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

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Michael O. Fryer

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

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GEND-INF--030

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Published April 1983

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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.

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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.¹ 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

Frequency of Recording

There are sixteen Rosemount Series 78 ambient air RTDs in the TMI-2 Reactor Building.² 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 1.¹ 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.

TABLE 1. RTD LOCATIONS

RTD	Location	Foot Elevation	RTD	Location	Foot Elevation
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

Accuracy

Steady state accuracy of the RTDs is $\pm 1^\circ\text{F}$ at 200°F ², and the strip chart recorder is accurate to $\pm 1^\circ\text{F}$. 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 ± 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.³

Response time of the RTDs is less than 5.5 s in 76°C water flowing at 3 ft/s.² 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.^a 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 postulating 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,

$$\frac{dT}{dt} = -\alpha (T - T_A) \quad (1)$$

where

t = time

T_A = ambient temperature

T = RTD temperature

α = 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,

$$T_A = \begin{cases} T_0 & t = t_s \\ T_1 + T_2 e^{-\beta(t-t_s)} & t > t_s \end{cases} \quad (2)$$

where

T_0 = initial temperature

T_1 , T_2 , and β = 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

$$T = e^{-\alpha(t-t_s)} \times T_0 + [1 - e^{-\alpha(t-t_s)}] \times T_1 \\ + [e^{-\beta(t-t_s)} - e^{-\alpha(t-t_s)}] \times \frac{T_2}{\alpha - \beta} \quad (3)$$

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

ESTIMATION OF MODEL PARAMETERS

A good technique for estimating model parameters 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 used⁴ because of the nonlinear relationship between RTD temperature and model parameters.

Filter Formulation

The filter state vector is

$$X = \begin{bmatrix} T_1 \\ T_2 \\ \alpha \\ \beta \end{bmatrix} . \quad (4)$$

The measurements (Z) are the RTD data and

$$Z = h(X) .$$

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

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

The initial state covariance matrix is

$$P_0 = \begin{bmatrix} 2.5 \times 10^3 & 0 & 0 & 0 \\ 0 & 2.5 \times 10^5 & 0 & 0 \\ 0 & 0 & 1.5 \times 10^{-2} & 0 \\ 0 & 0 & 0 & 6.5 \times 10^{-5} \end{bmatrix} . \quad (6)$$

The filter algorithm is as follows:

1. Save current state estimate

$$x_{\text{save}} = x_k,$$

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_k = measurement noise matrix

P_k = state estimate covariance matrix

3. Update state, using linearized measurement equation

$$x_k = x_{\text{save}} + K_k [Z_k - h(x_k) - H(x_k)(x_{\text{save}} - s_k)]$$

4. Test for convergence of each element of state vector

5. If converged, read in next measurement, Z_{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 1

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 , α , and β 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.⁵ 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.

TABLE 2. PARAMETER ESTIMATES

Sensor	T_1	σ	T_2	σ	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	--	--	0.0001	0.00002
5027	106	1	25	2	--	--	0.001	0.0003
5088	126	1	35	4	--	--	0.002	0.0003

The sensor time constants (α 's) were not calculated for several of the RTDs because the filter failed to converse. Since the values of T_1 , T_2 , and β are not very sensitive to the α value, T_1 , T_2 and β were estimated for these sensors with the value of α 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.

TABLE 3. MAXIMUM AIR TEMPERATURES ACCORDING TO MODEL

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

MODEL VALIDATION

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 between 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 $\pm 2^\circ\text{F}$. The model and data agree to better than this at nearly all points for most RTDs.

TABLE 4. MODEL VALIDATION

<u>Sensor</u>	<u>Average Difference (°F)</u>	<u>Standard Deviation (°F)</u>	<u>Maximum Difference (°F)</u>
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	-0.36	1.3	-6.2
5021	0.02	0.83	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

Figure 1. RTD 5010 data versus model.

Figure 2. RTD 5011 data versus model.

INEL 2 4223

Figure 3. RTD 5012 data versus model.

Figure 4. RTD 5013 data versus model.

Figure 5. RTD 5014 data versus model.

Figure 6. RTD 5015 data versus model.

INEL 2 4218

Figure 7. RTD 5021 data versus model.

Figure 8. RTD 5022 data versus model.

Figure 9. RTD 5023 data versus model.

Figure 10. RTD 5027 data versus model.

INEL 2 4219

Figure 11. RTD 5088 data versus model.

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 ($>1000^{\circ}\text{F}$) indicative of hydrogen burning must have ended considerably before the first data points were recorded after the hydrogen burn.

REFERENCES

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5. H. R. Keltner, Potential Enhancement of TMI Containment Thermal Sensor Data, Sandia Laboratories, TIO Control No. 7-18212, July 2, 1982.

APPENDIX A
PLOTS OF RTD DATA

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-1. RTD 5010 temperature excursions during the TMI-2 accident.

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

Figure A-3. RTD 5012 temperature excursions during the TMI-2 accident.

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

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

Figure A-6. RTD 5015 temperature excursions during the TMI-2 accident.

Figure A-7. RTD 5020 temperature excursions during the TMI-2 accident.

Figure A-8. RTD 5021 temperature excursions during the TMI-2 accident.

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 TMI-2 accident.

Figure A-12. RTD 5088 temperature excursions during the TMI-2 accident.

APPENDIX B
FILTER PROGRAMS

PROGRAM RTD(TAPE1,TAPE2,TAPE3)	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	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
TBOOM=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,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)	000282
READ(1,*) TIME	000290
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 ERRMAG(J)=ABS(XI(J)-XISAVE(J))	000400
NUM=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	000440
IF(I.EQ.20) WRITE(2,' (" FAILED TO CONVERGE ")')	000450
100 CONTINUE	000460
101 CONTINUE	000470
WRITE(2,105) (XI(I),I=1,NSTATE)	000480
105 FORMAT(' STATE ',E12.6)	000490
CALL PROPP	000500

WRITE(2,'(///, " COVARIANCE ",/))	000520
DO 110 I=1,NSTATE	000530
110 WRITE(2,112) (PMAT(I,J),J=1,NSTATE)	000540
112 FORMAT(4(2X,E12.6))	000550
1000 CONTINUE	000560
WRITE(3,'(" 1")')	000570
TIME=0.0	000580
C----- MAKE PLOT FILE OF MODEL FIT	000590
DO 1500 II=1,360	000600
EX3=EXP(-XI(3)*TIME)	000610
EX4=EXP(-XI(4)*TIME)	000620
DATA=EX3*TSTART+(1-EX3)*XI(1)+(EX4-EX3)*XI(2)*XI(3)/(XI(3)-XI(4))	000630
TIME=TIME+10.0	000640
1500 WRITE(3,*) TIME,DATA	000650
WRITE(3,'(" END")')	000660
AVE=0.0	000670
MAX=0.0	000672
SIG=0.0	000673
N=0	000674
TIME=STIME	000675
DO 2000 II=1,NDATA	000680
EX3=EXP(-XI(3)*TIME)	000690
EX4=EXP(-XI(4)*TIME)	000700
DATA=EX3*TSTART+(1-EX3)*XI(1)+(EX4-EX3)*XI(2)*XI(3)/(XI(3)-XI(4))	000710
A=AMEAS(II)-DATA	000720
TIME=TIME+360.0	000724
N=N+1	000730
IF(MAX.LT.ABS(A)) MAX=ABS(A)	000732
	000734
AVE=(AMEAS(II)-DATA)/N+AVE*(N-1)/N	000740
SIG=SIG+(AMEAS(II)-DATA)**2	000750
2000 CONTINUE	000760
SIG=SIG/(N-1)	000770
WRITE(2,'(///, " AVERAGE , MAXIMUM , SAMPLE VARIANCE OF ERROR")')	000780
WRITE(2,*) AVE,MAX,SIG	000790
STOP	000800
END	000810
SUBROUTINE HVALU	000820
COMMON/FILTER/X(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	000840
+,TSTART,ZMEAS(10)	000850
DELTA=TIME-TBOOM	000860
EX3=EXP(-XI(3)*DELTA)	000870
EX4=EXP(-XI(4)*DELTA)	000880
ABA=XI(3)/(XI(3)-XI(4))	000890
HMAT(1)=EX3*TSTART+(1-EX3)*XI(1)+(EX4-EX3)*XI(2)*ABA	000900

H(1,1)=1-EX3	000910
H(1,2)=(EX4-EX3)*ABA	000920
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	000950
+ +(EX4-EX3)*(ABA**2)*XI(2)/XI(3)	000960
RETURN	000970
END	000980
SUBROUTINE KGAIN	000990
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,NMEAS	001050
100 HT(I,J)=H(J,I)	001060
CALL VMULFF(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 200 I=1,NMEAS	001090
DO 200 J=1,NMEAS	001100
200 TEMP(I,J)=HPH(I,J)+RMAT(I,J)	001110
IDGT=0	001120
CALL LINV2F(TEMP,NMEAS,10,TEMPIV,IDGT,WRK,IER)	001130
CALL VMULFF(PH,TEMPIV,NSTATE,NMEAS,NMEAS,10,10,GAIN,10,IER)	001140
RETURN	001150
END	001160
SUBROUTINE STATE(NPASS)	001170
COMMON/FILTER/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
+,TSTART,ZMEAS(10)	001200
DIMENSION AKR(10),RESID(10),DIFF(10),HX(10)	001210
DO 100 I=1,NSTATE	001220
DIFF(I)=X(I)-XI(I)	001230
100 CONTINUE	001240
N=1	001250
CALL VMULFF(H,DIFF,NMEAS,NSTATE,N,10,10,HX,10,IER)	001260
DO 200 I=1,NMEAS	001270
200 RESID(I)=ZMEAS(I)-HMAT(I)-HX(I)	001280
CALL VMULFF(GAIN,RESID,NSTATE,NMEAS,N,10,10,AKR,10,IER)	001290
DO 300 I=1,NSTATE	001300
300 XI(I)=X(I)+AKR(I)	001310
RETURN	001320
END	001330
SUBROUTINE PROPST	001340
RETURN	001350
END	001360

SUBROUTINE PROPP	001370
COMMON/FILTER/X(10),XI(10),GAIN(10,10),Z(10),HMAT(10),H(10,10)	001380
+,PMAT(10,10),HT(10,10),RMAT(10,10),TIME,TBOOM,NMEAS,NSTATE	001390
+,TSTART,ZMEAS(10)	001400
REAL KH(10,10),TEMP(10,10),KH1(10,10)	001410
DATA KH/100*0.0/,KH1/100*0.0/,TEMP/100*0.0/	001420
CALL VMULFF(GAIN,H,NSTATE,NMEAS,NSTATE,10,10,KH,10,IER)	001430
DO 100 I=1,NSTATE	001440
DO 100 J=1,NSTATE	001450
KH1(I,J)=-KH(I,J)	001460
100 IF(I.EQ.J) KH1(I,J)=1+KH1(I,J)	001470
CALL VMULFF(KH1,PMAT,NSTATE,NSTATE,NSTATE,10,10,TEMP,10,IER)	001480
DO 200 I=1,NSTATE	001490
DO 200 J=1,NSTATE	001500
PMAT(I,J)=TEMP(I,J)	001510
IF(I.GT.J) PMAT(I,J)=TEMP(J,I)	001520
200 CONTINUE	001530
RETURN	001540
END	001550

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)	000150
DIMENSION ERRMAG(10)	000160
DIMENSION AMEAS(10)	000162
DATA XI/10*0.0/	000170
DATA PMAT/100*0.0/,H/100*0.0/,RMAT/100*0.0/	000180
DATA HT/100*0.0/,GAIN/100*0.0/,HMAT/10*0.0/	000190
TBOOM=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)	000282
READ(1,*) TIME	000290
IF(IDUMMY.EQ.1) STIME=TIME	000300
DO 50 I=1,NSTATE	000310
50 X(I)=XI(I)	000320
DO 100 I=1,100	000330
C----- 100 CHANCES TO CONVERGE	000340
CALL HVALU	000350
CALL KGAIRN	000360
DO 60 J=1,NSTATE	000370
60 XISAVE(J)=XI(J)	000380
CALL STATE(I)	000390
DO 75 J=1,NSTATE	000400
75 ERRMAG(J)=ABS(XI(J)-XISAVE(J))	000410
NUM=0	000420
DO 90 J=1,NSTATE	000430
90 IF(ERRMAG(J).LT.(.001*ABS(XI(J)))) NUM=NUM+1	000440
IF(NUM.EQ.NSTATE) GO TO 101	000450
IF(I.EQ.20) WRITE(2,' (" FAILED TO CONVERGE ")')	000460
100 CONTINUE	000470
101 CONTINUE	000480

101	CONTINUE	000480
	WRITE(2,105) (XI(I),I=1,NSTATE)	000490
105	FORMAT(' STATE ',E12.6)	000500
	CALL PROPP	000510
	CALL PROPS	000520
	WRITE(2,'(///, " COVARIANCE ",/)'')	000530
	DO 110 I=1,NSTATE	000540
110	WRITE(2,112) (PMAT(I,J),J=1,NSTATE)	000550
112	FORMAT(4(2X,E12.6))	000560
1000	CONTINUE	000570
	WRITE(3,'(" 1")'')	000580
	TIME=0.0	000590
C----	MAKE PLOT FILE OF MODEL FIT	000600
	DO 1500 II=1,360	000610
	EX3=EXP(-.02*TIME)	000620
	EX4=EXP(-XI(3)*TIME)	000630
	DATA=EX3*TSTART+(1-EX3)*XI(1)+(EX4-EX3)*XI(2)*.02/(.02-XI(3))	000640
	TIME=TIME+10.0	000650
1500	WRITE(3,*) TIME,DATA	000660
	WRITE(3,'(" END")'')	000670
	AVE=0.0	000680
	MAX=0.0	000690
	SIG=0.0	000700
	N=0	000710
	TIME=TIME	000720
	DO 2000 II=1,NDATA	000730
	EX3=EXP(-.02*TIME)	000740
	EX4=EXP(-XI(3)*TIME)	000750
	DATA=EX3*TSTART+(1-EX3)*XI(1)+(EX4-EX3)*XI(2)*.02/(.02-XI(3))	000760
	A=AMEAS(II)-DATA	000770
	TIME=TIME+360.0	000780
	N=N+1	000790
	IF(MAX.LT.ABS(A)) MAX=ABS(A)	000800
	AVE=(AMEAS(II)-DATA)/N+AVE*(N-1)/N	000810
	SIG=SIG+(AMEAS(II)-DATA)**2	000820
2000	CONTINUE	000830
	SIG=SQRT(SIG)/(N-1)	000840
	WRITE(2,'(///, " AVERAGE , MAXIMUM , SAMPLE VARIANCE OF ERROR")'')	000850
	WRITE(2,*) AVE,MAX,SIG	000860
	STOP	000870
	END	000880

STOP	000870
END	000880
SUBROUTINE HVALU	000890
COMMON/FILTER/X(10),XI(10),GAIN(10,10),Z(10),HMAT(10),H(10,10)	000900
+,PMAT(10,10),HT(10,10),RMAT(10,10),TIME,TBOOM,NMEAS,NSTATE	000910
+,TSTART,ZMEAS(10)	000920
DELTA=TIME-TBOOM	000930
EX3=EXP(-.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	000980
H(1,2)=(EX4-EX3)*ABA	000990
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)	001080
DO 100 I=1,NSTATE	001090
DO 100 J=1,NMEAS	001100
100 HT(I,J)=H(J,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 200 I=1,NMEAS	001140
DO 200 J=1,NMEAS	001150
200 TEMP(I,J)=HPH(I,J)+RMAT(I,J)	001160
IDGT=0	001170
CALL LINV2F(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)	001280
100 CONTINUE	001290
N=1	001300
CALL VMULFF(H,DIFF,NMEAS,NSTATE,N,10,10,HX,10,IER)	001310
DO 200 I=1,NMEAS	001320
200 RESID(I)=ZMEAS(I)-HMAT(I)+HX(I)	001330

CALL VMULFF(H,DIFF,NMEAS,NSTATE,N,10,10,HX,10,IER)	001310
DO 200 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)	001360
RETURN	001370
END	001380
SUBROUTINE PROPST	001390
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)	001450
REAL KH(10,10),TEMP(10,10),KH1(10,10)	001460
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

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

$$T_{AMB} = \begin{cases} T_0 & t < t_B \\ T_B & t_B < t < t_s \\ T_1 + T_2 e^{-\beta(t-t_s)} & t > t_s \end{cases}$$

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 t_D is

$$T_D - T_{AMB} = T_0 e^{-\alpha(t_D-t_B)} + T_B [e^{-\alpha(t_D-t_s)} - e^{-\alpha(t_D-t_B)}] \\ - T_1 e^{-\alpha(t_D-t_s)} + T_2 \left\{ \frac{\alpha}{\alpha - \beta} [e^{-\beta(t_D-t_s)} - e^{-\alpha(t_D-t_s)}] - e^{-\beta(t_D-t_s)} \right\}$$

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

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

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Figure C-1. Worst-case ambient temperature profile.

using the values

$$T_D = 110^\circ\text{F}$$

$$T_1 = 120^\circ\text{F}$$

$$T_2 = 30^\circ\text{F}$$

$$\alpha = 0.025/\text{s}$$

$$T_B = 1000^\circ\text{F}$$

$$\beta = 0.0009/\text{s}$$

$$t_D - t_B = 270 \text{ s}$$

and solving the resulting equation using Newton's method we get

$$t_D - t_s = 170.5 \text{ s.}$$