg/L.

NT denotes no transient.

D1 = plenum diameter = 59.31 cm

D2 = chimney diameter = 11.3 cm

D3 = exit nozzle diameter = 8.9 cm

Z1 = plenum height

Z2 = inlet height

Z3 = exit nozzle height

1 m^3/s = 15,849 gpm

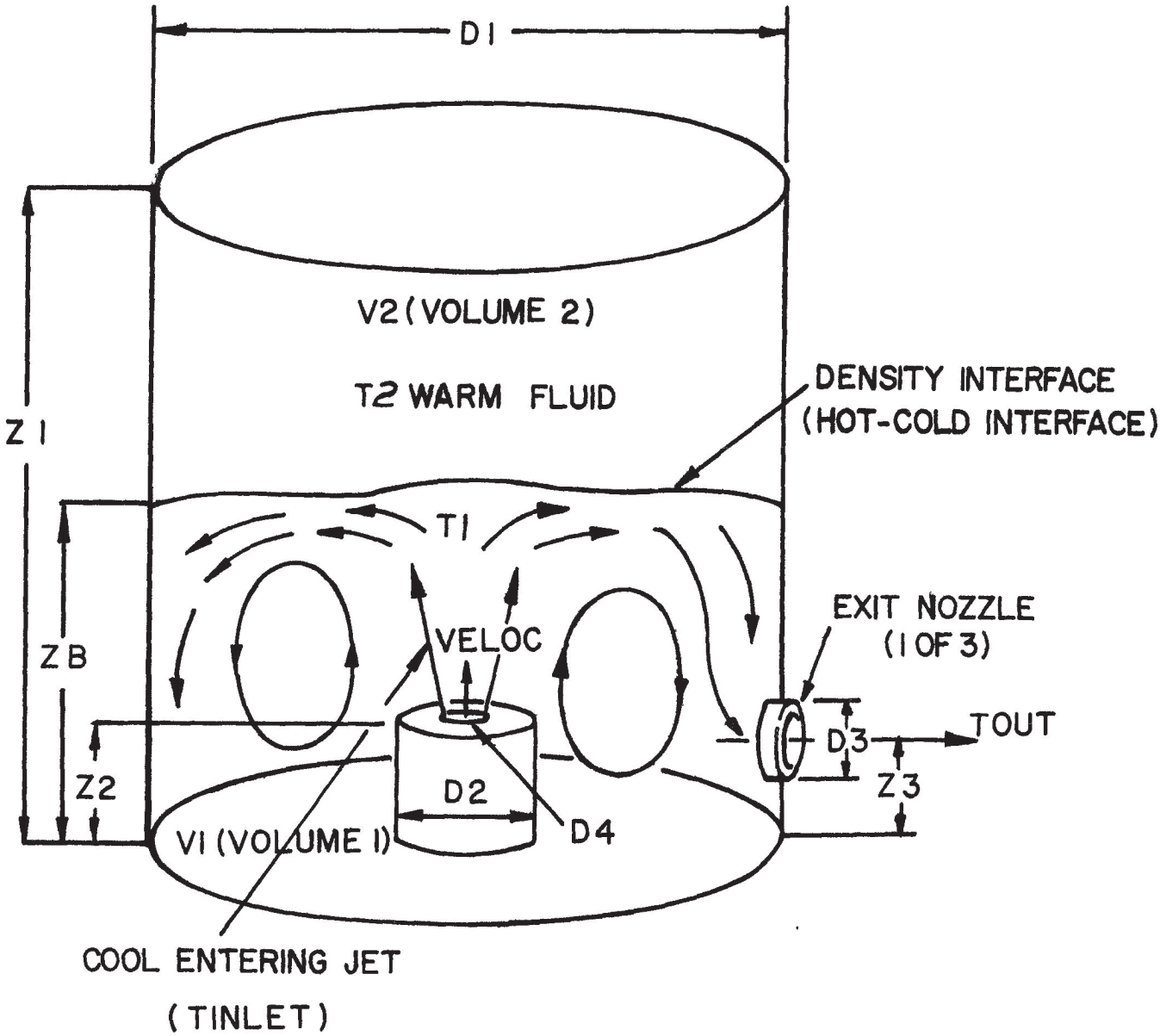

Fig. 1. A Generalized Outlet Plenum

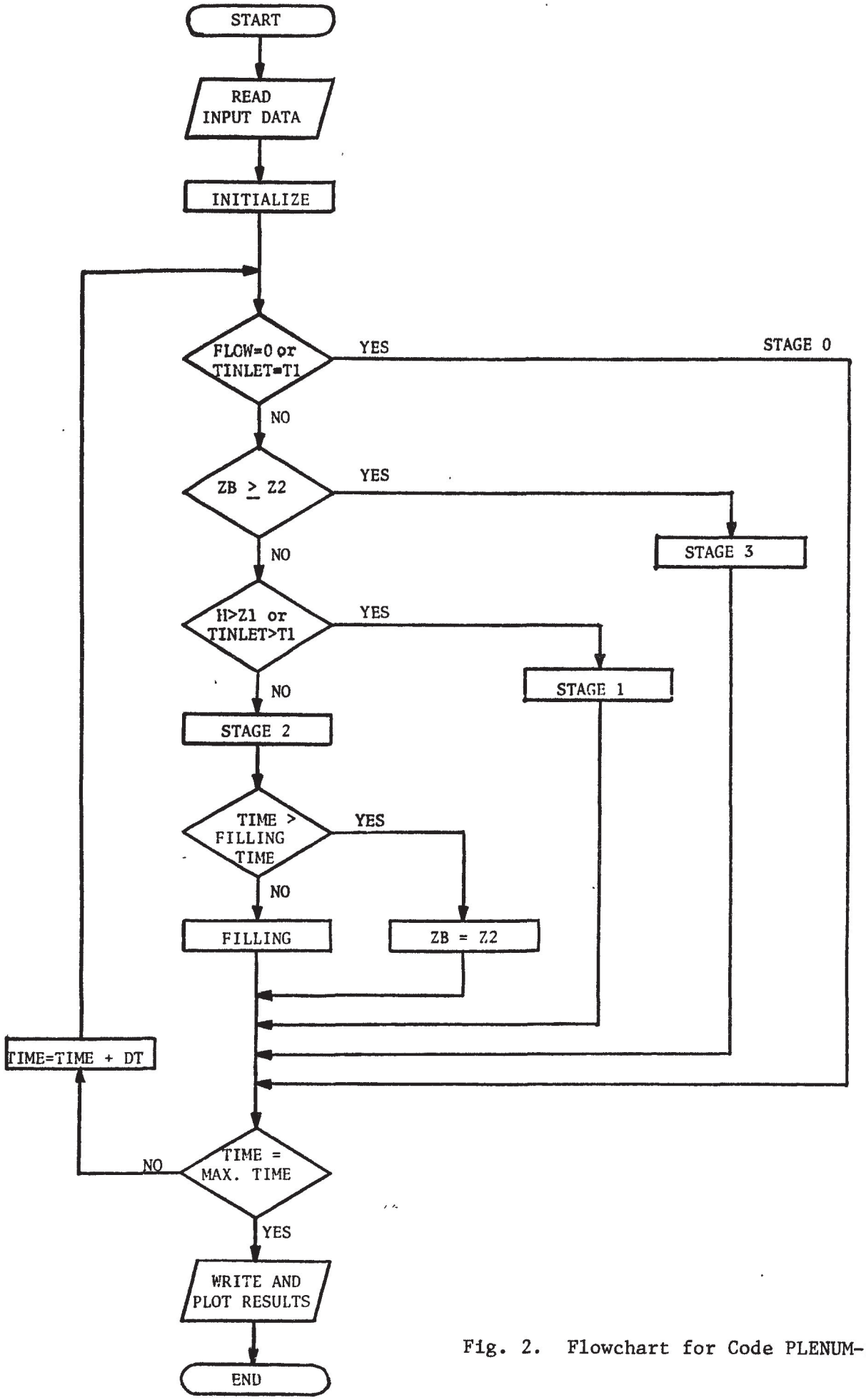

Fig. 2. Flowchart for Code PLENUM-2A

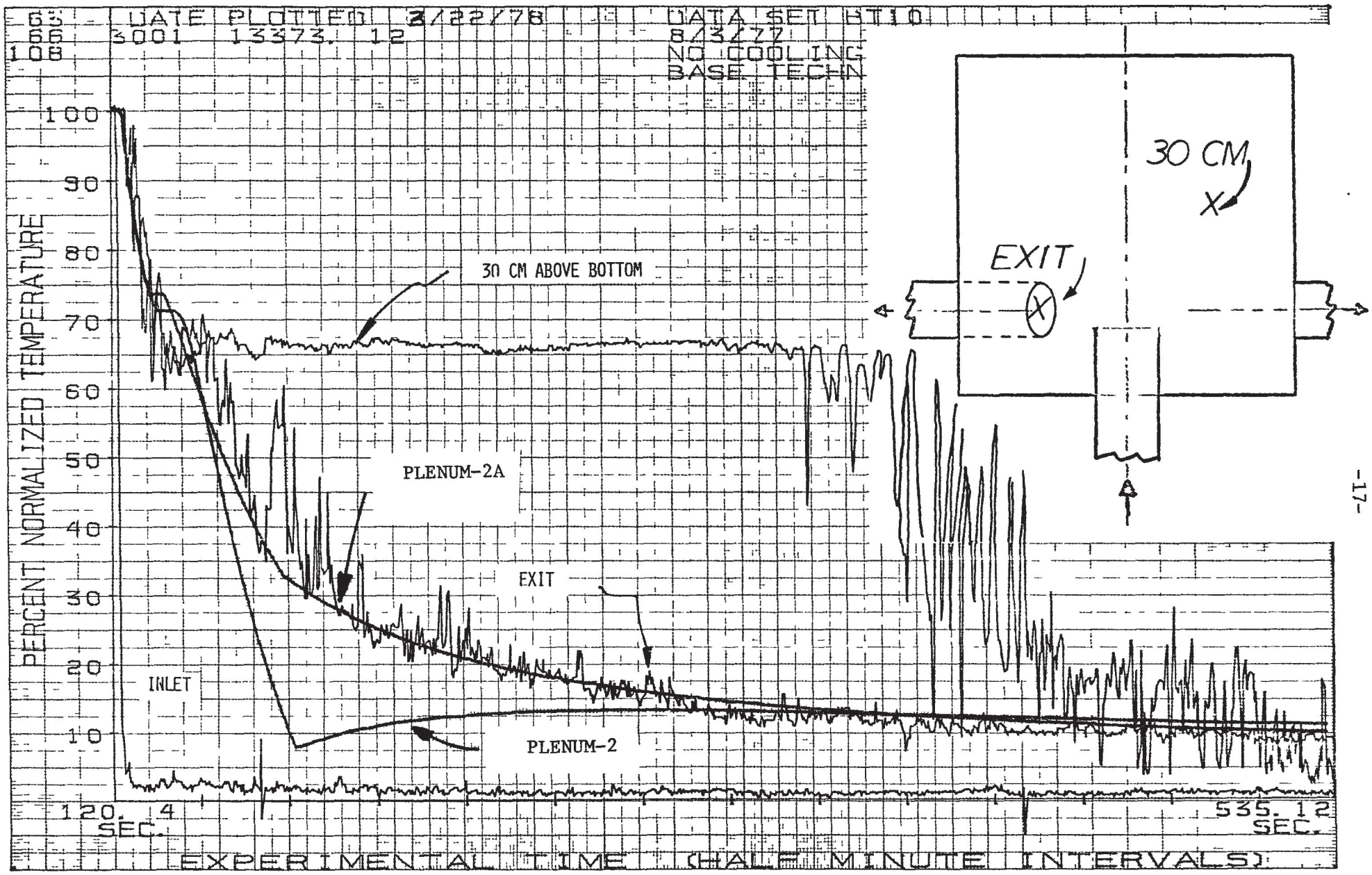

Fig. 3. Exit Nozzle Transients for Test BT10 as Predicted by PLENUM-2 and PLENUM-2A.

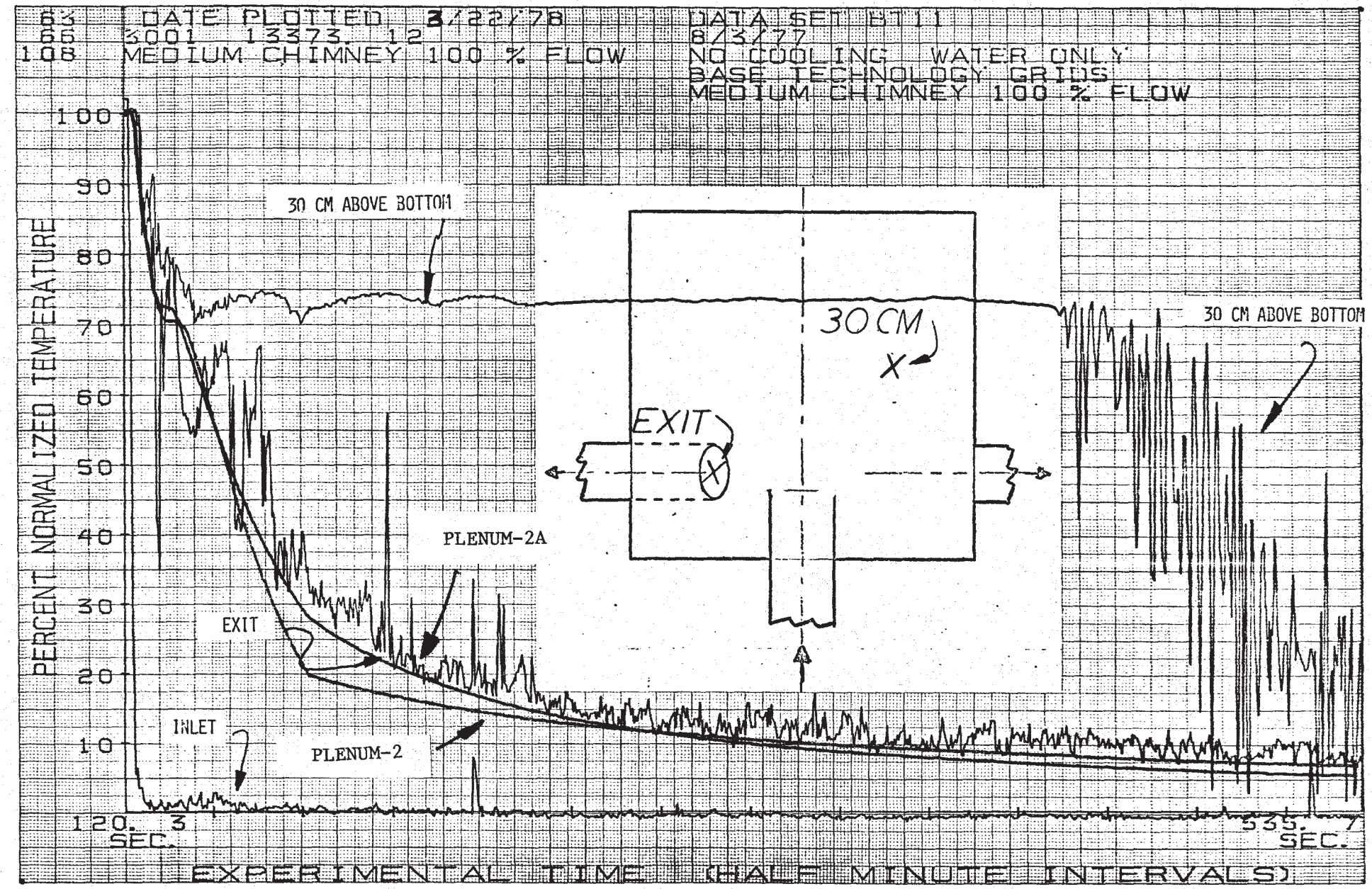

Fig. 4. Exit Nozzle Transients for Test BT11 as Predicted by PLENUM-2 and PLENUM-2A.

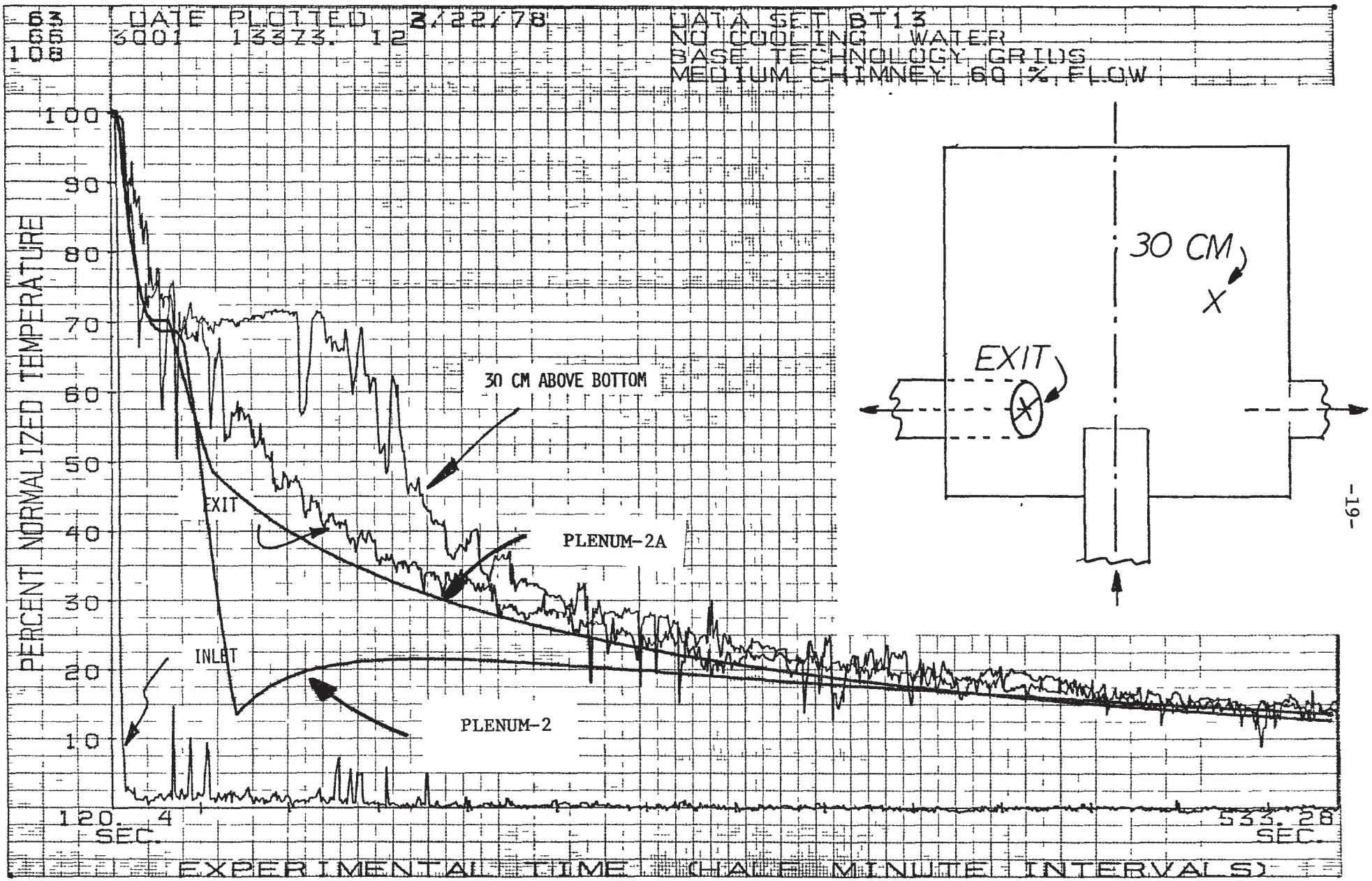

Fig. 5. Exit Nozzle Transients for BT13 as Predicted by PLENUM-2 and PLENUM-2A.

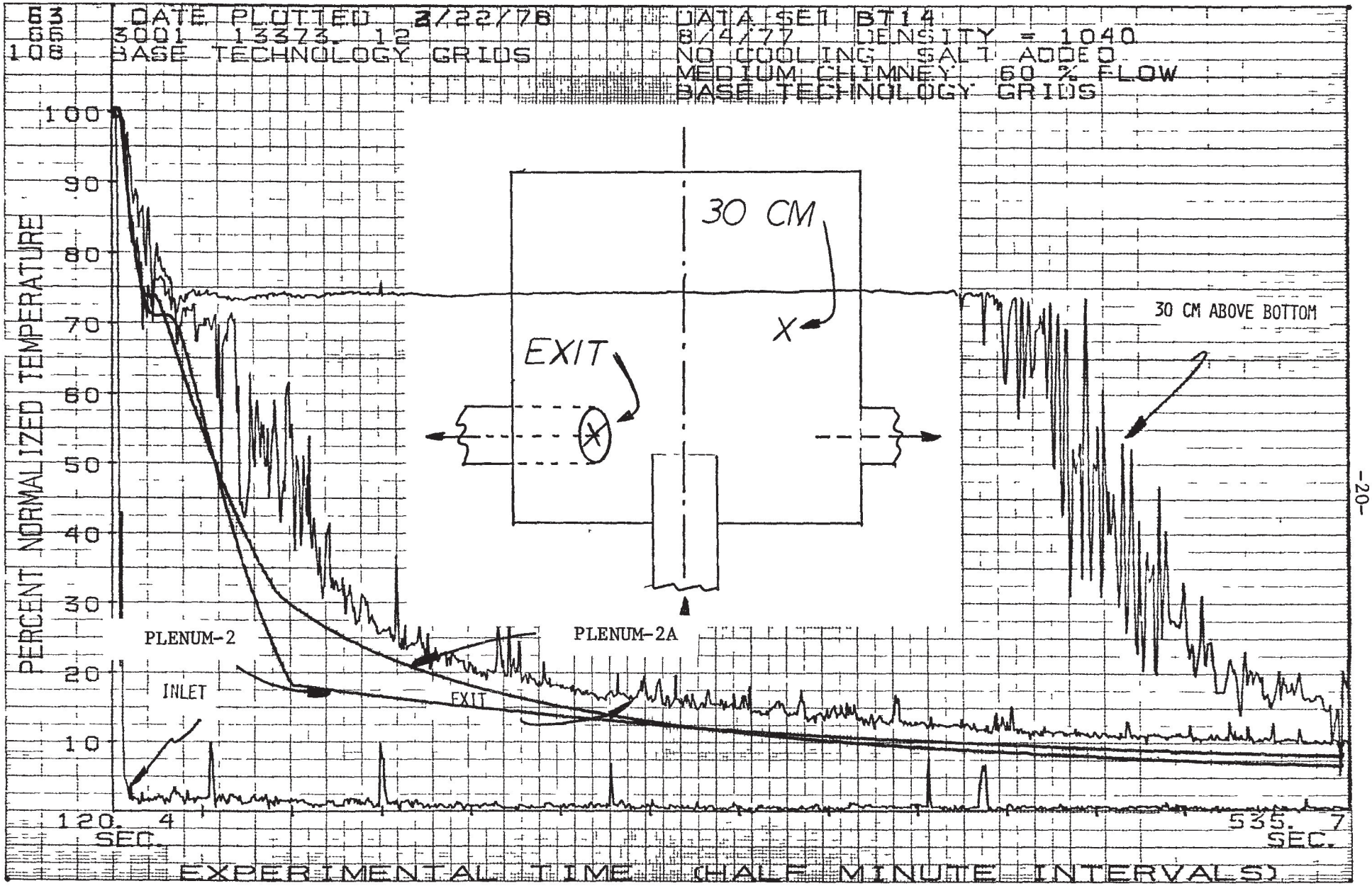

Fig. 6. Exit Nozzle Transients for Test BT14 as Predicted by PLENUM-2 and PLENUM-2A.

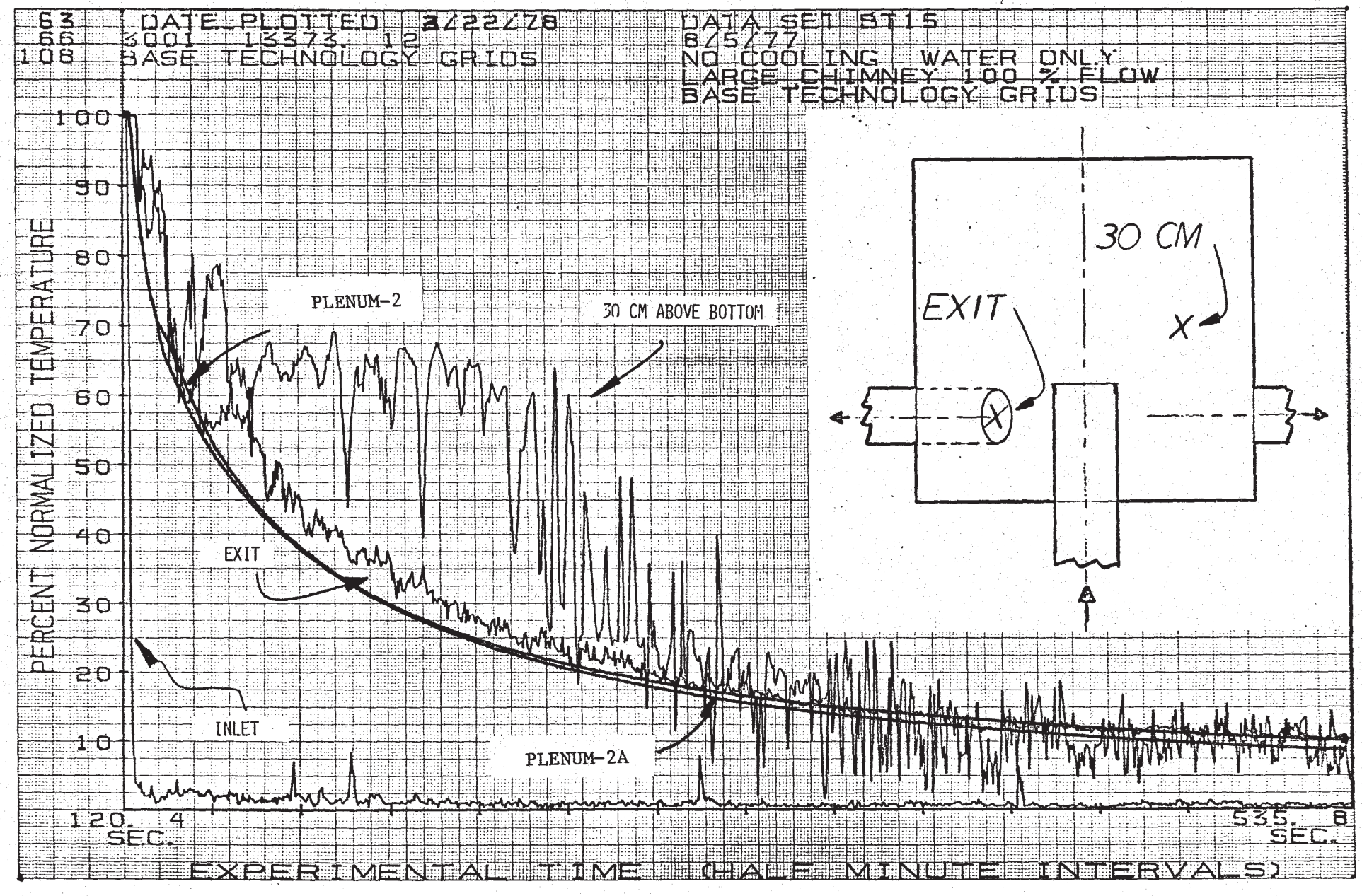

Fig. 7. Exit Nozzle Transients for Test BT15 as Predicted by PLENUM-2 and PLENUM-2A.

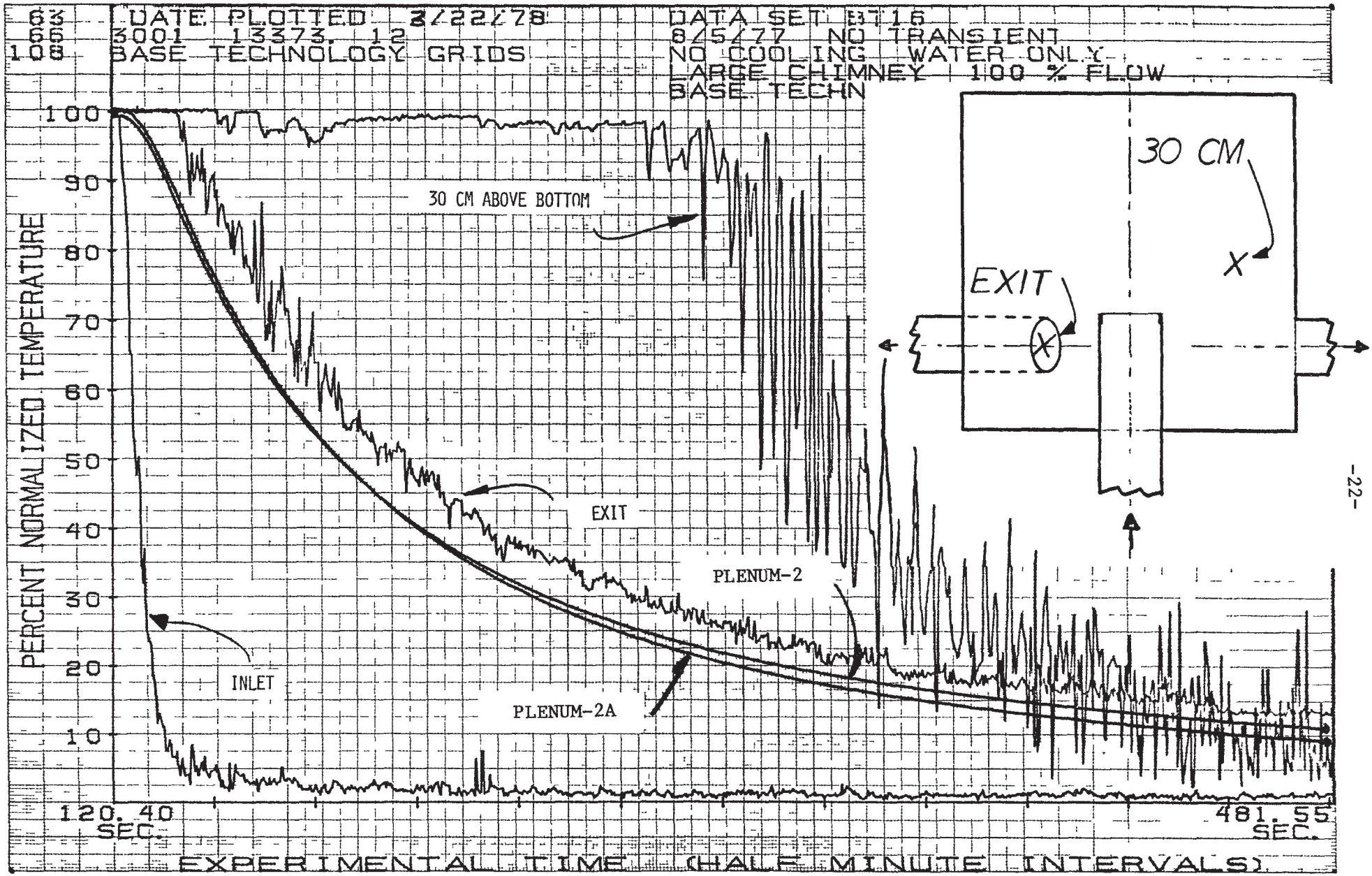

Fig. 8. Exit Nozzle Transients for Test BT16 as Predicted by PLENUM-2 and PLENUM-2A.

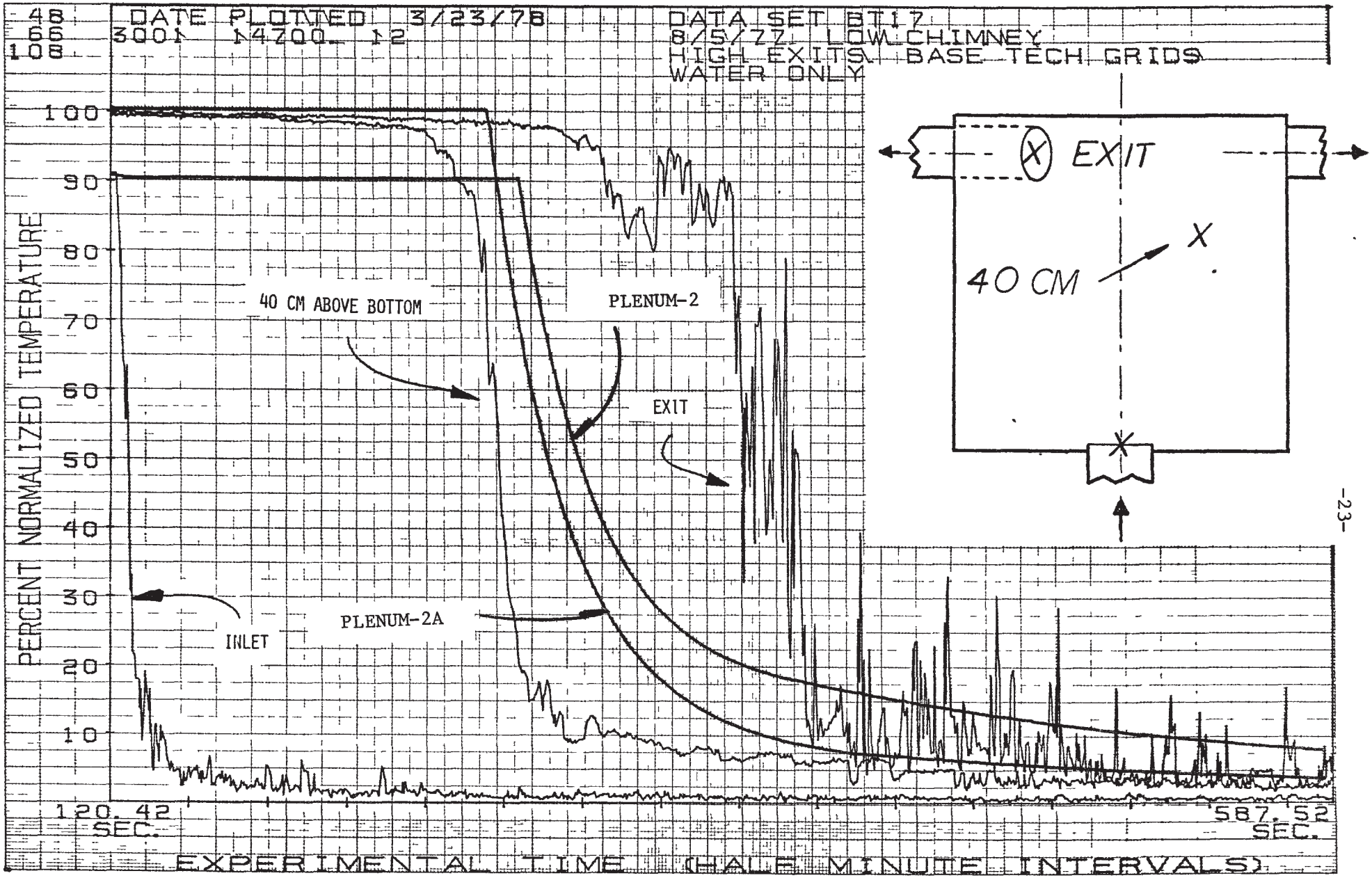

Fig. 9. Exit Nozzle Transients for Test BT17 as Predicted by PLENUM-2 and PLENUM-2A.

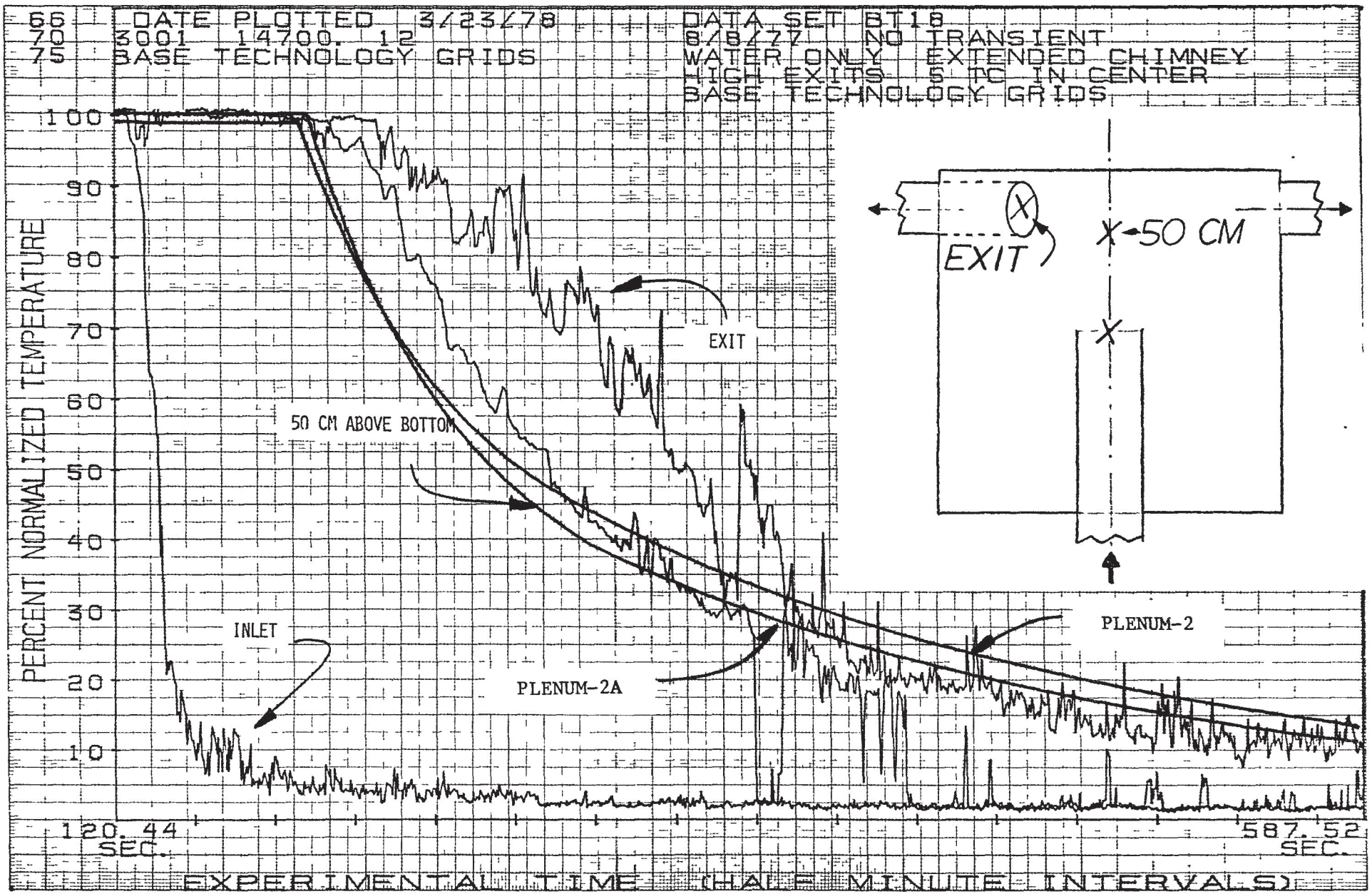

Fig. 10. Exit Nozzle Transients for Test BT18 as Predicted by PLENUM-2 and PLENUM-2A.

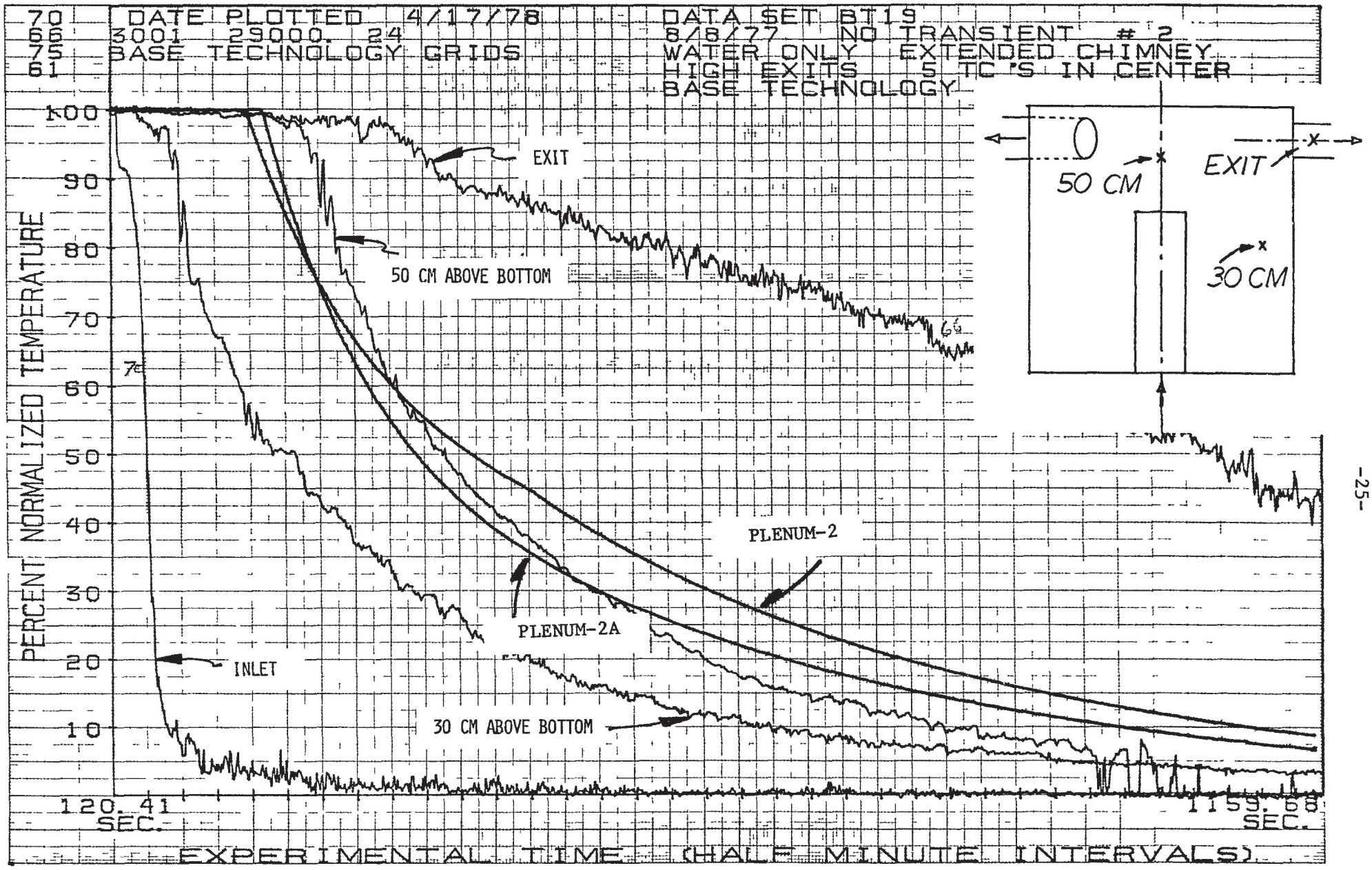

Fig. 11. Exit Nozzle Transients for Test BT19 as Predicted by PLENUM-2 and PLENUM-2A.

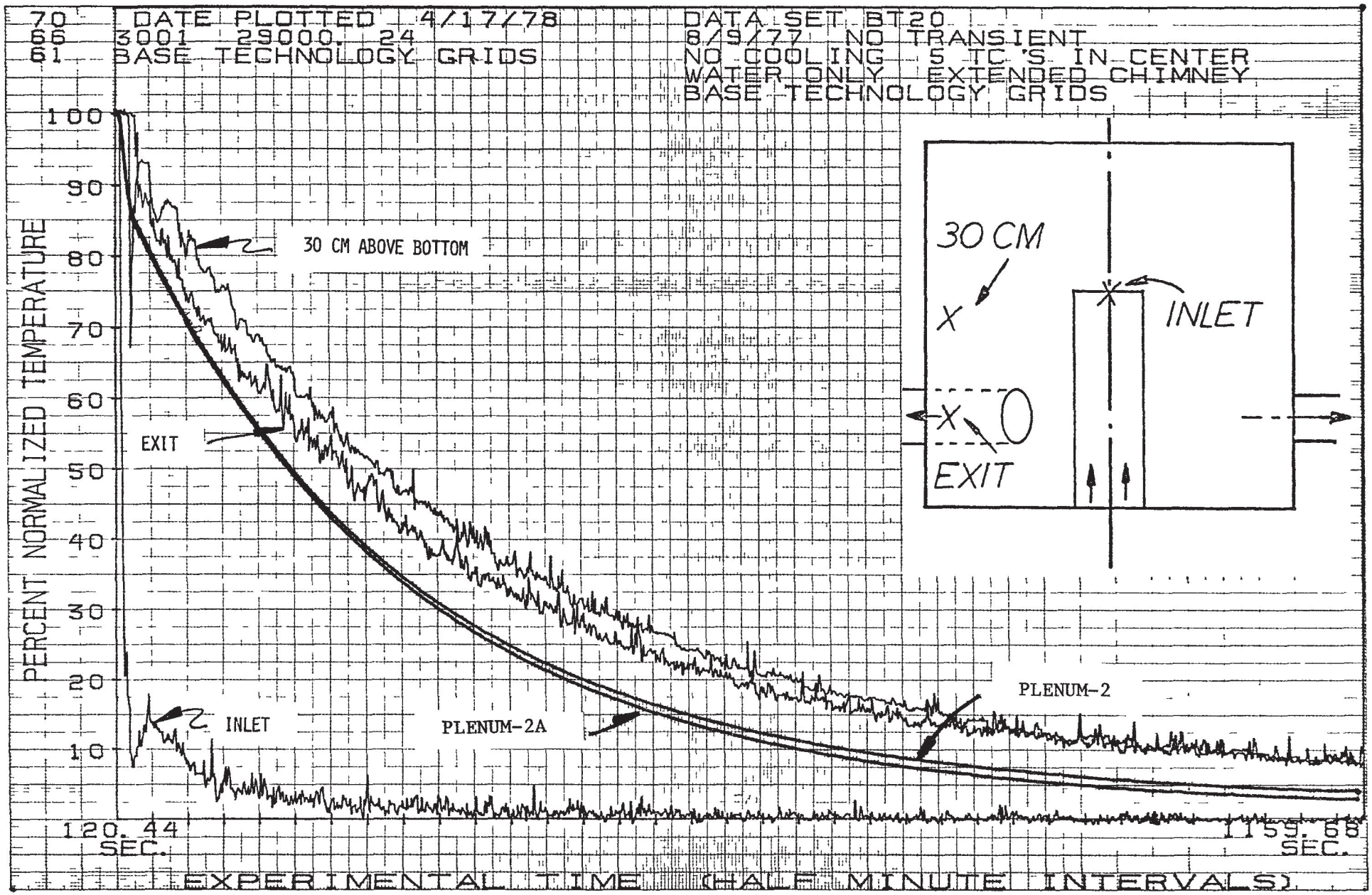

Fig. 12. Exit Nozzle Transients for Test BT20 as Predicted by PLENUM-2 and PLENUM-2A.

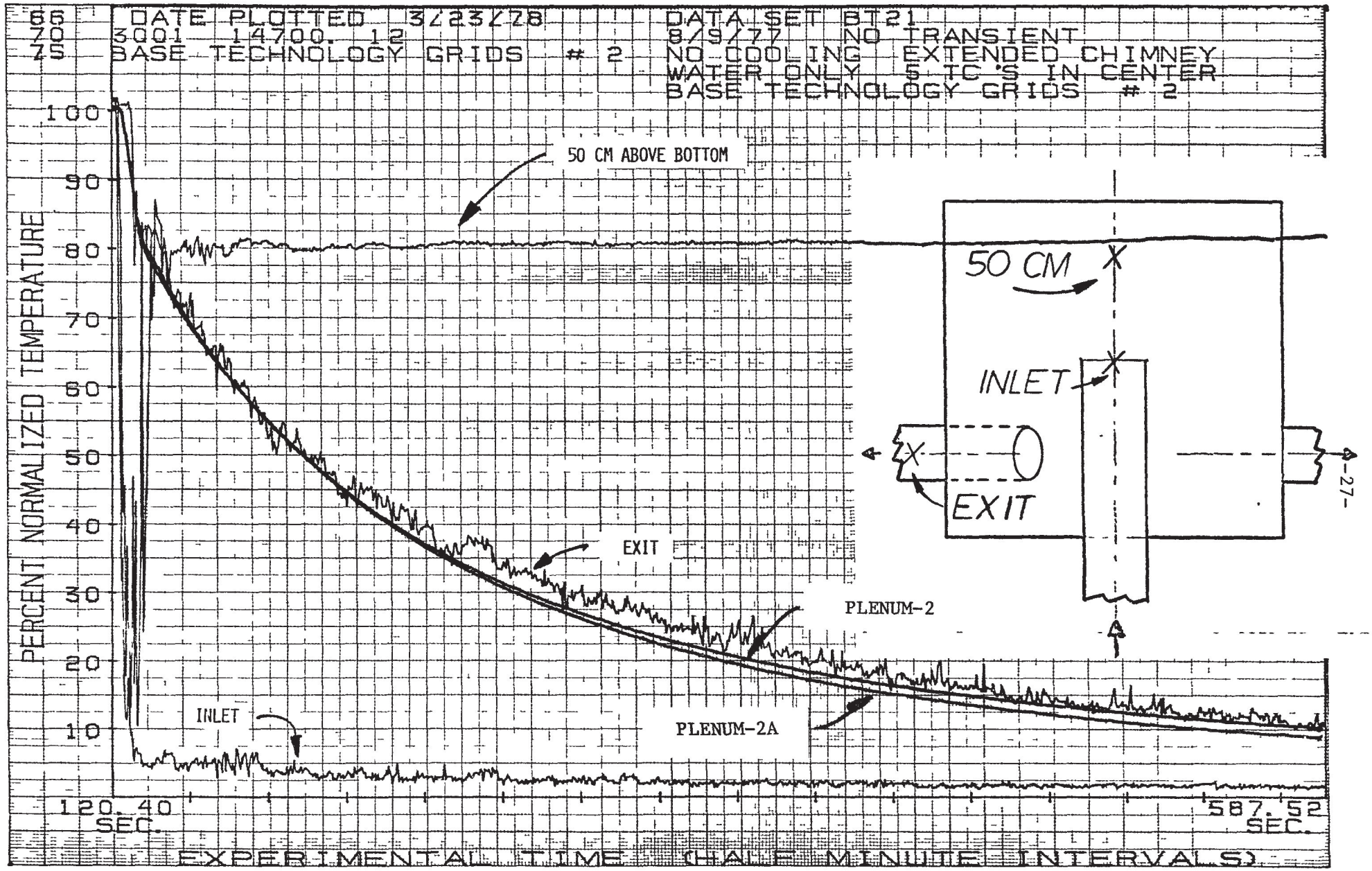

Fig. 13. Exit Nozzle Transients for Test BT21 as Predicted by PLENUM-2 and PLENUM-2A.

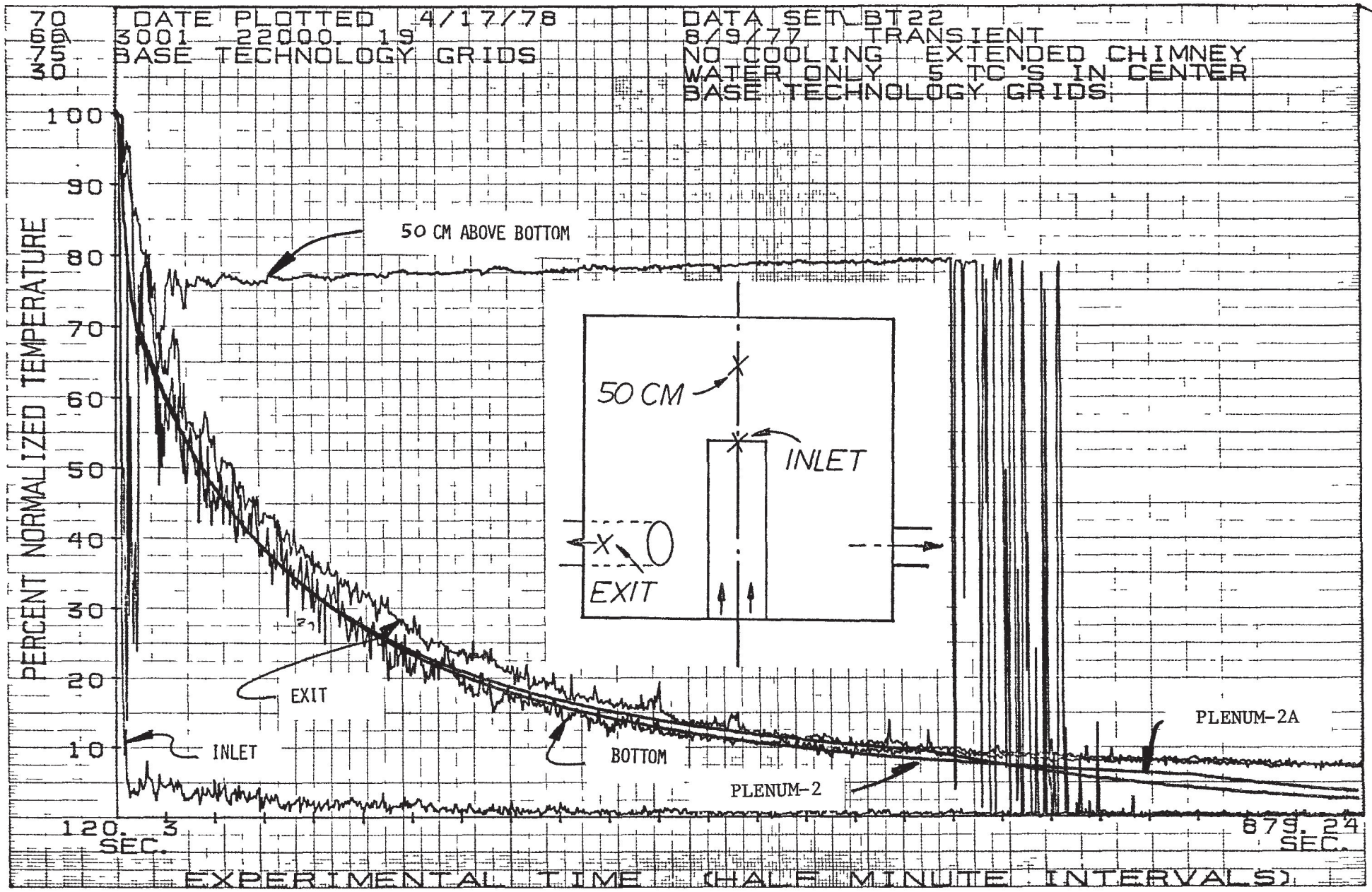

Fig. 14. Exit Nozzle Transients for Test BT22 as Predicted by PLENUM-2 and PLENUM-2A.

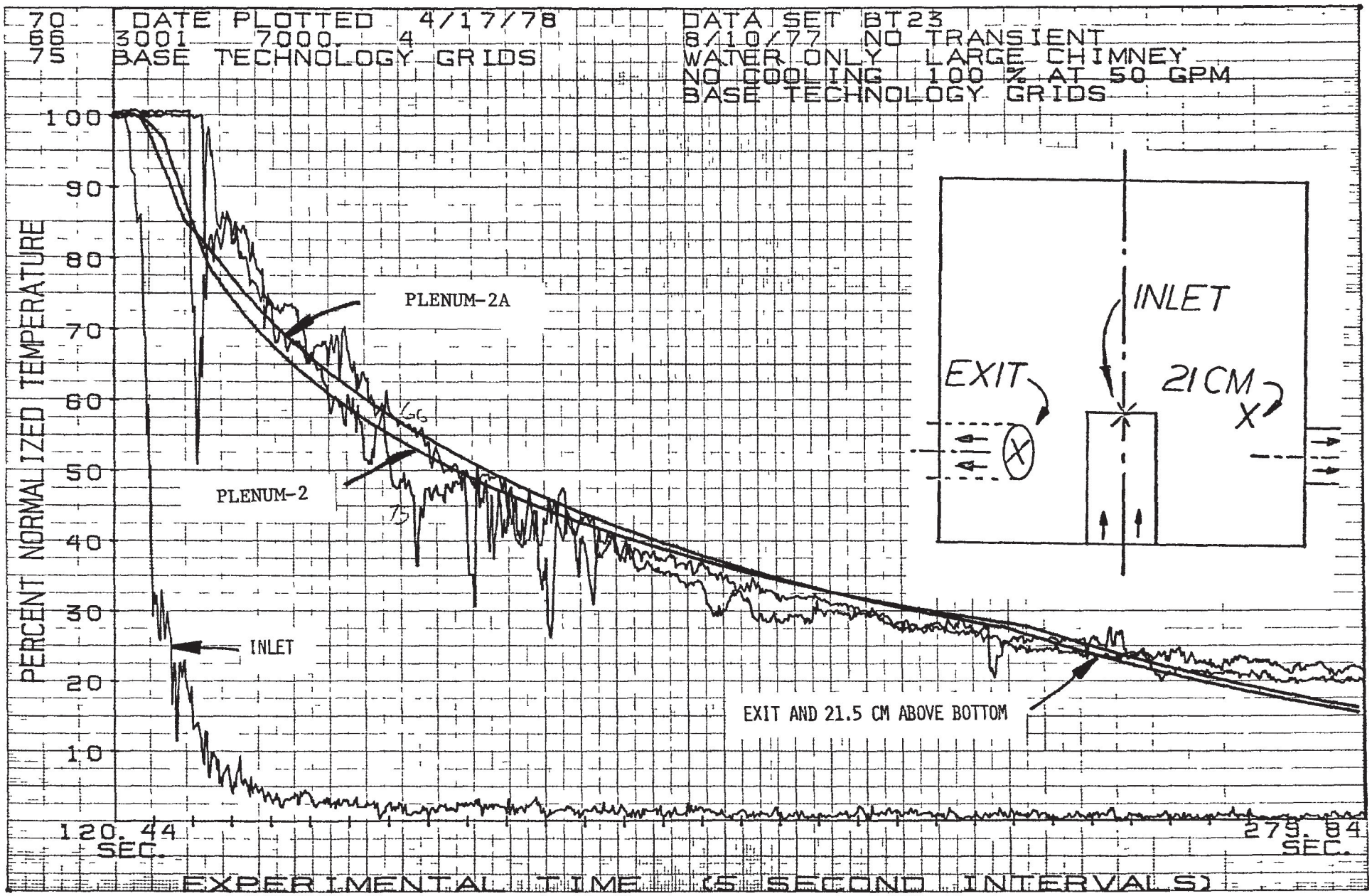

Fig. 15. Exit Nozzle Transients for Test BT23 as Predicted by PLENUM-2 and PLENUM-2A.

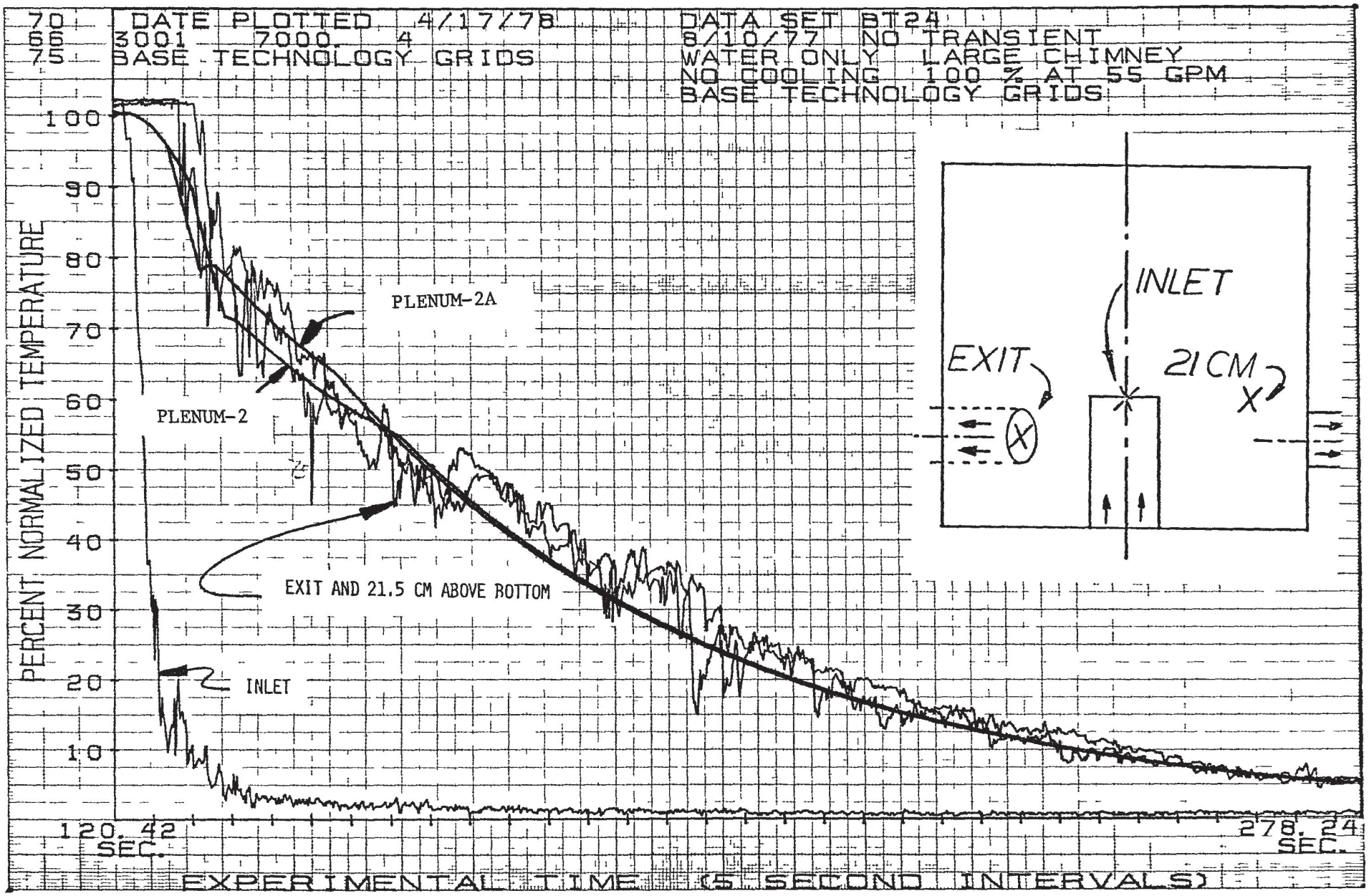

Fig. 16. Exit Nozzle Transients for Test BT24 as Predicted by PLENUM-2 and PLENUM-2A.

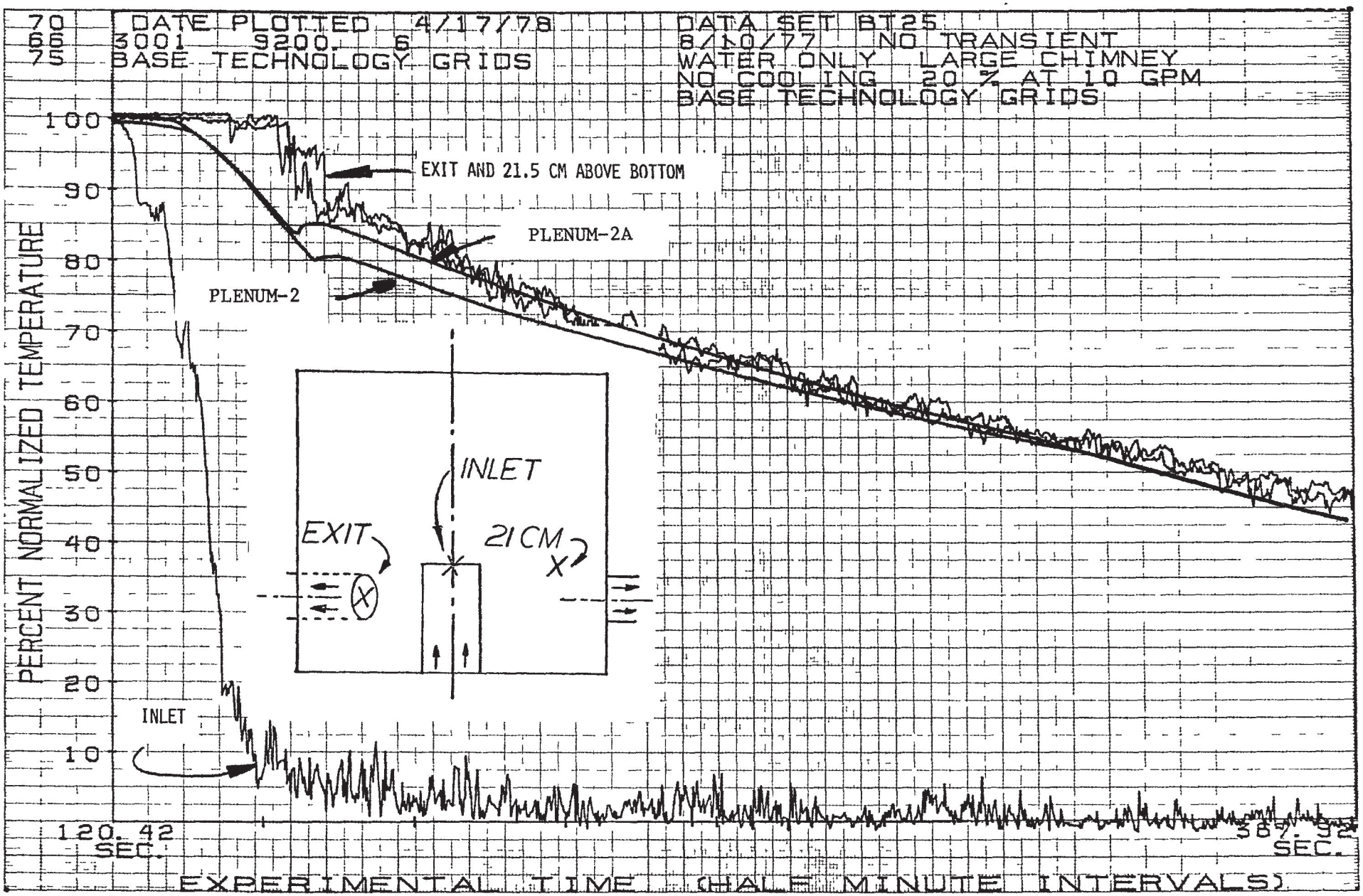

Fig. 17. Exit Nozzle Transient for Test BT25 as Predicted by PLENUM-2 and PLENUM-2A.

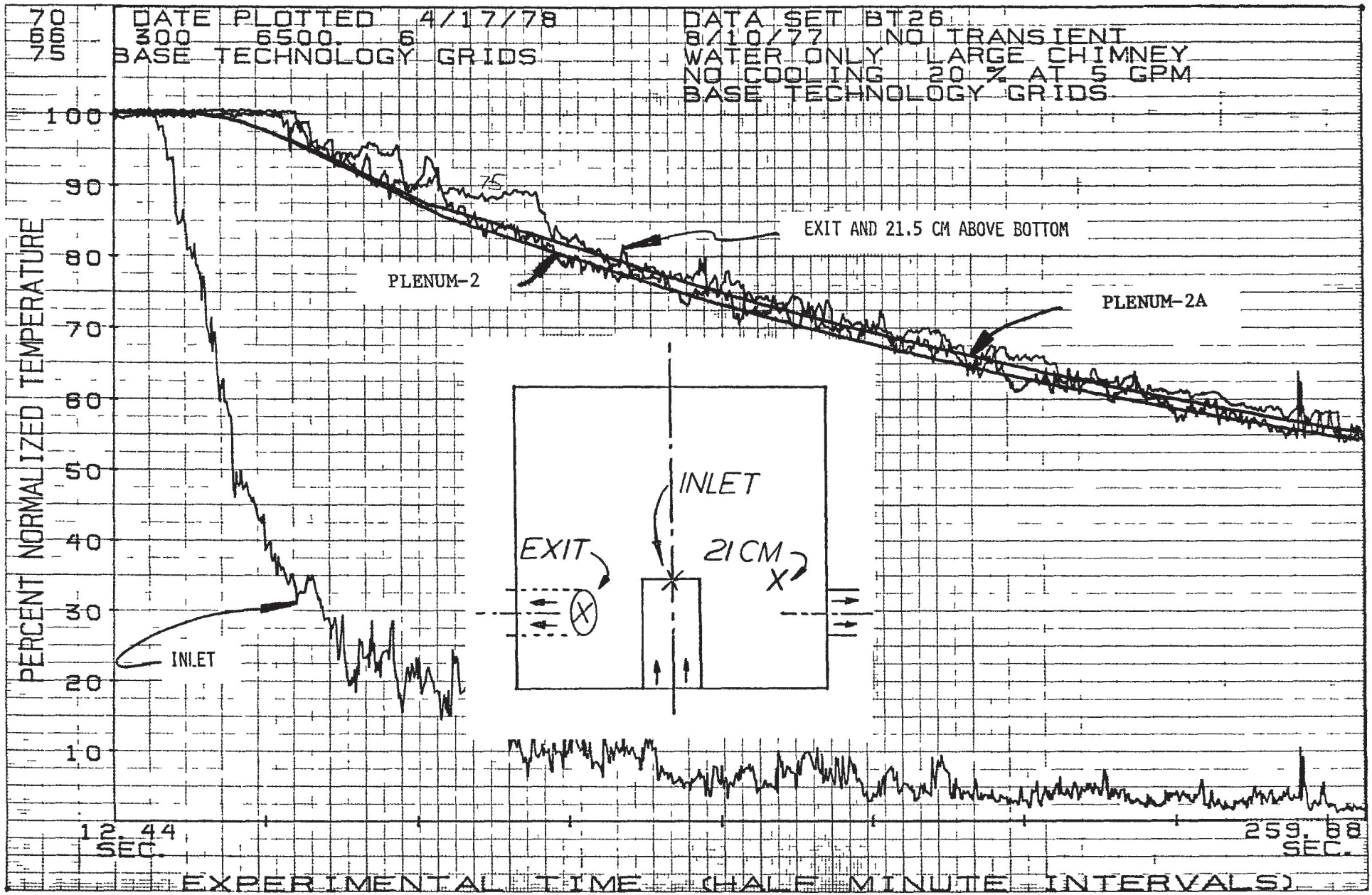

Fig. 18. Exit Nozzle Transient for Test BT26 as Predicted by PLENUM-2 and PLENUM-2A.

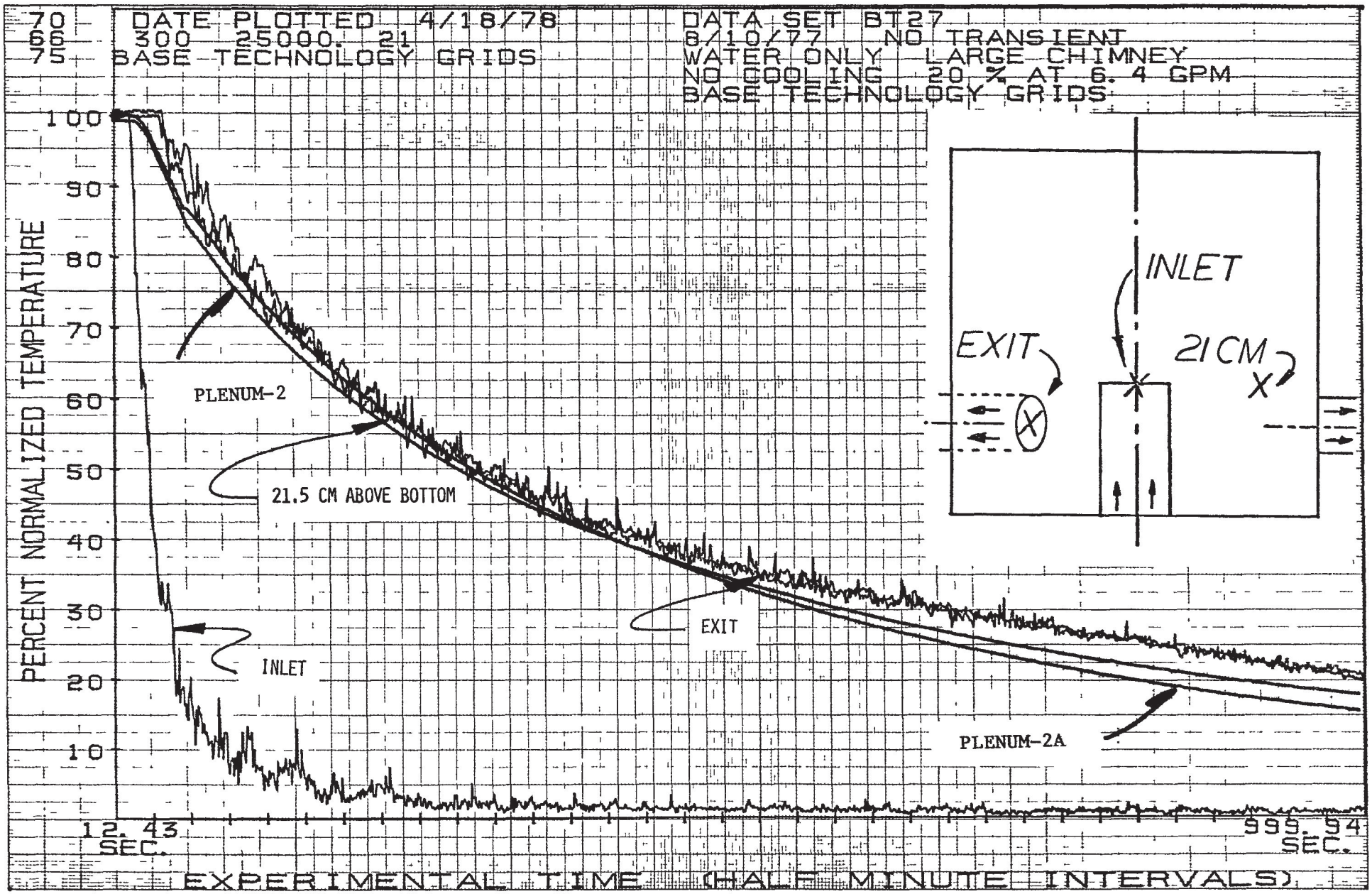

Fig. 19. Exit Nozzle Transients for Test BT27 as Predicted by PLENUM-2 and PLENUM-2A.

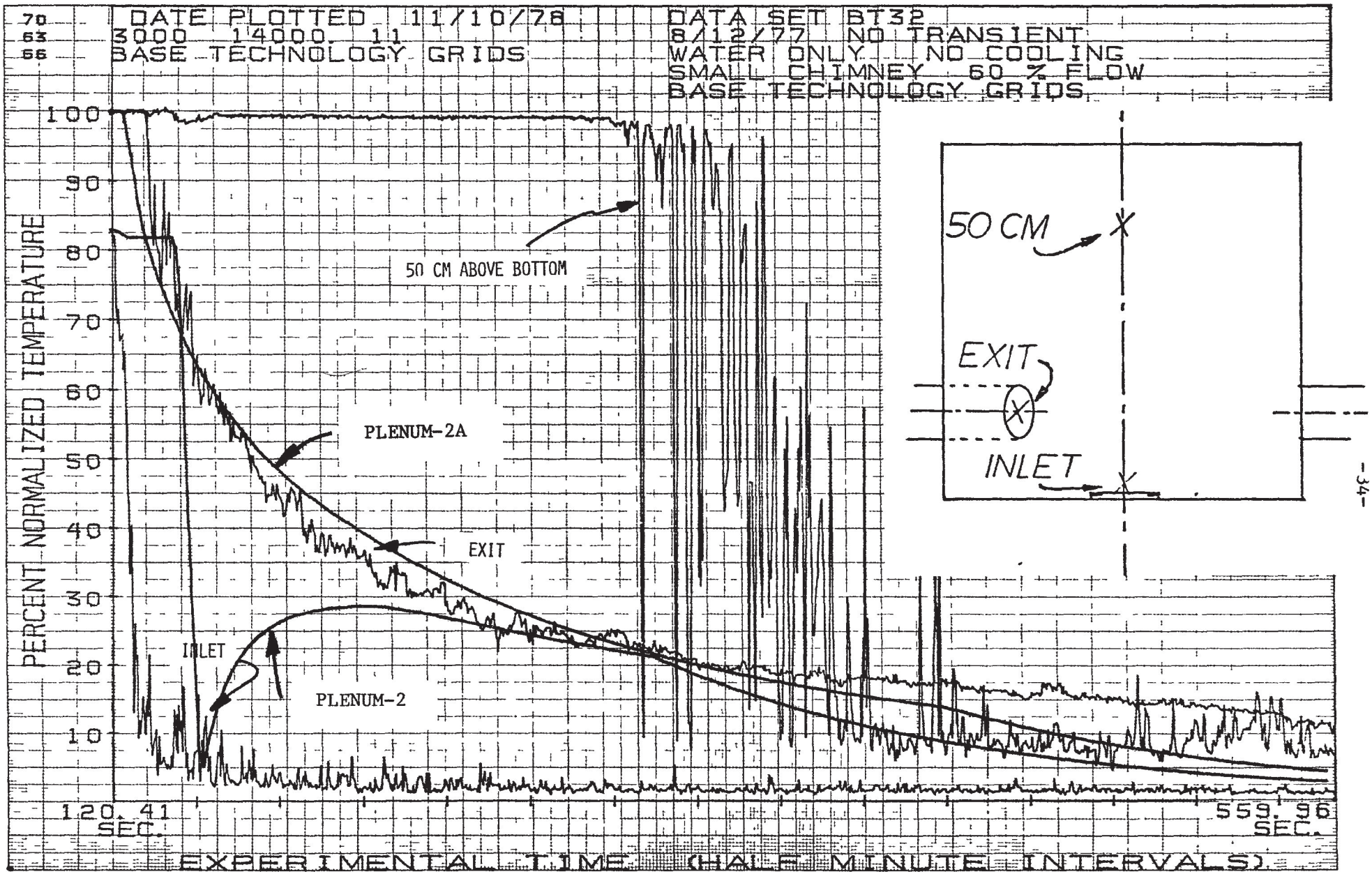

Fig. 20. Exit Nozzle Transients for Test BT32 as Predicted by PLENUM-2 and PLENUM-2A.

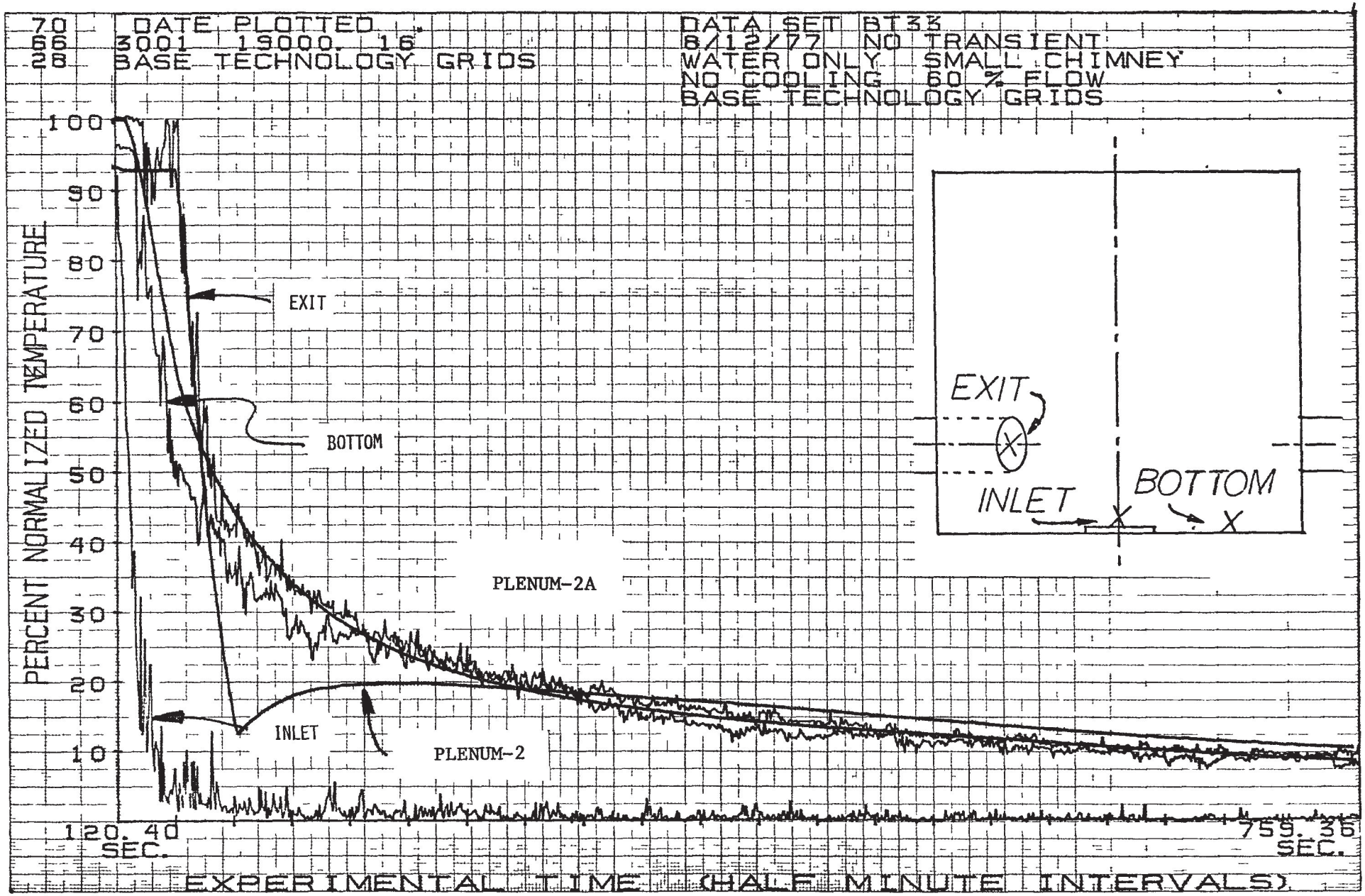

Fig. 21. Exit Nozzle Transients for Test BT33 as Predicted by PLENUM-2 and PLENUM-2A.

APPENDIX:

PROGRAM LISTING

```
FTN4,L
      PROGRAM P2
C
C     SOURCE FILE=PRO54
C
C      TWO REGION OUTLET PLENUM MODEL
C
      COMMON A(64)
      DIMENSION AT1(305),AV1(305),AV2(305),AT2(305),AZB(305)
      DIMENSION ATOUT(305),ATIME(305),AGPM(305),ATIN(305)
      DIMENSION IFILE(3),IBUF(40)
      EQUIVALANCE (Z1,A(1)),(Z2,A(2)),(Z3,A(3)),(D1,A(4)),(D2,A(5)),
     $(D3,A(6)),(D4,A(7))
      DATA IFILE/3*2H  /
C
C  INPUT  VARIABLES
C
      WRITE(1,104)
  104 FORMAT('ENTER DATA SET NAME TO BE ANALYZED')
      READ(1,105)IFILE
  105 FORMAT(3A2)
C
C      INPUT DATA ARRAY IS 64 REAL NUMBERS LONG
C      THE NUMBERS ARE DIVIDED INTO GROUPS
C      GEOMETRY: Z1,Z2,Z3,D1,D2,D3,D4
C      DENSITY: 3 PAIRS OF NUMBERS, TEMP AND RO
C      FLOWRATE: 10 PAIRS,  GPM AND TIME
C      TEMPERATURE: 10 PAIRS TEMPERATURE AND TIME
C      THOT AND TCOLD ARE WORD NUMBERS 54 AND 55
C
      CALL EXEC(14,103B,A,128,IFILE,0)
C
C      INITIALIZE ROUTINE
C
      WRITE(1,110)
  110 FORMAT('TURN ON SSW(0) TO ELIMINATE MOST OF THE PRINTING',/,
     $'TURN ON SSW(1) TO SET UP A FIGURE',/,
     $'TURN ON SSW(2) TO DO NORMALIZED TEMPERATURE PLOTS',/,
     $'TURN ON SSW(3) FOR DEBUGGING',/,
     $'ENTER THE START AND STOP TIMES')
C
C     THIS PROGRAM HAS BEEN SET UP TO RUN ON A HEWLETT PACKARD MINI
C     OCCATIONAL REFERENCE TO EXEC CAN BE FOUND IN THIS SOURCE
C     THESE ARE USUALLY USED FOR I/O OPERATIONS.  IN THE VERIFICATION
C     OF THIS MODEL MANY DIFFERENT DATA SETS CONTAINING EXPERIMENTAL
C     DATA WERE AVAILABLE.  THESE DATA SETS WERE INPUT THROUGH THE EXEC
C     CALLS.  ALL INPUT DATA IS IMMEDIATELY LISTED.
C
      CALL EXEC(1,20401B,IBUF,40)
      PI=3.14159
      VT=PI/4.*(D1**2*Z1-D2**2*Z2)
      V1=0.
      V2=0.
**** LIST END ****
```

```
      VO=0.0
      TIME2 = 0.
      FILLIN = 4.
      ZB=0.
      K=1
      ISTAGE = 0
      AREA1 = PI*D1**2/4.
      AREA2=PI*D2**2/4.
      AREA3=PI*(D1**2-D2**2)/4.
      AREA4=PI*D4**2/4.
      TH = A(54)
      TC = A(55)
      T1 = TH
      T2 = TH
      TOUT = TH
      EO=VT*RO(T1)*T1
C
C     PRINT INPUT DATA
C
      WRITE(13,100)IFILE
  100 FORMAT("  **** P-2 ****    **** INPUT DATA FROM",3A2,
     $"  ****",/,/)
      WRITE(13,101)Z1,D1,Z2,D2,D4,Z3,D3,VT,TC,TH
  101 FORMAT(" TOTAL HGHT :",F8.4," FT",/," OUTS DIAM  :",F8.4," FT",/,
     1" INLET HGHT :",F8.4," FT",/," INLET DIAM :",F8.4," FT",/,
     1" JET  DIAM  :",F8.4,"FT",/,
     2" OUTL CENT  :",F8.4," FT",/," OUTL DIAM  :",F8.4," FT",/,
     3" TOTAL VOLU :",F8.4," FT3",/," FINAL TEMP :",F8.4," DEGF",/,
     4" INIT TEMP  :",F8.4," F",/)
      WRITE(13,109)
  109 FORMAT(/,/,/)
      WRITE(13,106)(A(I),I=8,13)
  106 FORMAT("AT",F6.1," F, RO =",F6.2," LBM")
      WRITE(13,109)
      WRITE(13,107)(A(I),I=14,33)
  107 FORMAT("GPM = ",F6.1," AT TIME =",F6.1," SECONDS")
      WRITE(13,109)
      WRITE(13,108)(A(I),I=34,53)
  108 FORMAT("INLET TEMP =",F6.1," AT TIME =",F6.1," SECONDS")
  102 FORMAT("  **** PLENUM-2 ****    **** OUTPUT RESULTS ****",/,
     1"     TIME  FLOW    TI        V1        V2        T1        T2        TO"
     2     ZB")
      C2=.111*((-2.*ALOG(.15))**.5 -1.)
      C3=(2.*PI)**.5/2.*.948
      C5=.5*(-2.*ALOG(.15))
      C4=.111**2*(1.5-EXP(-C5) -C3)
      CG= 9.8*3.281
      CB=-1.45
      CA=1.1
C
C     READ START AND FINISH TIMES
C
    1 CONTINUE
**** LIST END ****
```

```
0107          CALL EXEC(13,1,ISTAT,ITLOG)
0108          IF(ISTAT.LT.0)GOTO1
0109          CALL CODE
0110          READ(IBUF,*)START,STOP
0111          DTIME = (STOP-START)/6000.
0112          WRITE(13,114)START,STOP,DTIME
0113      114 FORMAT('START TIME =',F7.2,'  STOP TIME =',F7.2,' DTIME=',F7.4)
0114          CALL EXEC(3,1115B,-1)
0115          WRITE(13,102)
0116    C
0117    C
0118    C     CALCULATIONS
0119    C
0120          DO 99 LOOP = 1,6000
0121          TIME = START+FLOAT(LOOP)*DTIME
0122          TINLET=TI(TIME)
0123          GPMO = GPM(TIME)
0124          FEET3 = GPMO/448.8
0125          DR = RO(TINLET)-RO(T2)
0126          VELOC = FEET3/AREA4
0127          FR = DR*CG*D4/2./RO(TINLET)/VELOC**2
0128          BFRAC=(ZB-Z3+D3/2.)/D3
0129          IF(ZB.EQ.0.0)BFRAC=(Z2-Z3+D3/2.)/D3
0130          IF(BFRAC.LT.0)BFRAC = 0.
0131          IF(BFRAC.GT.1)BFRAC = 1.
0132    C
0133    C CHECK STAGE OF THE TRANSIENT
0134    C
0135          IF(GPMO.LT.1.0)GO TO 2000
0136          IF(ZB.GE.Z2)GO TO 1003
0137          IF(TINLET.EQ.T1)GOTO2000
0138          IF(TINLET.GT.T1)GOTO1002
0139          ZPLUME = 1.048*FR**(-.785)*D4/2.
0140          IF(ZPLUME.GT.(Z1-Z2))GO TO 1002
0141    C
0142    C      STAGE 2
0143    C     WHEN ACTIVE MIXING REGION IS AT OR BELOW THE CHIMNEY
0144    C
0145          IF(ISTAGE.EQ.1)WRITE(13,202)TIME
0146      202 FORMAT(/,/,/,'END OF STAGE 1, STAGE 2 STARTED AT',F7.2,' SECONDS')
0147          IF(ISTAGE .EQ. 1) WRITE(13,201)V1,V2,T1,T2,ZPLUME,FR,DR
0148          E1=AREA3*Z2*RO(T1)*T1
0149          IF(ISTAGE.EQ.1)WRITE(13,102)
0150          ISTAGE = 2
0151          VO = VO+FEET3*DTIME*FILLIN
0152          V1 = AREA3*Z2
0153          IF(VO.GE.V1)ZB=Z2
0154          E1 = E1+FEET3*DTIME*(RO(TINLET)*TINLET-RO(T1)*T1)
0155          V2=VT-V1
0156          T1=E1/V1/RO(T1)
0157          TOUT = T1*BFRAC+T2*(1.0-BFRAC)
0158          GO TO 2000
0159    C
**** LIST END ****
```

```
0160  C      STAGE 3
0161  C
0162   1003 CONTINUE
0163        IF(ISTAGE.EQ.2)WRITE(13,203)TIME
0164    203 FORMAT(/,/,'END OF STAGE 2, STAGE 3 STARTED AT',F7.2,' SECONDS')
0165        IF(ISTAGE .EQ. 2)WRITE(13,201)V1,V2,T1,T2,ZPLUME,FR,DR
0166        IF(ISTAGE.EQ.2)WRITE(13,102)
0167        ISTAGE=3
0168        IF(ZB.GT.Z1)E1 = E1+DTIME*FEET3*(TINLET*RO(TINLET)-
0169       $T1*RO(T1))
0170        IF(ZB.GT.Z1) GOTO1006
0171        Z=(ZB-Z2)/D4
0172        ZO=D4/.222
0173        IF ((ZB-Z2) .GT. ZO) GO TO 1004
0174  C
0175  C      REGION OF ESTABLISHING FLOW
0176  C
0177        DI=2.*C2*(ZB-Z2) + D4
0178        VI=2.*VELOC*(Z**2*C4+.111*Z/2.*(C3-1.)+1./8.)/(C2*Z+.5)**2
0179        GO TO 1005
0180  C
0181  C      REGION OF ESTABLISHED FLOW
0182  C
0183   1004 DI = 2.*D4*Z*(-2.*.111**2*ALOG(.15))**.5
0184        VI=-.85/ALOG(.15)/.222/Z*VELOC
0185   1005 FRI=DR*DI*CG/RO(TINLET)/VI**2
0186        E=CA*FRI**CB*VI*DI**2/D1**2
0187        V1=V1+E*DTIME*AREA1+DTIME*FEET3*(1.0-BFRAC)
0188        E1 = E1+E*DTIME*AREA1*RO(T2)*T2+DTIME*FEET3*(TINLET*RO(TINLET)
0189       1-T1*RO(T1)*BFRAC)
0190        V2=VT-V1
0191        ZB=ZB+E*DTIME+DTIME*FEET3*(1.0-BFRAC)/AREA1
0192   1006 CONTINUE
0193        T1 = E1/V1/RO(T1)
0194        TOUT=T1*BFRAC+T2*(1.0-BFRAC)
0195        IF(ISSW(3).LT.0)WRITE(13,113)Z,DI,VI,VELOC,ERATIO,E
0196    113 FORMAT('Z=',F5.3,' DI=',F6.4,' VI=',F6.4,' VELOC=',F6.4,' ERATIO',
0197       $F6.5,' E=',F7.6)
0198         GO TO 2000
0199  C
0200  C       STAGE 1
0201  C
0202   1002 CONTINUE
0203        IF(ISTAGE.EQ.0)WRITE(13,200)TIME
0204    200 FORMAT(/,/,'END OF STEADY STATE, STAGE 1 STARTED AT',F7.2,
0205       $' SECONDS')
0206        IF(ISTAGE.EQ.0)WRITE(13,201)V1,V2,T1,T2,ZPLUME,FR,DR
0207    201 FORMAT('V1 =',F8.3,'  V2 =',F8.3,'  T1 =',F7.3,'  T2 =',F7.3,
0208       $'  ZPLUME =',F8.4,' FR =',F7.3,/,' DR =',
0209       $F8.4)
0210        IF(ISTAGE.EQ.0)WRITE(13,102)
0211        ISTAGE = 1
0212        EO = EO + DTIME*FEET3*(TINLET*RO(TINLET)-T1*RO(T1))
**** LIST END ****
```

```
0213          T1=EO/VT/RO(T1)
0214          T2=T1
0215          TOUT=T2
0216   C
0217   C STORE THE RESULTS AND PRINT
0218   C       STAGE 0
0219   C
0220    2000 CONTINUE
0221          IF(ISSW(3).LE.0)WRITE(13,112)LOOP,TIME,TINLET,T1,T2,TOUT,
0222         $V1,V2,GPMO,DR,FR,ZPLUME,ISTAGE,ZB,VO,EO
0223     112 FORMAT('LOOP =',I6,' TIME =',F7.2,' TINLET =',F7.2,/,' T1 =',
0224         $F7.2,' T2=',F7.2,' TOUT=',F7.2,' V1=',F6.3,/,
0225         $'V2=',F6.3,' GPMO=',F7.2,' DR=',F7.3,' FR=',F7.3,/,
0226         $'ZPLUME=',F7.3,' ISTAGE=',I3,' ZB=',F7.3,' VO=',F7.3,
0227         $' EO=',F8.3)
0228          IF((LOOP-1)/20*20.NE.(LOOP-1))GOTO99
0229          AT1(K) = T1
0230          AV1(K) =V1
0231          AT2(K) = T2
0232          AV2(K) = V2
0233          AZB(K) = ZB
0234          ATOUT(K) = TOUT
0235          ATIME(K) = TIME
0236          AGPM(K) = GPMO
0237          ATIN(K) = TINLET
0238          IF(ISSW(0))6,5
0239        5 CONTINUE
0240          WRITE(13,103)ATIME(K),AGPM(K),ATIN(K),AV1(K),AV2(K),AT1(K)
0241         1,AT2(K),ATOUT(K),AZB(K)
0242     103 FORMAT(9F8.3)
0243        6 K = K+1
0244       99 CONTINUE
0245          IF(ISSW(1))12,3
0246       12 CONTINUE
0247          WRITE(1,115)
0248     115 FORMAT('ENTER XO,YO,SIZE  CHECK SIZE  TURN OFF SSW(1)
0249         $ WHEN OK')
0250          READ(1,*)XO,YO,SIZE
0251          XOY = 38./25.
0252          IXX = XO
0253          IXY = XO+SIZE
0254          IYX = YO
0255          IYY = YO+SIZE*XOY
0256          WRITE(9)-1,1,IXX,IYX
0257          WRITE(9)-1,1,IXY,IYX
0258          WRITE(9)-1,1,IXY,IYY
0259          WRITE(9)-1,1,IXX,IYY
0260          WRITE(9)-1,1,IXX,IYX
0261          GOTO 99
0262   C
0263   C      PLOTTING ROUTINE
0264   C      USE WITH A PLOT10 PACKAGE,  CRUDE SOFTWARE
0265   C
**** LIST END ****
```

```
      3 WRITE(1,111)
        SIZE=SIZE/2
    111 FORMAT('ENTER CODE FOR THE ONE THAT IS TO BE PLOTTED',/,
       $'0 = QUIT',/,
       $'1 = TOUT',/,'2 = GPM',/,'3 = TIN',/,'4 = T1',/,'5 = T2',
       $/,'6 = ZBOUND',/)
        READ(1,*)ICODE
        IF(ICODE.EQ.0)GOTO2
        IF(ICODE.EQ.6)CALL FIG(XO,YO,SIZE,XOY)
        DO 4 I = 1,300
        X = (ATIME(I)-START)/(STOP-START)*9210.
        IX = IFIX(X)+789
        DUMMY = ATOUT(I)
        IF(ICODE.EQ.2)DUMMY = AGPM(I)
        IF(ICODE.EQ.3)DUMMY = ATIN(I)
        IF(ICODE.EQ.4)DUMMY = AT1(I)
        IF(ICODE.EQ.5)DUMMY = AT2(I)
        IF(ICODE.EQ.6)GOTO9
        IF(ISSW(2))7,8
      7 IF(ICODE.EQ.2)GOTO8
        DUMMY = (DUMMY-TC)/(TH-TC)*200.
      8 CONTINUE
        IY = 800.+40.*DUMMY
     10 CONTINUE
        IF(I.EQ.1)WRITE(9)-1,1,IX,IY
        WRITE(9)1,1,IX,IY
      4 CONTINUE
        GOTO 3
      9 CONTINUE
        IX = XO+FLOAT(I)/300.*SIZE*A(4)
        IY = YO+SIZE*XOY*AZB(I)
        GOTO 10
      2 CONTINUE
        STOP
        END
        SUBROUTINE FIG(XO,YO,SIZE,XOY)
C
C        THIS SIMPLE ROUTINE DRAWS A CROSS
C        SECTION OF THE MODEL.
C
        COMMON A(64)
        IXO = XO
        IYO = YO
        WRITE(9)-1,1,IXO,IYO
        WRITE(9)1,1,IXO,IYO
        IX1 = XO+SIZE*A(4)
        IY1 = YO+SIZE*A(1)*XOY
        WRITE(9)1,1,IX1,IYO
        WRITE(9)1,1,IX1,IY1
        WRITE(9)1,1,IXO,IY1
        WRITE(9)1,1,IXO,IYO
        IXC = (IXO+IX1)/2
        IX1 = IXC-SIZE*A(5)/2.
**** LIST END ****
```

```
0319          IX2 = IXC+SIZE*A(5)/2.
0320          IY1 = IY0+SIZE*A(2)*XOY
0321          WRITE(9)-1,1,IX1,IY0
0322          WRITE(9)1,1,IX1,IY0
0323          WRITE(9)1,1,IX1,IY1
0324          WRITE(9)1,1,IX2,IY1
0325          WRITE(9)1,1,IX2,IY0
0326          IX1 = X0+SIZE*A(4)
0327          IX2 = IX1+SIZE*A(6)
0328          IYC = Y0+SIZE*A(3)*XOY
0329          IY1 = IYC  - SIZE*XOY*A(6)/2.
0330          IY2 = IYC + SIZE*XOY*A(6)/2.
0331          WRITE(9)-1,1,IX1,IY1
0332          WRITE(9)1,1,IX1,IY1
0333          WRITE(9)1,1,IX2,IY1
0334          WRITE(9)1,1,IX2,IY2
0335          WRITE(9)1,1,IX1,IY2
0336          RETURN
0337          END
0338          FUNCTION RO(TEMP)
0339    C
0340    C      CALCULATE THE DENSITY OF THE FLUID USING THREE DATA POINTS.
0341    C      THE MATIN SUBROUTINE USES THESE THREE POINTS AND GENERATES
0342    C      A PARABOLA.  IF THE FLUID IS WATER OR SODIUM IT MAKES NO DIFFERE
0343    C      ENCE.  A PARABOLA HAS BEEN FOUND TO GIVE GOOD RESULTS.
0344    C
0345          COMMON A(64)
0346          DIMENSION A1(6,6),B1(6,2)
0347          IF(IFLAG.EQ.1)GOTO1
0348          A1(1,1) = A(8)
0349          A1(2,1) = A(9)
0350          A1(3,1) = A(10)
0351          A1(4,1) = A(11)
0352          A1(5,1) = A(12)
0353          A1(6,1) = A(13)
0354          CALL MATIN(A1,B1,3,DELTA)
0355          IFLAG = 1
0356        1 CONTINUE
0357          RO = B1(1,1)*TEMP**2+B1(2,1)*TEMP+B1(3,1)
0358          RETURN
0359          END
0360          FUNCTION GPM(TIME)
0361    C
0362    C     THIS IS A PIECE WISE LINEAR INTERPOLATION ROUTINE FOR CALCULATEING
0363    C     THE INLET FLOWRATE.
0364    C
0365          COMMON A(64)
0366          DO 1 I = 14,30,2
0367          IF(TIME.GT.A(I+3))GOTO1
0368          GPM = A(I)+(A(I+2)-A(I))/(A(I+3)-A(I+1))*(TIME-A(I+1))
0369          IF(TIME.GE.A(I+1))RETURN
0370        1 CONTINUE
0371          WRITE(1,100)
**** LIST END ****
```

```
0372    100 FORMAT('ERROR IN GPM, I QUIT')
0373        STOP
0374        END
0375        FUNCTION TI(TIME)
0376  C
0377  C     TEMPERATURE INPUT ROUTINE
0378  C
0379        COMMON A(64)
0380  C     PIECE-WISE LINEAR.
0381        DO 1 I = 34,50,2
0382        IF(TIME.GT.A(I+3))GOTO1
0383        TI = A(I)+(A(I+2)-A(I))/(A(I+3)-A(I+1))*(TIME-A(I+1))
0384        IF(TIME.LT.A(I+3))RETURN
0385      1 CONTINUE
0386        WRITE(1,100)
0387    100 FORMAT('ERROR IN TI, I QUIT')
0388        STOP
0389        END
0390  $END
**** LIST END ****
```