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DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING
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**SUPPORT OF THE EIGHT-FOOT HIGH TEMPERATURE
TUNNEL MODIFICATION PROJECT**

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HIGH TEMPERATURE TUNNEL MODIFICATION PROJECT
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By

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Final Report

For the period ended August 16, 1987

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SUPPORT OF THE EIGHT-FOOT HIGH TEMPERATURE TUNNEL MODIFICATION PROJECT

By

Kim Chi Ngo¹ and Roland R. Mielke²

LIQUID OXYGEN-LIQUID NITROGEN MIXING AND SELF-CLEANING STUDY

INTRODUCTION

In the past several years, there has been a resurgent interest in hypersonics. In order to meet the need for propulsion testing in the high supersonic range from Mach 4 to Mach 7, NASA has undertaken the modification of the Langley Eight-Foot High Temperature Tunnel to add alternate Mach number capability and add oxygen enrichment to allow the testing of operating engines at these Mach numbers and at true temperature tunnel.

The transfer of liquid oxygen (LOX) from a storage vessel to a rocket engine generally requires the use of a pressurizing gas at high pressures. Among the common gases, helium, oxygen, and nitrogen have been considered. However, helium is expensive, and oxygen is hazardous at high pressures. Therefore, nitrogen is preferred. Unfortunately, when gaseous nitrogen (GN_2) is used as the pressurant to transfer liquid oxygen from a storage tank to the tunnel combustor, it contaminates the liquid oxygen and effects a loss of performance in the engine.

The purpose of this study is to describe the contamination of the LOX by the pressurizing GN_2 , which may prove to be an important operational constraint. It is desirable to have reliable data concerning the penetration of GN_2 into LOX during pressurization and the subsequent of self-cleaning after "blowdown."

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EXPERIMENTAL PROCEDURE

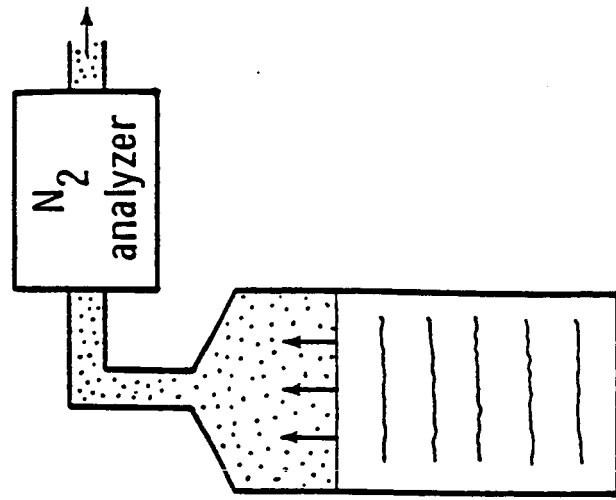
The experiment was carried out at the 7" Mach Seven Tunnel, the pilot tunnel for the 8 Foot High Temperature Tunnel. The LOX-LN₂ contamination experimental set-up is shown in Appendix A, and the experimental procedure is illustrated in Fig. 1. The test procedure consisted of three steps. First, the 2-gallon cylindrical vessel was filled to a level of 46 inches with LOX, as measured by a nuclear monitor. At this point the LOX was pressurized by GN₂ and held at a specific pressure for a period of time. Secondly, after the pressurization was completed, the nitrogen was blown down to 0 psig. Finally, the evaporating liquid from the tank was vented through a 100% Beckman Oxygen Analyzer. The data were taken by an analog to digital converter in an Apple II⁺ computer, which records the reading from the analog instrumentation.

RESULTS AND ANALYSIS

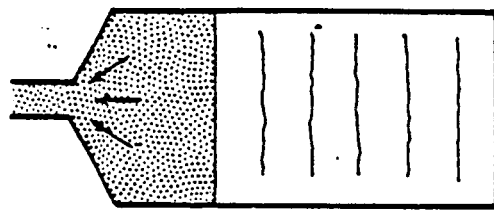
The interpretation of the experimental results is based on the following model:

- 1) During pressurization N₂ penetrates into the LOX by simple molecular diffusion.
- 2) The depth of penetration depends upon the GN₂ pressure, which determines the surface concentration, and the holding time.
- 3) After blowdown the liquid evaporates. At any given time the composition of the evaporating liquid reflects the concentration profile established in the liquid by diffusion.

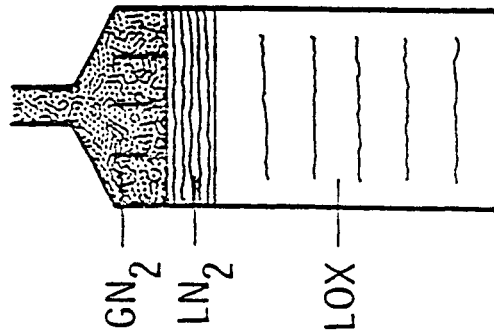
To analyze this experiment, the first step is to derive the continuity equation for the number of GN₂ moles in the large volume. This well known concentration profile due to diffusion equation can be written as:



(3) Analysis



(2) Blowdown



(1) Pressurization

Figure i. Illustration of the test procedure.

$$n_T \frac{dx_n}{dt} + R x_n = \frac{R}{2} \left[1 - \operatorname{erf} \left(\frac{Z_0}{h} + \frac{RV_L t}{Ah} \right) \right] \quad (1)$$

where

- n_T : the number of moles of N_2 at time t
- x_n : the instantaneous mole fraction N_2 in the liquid
- R : the evaporation rate in mole/sec
- V_L : the molar volume of the liquid
- A : the cross sectional area of the dewar
- Z_0/h : starting depth penetration
- $\operatorname{erf}(x)$: error function of x

since

$$\tau_1 = \frac{n_T}{R} \quad (2)$$

$$\tau_2 = \frac{Ah}{RV_L} \quad (3)$$

substitute Eqs. (2) and (3), into Eq. (1), it yields in the form as:

$$\frac{dx_n}{dt} + \frac{1}{\tau_1} x_n = \frac{1}{2\tau_1} \left[1 - \operatorname{erf} \left(t/\tau_2 + \frac{Z_0}{h} \right) \right]. \quad (4)$$

By using the Laplace transform to solve for the differential Eq. (4), the solution of the continuity equation can be written as:

$$\begin{aligned}
x_n(t) = & x_{n_0} e^{-t/\tau_1} + \frac{1}{2} [1 - \text{Erf}(Z_0/h)] (1 - e^{-t/\tau_1}) \\
& - \frac{1}{2} [\text{Erf}(t/\tau_2 + Z_0/h) - \text{Erf}(Z_0/h)] \\
& + \frac{1}{2} e^{-\left(t/\tau_1 + \frac{Z_0\tau_2}{h\tau_1} - \frac{\tau_2^2}{4\tau_1^2}\right)} \left[\text{Erf}\left(t/\tau_2 + \frac{Z_0}{h} - \frac{\tau_2}{2\tau_1}\right) \right. \\
& \left. - \text{Erf}\left(\frac{Z_0}{h} - \frac{\tau_2}{2\tau_1}\right) \right] \quad (5)
\end{aligned}$$

where

$$x_{n_0} = \frac{1}{2} \left[1 - \text{Erf}\left(\frac{Z_0}{h} + \frac{t}{\tau_2}\right) \right].$$

Using a best-fit procedure, one can determine the values for the time constants τ_1 and τ_2 for each test.

Plots of the data and Eq. (5) using preliminary estimates of τ_1 and τ_2 are shown in Figs. 2, 3, 4 and 5. Once the values of τ_1 and τ_2 were established, the evaporation rate R and the penetration depth can be determined from Eqs. (2) and (3).

ENTERDATA, PLOTDATA, BEST-FIT, and SUMT2 are the four computer softwares which were written in the BASIC to analyze the experiment. The flowcharts and the programs are listed in the Appendixes B, C, D, and E.

CONCLUSION

As of this writing the final data analysis is not yet completed, but preliminary analysis indicates that at the low pressure < 1000 psi, the

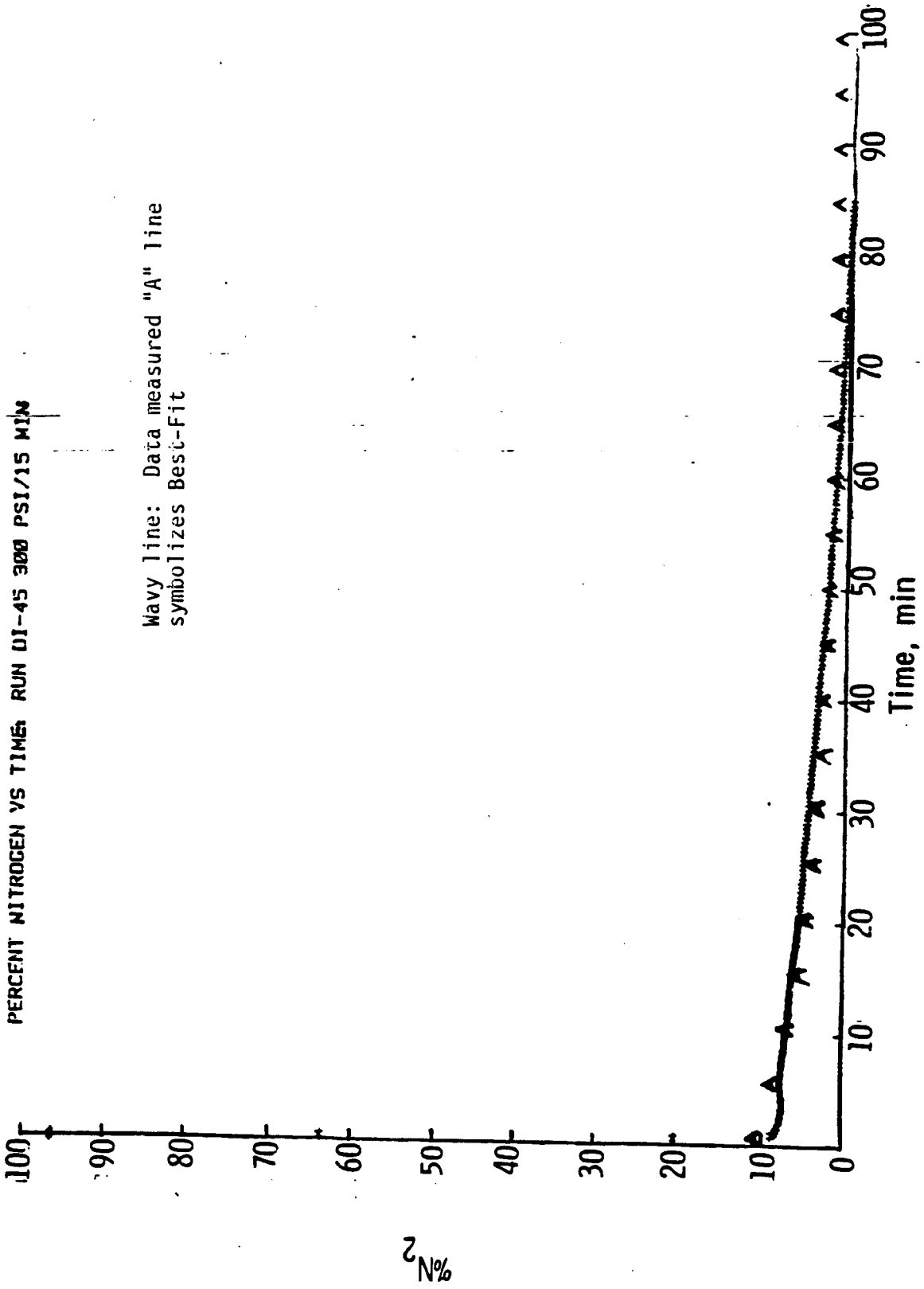


Figure 2. Percent nitrogen vs. time: 300 psi/15 min.

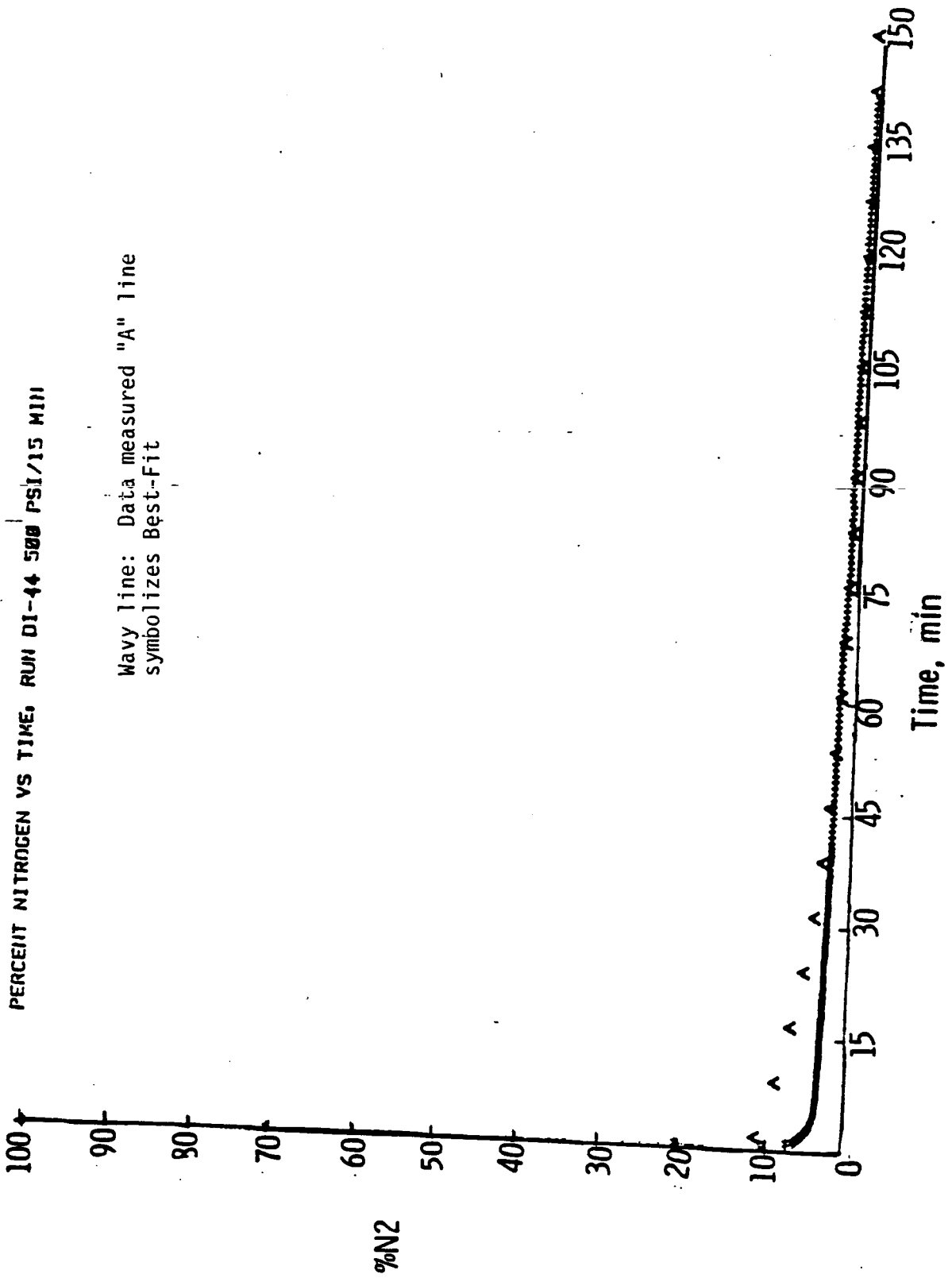


Figure 3. Percent nitrogen vs. Time: 500 psi/15 min.

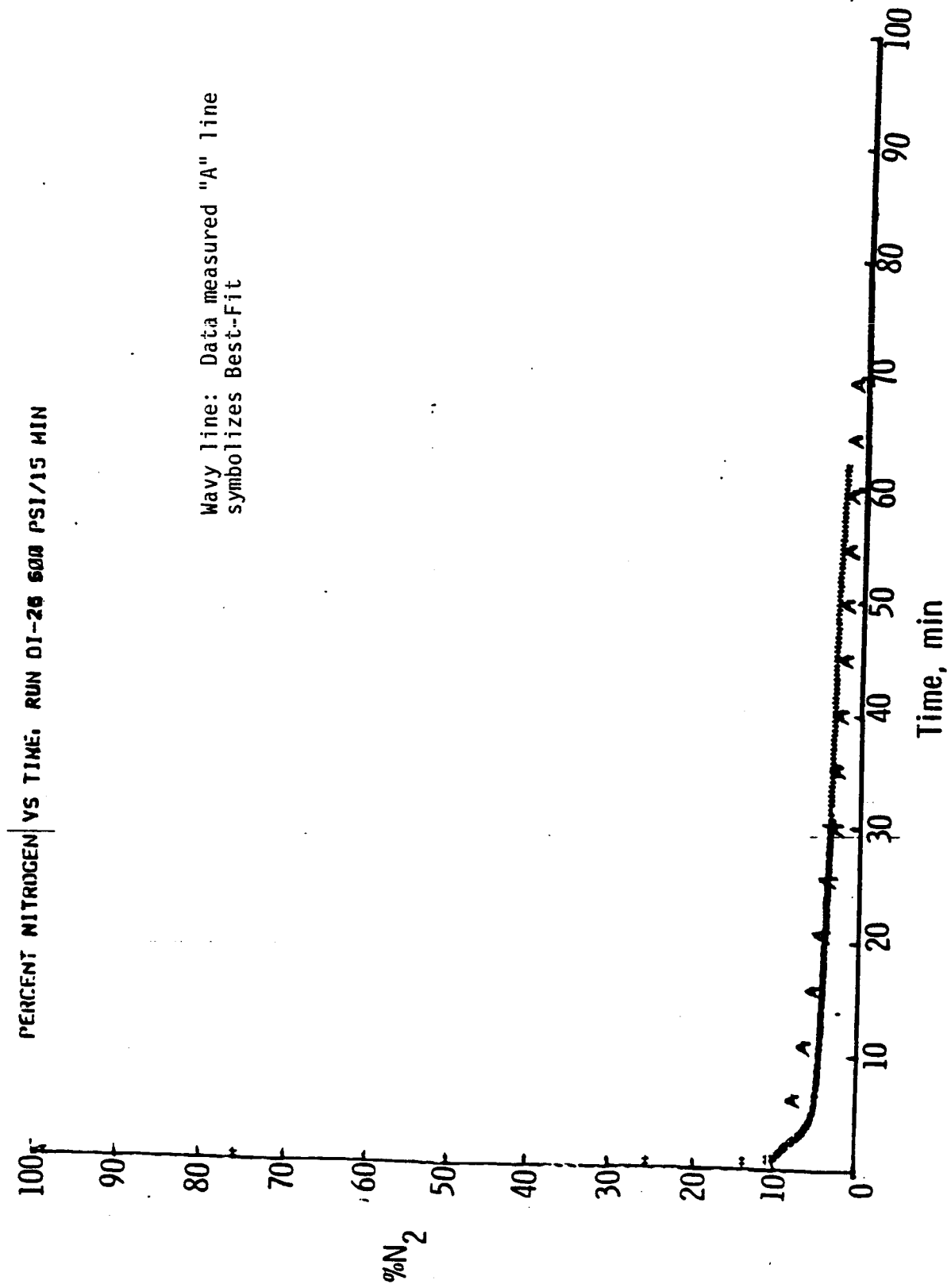


Figure 4. Percent nitrogen vs. time: 600 psi/15 min.

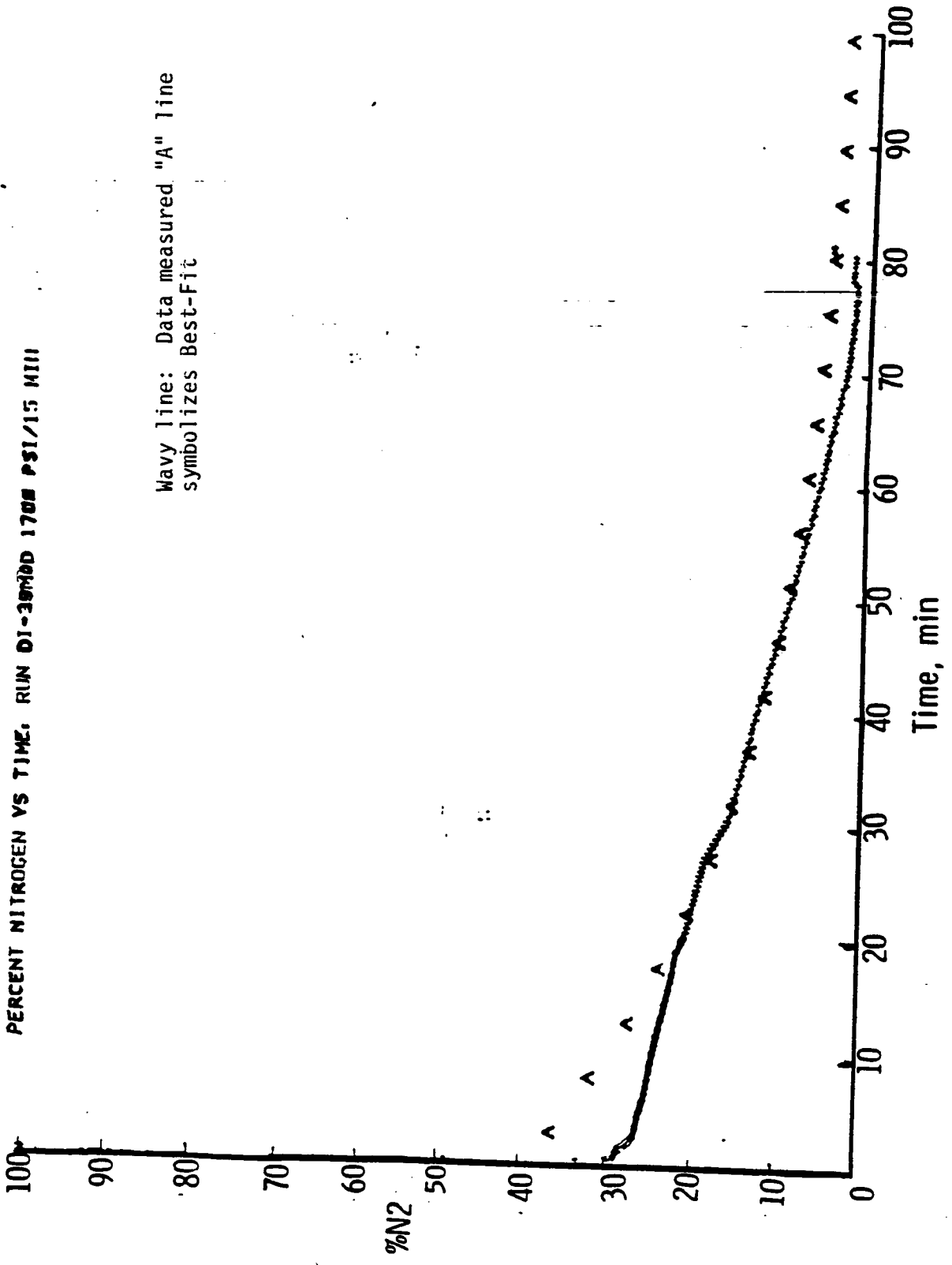


Figure 5. Percent nitrogen vs. time: 1700 psi/15 min.

depth penetration is very small. In some tests, there were evidences that LN_2 was at the bottom of the vessel. It is hoped that the additional testing can be undertaken at 7" Mach Seven Tunnel in the near future to fully define the significances of the evaporation rate and the depth penetration of GN_2 into LOX during pressurization.

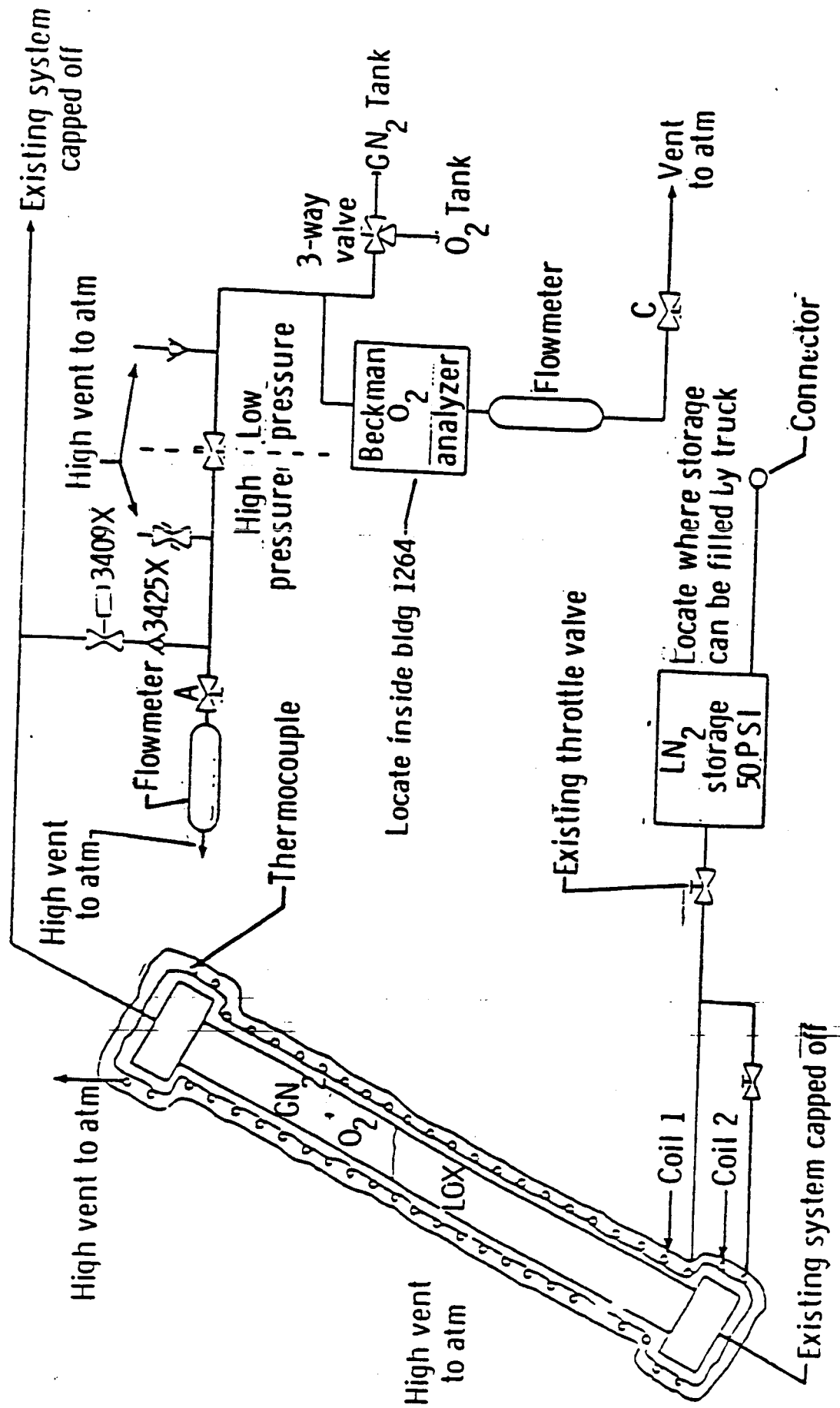
REFERENCES

1. Allan J. Zuckerwar, "Preliminary Study of Gaseous Nitrogen-Liquid Oxygen Mixing and Self-Cleaning," NASA Technical Memorandum 87658, December 1985.

APPENDIX A

LOX-LN₂ CONTAMINATION EXPERIMENTAL SET-UP

LOX-LN₂ CONTAMINATION EXPERIMENT



LOX Contamination Monitoring Test DI-_____ Date _____

A. Set Up Procedure

- 1. Install connector for cooling coil 2.
- 2. Cap off run tank.
- 3. Connect valves 3409X and 3425X to monitoring system.
- 4. Install and check out nuclear monitor. Locate at 46 inches.
- 5. Calibrate Beckmann O2 Analyzer.
- 6. Close valves "A", "B", "C", and "D".

B. Precooling Procedure

- 1. Open valve "A."
- 2. Follow existing checklist for "Cooldown with LN2."
- 3. Drain LN2.
- 4. Run LN2 through cooling coils 1 and 2.
- 5. Follow existing checklist for "LOX Transfer Operation."
- 6. Fill to 46 inches, as observed on nuclear monitor.
- 7. Wait _____ min.

C. Pressurization and Blowdown Procedure

- 1. Close valve "A."
- 2. Follow existing checklist for pressurizing with GN2 to _____ psi.
- 3. Maintain pressure for _____ min.
- 4. Close 3431N.
- 5. Open 3411N.
- 6. Open valve 3412X to vent pressure.

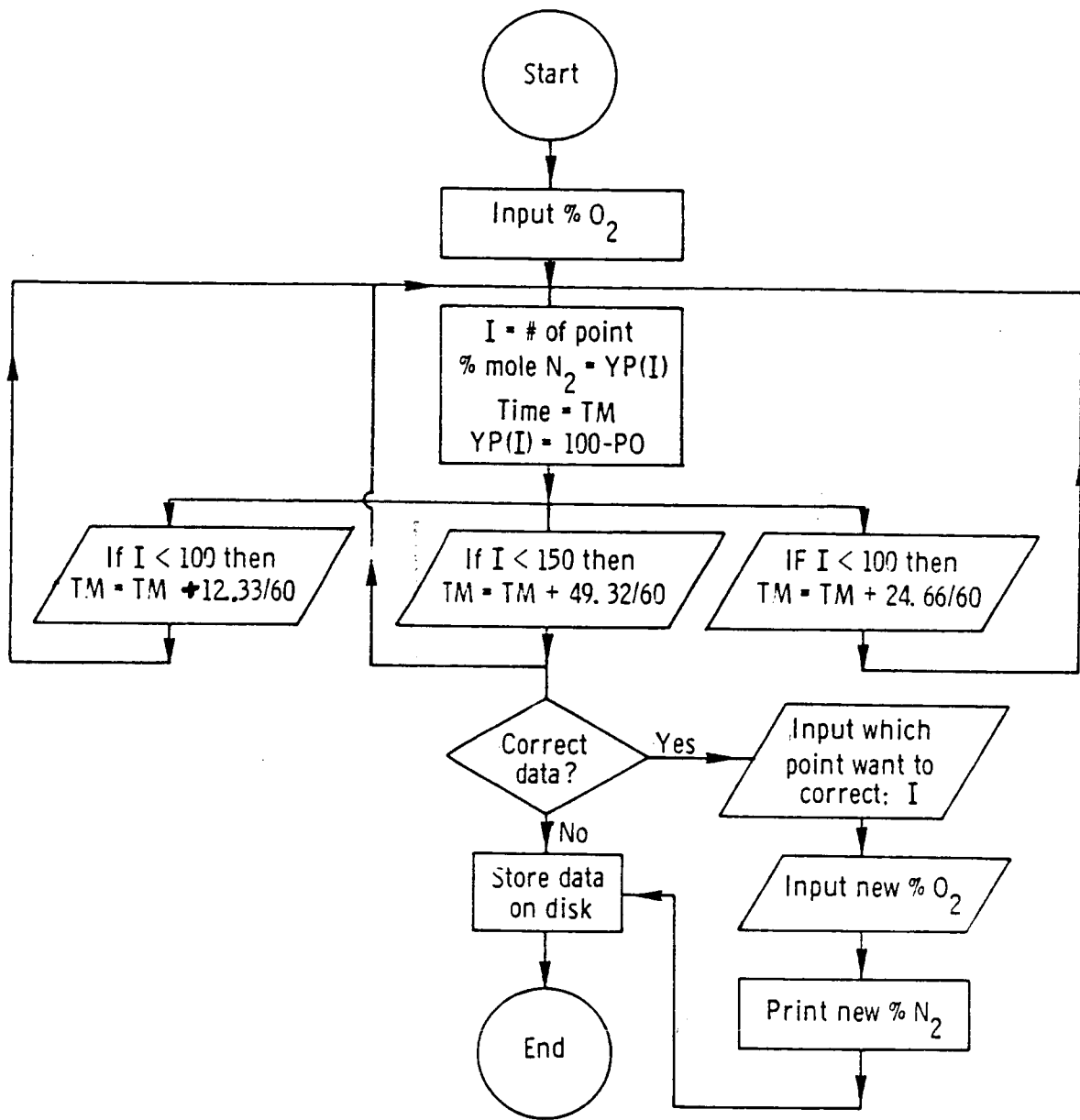
D. GO2 Monitoring Procedure

- 1. Close valve 3412X at 0 psi.
- 2. Close 3410N. (3411N optional).
- 3. Open valve 3409X.
- 4. Open valve "A". NOTE: This insures that pressurized GN2 is completely blown down.
- 5. Open valve "C".
- 6. Adjust valve "B" until flow rate reads _____ units.
- 7. Monitor thermocouple, Beckmann, O2 pressure, and both flowmeter readings continuously.

E. Shutdown Procedure

Follow existing checklist for "Vent and Shutdown Procedure".

APPENDIX B
SOFTWARE ENTERDATA



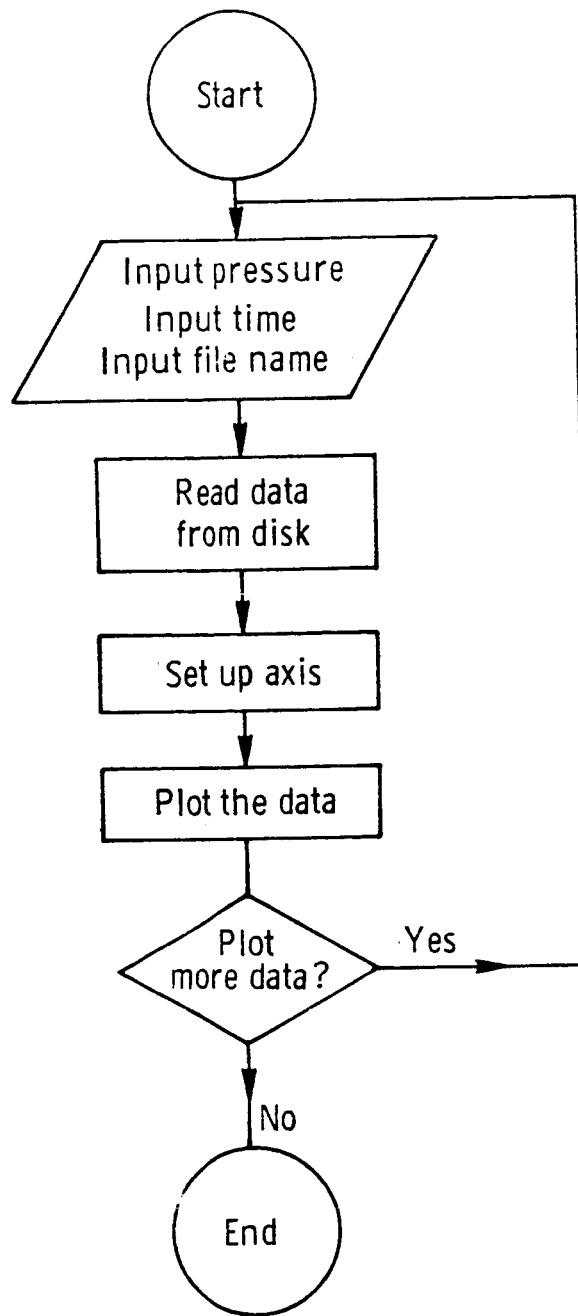
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LIST

```
10  REM PROGRAM FOR ENTER DATA
20  DIM XP(400),YP(400)
30  I = 0:TM = 0
40  HOME : PRINT "INPUT %02": PRINT
50  PRINT "IF END OF DATA TYPE 111": PRINT
60  INPUT "PERCENT=";PO
70  IF PO = 111 THEN GOTO 130
80  XP(I) = TM
90  YP(I) = 100 - PO
100 I = I + 1
101 IF I > 150 THEN GOTO 111
102 IF I > 100 THEN GOTO 113
109 TM = I * 12.33 / 60
110 GOTO 40
111 TM = TM + 49.32 / 60
112 GOTO 40
113 TM = TM + 24.66 / 60
120 GOTO 40
130 NP = I
140 REM CORRECT DATA
150 INPUT "DO YOU WISH TO CORRECT DATA (Y OR N) ";A$
160 IF A$ < > "Y" THEN GOTO 300
170 INPUT "DATA POINT? ";I
180 PRINT "PO= ";100 - YP(I): PRINT
190 INPUT "NEW % 02 ";PO
200 YP(I) = 100 - PO: PRINT : PRINT "YP( ";I; ") = ";YP(I): PRINT
210 GOTO 150
300 REM WRITE DATA TO DISK
310 D$ = CHR$(4)
320 INPUT "FILE NAME ";R$
330 PRINT D$;"OPEN";R$
340 PRINT D$;"DELETE";R$
350 PRINT D$;"OPEN";R$
360 PRINT D$;"WRITE";R$
370 PRINT NP
380 FOR I = 0 TO NP - 1
390 PRINT XP(I): PRINT YP(I)
400 NEXT I
410 PRINT D$;"CLOSE";R$
420 PRINT D$;"LOCK";R$
430 END
```

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APPENDIX C
SOFTWARE PLOTDATA



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```
10 REM PROGRAM TO PLOT DATA :PLOTS
20 REM DEFINE VARIABLES
30 DIM X(400),Y(400)
40 REM INPUT AXIS PARAMETER VALUES
50 DATA 0,0,100,10,1,0,0,5,.5 ,1,100,10
60 READ NO,X1,X2,X3,YL,Y0,Y1,Y2,Y3,YL,SX,SY
65 INPUT "PRESSURE=" ;P$
66 INPUT "TIME=" ;TM$
70 REM READ DATA FROM DISK
80 GOSUB 1000
90 REM LABEL PLOT:
100 X$ = "TIME,MIN.":Y$ = "%N2":TI$ = "PERCENT NITROGEN VS TIME: RUN " +
    R$ + " " + P$ + " PSI" + "/" + TM$ + " MIN"
110 REM SUBROUTINE TO SETUP AXIS
115 CALL 1002
120 GOSUB 2000
130 REM SUBROUTINE TO PLOT DATA
140 GOSUB 2500
150 J = 0
160 HOME : INPUT "DO YOU WANT TO PLOT MORE DATA? (YES OR NO) " ;A$
180 IF LEN (A$) = 2 THEN GOTO 260
190 J = J + 1
200 GOSUB 1000
205 CALL 1002
210 GOSUB 3000
220 CALL 1002
245 GOSUB 2500
250 GOTO 160
260 END

1000 REM SUBROUTINE READ DATA FROM DISK
1010 D$ = CHR$ (4)
1020 INPUT "FILE NAME " ;R$
1030 PRINT D$;"OPEN";R$
1040 PRINT D$;"READ";R$
1050 INPUT NP
1060 FOR I = 0 TO NP - 1
1070 INPUT XP(I): INPUT YP(I)
1080 NEXT I
1090 PRINT D$;"CLOSE";R$
1100 RETURN

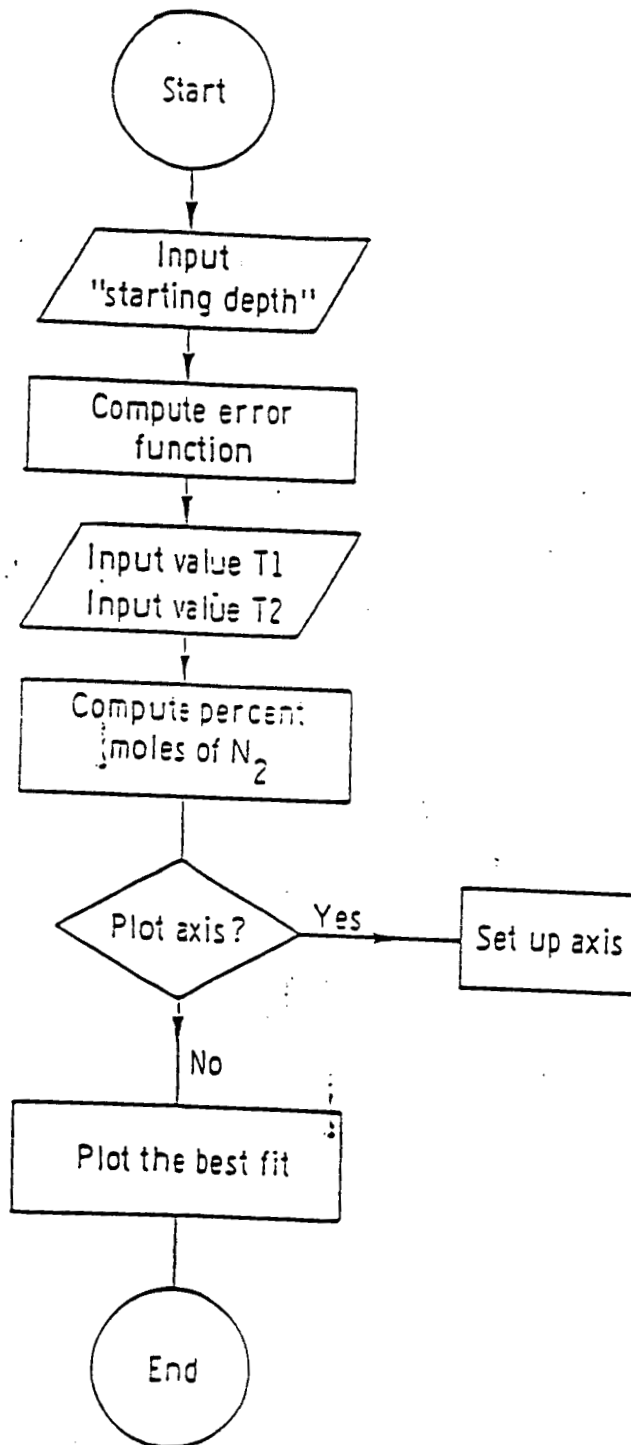
2000 REM SUBROUTINE PLOT AXES W/O INPUTS (IIE)
2010 REM VALUES ARE NEEDED FOR X0=X0,XMIN=X1,XMAX=X2,XTIC=X3,XLAB=X
L,Y0=Y0,YMIN=Y1,YMAX=Y2,YTIC=Y3,YLAB=YL,NO. PTS=NP,SFX=SX,SFY=SY,DAT
A COORDINATES=XP(I),YP(I),LABEL XAXIS=X$,LABEL YAXIS=Y$,TITLE=TI$
2020 T$ = "WT%":D$ = CHR$ (4):Z$ = CHR$ (26)
2030 X1 = X1 * SX:X2 = X2 * SX:X3 = X3 * SX:Y1 = Y1 * SY:Y2 = Y2 * SY:Y3 =
Y3 * SY:X0 = X0 * SX:Y0 = Y0 * SY
2040 PRINT D$;"PR#3": PRINT T$;Z$;"IN;IP1328,1000,9328,6760;SC"X1","X2",
"Y1","Y2";PA"X1","Y0";PD;"
2050 X4 = 0
2060 FOR X = X1 TO X2 STEP X3
2070 IF INT (X4 / XL) = X4 / XL THEN 2090
2080 PRINT T$;Z$;"TL ;PA"X","Y0";XT;": GOTO 2100
2090 PRINT T$;Z$;"TL1;PA"X","Y0";XT;PU;CP-.4,-.9;LB"X / SX";PA"X","Y0";P
D;"
2100 X4 = X4 + 1
2110 NEXT X
2120 PRINT T$;Z$;"PU;PA" INT (X1 + (X2 - X1) / 2.5)," INT (Y1 - (Y2 - Y
1) / 2.5);LB"X$";PA"X0","Y1";PD;"
2130 Y4 = 0
```

```

2130 Y4 = 0
2140 FOR Y = Y1 TO Y2 STEP Y3
2150 IF INT (Y4 / YL) = Y4 / YL THEN 2170
2160 PRINT T$;Z$;"TL";PA"X0","Y";IT;": GOTO 2130
2170 PRINT T$;Z$;"TL1";PA"X0","Y";YT;PU;CF-4.5,-.3;LB"Y / SY";PA"X0","Y";
PD;
2180 Y4 = Y4 + 1
2190 NEXT Y
2200 PRINT T$;Z$;"PU;PA" INT (X1 - (X2 - X1) / 10)," INT (Y1 + (Y2 - Y1
) / 4)";DI10,1;LB"Y$";
2210 PRINT T$;Z$;"PU;PA" INT (X1 + (X2 - X1) / 10)," INT (Y2)";DI1,0; L
B"TI$";
2220 PRINT D$;"PR#0": PRINT C$;"IN#0":X0 = X0 / SX:X1 = X1 / SX:X2 = X2 /
SX:X3 = X3 / SX:Y0 = Y0 / SY:Y1 = Y1 / SY:Y2 = Y2 / SY:Y3 = Y3 / SY
2230 RETURN
2240 REM TO PLOT ON GRAPH PAPER CHANGE LINE 2040 TO IP1150,960,9150,696
0
2500 REM SUBROUTINE PLOT DATA (IIE)
2510 REM MUST FOLLOW A PLOT AXES ROUTINE. TO PLOT ON GRAPH PAPER CHA
NGE LINE 2550 TO IP1150,960,9150,6960.
2520 PRINT D$;"PR#0": PRINT D$;"IN#0": INPUT "CHOOSE SYMBOL ";SP$
2530 T$ = "WT%":D$ = CHR$(4):Z$ = CHR$(26)
2540 X1 = X1 * SX:X2 = X2 * SX:X3 = X3 * SX:Y1 = Y1 * SY:Y2 = Y2 * SY:Y3 =
Y3 * SY:X0 = X0 * SX:Y0 = Y0 * SY
2550 PRINT D$;"PR#3": PRINT T$;Z$;"IN";IP1328,1000 ,9328,6760;SC"X1","X2"
,"Y1","Y2";PU;
2560 PRINT T$;Z$;"SI.2,.2;DI;
2570 FOR I = 0 TO NP - 1
2580 X = INT (SX * XP(I)):Y = INT (SY * YP(I))
2590 PRINT T$;Z$;"SM"SP$";PA"X","Y";SM;
2600 NEXT I
2610 PRINT D$;"PR#0": PRINT D$;"IN#0":X0 = X0 / SX:X1 = X1 / SX:X2 = X2 /
SX:X3 = X3 / SX:Y0 = Y0 / SY:Y1 = Y1 / SY:Y2 = Y2 / SY:Y3 = Y3 / SY
2620 RETURN
3000 REM SUBROUTINE TO PLOT MORE DATA
3010 SI$ = " " + R$
3020 T$ = "WT%":D$ = CHR$(4):Z$ = CHR$(26)
3030 X1 = X1 * SX:X2 = X2 * SX:X3 = X3 * SX:Y1 = Y1 * SY:Y2 = Y2 * SY:Y3 =
Y3 * SY:X0 = X0 * SX:Y0 = Y0 * SY
3040 PRINT D$;"PR#3": PRINT T$;Z$;"IN";IP1328,1000,9328,6760;SC"X1","X2",
"Y1","Y2";PA"X1","Y0";PD;
3050 PRINT T$;Z$;"PU;PA" INT (X1 + (X2 - X1) / 10 + (J * 6 * SX))," INT
(Y2)";DI1,0;LB"SI$";
3060 PRINT D$;"PR#0": PRINT D$;"IN#0":X0 = X0 / SX:X1 = X1 / SX:X2 = X2 /
SX:X3 = X3 / SX:Y0 = Y0 / SY:Y1 = Y1 / SY:Y2 = Y2 / SY:Y3 = Y3 / SY
3070 RETURN

```

APPENDIX D
SOFTWARE BEST-FIT



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```
10 REM PROGRAM TO PLOT MOLES VS TIME : BEST-FIT
20 DIM XP(500),YP(500)
30 X# = "TIME,MIN.":Y# = "XN(T),NO. OF MOLES":T1# = "XN(T) VS TIME"
40 A = 5.94:NT = 1.08:R = .066:UL = 1.9098
50 INPUT "STARTING DEPTH Z0/H= ";Z0
60 ARG = ABS(Z0)
62 GOSUB 1000: REM COMPUTE ERF
64 XN = .5 * (1 - RF * SGN(Z0))
66 PRINT "XN0= ";XN
70 INPUT "VALUE OF TAU1= ";T1
80 INPUT "VALUE OF TAU2= ";T2
90 INPUT "PLOT AXES (Y OR N) ";PL$
100 L = 100
110 REM COMPUTE XN(T)
120 FOR I = 0 TO L STEP 5
130 XP(I) = I:B1 = EXP(-I/T1)
140 Q0 = Z0:G = SGN(Q0):ARG = ABS(Q0)
150 GOSUB 1000: REM COMPUTE ERF
160 E0 = RF:G0 = G
170 Q1 = I/T2 + Z0:G = SGN(Q1):ARG = ABS(Q1)
180 GOSUB 1000: REM COMPUTE ERF
190 E1 = RF:G1 = G
200 Q2 = I/T2 + Z0 - T2/2/T1:G = SGN(Q2):ARG = ABS(Q2)
210 GOSUB 1000: REM COMPUTE ERF
220 E2 = RF:G2 = G
230 Q3 = Z0 - T2/2/T1:G = SGN(Q3):ARG = ABS(Q3)
240 GOSUB 1000: REM COMPUTE ERF
250 E3 = RF:G3 = G
260 AX = I/T1 + Z0 * T2/T1 - (T2/2/T1) ^ 2
270 IF (G2 * E2 - G3 * E3) = 0 THEN EX = (A1/P) * (-EXP(-AX - Q2
  ^ 2)/Q2 + EXP(-AX - Q3 ^ 2)/Q3): GOTO 310
280 IF AX > 0 THEN EX = EXP(-AX) * (G2 * E2 - G3 * E3): GOTO 310
290 LX = -AX + LOG(G2 * E2 - G3 * E3)
300 EX = EXP(LX)
310 YP(I) = XN * B1 + (1 - G0 * E0) * (1 - B1) / 2 - (G1 * E1 - G0 * E0) /
  2 + EX / 2:YP(I) = YP(I) * 100
320 PRINT I;" ";YP(I)
330 NEXT I
340 X0 = 0:X1 = 0:Y0 = 0:Y1 = 0
350 X2 = L
360 X3 = X2 / 10
370 XL = 5
380 SX = 100
390 PRINT "MAX. MOLE VALUE = ";XN0
400 Y2 = 100
410 Y3 = Y2 / 10
420 YL = 5
430 SY = 10
440 NP = L
450 IF PL$ < > "Y" THEN GOTO 480
460 REM PLOT AXIS
470 GOSUB 2000
480 REM PLOT DATA
490 GOSUB 3500
500 END
1000 REM SUBROUTINE TO CALCULATE ERF(X)
1010 REM BASED ON 7.1.26 RATIONAL APPROXIMATION
1020 P = .3275911:A1 = .254829592:A2 = -.284496736:A3 = 1.421413741:A4 =
  -1.453152027:A5 = 1.061405430
1030 T = 1 / (1 + P * ARG)
```

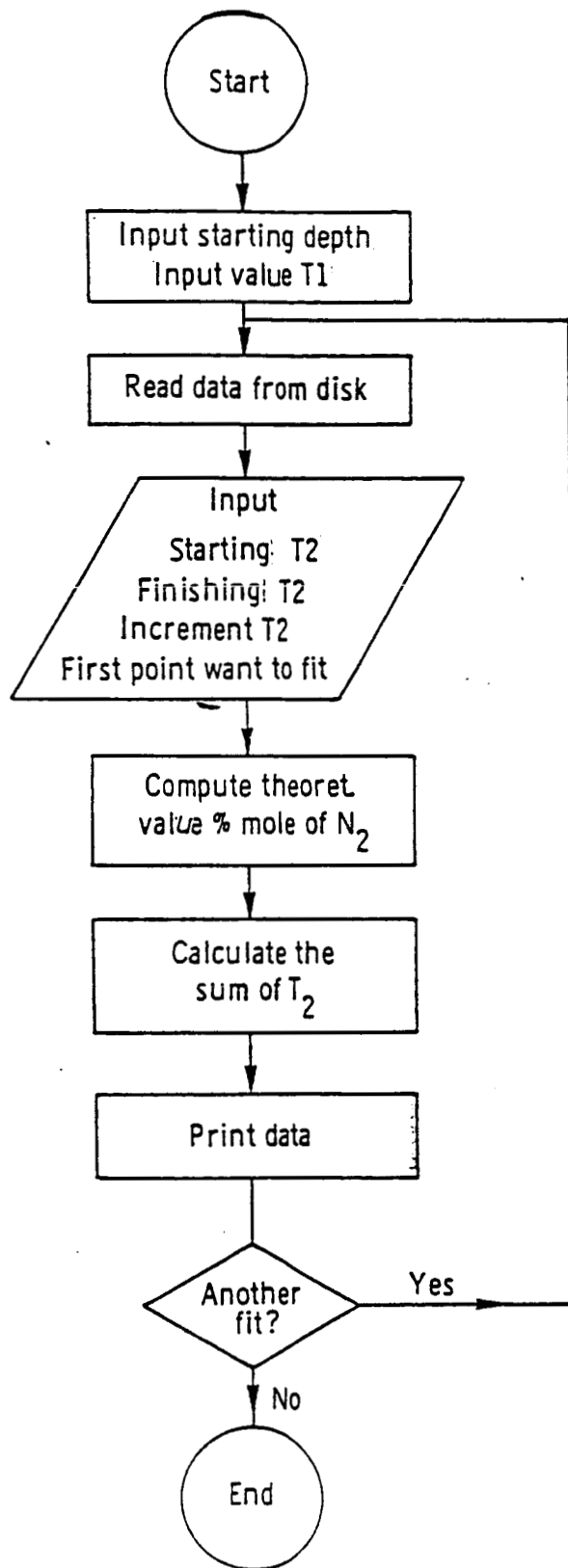

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1030 T = 1 / (1 + P + ARG)
1040 RF = (A1 * T) + (A2 * T ^ 2) + (A3 * T ^ 3) + (A4 * T ^ 4) + (A5 * T
    ^ 5)
1050 RF = RF * EXP (- (ARG ^ 2))
1060 RF = 1 - INT (1E3 * RF + 0.5) / 1E3
1070 RETURN
2000 REM SUBROUTINE PLOT AXES W/O INPUTS (IIE)
2010 REM VALUES ARE NEEDED FOR X0=X0,XMIN=X1,XMAX=X2,XTIC=X3,XLAB=X
    L,Y0=Y0,YMIN=Y1,YMAX=Y2,YTIC=Y3,YLAB=YL,NO. PTS=NP,SFX=SX,SFY=SY,DAT
    A COORDINATES=XP(I),YP(I),LABEL XAXIS=X$,LABEL YAXIS=Y$,TITLE=TI$
2020 T$ = "WT%":D$ = CHR$(4):Z$ = CHR$(26)
2030 X1 = X1 * SX:X2 = X2 * SX:X3 = X3 * SX:Y1 = Y1 * SY:Y2 = Y2 * SY:Y3 =
    Y3 * SY:X0 = X0 * SX:Y0 = Y0 * SY
2040 PRINT D$;"PR#3": PRINT T$;Z$;"IN;PI328,1000,9328,6760;SC"X1","X2",
    "Y1","Y2";PA"X1","Y0";PD;"
2050 X4 = 0
2060 FOR X = X1 TO X2 STEP X3
2070 IF INT (X4 / XL) = X4 / XL THEN 2090
2080 PRINT T$;Z$;"TL ;PA"X","Y0";XT;": GOTO 2100
2090 PRINT T$;Z$;"TL1;PA"X","Y0";XT;PU;CP-.4,-.9;LB"X / SX";PA"X","Y0";P
    D;"
2100 X4 = X4 + 1
2110 NEXT X
2120 PRINT T$;Z$;"PU;PA" INT (X1 + (X2 - X1) / 2.5)"," INT (Y1 - (Y2 - Y
    1) / 12.5)";LB"X$";PA"X0","Y1";PD;"
2130 Y4 = 0
2140 FOR Y = Y1 TO Y2 STEP Y3
2150 IF INT (Y4 / YL) = Y4 / YL THEN 2170
2160 PRINT T$;Z$;"TL ;PA"X0","Y";YT;": GOTO 2180
2170 PRINT T$;Z$;"TL1;PA"X0","Y";YT;PU;CP-4.9,-.3;LB"Y / SY";PA"X0","Y";
    PD;"
2180 Y4 = Y4 + 1
2190 NEXT Y
2200 PRINT T$;Z$;"PU;PA" INT (X1 - (X2 - X1) / 10)"," INT (Y1 + (Y2 - Y1
    ) / 4)";DI0,1;LB"Y$";"
2210 PRINT T$;Z$;"PU;PA" INT (X1 + (X2 - X1) / 10)"," INT (Y2)";DI1,0; L
    B"TI$";"
2220 PRINT D$;"PR#0": PRINT D$;"IN#0":X0 = X0 / SX:X1 = X1 / SX:X2 = X2 /
    SX:X3 = X3 / SX:Y0 = Y0 / SY:Y1 = Y1 / SY:Y2 = Y2 / SY:Y3 = Y3 / SY
2230 RETURN
2240 REM TO PLOT ON GRAPH PAPER CHANGE LINE 2040 TO IP1150,960,9150,696
    0
2500 REM SUBROUTINE PLOT DATA (IIE)
2510 REM MUST FOLLOW A PLOT AXES ROUTINE. TO PLOT ON GRAPH PAPER CHA
    NGE LINE 2550 TO IP1150,960,9150,6960.
2520 PRINT D$;"PR#0": PRINT D$;"IN#0": INPUT "CHOOSE SYMBOL ";SP$
2530 T$ = "WT%":D$ = CHR$(4):Z$ = CHR$(26)
2540 X1 = X1 * SX:X2 = X2 * SX:X3 = X3 * SX:Y1 = Y1 * SY:Y2 = Y2 * SY:Y3 =
    Y3 * SY:X0 = X0 * SX:Y0 = Y0 * SY
2550 PRINT D$;"PR#3": PRINT T$;Z$;"IN;IP1328,1000,9328,6760;SC"X1","X2",
    "Y1","Y2";PU;"
2560 PRINT T$;Z$;"SI.2,.2;DI;"
2570 FOR I = 0 TO NP STEP 5
2580 X = INT (SX * XP(I));Y = INT (SY * YP(I))
2590 PRINT T$;Z$;"SM"SP$";PA"X","Y";SM;"
2600 NEXT I
2610 PRINT D$;"PR#0": PRINT D$;"IN#0":X0 = X0 / SX:X1 = X1 / SX:X2 = X2 /
    SX:X3 = X3 / SX:Y0 = Y0 / SY:Y1 = Y1 / SY:Y2 = Y2 / SY:Y3 = Y3 / SY
2620 RETURN

```

APPENDIX E
SOFTWARE MINIMUM T2



IBIST

```
10 REM PROGRAM TO COMPUTE THE MINIMUM VALUE OF T2 :MT2
20 DIM XP(500),YP(500),YT(200)
30 INPUT "STARTING DEPTH Z0/H= ";Z0
40 ARG = ABS (Z0)
50 GOSUB 1000: REM COMPUTE ERF
60 XN = .5 * (1 - RF * SGN (Z0))
70 PRINT "MAX. MOLE VALUE = ";XN
80 INPUT "VALUE OF TAU1= ";T1
90 REM READ DATA FROM DISK
100 D$ = CHR$(4)
110 INPUT "FILE NAME ";R$
120 PRINT D$;"OPEN";R$
122 PRINT D$;"READ";R$
124 INPUT NP
126 FOR I = 0 TO NP - 1
128 INPUT XP(I): INPUT YP(I)
130 NEXT I
150 PRINT D$;"CLOSE";R$
155 REM FIT DATA
160 INPUT "STARTING T2= ";TS
170 INPUT "FINISHING T2= ";TF
180 INPUT "STEP T2= ";TC
190 INPUT "FIRST POINT WANT TO PLOT= ";I1
195 PR# 1: PRINT "T2","SUM": PR# 0
200 FOR T2 = TS TO TF STEP TC
210 S = 0
220 FOR I = I1 TO NP - 1
230 REM COMPUTE THEORETICAL VALUE YT(I)
300 B1 = EXP (- XP(I)/ T1)
310 Q0 = Z0:G = SGN (Q0):ARG = ABS (Q0)
350 GOSUB 1000: REM COMPUTE ERF
360 E0 = RF:G0 = G
370 Q1 = XP(I) / T2 + Z0:G = SGN (Q1):ARG = ABS (Q1)
380 GOSUB 1000: REM COMPUTE ERF
390 E1 = RF:G1 = G
400 Q2 = XP(I) / T2 + Z0 - T2 / 2 / T1:G = SGN (Q2):ARG = ABS (Q2)
410 GOSUB 1000: REM COMPUTE ERF
420 E2 = RF:G2 = G
430 Q3 = Z0 - T2 / 2 / T1:G = SGN (Q3):ARG = ABS (Q3)
440 GOSUB 1000: REM COMPUTE ERF
450 E3 = RF:G3 = G
460 AX = XP(I) / T1 + Z0 * T2 / T1 - (T2 / 2 / T1) ^ 2
470 IF (G2 * E2 - G3 * E3) = 0 THEN EX = (A1 / P) * ( - EXP ( - AX - Q2
    ^ 2) / Q2 + EXP ( - AX - Q3 ^ 2) / Q3): GOTO 510
480 IF AX > 0 THEN EX = EXP ( - AX) * (G2 * E2 - G3 * E3): GOTO 510
490 LX = - AX + LOG (G2 * E2 - G3 * E3)
500 EX = EXP (LX)
510 YT(I) = XN * B1 + (1 - G0 * E0) * (1 - B1) / 2 - (G1 * E1 - G0 * E0) /
    2 + EX / 2:YT(I) = YT(I) * 100
520 REM CALCULATE THE SUM OF T2
530 S = S + (YP(I) - YT(I)) ^ 2
540 NEXT I
550 PR# 1: PRINT T2,S: PR# 0
560 NEXT T2
570 INPUT "ANOTHER FIT ? (Y OR N) ";FT$
580 IF FT$ < "Y" THEN GOTO 600
590 GOTO 155
600 END
```