#### DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or restect those of the United States Government or any agency thereof. GEND-INF-030

GEND-INF--030

DE83 011491

ANALYSIS OF AIR-TEMPERATURE MEASUREMENTS FROM THE THREE MILE ISLAND UNIT 2 REACTOR BUILDING

Michael O. Fryer

Published April 1983

EG&G Idaho, Inc. Idaho Falls, Idaho 83415

Prepared for the U.S. Department of Energy Three Mile Island Operations Office Under DOE Contract No. DE-AC07-76ID01570



# ABSTRACT

The performance of the ambient air resistance temperature detectors (RTDs) just after the hydrogen burn in the TMI-2 Reactor Building is examined. The performance of the sensors is compared with physical models of the sensor/ambient air system. With one exception, the RTD data appear to be valid for the period examined. Based on the data, the hydrogen burn ended considerably before the first data points were recorded.

# CONTENTS

11 N

ABSTRACT	ii
INTRODUCTION	1
RTD DATA	2
Frequency of Recording	2
Locations of Instruments	2
Accuracy	2
MODELS	4
Sensor Model	4
Ambient Air Temperature Model	4
Sensor Response	5
ESTIMATION OF MODEL PARAMETERS	6
Filter Formulation	6
Parameter Estimates	8
MODEL VALIDATION	10
DURATION OF HIGH TEMPERATURES	17
CONCLUSIONS	17
REFERENCES	17
APPENDIX APLOTS OF RTD DATA	A-1
APPENDIX BFILTER PROGRAMS	B-1
APPENDIX CANALYSIS OF WORST_CASE AMBIENT TEMPEDATURE PROFILE	(-1

# ANALYSIS OF AIR TEMPERATURE MEASUREMENTS FROM THE THREE MILE ISLAND UNIT 2 REACTOR BUILDING

#### INTRODUCTION

This is the second in a series of reports on the resistance temperature detectors (RTDs) used to measure ambient air temperature in the TMI-2 Reactor Building. The first report detailed the current status of the RTDs and compiled data for the period of the TMI accident.<sup>1</sup> This report deals with the performance of the RTDs for the period just after the hydrogen burn in the TMI-2 Reactor Building. During this period, the ambient air sensors were subjected to extreme temperature changes, and some of them were sprayed with a water and sodium hydroxide solution.

The performance of these instruments during and after the hydrogen burn is important because of what the RTD data imply about the survivability of the instruments and about the hydrogen burn.

#### **RTD DATA**

# Frequencey of Recording

There are sixteen Rosemount Series 78 ambient air RTDs in the TMI-2 Reactor Building.<sup>2</sup> The readings of these instruments were recorded in a round robin fashion on a strip chart recorder. Fifteen seconds elapsed between each recording, and no data were taken for 2 min between the first and last sensor. Each sensor reading was recorded once every 6 min. The slow frequency of recording precludes obtaining information about the first few seconds after hydrogen ignition from the RTD data. Longer term building heating and cooling information can be obtained, as will be shown.

# Locations of Instruments

The locations of the sensors are given in Table 1.<sup>1</sup> Nine of the RTDs are at the 282-ft elevation of the Reactor Building, five between the 305-and 330-ft elevation, and two at the 353-ft elevation.

<u>rtd</u>	Location	Foot <u>Elevation</u>	RTU	Location	Foot <u>Elevation</u>
5010	Sump pump	282	5018	Primary shield	282
5011	Letdown cooler	282	5019	Primary shield	282
5012	RC drain tank	282	5020	Top ceiling	353
5013	Impinge barrier	282	5021	Top ceiling	353
5014	NR equipment hatch	305	5022	SE stairwell	330
5015	A/C plenum out	319	5023	WE stairwell	330
5016	Primary shield	282	5027	A/C plenum out	305
5017	Primary shield	282	5088	SE stairwell	310

TABLE ]. RTD LOCATIONS

### Accuracy

Steady state accuracy of the RTDs is  $\pm 1^{\circ}F$  at  $200^{\circ}F^2$ , and the strip chart recorder is accurate to  $\pm 1^{\circ}F$ . The time calibration of the strip chart recorder was rather poor, and timing for data reduction and modeling was taken relative to the hydrogen burn. The time origin of the data is

uncertain to  $\pm 90$  s because the burn occurred during a period when no data were recorded and the primary shield sensors showed no response to the burn.<sup>3</sup>

Response time of the RTDs is less than 5.5 s in 76°C water flowing at 3 ft/s.<sup>2</sup> The response time in air is not specified in the manufacturer's literature, so it was estimated as part of the modeling effort described in this report.<sup>a</sup> Appendix A contains plots of the RTD data recorded during the time of the TMI-2 accident. In all the plots (except for the RTDs in the primary shield) a jump in temperature is seen at the time of the hydrogen burn. The primary shield data are not analyzed further because they do not provide any information about the hydrogen burn. One of the RTDs on the 353-ft elevation shows a jump decrease in temperature at the time of the hydrogen burn. This is probably due to its being sprayed with water. The instrument is obviously suspect and is not analyzed further in this report. The data from the remaining eleven sensors were analyzed to estimate what temperatures the RTDs experienced and the RTD's time response characteristics.

a. The manufacturers claim that response time should be less than 40 s.

#### MODELS

After a preliminary examination of the RTD data, it appeared that they could be explained by postulationg a jump in ambient air temperature at the time of the hydrogen burn, followed by an exponential temperature decay. The RTD behavior was modeled with a first order heat transfer equation.

#### Sensor Model

The rate of change of RTD temperature was assumed proportional to the temperature difference between the RTD and the ambient air,

$$\frac{dT}{dt} = -\alpha \left(T - T_{A}\right) \tag{1}$$

where

- t = time
- $T_A =$  ambient temperature
- T = RTD temperature
- an unknown parameter depending, in a complicated way, on the construction of the RTD, the ambient conditions, and T; α was assumed constant over the time interval of interest, i.e., the first hour after the burn.

#### Ambient Air Temperature Model

The model assumed for the ambient air temperature was a step followed by an exponential decay. Specifically,

$$T_{A} = \begin{cases} T_{0} & t = t_{s} \\ T_{1} + T_{2} e^{-\beta (t-t_{s})} & t > t_{s} \end{cases}$$
(2)

 $T_0 = initial temperature$  $T_1, T_2, and \beta = constant parameters$  $t_s = time of the burn.$ 

Obviously, this model does not account for the details of the hydrogen burn, but is probably adequate on average for long-time intervals after the burn.

#### Sensor Response

Inserting the ambient temperature expression (2) in the RTD sensor response Equation (1), and solving the resulting differential equation, gives

$$T = e^{-\alpha (t-t_s)} \times T_0 + [1 - e^{-\alpha (t-t_s)}] \times T_1$$

+ 
$$[e^{-\beta(t-t_s)} - e^{-\alpha(t-t_s)}] \times \frac{T_2}{\alpha - \beta} \alpha$$
 (3)

for  $\alpha \neq \beta$ , which is the case.

where

### ESTIMATION OF MODEL PARAMETERS

A good technique for estimating model paramenters based on repeated measurements is Kalman filtering. The filter produces minimum variance estimates of the model parameters. Several excellent references are available on Kalman filtering, so a theoretical development of the method will not be presented in this report. An iterated and extended Kalman filter was used<sup>4</sup> because of the nonlinear relationship between RTU temperature and model parameters.

#### Filter Formulation

(4)

The filter state vector is

$$X = \begin{bmatrix} T_1 \\ T_2 \\ \alpha \\ \beta \end{bmatrix}$$

The measurements (Z) are the RTD data and

The measurement equation relating the states to the measurements is given by (3). The H matrix is defined as

$$H = \begin{bmatrix} \frac{\partial h}{\partial T_1}, & \frac{\partial h}{\partial T_2}, & \frac{\partial h}{\partial a}, & \frac{\partial h}{\partial \beta} \end{bmatrix}.$$
 (5)

The initial state covariance matrix is

$$P_{0} = \begin{bmatrix} 2.5 \times 10^{3} & 0 & 0 & 0 \\ 0 & 2.5 \times 10^{5} & 0 & 0 \\ 0 & 0 & 1.5 \times 10^{-2} & 0 \\ 0 & 0 & 0 & 6.5 \times 10^{-5} \end{bmatrix} .$$
(6)

The filter algorithm is as follows:

1. Save current state estimate

 $xsave = x_k$ ,

where

k is the discrete time index

2. Calculate gain

$$K_{k} = P_{k}H^{T}(x_{k}) [H(x_{k}) P_{k}H^{T}(x_{k}) + R_{k}]^{-1}$$

where

- R<sub>k</sub> = measurement noise matrix P<sub>k</sub> = state estimate covariance matrix
- 3. Update state, using linearized measurement equation

$$x_k = xsave + K_k [Z_k - h(x_k) - H(x_k)(xsave - s_k)]$$

- 4. Test for convergence of each element of state vector
- 5. If converged, read in next measurement,  $2_{k+1}$ , and update the covariance matrix and state,

 $P_{k+1} = [I - K_k H(x_k)] P_k$ 

 $x_{k+1} = x_{k}$ 

then go to l

6. If not, go to 2.

The filter was run on the data for each sensor, covering the period of 1 h after the hydrogen burn. Estimates of the model parameters  $T_1$ ,  $T_2$ ,  $\alpha$ , and  $\beta$  were obtained for each sensor. Covariances of these estimates were also obtained. The results are discussed in the next section.

Appendix B contains a list of filter computer programs designed to be executed on the INEL CYBER 176 system, and these programs use library routines available on the system.

#### Parameter Estimates

Table 2 shows the temperature values and time constant estimates for each RTD. The standard deviations of these estimates are included in the table.

The standard deviations are probably somewhat too small because the RTD and ambient air models were assumed correct in their calculation. The average value of the sensor time constant is 41 s, with a standard deviation of less than 24 s. This is not an extremely precise estimate of the time constant, but it limits the expected values to much shorter times than previously estimated.<sup>5</sup> Time constants of the magnitude calculated in this report are consistent with the plots of RTD shown in Appendix A; i.e., RTD readings are rapidly declining within 90 s after the hydrogen burn.

Sensor	Tl	<u></u>	т <sub>2</sub>	<u>_</u>	α	σ	β	σ
5010	112	6	20	4	0.031	0.015	0.0006	0.0005
5011	114	2	15	4	0.027	0.022	0.0009	0.0006
5012	124	3	31	4	0.025	0.015	0.0009	0.0004
5013	121	7	41	4	0.022	0.009	0.0007	0.0004
5014	122	2	32	3			0.0006	0.0001
5015	106	8	33	3		-	0.003	0.0004
5021	144	8	59	3			0.004	0.0004
5022	139	6	51	3	0.020	0.03	0.0009	0.0004
5023	123	2	51	3			0.001	0.00002
502 <b>7</b>	106	1	25	2			0.001	0.0003
5088	126	1	35	4			0.002	0.0003

TABLE 2. PARAMETER ESTIMATES

The sensor time constants ( $\alpha$ 's) were not calculated for several of the RTDs because the filter failed to converse. Since the values of T<sub>1</sub>, T<sub>2</sub>, and  $\beta$  are not very sensitive to the  $\alpha$  value, T<sub>1</sub>, T<sub>2</sub> and  $\beta$  were estimated for these sensors with the value of  $\alpha$  fixed at 0.02/s. A 3-state filter was used for these RTDs.

The maximum air temperature experienced at each RTD is the sum of  $T_1$  and  $T_2$ . The maximum temperatures are given in Table 3. As would be expected, the higher elevation sensors got hotter than lower elevation sensors, with the exception of 5015 and 5027, which are located at air conditioning plenum outlets. These sensors experienced different cooling than the others, probably because of better heat exchange.

The maximum air temperatures are subject to considerable uncertainty, especially at higher elevations, because of the water spraying that occurred just after the burn. But the maximum temperature estimates are probably good upper bounds on the air temperatures a few minutes after burn. Most sensors are on the long-term cooling trend by the time the first data were recorded after the burn. Extremely high temperatures, of more than 1000°F, could not have lasted for more than a few minutes, according to the RTD data. This information will be useful in any consideration about fire resistant design of items in the Reactor Building.

Sensor	Temperature (°F)
5010	132
5011	129
5012	155
5013	162
5014	154
5015	139
5021	203
5022	190
5023	184
5027	131
5088	161

TABLE 3. MAXIMUM AIR TEMPERATURES ACCORDING TO MODEL

Figures 1 through 11 show plots of model temperatures and RTD data. As can be seen from the plots, the model fits the data well in most cases. The air conditioning plenum outlet sensors and higher elevation sensors show the most disagreement betwee: the model and the data. Again, this is probably the result of better heat transfer at the AC outlets and spraying at higher levels, respectively.

Table 4 shows the average difference, maximum difference, and standard deviation of the difference between the model and data for each sensor. The accuracy of the sensor/strip chart recorder is within  $\pm 2^{\circ}$ F. The model and data agree to better than this at nearly all points for most RTUs.

Sensor	Average Difference (°F)	Standard Deviation (°F)	Maximum Difference (°F)
5010	0.13	0.17	-1.5
5011	-0.07	0.28	-1.7
5012	0.04	0.12	-0.87
5013	-0.19	0.10	-0.48
5014	-0.45	0.42	-3.1
5015 5021	-0.36 0.02	1.3 0.83	-6.2 4 1
5022	-0.21	0.30	-2.12
5023	-3.3	3.3	-29.7
5027	-1.6	1.4	-12
5088	-0.35	0.58	3.1

TABLE 4. MODEL VALIDATION



Figure 2. RTD 5011 data versus model.



Figure 4. RTD 5013 data versus model.



Figure 6. RTD 5015 data versus model.



Figure 8. RTD 5022 data versus model.



Figure 10. RTD 5027 data versus model.



STE TE STATE

영화(전/영

Figure 11. RTD 5088 data versus model.

ź

# DURATION OF HIGH TEMPERATURES

Information about the duration of the hydrogen burn can be obtained from the RTD data. An analysis was done for an RTD with average time response characteristics and average initial temperature to determine when the burning must have ended. Appendix C contains the mathematical details of the analysis. The results indicated that temperatures of greater than 1000°F must have persisted for less than 100 s after the start of the burn.

#### **CONCLUSIONS**

The RTDs behaved in a manner predictable from simple physical models. When these models were used to fit the data, good agreement was obtained in nearly all cases. It appears that the RTD data are valid for the period examined, with the exception of RTD 5020, which showed lower temperatures just after the hydrogen burn.

The high temperatures (>1000°F) indicative of hydrogen burning must have ended considerably before the first data points were recorded after the hydrogen burn.

#### REFERENCES

- 1. James W. Mock, <u>Current Status and Accident Data Presentation of</u> <u>Containment Air Temperature Resistance Temperature Detectors</u>, <u>EU-E3-82-017</u>, EG&G Idaho Internal Report, June 1982.
- 2. <u>Series 78 Platinum Resistance Temperature Sensors</u>, Product data sheet 2178, Rosemount, Inc.
- 3. Letter from H. F. Ring to D. L. Reeder (Еб&в Idaho), TIO Control No. 007013099, June 25, 1982.
- 4. Arthur Gelb, Applied Optimal Estimation, Cambridge: M.I.T. Press, 1974.
- 5. H. R. Keltner, <u>Potential Enhancement of TMI Containment Thermal Sensor</u> Data, Sandia Laboratories, TIO Control No. 7-18212, July 2, 1982.

APPENDIX A PLOTS OF RTD DATA

A-1/2

# APPENDIX A PLOTS OF RTD DATA

Figures A-1 through A-12 are RTD data plots of temperature excursions for the duration of the TMI-2 accident. The temperature excursion caused by the hydrogen burn is indicated on each plot. Other temperature excursions on the plots are closely correlated with operator actions, such as opening and closing the block valve.



-





Figure A-2. RTD 5011 temperature excursions during the TMI-2 accident.



Figure A-4. RTD 5013 temperature excursions during the TMI-2 accident.



22.42.26

Figure A-5. RTD 5014 temperature excursions during the TMI-2 accident.







A-7



Figure A-9. RTD 5022 temperature excursions during the TMI-2 accident.



Figure A-10. RTD 5023 temperature excursions during the TMI-2 accident.



Figure A-11. RTD 5027 temperature excursions during the TM1-2 accident.





APPENDIX B FILTER PROGRAMS

	PROGRAM RTD(TAPE1.TAPE2.TAPE3)	000100
	CONTON/FILTER/X(10),XI(10),GAIN(10,10),Z(10),HMAT(10),H(10,10)	<b>0</b> 00110
-	+. PMAT(10, 10). HT(10, 10). RMAT(10, 10). TIME. TBOOM. NMEAS. NSTATE	000120
-	+, TSTART, ZMEAS(10)	<b>60</b> 01 30
	REAL MAX	000132
	DIMENSION XISAVE(10)	000140
	DIMENSION ERRMAG(10)	000150
	DIMENSION AMEAS(10)	000155
	DATA XI/10*0.0/	000160
	DATA PMAT/100×0.0/,H/100×0.0/,RMAT/100×0.0/	000170
	DATA HT/100+0.0/,GAIN/100+0.0/,HMAT/10+0.0/	000180
	TB00M=0.0	000190
	PMAT(1,1)=2.5E+03	000200
	PMAT(2,2)=2.5E+05	000210
	PMAT(3,3)=.015	000220
	PMAT(4,4)=6.5E-05	000230
	RMAT(1,1)=4.24	000240
	READ(1,*) NDATA, NMERS, NSTATE	000250
	READ(1,*) TSTART, (XI(J), J=1, NSTATE)	000260
	DO 1020 IDUMMY=1, NDATA	000270
	READ(1,*) (ZMEAS(I), I=1, NMEAS)	000280
	AMEAS(IDUMMY)=ZMEAS(1)	000282
	READ(1,*) TIME	00230
	IF(IDUMMY.EQ.1) STIME TIME	000292
	DO 50 I-1,NSTATE	000300
50	X(I)=XI(I)	000310
	DO 100 I=1,100	000320
C	100 CHANCES TO CONVERGE	000330
	CALL HVALU	000340
	CALL KGAIN	000350
	DO 60 J=1,NSTATE	000360
60	XISAVE(J)-XI(J)	000370
	CALL STATE(I)	000380
	DO 75 J-1.NSTATE	000390
75	ERMAG(J)=ABS(XI(J)-XISAVE(J))	000400
	NLM-0	000410
	DO 90 J-1.NSTATE	000420
90	IF (ERRMAG(J), LT, (, 001*ABS(XI(J)))) NUM=NUM+1	000430
. –	IF(NUM.EQ.NSTATE) GO TO 101	003446
	IF(I.EQ.20) WRITE(2.' ( " FAILED TO CONVERGE ")')	000450
100	CONTINUE	000460
101	CONTINUE	000470
	LETTE(2 105) (VI(I) I-1 NETATE)	000400

المحاج والمحجود الأحمام ومحمد والمحمول والمحمول والمحاج

WRITE(2,105) (XI(I),I=1,NSTATE) 105 FORMAT('STATE ',E12.6) CALL PROPP

فالمديد وماستوليان بالواري

.

.

-1

...

an an an ann an Incarain

003496) 000500

WRITE(2, '(///, " COVARIANCE ",/)') 000520 000530 DO 110 I-1,NSTATE 020540 110 WRITE(2,112) (PMAT(I,J), J=1, NSTATE) 000550 112 FORMAT(4(2X,E12.6)) 828568 1000 CONTINUE WRITE(3,'( " 1")') 000570 000590 TIME-0.0 000600 C---- MAKE PLOT FILE OF MODEL FIT DO 1500 II-1,360 000610 000620 EX3=EXP(-XI(3)\*TIME) 000630 EX4=EXP(-XI(4)\*TIME)DATA=EX3\*TSTART+(1-EX3)\*XI(1)+(EX4-EX3)\*XI(2)\*XI(3)/(XI(3)-XI(4)) 020640 000650 TIME=TIME+10.0 000660 1500 WRITE(3,\*) TIME, DATA WRITE(3, '( " END")') 000670 000672 AVE-0.0 000673 MAX-0.0 000674 SIG-0.0 000675 N-0 002680 TIME-STIME DO 2000 II-1, NDATA 000690 000700 EX3=EXP(-XI(3)\*TIME) EX4=EXP(-XI(4)\*TIME)000710 DATA=EX3\*TSTART+(1-EX3)\*XI(1)+(EX4-EX3)\*XI(2)\*XI(3)/(XI(3)-XI(4)) 000720 A-AMEAS(II)-DATA 000724 000730 TIME-TIME+360.0 000732 N=N+1 000734 IF(MAX.LT.ABS(A)) MAX=ABS(A) AVE=(AMEAS(II)-DATA)/N+AVE\*(N-1)/N 000740 000750 SIG=SIG+(AMEAS(II)-DATA)\*\*2 000760 2000 CONTINUE SIG-SORT(SIG)/(N-1) 000770 WRITE(2, '(//, " AVERAGE , MAXIMUM , SAMPLE VARIANCE OF ERROR")') 000780 WRITE(2,\*) AVE, MAX, SIG 000790 008880 STOP END 000B10 SUBROUTINE HVALU 000820  $COPPON \neq FILTER \times (10), XI(10), GAIN(10, 10), Z(10), HMAT(10), H(10, 10)$ 000830 +,PMAT(10,10),HT(10,10),RMAT(10,10),TIME,TBOOM,NMEAS,NSTATE 666649 +, TSTART, ZMEAS(10) 00085-9 0000000 DELTA-TIME-TBOOM 000000 EX3=EXP(-XI(3)\*DELTA) (200H) EX4=EXP(-XI(4)\*DELTA) ABA=XI(3)/(XI(3)-XI(4))626899 HMAT(1)=EX3+TSTART+(1-EX3)+XI(1)+(EX4-EX3)+XI(2)+ABA 

Historia Martin Carlo and a state of the second second second second second second second second second second

.

	H(1,1)=1-EX3	0063910
	H(1,2)=(EX4-EX3)*ABA	0001920
	H(1,3)=-DELTA*EX3*(TSTART-XI(1)-XI(2)*ABA)	000930
-	+ +(EX4-EX3)*ABA*XI(2)/XI(3)-(EX4-EX3)*(ABA**2)*XI(2)/XI(3)	000940
	H(1,4)=-DELTA*EX4*XI(2)*ABA	666950
-	+ +(EX4-EX3)*(ABA**2)*XI(2)/XI(3)	000360
	RETURN	000970
	END	000380
	SUBROUTINE KGAIN	009590
	COMMON/FILTER/X(10),XI(10),GAIN(10,10),Z(10),HMAT(10),H(10,10)	001000
-	+,PMAT(10,10),HT(10,10),RMAT(10,10),TIME,TBOOM,NMEAS,NSTATE	001010
-	+,TSTART,ZMEAS(10)	001020
	DIMENSION PH(10), HPH(10, 10), TEMP(10, 10), TEMPIV(10, 10), WRK(1000)	001030
	DO 100 I=1,NSTATE	001040
	DO 100 J-1, NEAS	001058
100	HT(I,J)=H(J,I)	001868
	CALL VMLLFF (PMAT, HT, NSTATE, NSTATE, NMEAS, 10, 10, PH, 10, IER)	001070
	CALL VMULFF(H,PH,NMEAS,NSTATE,NMEAS,10,10,HPH,10,IER)	001080
	DO 2000 I-1, NMEAS	001090
	DO 200 J-1, NMEAS	001100
200	TEMP(I, J)-HPH(I, J)+RMAT(I, J)	001110
	IDGT-Ø	001150
	CALL LINV2F(TEMP, NMEAS, 10, TEMPIV, IDGT, WRK, IER)	001130
	CALL VMULFF (PH, TEMPIV, NSTATE, NMEAS, NMEAS, 10, 10, GAIN, 10, IER)	<b>0</b> 01140
	RETURN	001150
	END	001160
	SUBROUTINE STATE (NPASS)	001179
	$COMMON \neq FILTER \times X(10), XI(10), GAIN(10, 10), Z(10), HMAT(10), H(10, 10)$	001180
	+, PMAT(10, 10), HT(10, 10), RMAT(10, 10), TIME, TBOOM, NMEAS, NSTATE	001190
	+, 15(AR), 200(10)	001200
	$D_{1} = D_{1} = D_{1$	001210
	DU 102 I-1,NSIHIE	001241
		1001230
100	CONTINUE	001240
	N=1	001250
	CALL VMULFF(H, DIFF, NMEAS, NSTATE, N, 10, 10, HX, 10, IER)	001260
	DO 200 I-1, NMEAS	061279
200	RESID(I)=ZMEAS(I)-HMAT(I)-HX(I)	0012149
	CALL VMULFF(GAIN, RESID, NSTATE, NMEAS, N, 10, 10, AKR, 10, IER)	001250
	DO 300 I=1,NSTATE	001300
300	XI(I)=X(I)+AKR(I)	001310
	RETURN	001320
	END	Ø61336
	SUBROUTINE PROPST	001340
	RETURN	001350
	END	001350

.

001370
001390
001350
001400
001410
001420
001430
001440
001450
001460
001470
001480
001490
001500
001510
001520
001530
001540
001550

4

4

The second second

)

	PROGRAM RTD(TAPE1, TAPE2)	000100
	COMMON/FILTER/X(10), XI (10), GAIN(10, 10), Z(10), HMAT(10), H(10, 10)	000110
-	-PMAT(10.10).HT(10.10).RMAT(10.10).TIME.TBOOM.NMEAS.NSTATE	000120
-	TSTART. ZMEAS(10)	000130
	REAL MAX	000140
	DIMENSION XISAVE(10)	<b>8001</b> 50
	DIMENSION ERRMAG(10)	000160
	DIMENSION AMERS(10)	000162
	DATA XI/10+0.0/	000170
	DATA PMAT/100+0.0/.H/100+0.0/.RMAT/100+0.0/	000189
	DATA HT/100+0.0/.GAIN/100+0.0/.HMAT/10+0.0/	000190
	TB00M-0.0	000200
	PMAT(1.1)=2.5E+03	000210
	PMAT(2,2)=2.5E+05	000220
	PMAT(3,3)=6.5E-05	000230
	RMAT(1,1)=4.24	000240
	READ(1,*) NDATA, NMEAS, NSTATE	000250
	READ(1,*) TSTART, (XI(J), J=1, NSTATE)	000260
	DO 1000 IDUMMY-1, NDATA	000270
	READ(1,*) (ZMEAS(I),I=1,NMEAS)	000280
	AMEAS(IDUMMY)=ZMEAS(1)	<b>02</b> 0282
	READ(1,*) TIME	000290
	IF(IDUMMY.EQ.1) STIME-TIME	000300
	DO 50 I-1,NSTATE	000310
50	×(I)=×I(I)	000320
	DG 100 I=1,100	000330
C	100 CHANCES TO CONVERGE	008340
	CALL HVALU	000350
	CALL KGAIN	00A3÷3
	DO 60 J=1,NSTATE	000370
60	XISAVE(J)=XI(J)	000380
	CALL STATE(I)	000390
	DO 75 J=1,NSTATE	000-400
75	ERRMAG(J)+ABS(XI(J)-XISAVE(J))	0010410
	NLM=0	000426
	DO 90 J=1,NSTATE	<b>900-</b> ; 70
90	IF(ERRMAG(j).LT.(.001*ABS(XI(J)))) NUM=NUM+1	000-1-18
	IF(NUM.EQ.NSTATE) GO TO 101	000458
	IF(I.EQ.20) WRITE(2,' ( " FAILED TO CONVERGE ")')	000468
100	CONTINUE	000478
101	CONTINE	008486

000480 101 CONTINUE WRITE(2,105) (XI(I), I=1, NSTATE) 000450 000500 105 FORMAT(' STATE ', E12.6) 000510 CALL PROPP 0005:20 CALL PROPST WRITE(2,'(///, " COVARIANCE ",/)') 000530 DO 110 I=1,NSTATE 000540 000550 110 WRITE(2,112) (PMAT(I,J), J=1, NSTATE) 000560 112 FORMAT(4)(2X,E12.6)) 000578 1000 CONTINUE WRITE(3,'( " 1")') 000580 000590 TIME=0.0 C---- MAKE PLOT FILE OF MODEL FIT ALL TH 003510 DO 1500 II=1,360 0999520 EX3=EXP(-.02\*TIME) 020530 EX4=EXP(-XI(3)\*TIME) DATA=EX3\*TSTART+(1-EX3)\*XI(1)+(EX4-EX3)\*XI(2)\*.02/(.02-XI(3)) 000640 0006543 TIME=TIME+10.0 000650 1500 WRITE(3,\*) TIME, DATA WRITE(3, '( " END")') 000670 AVE-0.0 000680 000690 MAX-0.0 000701 SIG=0.0 000710 N=0 000720 TIME-STIME 000730 DO 2000 II=1,NDATA 000740 EX3=EXP(-.02\*TIME) EX4=EXP(-XI(3)\*TIME) 000750 DATA=EX3\*TSTART+(1-EX3)\*XI(1)+(EX4-EX3)\*XI(2)\*.02/(.02-XI(3)) 000760 000770 R=AMEAS(II)-DATA 000780 TIME=TIME+360.0 000790 N=N+1 0008000 IF(MAX.LT.ABS(A)) MAX=ABS(A) AVE=(AMEAS(II)-DATA)/N+AVE\*(N-1)/N 000810 SIG=SIG+(AMEAS(II)-DATA)\*\*2 000820 000830 2000 CONTINUE SIG=SQRT(SIG)/(N-1) 000840 WRITE(2, '(//, " AVERAGE , MAXIMUM , SAMPLE VARIANCE OF ERROR")') 000850 WRITE(2,\*) AVE, MAX, SIG 000850 STOP 0008711 END 000EFA)

STOP	044870
END	000880
SUBROUTINE HVALU	<b>MMB90</b>
CONTION/FILTER/X(10).XI(10).GAIN(10,10).Z(10).HMAT(10).H(10,10)	000500
+, PMAT(10, 10), HT(10, 10), RMAT(10, 10), TIME, TBOOM, NMEAS, NSTATE	000910
+, TSTART, ZMEAS(10)	000920
DEL TA-TIME-TBOOM	000330
EX3=DXP(02*DELTA)	000940
EX4=EXP(-XI(3)*DELTA)	000950
ABA=.02/(.02-XI(3))	000960
HMAT(1)=EX3*TSTART+(1-EX3)*XI(1)+(EX4-EX3)*XI(2)*ABA	000970
H(1.1)=1-EX3	000300
H(1,2)=(EX4-EX3)*ABA	000000
H(1,3)=-DELTA*EX4*XI(2)*ABA	001000
+ +(EX4-EX3)*(ABA**2)*XI(2)/.02	001010
RETURN	001020
END	001030
SUBROUTINE KGAIN	001040
COMMON/FILTER/X(10).XI(10).GAIN(10.10).Z(10).HMAT(10).H(10.10)	001050
+. PMAT(10, 10). HT(10, 10). RMAT(10, 10), TIME, TBOOM, NMEAS, NSTATE	001060
+, TSTART, ZMEAS(10)	001070
DIMENSION PH(10), HPH(10, 10), TEMP(10, 10), TEMPIV(10, 10), WRK(1000)	001090
DO 100 I-1,NSTATÉ	001090
DO 100 J-1, NMEAS	001100
100 HT(I,J)=H(Ĵ,I)	001110
CALL VMULFF(PMAT, HT, NSTATE, NSTATE, NMEAS, 10, 10, PH, 10, IER)	001120
CALL VMULFF(H, PH, NMEAS, NSTATE, NMEAS, 10, 10, HPH, 10, IER)	001130
DO 2010 I=1,NMEAS	001140
DO 2010 J=1,NMEAS	001150
200 TEMP(I,J)=HPH(I,J)+RMAT(I,J)	001160
IDGT-0	001170
CALL LINVZF(TEMP, NMEAS, 10, TEMPIV, IDGT, WRK, IER)	001180
CALL VMULFF(PH, TEMPIV, NSTATE, NMEAS, NMEAS, 10, 10, GAIN, 10, IER)	001190
RETURN	001200
END	001210
SUBROUTINE STATE (NPASS)	001220
COMMON/FILTER/X(10),XI(10),GAIN(10,10),Z(10),HMAT(10),H(10,10)	001230
+, PMAT(10, 10), HT(10, 10), RMAT(10, 10), TIME, TBOOM, NMEAS, NSTATE	001240
+,TSTART,ZMEAS(10)	001250
DIMENSION AKR(10), RESID(10), DIFF(10), HX(10)	001260
DO 100 I-1,NSTATE	001270
DIFF(I)=X(I)-XI(I)	<b>601</b> .280
100 CONTINUE	001290
N=1	001300
CALL VMLLFF(H, DIFF, NMEAS, NSTATE, N, 10, 10, HX, 10, IER)	001310
DO 2010 I+1, NMEAS	001320
ZUU RESID(I)=ZMEAS(I)-HMAT(I)-HL(I)	001330

	CALL VMULFF(H, DIFF, NMEAS, NSTATE, N, 10, 10, HX, 10, IER)	001310
	DO 2020 I=1, NMEAS	001320
200	RESID(I)=ZMEAS(I)-HMAT(I)-HX(I)	001330
	CALL VMULFF(GAIN, RESID, NSTATE, NMEAS, N, 10, 10, AKR, 10, IER)	001340
	DO 300 I=1,NSTATE	001350
300	XI(I)=X(I)+AKR(I)	001350
	RETURN	001370
	END	001380
	SUBROUTINE PROPST	001350
	RETURN	001400
	END	001410
	SUBROUTINE PROPP	001420
	COMMON/FILTER/X(10),XI(10),GAIN(10,10),Z(10),HMAT(10),H(10,10)	001430
-	+, PMAT(10, 10), HT(10, 10), RMAT(10, 10), TIME, TBOOM, NMEAS, NSTATE	001440
-	+, TSTART, ZMEAS(10)	0014543
	REAL KH(10,10), TEMP(10,10), KH1(10,10)	<b>00</b> 1468
	DATA KH/100+0.0/,KH1/100+0.0/,TEMP/100+0.0/	001470
	CALL VMULFF (GAIN, H, NSTATE, NMEAS, NSTATE, 10, 10, KH, 10, IER)	001480
	DO 100 I=1,NSTATE	001490
	DO 100 J=1,NSTATE	001500
	KH1(I,J)=-KH(I,J)	001510
100	IF(I.EQ.J) KH1(I,J)=1+KH1(I,J)	001520
	CALL VMULFF(KH1, PMAT, NSTATE, NSTATE, NSTATE, 10, 10, TEMP, 10, IER)	001530
	DO 200 I=1,NSTATE	001540
	DO 200 J=1,NSTATE	001550
	PMAT(I,J)=TEMP(I,J)	001560
	IF(I.GT.J) PMAT(I,J)=TEMP(J,I)	001570
200	CONTINUE	001580
	RETURN	001590
	END	001600

.

.

......

APPENDIX C ANALYSIS OF WORST-CASE AMBIENT TEMPERATURE PROFILE

53

\$

c-1/2

# APPENDIX C

#### ANALYSIS OF WORST-CASE AMBIENT TEMPERATURE PROFILE

Consider the worst-case ambient temperature profile shown in Figure C-1. This profile will give the longest duration of high temperatures without large differences with recorded data. A mathematical expression for the ambient temperature is

$$T_{AMB} = \begin{cases} T_{U} & t < t_{B} \\ T_{B} & t_{B} < t < t_{s} \\ T_{1} + T_{2} e^{-\beta(t-t_{s})} & t > t_{s} \end{cases}$$

Given this, the RTD temperature is

 $T(t) = T_0 e^{-\alpha (t-t_B)} + T_B [e^{-\alpha (t-t_S)} - e^{-\alpha (t-t_B)}]$ 

+ 
$$T_1 [1-e^{-\alpha(t-t_s)}] + \frac{\alpha T_2}{\alpha - \beta} [e^{-\beta(t-t_s)} - e^{-\alpha(t-t_s)}]$$

and the difference between the RTD temperature and the ambient at the first data point time  ${\bf t}_{\rm D}$  is

$$T_{D} - T_{AMB} = T_{0} e^{-\alpha (t_{D} - t_{B})} + T_{B} [e^{-\alpha (t_{D} - t_{S})} - e^{-\alpha (t_{D} - t_{B})}]$$
$$- T_{1} e^{-\alpha (t_{D} - t_{S})} + T_{2} \{ \frac{\alpha}{\alpha - \beta} [e^{-\frac{\beta}{2} (t_{D} - t_{S})}]$$
$$- e^{-\alpha (t_{D} - t_{S})} - e^{-\beta (t_{D} - t_{S})} \}$$

where  $T_D = T(t_D)$ . We want to find the maximum  $t_s$  so that the difference between the ambient and sensor temperature is small, say 10°F. Such a  $t_s$  can be found by solving the equation

 $10^{\circ}F = T_{D} - T_{AMB}$ 

C-3





S.

 $\mathbf{h}$ 



using the values

٢,

T <sub>D</sub> = 110°F	β	= 0.0009/s
$T_{1} = 120^{\circ}F$	t <sub>D</sub> - t <sub>B</sub>	= 270 s
$T_2 = 30^{\circ}F$	-	
a = 0.025/s		
T <sub>B</sub> = 1000°F		

and solving the resulting equation using Newton's method we get  $t_D - t_s = 170.5$  s.

