**Verification of Fuel Centerline
Thermocouple Readings Through
Response to Linear Power
Decreases**

by
**D. D. Lanning
C. R. Hann**

April 1977

**Prepared for
Nuclear Regulatory Commission
Division of Reactor Safety Research
Fuel Behavior Research Branch**

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CONTENTS

LIST OF FIGURES.	iii
LIST OF TABLES	iii
I - SUMMARY AND CONCLUSIONS.	1
II - INTRODUCTION	3
III - ANALYSIS OF QUASI-STEADY-STATE TIME DERIVATIVE OF CENTERLINE TEMPERATURE	7
IV - IFA-431 POWER DROP ANALYSIS.	13
V - RECOMMENDATIONS FOR FUTURE WORK.	19
REFERENCES	22
APPENDIX A: NOTATION AND SI UNITS	A.1
APPENDIX B: DERIVATION OF THE CENTERLINE TEMPERATURE RESPONSE TO A LINEAR DECREASE IN POWER.	B.1
APPENDIX C: REVIEW OF THE TEST FOR EQUALITY OF SLOPE OF TWO LEAST SQUARES FIT LINES.	C.1
APPENDIX D: RAW AND NORMALIZED DATA, AND REGRESSION RESULTS	D.1

LIST OF FIGURES

1	Schematic of Instrumented Fuel Assembly - IFA-431.	4
2	Qualitative Expected Behavior of q_N and T_N	10
3	Normalized Data for TF2, Run 3	15

LIST OF TABLES

1	Test Parameters in IFA-431	5
2	IFA-431 Power Drops.	13
3	Summary of Regression Results.	16
4	One-Sided 95% Significance Interval for Centerline Temperature (In Degrees C)	16
5	Estimated True Centerline Temperature Minus Initial Thermocouple Reading (In Degrees C).	17
6	Frequency Distribution for the Data in Table 5	18

VERIFICATION OF FUEL CENTERLINE THERMOCOUPLE READINGS THROUGH RESPONSE TO LINEAR POWER DECREASES

I - SUMMARY AND CONCLUSIONS

A method is presented whereby the true value and 95% confidence limits for fuel centerline temperatures are estimated from fuel thermocouple response to a linear decrease in rod power. Furthermore, it is shown that for moderate power decreases, these estimates are independent of uncertainties in the fuel rod thermal properties (including its gap conductance). The estimates are also independent of the absolute values of the initial thermocouple reading and power level.

Data is presented from power decreases on the U.S. Nuclear Regulatory Commission - Battelle Pacific Northwest Laboratories assembly IFA-431 in the Halden reactor. The reactor power was linearly decreased approximately 20% in 30 seconds on several different occasions. The one-sided 95% confidence limits on centerline temperature from analysis of these runs varied from 67 to 292 C, depending on the run, the rod, and the power level. However, in 33 of the 40 cases examined, thermocouples agreed with the estimated true value centerline temperature within 80 C.

Future work is recommended which could narrow the confidence limits and provide an independent measure of the fuel-to-cladding gap conductance.

II - INTRODUCTION

This report discusses the relationship between time-varying and steady-state fuel temperature measurements from Halden Reactor instrumented fuel assembly IFA-431. The design and fuel preparation for IFA-431 was done by Battelle-Northwest under the sponsorship of the USNRC. A major purpose of the test was to reduce the present uncertainty in stored energy calculations by gaining more precise measurements of fuel-clad gap conductance. That meant that uncertainty on factors that affect gap conductance (such as rod power, fuel thermal conductivity, gap size, and fill gas composition and pressure) had to be minimized. Careful preparation and precharacterization of the fuel was part of this effort; another part was the development of cross-checks on the power and fuel temperature data.

In particular this report shows that time-varying fuel thermocouple and assembly power measurements provide a cross-check on the accuracy of indicated steady-state fuel temperatures. Good reasons exist for seeking such a cross-check. There is continuous uncertainty in thermocouple performance, due to the possibility of shunting along the length, axial temperature gradient effects, and response change due to radiation effects.

A sketch of the 6-rod, IFA-431 assembly appears as Figure 1. All of the rods consisted of 10% enriched UO_2 pellets clad in Zircaloy-4 tubing, with nominal dimensions 0.01279×0.01090 m (OD x ID). The rods differed in gap size, fill gas and fuel density, as indicated in Table 1.

The assembly carried 12 fuel thermocouples and 6 vanadium neutron detectors, in two coplanar sets, as shown in Figure 1. The arrangement of neutron detectors facilitated axial and radial definition of the thermal neutron flux in the assembly.

FIGURE 1. Schematic of Instrumented Fuel Assembly--IFA-431

TABLE 1. Test Parameters in IFA-431

Rod Number	Density of UO_2 , % TD	Diametral Gap,** $\text{m} \times 10^{-4}$	Fill Gas (all at 1 atm at 293°K)
1	95	2.3	He
2	95	3.8	He
3	95	0.5	He
4	95	2.3	Xe
5	92% S*	2.3	He
6	92% U*	2.3	He

* The 92% S fuel was stable with respect to probable in-reactor densification; the 92% U was unstable, and was expected to densify.

** The values for diametral gap (i.e., the cladding ID less the pellet diameter) are for the as-fabricated fuel rods at room temperature.

The assembly also carried a cobalt neutron detector, which has a response time to flux changes on the order of milliseconds and was capable of following and recording rapid relative changes in power. During special power changes, the cobalt detector output was recorded, along with that from all 12 thermocouples, on a fast-scan system that records a complete data set every 3 sec. This was the feature that enabled the cross-check on centerline temperature described in the next section.

III - ANALYSIS OF QUASI-STEADY-STATE TIME DERIVATIVE OF CENTERLINE TEMPERATURE (SLOPE ANALYSIS)

The time variation of fuel temperatures offers a measure of the fuel centerline temperature which is independent of the measured steady-state value. To see why this is true, consider a very simplified model of a fuel rod: consider it to be a lump characterized by a volumetric average temperature $\bar{T}$, surface area A , conductance H , heat capacity C , volume V , density d , and length L , producing q power units per unit length.* The steady-state heat balance equation for this model is simply

$$\text{"Heat produced = Heat lost"}$$

or,

$$qL = H A (\bar{T} - T_{\infty}), \text{ where } T_{\infty} \text{ is the coolant temperature.} \quad (1)$$

The time-varying equation for the model is (per unit time, t),

$$\text{"Change in stored energy = Heat produced - Heat lost"}$$

or,

$$dVC \frac{d\bar{T}(t)}{dt} = q(t)L - HA (\bar{T} - T_{\infty}). \quad (2)$$

We will now investigate a specific choice for $q(t)$, namely linear variation with time. This choice results in a linear change in temperature with time (after transient terms have died away). Furthermore, as we shall see, the relative change in the quantity $(\bar{T} - T_{\infty})$ is equal to the relative change

* See Appendix A for a complete listing of the variables discussed in this report, the symbols used for them, and their appropriate SI units.

in power, per unit time. This result occurs irrespective of the particular conductivity, conductance, or flux depression of a given rod.*

The advantages of the foregoing will be used to fix a limit of error on true T_0 given q . This uncertainty will be found to involve (in a straightforward way) only the uncertainties in relative changes of T_0 and q , and not the uncertainties in their absolute values. Furthermore the uncertainties in conductivity and conductance will not be involved.

The particular choice proposed for local rod power variation with time, i.e.

$$q(t) = a + b t$$

does not make the transient equation of heat transfer for a fuel rod any more tractable analytically. It is still highly nonlinear. However, as shown in Appendix B, approximations can be made which do allow an analytical solution for the time variation in quasi-steady state of the centerline temperature. In this section we will follow through the solution of the lumped-parameter model (Equation 2) for the case of linear change in rod power. The main features and the conclusion will be the same as that found in Appendix B, without especially cumbersome mathematics.

Recall that Equations (1) and (2) were

$$q_i L = (\bar{T}_i - T_\infty) HA \quad (\text{steady-state})$$

$$\left(\frac{dVC}{HA} \right) \frac{d\bar{T}}{dt} = \frac{qL}{HA} - (\bar{T} - T_\infty) \quad (\text{transient})$$

* Provided that the effective values of these quantities do not change significantly in the course of the power change. Appendix B discusses the adequacy of this assumption for the data in this report.

Define q_N as $q_N = qL/HA(\bar{T}_i - T_\infty)$ such that

$$1 = q_i L/HA(\bar{T}_i - T_\infty) = q_{N_i} \quad (\text{from the steady-state equation}) \quad (3)$$

If one defines

$$T_N = \frac{\bar{T} - T_\infty}{\bar{T}_i - T_\infty}$$

and divides the transient equation by $(\bar{T}_i - T_\infty)$, one obtains

$$\left(\frac{dVC}{HA}\right) \frac{dT_N}{dt} = q_N - T_N$$

or

$$\frac{1}{Z} \frac{dT_N}{dt} = q_N - T_N, \quad Z = HA/dVC = \text{time constant} \quad (4)$$

Now let $q_N(t) = 1 + bt$, where $b = \text{specified power "slope"}$

$$T_N = 1 + \Delta T_N(t), \quad \Delta T_N(t) = \text{temperature response (to be determined)}$$

Substituting in Equation (4) and eliminating steady-state terms yields

$$\frac{1}{Z} \frac{d}{dt} (\Delta T_N) = bt - \Delta T_N(t)$$

with initial condition

$$\Delta T_N(0) = 0$$

Laplace transformation yields an algebraic equation:

$$\frac{1}{Z} \left[S \Delta T_N^*(s) - \Delta T_N(0) \right] = \frac{b}{s^2} - \Delta T_N^*$$

or

$$\Delta T_N^* = \frac{bZ}{s^2(s + Z)} \quad (5)$$

Now our concern will be with $\frac{d\Delta T_N}{dt}$, the Laplace transform of which in this case will be just $S\Delta T_N^*(s)$. So multiply both sides of (5) by "s" to obtain

$$S\Delta T_N^* = \frac{b}{S(S + Z)}$$

Taking the antitransformation of both sides,

$$\frac{d}{dt}(\Delta T_N) = b(1 - e^{-Zt}) \quad (\text{See Reference 1 for example})$$

In quasi-steady state, we have

$$\frac{d}{dt}(\Delta T_N) = b \quad (6)$$

Equation (6) says that as t gets larger than $\sim 3/Z$, the change/unit time in normalized relative temperature is equal to the slope of normalized power regardless of the value of the conductance or the absolute value of q or $\bar{T}$. Appendix B comes to this same conclusion for the centerline temperature of the actual fuel rod. A plot of normalized temperature and power should appear as in Figure 2.

Now suppose, when actual data is plotted in this way, the slopes of least-squares-fit lines are unequal to a statistically significant degree. This means that the two vertical scales drawn in Figure 2 do not in fact coincide. Furthermore, the degree to which the slopes do not match is directly proportional to the degree to which the scales do not match. For example, if the slopes do not match to the extent of 10%, then T_i , the initial thermocouple reading, is incorrect by 10% of the quantity $(T_i - T_\infty)$, which is the scale factor for the normalized temperature.

We are now in a position to consider actual data, calculate typical limits of error, and compare with typical limits of error from steady-state calculations. That is the subject of the next section.

FIGURE 2. Qualitative Expected Behavior of q_N and T_N

IV - IFA-431 POWER DROP ANALYSIS

The power changes used to create time-temperature data consisted of power decreases of 20% in approximately 30 sec. These power decreases were accomplished by control rod movement far from IFA-431. The whole reactor appeared to change power quite uniformly, based on the output of several widely spaced cobalt neutron detectors. A set of 3 such power drops were run after each operating month. The numbering system used by Halden to designate these power drops, and the dates on which they occurred, are shown in Table 2.

TABLE 2. IFA-431 Power Drops

<u>Halden Run Number</u>	<u>Date</u>	<u>Approximate Burnup (MWd/MTU)</u>
1	6/22/75	0.
3*	6/22/75	
5	6/22/75	
7	6/26/75	0.
9	6/26/75	
11*	6/26/75	
13*	8/8/75	1,000
15	8/8/75	
17*	8/8/75	
19	9/10/75	2,000
21*	9/10/75	
23	9/10/75	

* An asterisk (*) marks runs which were sufficiently linear for this report.

Sample data from Rod 1 (the typical BWR rod) is presented in Figure 3, in normalized form. The data for this figure is that for thermocouple TF 2 from Run 3, tabulated in Appendix D.

Appendix D contains a listing of raw and normalized data from all the "linear" power drops (Runs 3, 11, 13, 17, 21). The results of least-squares fitting of straight lines to the most linear portions of these drops are also presented in Appendix D. These tables show the slope of the least-squares-fit line for the power and for each of the eight thermocouples examined.* For each thermocouple they also show the difference between the thermocouple (temperature) slope and the power slope, and the value of this difference which is statistically significant (from a one-sided "t" test) at the 95% confidence level. The basis for this latter value is reviewed in Appendix C.

Table 3 below summarizes these results by showing, for each thermocouple and each selected power drop, the difference between the temperature and power slopes. This difference is expressed as a percentage of the statistically significant difference. A(+) indicates the temperature slope is greater than the power slope and a(-) indicates that the temperature slope is less than the power slope. One would expect these percentages to be randomly distributed in both sign and magnitude. Note that the significant intervals are generally 15 to 20% of the slope values, which means that the "detection limit" of erroneous thermocouple readings with the present data is about 15-20% of $(T_0 - T_\infty)$. These limits (one-sided) are presented in Table 4. Appendix C gives a sample calculation for the entries in Table 4. These limits are comparable to the $\pm 170^\circ\text{C}$ estimated as a 95% confidence limit for T_0 calculated

* Data from Rods 2 and 4 was excluded, since these rods had too much thermal inertia to come into quasi-steady state during the short power drops discussed here.

FIGURE 3. Normalized Data for Thermocouple TF2, Run 3

TABLE 3. Summary of Regression Results

<u>Rod Number</u>	<u>Thermocouple Number</u>	Temperature Slope Minus Power Slope (Expressed as Percent of 95% Significance Interval)				
		<u>Run 3</u>	<u>Run 11</u>	<u>Run 13</u>	<u>Run 17</u>	<u>Run 21</u>
1	TF 1	-19	+47	+12	-42	-23
	TF 2	-56	+20	+2	-50	-43
3	TF 5	+39	+96	+21	-13	-1
	TF 6	+97	+115	+39	-8	-37
5	TF 9	-36	+40	+30	-4	-6
	TF 10	-44	+81	+70	+10	+32
6	TF 11	-6	+53	+40	-24	-9
	TF 12	-64	+48	+69	-4	-30

TABLE 4. One-Sided 95% Significance Interval for Centerline
Temperature (in Degrees C)

<u>Thermocouple</u>	<u>Run 3</u>	<u>Run 11</u>	<u>Run 13</u>	<u>Run 17</u>	<u>Run 21</u>
TF 1	86	137	115	102	146
TF 2	109	174	99	148	201
TF 5	67	107	58	68	148
TF 6	73	145	85	107	148
TF 9	65	135	87	99	142
TF 10	96	198	134	178	215
TF 11	67	146	84	115	150
TF 12	97	292	111	214	218

from steady-state conditions (Reference 2). In addition the estimates of T_0 from the power drop data are completely independent of either steady-state readings or calculations. They thus form a cross-check on the thermocouple readings which is capable of detecting significant thermocouple bias or decalibration. This has the effect of removing some bias from the gap conductance values which are inferred from the thermocouple readings.

Table 5 presents the difference between initial thermocouple readings and estimated true centerline temperatures. Table 5 was produced by simply combining the results of Tables 3 and 4. Table 6 shows the frequency distribution of the data in Table 5. From Table 6 we see that the median of the data is very nearly zero, and that data is pretty evenly scattered in the range ± 80 C, with a mode at -10 C. The mean of the data is +16 C, and its standard deviation is 62 C.

TABLE 5. Estimated True Centerline Temperature Minus Initial Thermocouple Reading (in Degrees C)

<u>Thermocouple</u>	<u>Run 3</u>	<u>Run 11</u>	<u>Run 13</u>	<u>Run 17</u>	<u>Run 21</u>
TF 1	-16	+65	+14	-43	-34
TF 2	-61	+36	+2	-74	-87
TF 5	+26	+103	+12	-9	-1
TF 6	+71	+167	+34	-9	-55
TF 9	-24	+54	+26	-4	-8
TF 10	-42	+161	+94	+18	+68
TF 11	-4	+78	+33	-28	-14
TF 12	-62	+139	+76	-8	-66

Note that the three values in excess of 120 C all occur in Run 11. This indicates that Run 11 may involve a power slope estimate that is simply too low. If data from this run is excluded, the remaining data has a standard deviation of 45 C and a mean of -4 C. This latter data can be said to indicate that the thermocouple readings agree with the estimated true value within 80 C at the 95% confidence level.

TABLE 6. Frequency Distribution for Data in Table 5

<u>Sub-Range, Degrees C</u>	<u>Number of Data Points in the Sub-Range</u>
Below -80	1
-80 to -60	4
-60 to -40	3
-40 to -20	3
-20 to 0	9
0 to +20	4
+20 to +40	4
+40 to +60	2
+60 to +80	5
+80 to + 100	1
+100 to +120	1
Above 120	3

V - RECOMMENDATIONS FOR FUTURE WORK

There are several ways the results in this report could be improved or extended in future experiments. We will discuss only two aspects here:

- 1) ways to narrow the confidence limits on centerline temperature and
- 2) ways to derive estimates of the gap conductance.

1. Narrowing the Confidence Limits

From the experience so far it is apparent that the overall rate of 0.67%/sec is nearly ideal for a power decrease; steeper rates produce too few data points in the linear region, and shallower rates produce power histories that are decidedly nonlinear. It is also apparent that increasing the number of data points taken per run will not decrease the residual standard deviation, which determines the confidence limits. Thus the only avenue open for narrowing the confidence limits is to make the power decreases more truly linear, which means altering the method by which they are achieved. This could probably be done in the helium-3 rig in the Halden reactor. It could also be done by surrounding the assembly by a rotatable shroud (similar to the shroud on IFA-429). The shroud could be tapered or graded in composition around its circumference, such that as it rotates it casts a linearly increasing shadow to neutron radiation across a rod site. Juxtaposition of a cobalt detector near the rod site would adequately determine the variation of the flux at the rod site since it is the slope of the power that is important, not its instantaneous absolute value.

2. Deriving Gap Conductance Values

The data in this report indicated that the limiting value of the power-to-centerline-temperature transfer function does not vary typically

more than $\sim 5\%$ over a power range of 20% and its variation is typically less than 3% over a power range of 10%. This is not a new or startling result. But it does point to a way to independently estimate the gap conductance. If a rapid but accurately calibrated change in power were made (say 10% in less than 5 sec) then the centerline temperature behavior about 20 sec after that change would be exponential with a time constant directly related to the ratio of the fuel-to-coolant conductance divided by the fuel conductivity. This independent check on both conductivity and conductance could be achieved by the same rotatable shroud described above, by simply making a rapid twist. Again, the fact that the neutron detector recording the power change is not exactly at the rod site will not affect the results, since it is the ultimate relative value of the power change that is important, not the instantaneous absolute value of the power.

Note that the shroud could be graded axially rather than circumferentially, and lowered past a thermocouple elevation at constant speed to produce linear and rapid power variations.

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APPENDIX A

NOTATION AND SI UNITS

APPENDIX A

NOTATION AND SI UNITS

The variables discussed in this report are listed below, together with their symbol and appropriate SI units.

<u>Symbol</u>	<u>Meaning</u>	<u>SI Units</u>
A	Fuel rod surface area	m^2
b	"slope" of normalized power data, i.e. $\frac{dq_N}{dt}$	(fraction)/sec
C	Effective fuel rod heat capacity	joules/kg-C
d	Fuel density	kg/m^3
G	Rod power-to-centerline temperature transfer function	C/W/m
H	Fuel surface-to-coolant conductance	W/m^2-C
L	Fuel rod length	m
q	Rod linear power	W/m
S	Laplace transform variable	
S_r	Residual standard deviation	varies
T_o	Centerline temperature	C
T	Volumetric average temperature	C
T_i	Initial value of T	C
T_N	Normalized relative temperature	C
T_∞	Coolant temperature (~ 240 C)	C
$\Delta T(t)$	Time-varying portion of temperature T	C
Z	Time constant for a fuel rod	sec^{-1}

APPENDIX B

DERIVATION OF THE CENTERLINE TEMPERATURE RESPONSE TO A LINEAR DECREASE IN POWER

APPENDIX B

DERIVATION OF THE CENTERLINE TEMPERATURE RESPONSE TO A LINEAR DECREASE IN POWER

In Part III of the text it was shown that

$$\frac{dT_N}{dt} = \frac{dq_N}{dt}, \text{ as } t \rightarrow \infty \quad (\text{B.1})$$

that is, the slope of the normalized relative (volumetric averaged) temperature approaches the slope of the normalized power. This result was derived for a lumped-parameter model of the fuel rod, under the assumption of temperature-independent thermal properties. It is by no means obvious (nor is it generally true) that the same result holds for centerline temperature of real fuel rods whose thermal properties certainly are temperature dependent. It is the purpose of this Appendix to show that the result (B.1) does hold approximately for the tests reported, and that the degree of approximation is well within the limits of error resultant from the intrinsic scatter in the data.

First, we shall derive the equivalent of (B.1) for the centerline temperature, T_0 . Let

$$T_r(t) = T_{r_i} + \Delta T(t) \quad \text{where, } T_r = T_0 - T_\infty$$

$$q(t) = q_i + \Delta q(t)$$

i.e., the sum of known initial components and unknown time varying components.

Now let the fuel rod be characterized by a transfer function $G(s)$ relating $\Delta T_r(t)$ to $\Delta q(t)$, such that the Laplace transform of ΔT_r (i.e., the "output") is equal to the transform of Δq (the "input") times this transfer function:

$$\Delta T_r^*(s) = G(s) \Delta q^*(s)$$

The transfer function of course contains all the aspects of the fuel rod (its fuel and clad thermal properties, its gap conductance, its geometry, its film coefficient and its flux depression), and is a very complicated and temperature-dependent function. But let $G_Q(s)$ be the effective transfer function at a given power level $q = Q$, so that $G_Q(s)$ is assumed independent of $\Delta T_r^*(s)$. We will investigate the limitations of this assumption in a moment. Note that the temperature-dependent components of G_Q have been evaluated at the steady-state temperature distribution at $q = Q$. Now let us take a power step all the way from $q = 0$ to $q = Q$, and write down the Laplace transform of ΔT_o , the resultant temperature rise. Our initial conditions are

$$\begin{aligned} T_r &= 0 \\ q_i &= 0, \quad t \leq 0 \end{aligned}$$

and

$$\Delta q = Q(t > 0)$$

Thus

$$\Delta T_r^* = \frac{G_Q(s)Q}{s}$$

We know that this expression will only lead to a correct answer as $t \rightarrow \infty$ or $s \rightarrow 0$, since we are using G_Q for the transfer function. Furthermore we know that as $t \rightarrow \infty$, $\Delta T_r \rightarrow (T_Q - T_\infty)$, where T_Q is the steady-state centerline temperature at $q = Q$. Thus

$$\lim_{t \rightarrow \infty} (\mathcal{L}^{-1} \Delta T_r^*) = Q \lim_{s \rightarrow 0} \mathcal{L}^{-1} \left(\frac{G_Q}{s} \right) = T_Q - T_\infty = T_r^Q \quad (\text{B.2})$$

This result will be useful in a moment.

Now consider a small, linear power decrease from power level $q = Q$.

Variables T_r and q are

$$T_r(t) = T_r^Q + \Delta T_r(t)$$

$$q(t) = Q - bt$$

so $\Delta q = -bt$. Note initial conditions are

$$\Delta q = \Delta T_r = 0$$

$$\text{at } t = 0$$

We can write down the transform of the resultant $\Delta T_0(t)$ as

$$\Delta T_r^* = \frac{G_Q b}{s^2}$$

We can also write down the transform of the time derivative of $\Delta T_0(t)$, since

$$\mathcal{L} \left[\frac{d(\Delta T_r)}{dt} \right] = s \Delta T_r^*(s) - \Delta T_r(t=0) = s \Delta T_r^*$$

Thus

$$s \Delta T_r^* = \mathcal{L} \left[\frac{d(\Delta T_r)}{dt} \right] = \frac{b G_Q}{s}$$

The quasi steady-state value of this derivative will be

$$\lim_{t \rightarrow \infty} \frac{d(\Delta T_r)}{dt} = b \lim_{t \rightarrow \infty} \left[\mathcal{L}^{-1} \left(\frac{G_Q}{s} \right) \right] \quad (\text{B.3})$$

Now let us divide B.3 by B.2:

$$\left(\frac{1}{T_Q - T_\infty} \right) \lim_{t \rightarrow \infty} \frac{d(\Delta T_r)}{dt} = \frac{b}{Q} = b_N \quad (\text{B.4})$$

If we define

$$T_N = \frac{T_r - T_\infty}{T_Q - T_\infty}$$

much as before, and recognize that

$$\frac{d(\Delta T_r)}{dt} = \frac{d(T_0 - T_\infty)}{dt}$$

then we have, from B.4

$$\frac{dT_N}{dt} = b_N \text{ as } t \rightarrow \infty$$

that is, the slope of the normalized relative centerline temperature approaches the slope of the normalized power, under the assumption that G_Q is independent of ΔT_r . Note that it is the quantity

$$\lim_{t \rightarrow \infty} \left[\mathcal{L}^{-1} \left(\frac{G_Q}{S} \right) \right]$$

that determines the quasi-steady state slope during a linear power decrease. Thus an examination of $T_r(t \rightarrow \infty)$ at different power levels would reveal the dependence of G on q . This information could be used to determine "acceptable" ranges of linear power decreases, for which a constant (initial value) transfer function could be used. This examination of G could be done experimentally by bringing the assembly up to a given power, waiting for and recording steady-state centerline temperatures, then increasing the power and recording the steady-state temperatures again. The process would be repeated for many different power levels. Quite comparable results, however, may be obtained by using a computer program such as GAPCON-II⁽³⁾ or FRAP-S⁽⁴⁾ which reliably incorporates all the temperature-dependent properties of the fuel rod. The results of such a procedure are presented in Table B.1, for computer input

conditions appropriate to TF 2 at full reactor power. As can be seen, the transfer function does not change greatly over the typical range of the power drops described in this report.*

Similar analyses have been performed for all the thermocouple locations considered in this report, with similar results.

TABLE B.1. Apparent Limiting Values of Effective TF 2 Transfer Function

Power Level, $\text{W/m} \times 10^4$	Temperature Change Due to Unit Step Power Input, $[\text{C}/(\text{W/m})] \times 10^{-2}$
1.0	2.56
1.4	2.58
1.8	2.63
2.2	2.67
2.6	2.70

2.8	2.72
3.0	2.75
3.2	2.71
3.4	2.69

Note: The dashed lines represent the approximate limits of a typical power drop.

* In this example, the change is <2% which leads to a -6% bias in the slope of the temperature response to a perfectly linear power decrease. However, the confidence limits on power and temperature slopes are generally 2-3 times as large.

APPENDIX C

REVIEW OF THE TEST FOR EQUALITY OF
SLOPE OF TWO LEAST SQUARES FIT LINES

APPENDIX C

REVIEW OF THE TEST FOR EQUALITY OF SLOPE OF TWO LEAST SQUARES FIT LINES

The selected normalized power data for each run is used to establish an estimated power slope by the familiar method of least squares fitting of a straight line. The computer program MARTHA^{*} was used to do this. Likewise, least-squares-fit lines were established for selected normalized temperature data from each thermocouple during each run. Now let b_1 be the power slope for a given run and b_2 be the slope of the normalized temperature for some specific thermocouple. Then it is a well-known result that the quantity

$$S_p \frac{b_1 - b_2}{\sqrt{\frac{1}{SS_{x_1}} + \frac{1}{SS_{x_2}}}} = t \quad (C.1)$$

is distributed as "t" with $(n_1 + n_2 - 4)$ degrees of freedom where n_1 , n_2 are the number of data points used for power and temperature, respectively (see, for example, Reference 5, p. 555). In the above quantity, S_p represents the pooled standard deviation, which is defined from

$$S_p^2 = \frac{(n_1 - 2) S_{r_1}^2 + (n_2 - 2) S_{r_2}^2}{n_1 + n_2 - 4} \quad (C.2)$$

* MARTHA is a package of subroutines facilitating input and output from the main program described in Ref. 6. The "normal equations" of least-squares analysis are solved by an iterative technique, and the results manipulated to present confidence limits.

where $S_{r_1}^2$ and $S_{r_2}^2$ are the "residual mean squares," i.e., the sum of the squared deviations from the least-squares-fit line, divided by $(n - 2)$.

Similarly SS_{X_1} and SS_{X_2} are the "adjusted sums of squares" of the independent variable X (in this case, time). They are defined as

$$\sum_{i=1}^n (x_i - \bar{X})^2$$

where $\bar{X}$ is the mean value for the particular data set.

As an example of the calculation of a significant difference in slopes at the 95% confidence level, consider the regression results listed for TF 1, Run 3 (Table D-3). We see that

$$n_1 = 7 \quad (\text{Power})$$

$$n_2 = 5 \quad (\text{TF 1})$$

$$SS_{X_1} = 252$$

$$SS_{X_2} = 90$$

$$S_{r_1} = 0.00155$$

$$S_{r_2} = 0.00188$$

The pooled standard deviation is

$$S_p = \sqrt{(5S_{r_1}^2 + 3S_{r_2}^2)/8} = 0.00168$$

Therefore

$$"t" = \frac{b_1 - b_2}{0.00168 \sqrt{\frac{1}{\sqrt{252}} + \frac{1}{\sqrt{90}}}} = \frac{b_1 - b_2}{0.000690}$$

The critical "t" for a one-sided test with 8 degrees of freedom is 1.860.

Therefore, the significant value for the difference in slopes $(b_1 - b_2)$ is

$(0.000690) \times 1.860 = 0.00128$. Since the power slope in this case was 0.00938, the relative difference that is significant is

$$\frac{0.00128}{0.00938} = 13.6\%$$

This relative difference can be translated into a significance interval for a centerline temperature from the fact that the normalized temperature is proportional to $1/(T_0 - T_\infty)$. For this case T_0 is 871 C, and T_∞ is taken as 240 C for all cases. Thus the significance interval is

$$13.6\% \times (871 - 240) = 86 \text{ C}$$

(cf. Table 4).

APPENDIX D

RAW AND NORMALIZED DATA, AND REGRESSION RESULTS

APPENDIX D

RAW AND NORMALIZED DATA, AND REGRESSION RESULTS

The tables in this appendix occur in sets of three each. The first table of each set presents the actual cobalt neutron detector and thermocouple readings from a given power drop. The second table in the set presents the same data in normalized form, where power and measured centerline temperature have been normalized as

$$T_N = \frac{T_o(t) - T_\infty}{T_i - T_\infty}, \quad T_\infty = 240 \text{ C}$$

and

$$q_N = q(t)/q_i .$$

The dashed lines in tables of normalized data represent the limits of the linear portions of these data. The third table in each set presents the results of fitting a straight line through these linear portions by the method of least squares. This is called simple linear regression, and the "regression results" listed include the 1) slope of the regression line, 2) the difference between the power slope and the slope from the temperature data of each thermocouple, and 3) the value of this slope difference that is significant at the 95% confidence level.*

Also included in the "regression results" tables are the residual standard deviation and the adjusted mean square of the time variable. These quantities determine the 95% significance interval, and they are defined and discussed in Appendix C.

* This is referred to as the "95% significance interval."

TABLE D-1. Power and Temperature Data for Run 3
(Temperatures in Degrees C)

Time, (sec)	Normalized Cobalt Detector Output	Thermocouple No.							
		TF 1	TF 2	TF 5	TF 6	TF 9	TF 10	TF 11	TF 12
0	1.0000	871	1079	704	890	879	1128	891	1130
3	1.0014	871	1081	704	890	879	1130	891	1130
6	1.0026	873	1081	705	891	880	1130	893	1131
9	1.0103	874	1082	706	891	881	1132	893	1132
12	1.0077	876	1083	708	895	882	1134	895	1135
15	0.9986	874	1083	708	892	881	1132	895	1132
18	0.9957	874	1082	706	891	881	1130	894	1133
21	0.9952	872	1079	705	889	880	1128	893	1130
24	0.9937	872	1078	704	889	879	1128	893	1130
27	0.9749	867	1073	704	883	875	1123	888	1123
30	0.9470	858	1060	698	872	867	1111	880	1111
33	0.9199	846	1046	690	854	854	1093	869	1094
36	0.8885	831	1027	680	834	839	1073	853	1075
39	0.8649	816	1006	668	814	822	1050	835	1052
42	0.8344	798	986	654	795	805	1027	817	1030
45	0.8056	779	961	640	772	787	1002	799	1005
48	0.7908	763	940	625	753	770	978	780	982
51	0.7950	745	930	612	743	761	964	771	969
54	0.7822	748	922	607	738	754	954	763	961
57	0.7777	742	915	604	732	748	943	757	951

TABLE D-2. Normalized Temperature Data for Run 3

Time, (sec)	Thermocouple No.							
	TF 1	TF 2	TF 5	TF 6	TF 9	TF 10	TF 11	TF 12
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3	1.0000	1.0024	1.0000	1.0000	1.0000	1.0023	1.0000	1.0000
6	1.0032	1.0024	1.0022	1.0015	1.0016	1.0023	1.0031	1.0011
9	1.0048	1.0036	1.0043	1.0015	1.0032	1.0046	1.0031	1.0022
12	1.0079	1.0048	1.0086	1.0077	1.0047	1.0068	1.0061	1.0056
15	1.0048	1.0048	1.0086	1.0031	1.0032	1.0046	1.0061	1.0022
18	1.0048	1.0036	1.0043	1.0015	1.0032	1.0023	1.0041	1.0034
21	1.0016	1.0000	1.0022	0.9985	1.0016	1.0000	1.0031	1.0000
24	1.0016	0.9988	1.0000	0.9985	1.0000	1.0000	1.0031	1.0000
27	0.9937	0.9928	1.0000	0.9892	0.9937	0.9944	0.9954	0.9921
30	0.9794	0.9774	0.9871	0.9723	0.9812	0.9809	0.9831	0.9787
33	0.9604	0.9607	0.9698	0.9446	0.9609	0.9606	0.9662	0.9596
36	0.9366	0.9380	0.9483	0.9138	0.9374	0.9381	0.9416	0.9382
39	0.9128	0.9130	0.9224	0.8831	0.9108	0.9122	0.9140	0.9124
42	0.8843	0.8892	0.8922	0.8538	0.8842	0.8863	0.8863	0.8876
45	0.8542	0.8594	0.8621	0.8185	0.8560	0.8581	0.8587	0.8596
48	0.8288	0.8343	0.8297	0.7892	0.8294	0.8311	0.8295	0.8337
51	0.8003	0.8224	0.8017	0.7738	0.8153	0.8153	0.8157	0.8191
54	0.8050	0.8129	0.7909	0.7662	0.8044	0.8041	0.8034	0.8101
57	0.7956	0.8045	0.7845	0.7569	0.7950	0.7917	0.7942	0.7989

TABLE D-3. Regression Results for Run 3

Data Source	Slope of Best-Fit Line, sec^{-1}	Slope Difference, sec^{-1}	Significant Slope Difference, sec^{-1}	Residual Standard Deviation, sec^{-1}	Adjusted Mean Square for Time, sec^2
Cobalt Detector	0.00938	--	--	0.00155	252
TF 1	0.00914	-0.00024	0.00128	0.00188	90
TF 2	0.00870	-0.00068	0.00122	0.00169	90
TF 5	0.00991	+0.00053	0.00135	0.00208	90
TF 6	0.01040	+0.00102	0.00105	0.00149	157.5
TF 9	0.00903	-0.00035	0.00096	0.000506	90
TF 10	0.00894	-0.00044	0.00101	0.000831	90
TF 11	0.00932	-0.00006	0.00097	0.000566	90
TF 12	0.00873	-0.00065	0.00102	0.000863	90

TABLE D-4. Power and Temperature Data for Run 11
(Temperatures in Degrees C)

Time, sec	Normalized Cobalt Detector Output	Thermocouple No.							
		TF 1	TF 2	TF 5	TF 6	TF 9	TF 10	TF 11	TF 12
0	1.0000	867	1124	703	935	878	1177	895	1182
3	0.9993	866	1124	704	936	877	1176	894	1183
6	1.0063	870	1128	705	936	880	1177	895	1184
9	1.0037	871	1130	707	940	882	1181	897	1187
12	1.0054	871	1131	707	940	882	1182	898	1188
15	0.9994	872	1131	709	941	883	1183	899	1190
18	0.9905	870	1128	705	937	879	1180	897	1186
21	0.9917	866	1124	702	934	877	1176	892	1181
24	0.9905	861	1121	698	927	895	1169	892	1178
27	0.9834	864	1122	701	931	875	1171	891	1176
30	<u>0.9727</u>	858	1112	695	920	871	1163	884	1169
33	0.9547	852	1105	691	914	864	1154	880	1162
36	0.9373	842	1089	682	902	853	1140	872	1146
39	0.9208	832	1076	673	887	841	1124	859	1132
42	0.9022	819	1059	661	870	831	1103	848	1113
45	<u>0.8861</u>	806	1041	652	855	816	1083	833	1095
48	0.8776	797	1028	645	840	806	1066	823	1081
51	0.8676	789	1017	638	831	797	1052	812	1067
54	0.8576	781	1009	635	823	790	1041	806	1058
57	0.8469	777	1002	632	818	786	1031	800	1050
60	0.8432	771	996	628	812	780	1022	796	1042
63	0.8359	767	991	625	806	775	1013	789	1037

TABLE D-5. Normalized Temperature Data for Run 11

Time, Sec	Thermocouple No.							
	TF 1	TF 2	TF 5	TF 6	TF 9	TF 10	TF 11	TF 12
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3	0.9984	1.0000	1.0022	1.0014	0.9984	0.9989	0.9985	1.0011
6	1.0048	1.0045	1.0043	1.0014	1.0031	1.0000	1.0000	1.0021
9	1.0064	1.0068	1.0086	1.0072	1.0063	1.0043	1.0031	1.0053
12	1.0064	1.0079	1.0086	1.0072	1.0063	1.0053	1.0046	1.0064
15	1.0080	1.0079	1.0130	1.0086	1.0078	1.0064	1.0061	1.0085
18	1.0048	1.0045	1.0043	1.0029	1.0016	1.0032	1.0031	1.0042
21	0.9984	1.0000	0.9978	0.9986	0.9984	0.9989	0.9954	0.9989
24	0.9904	0.9966	0.9892	0.9885	0.9953	0.9915	0.9954	0.9958
27	0.9952	0.9977	0.9957	0.9942	0.9953	0.9936	0.9939	0.9943
30	0.9856	0.9864	0.9827	0.9784	0.9875	0.9851	0.9832	0.9857
33	0.9761	0.9785	0.9741	0.9698	0.9781	0.9755	0.9771	0.9783
36	0.9601	0.9604	0.9546	0.9525	0.9608	0.9605	0.9649	0.9618
39	0.9442	0.9457	0.9352	0.9309	0.9420	0.9434	0.9450	0.9469
42	0.9234	0.9265	0.9092	0.9069	0.9263	0.9210	0.9282	0.9268
45	0.9027	0.9061	0.8898	0.8849	0.9028	0.8997	0.9053	0.9076
48	0.8884	0.8914	0.8747	0.8633	0.8871	0.8815	0.8901	0.8928
51	0.8756	0.8790	0.8596	0.8504	0.8730	0.8666	0.8733	0.8779
54	0.8628	0.8699	0.8531	0.8388	0.8621	0.8549	0.8641	0.8684
57	0.8565	0.8620	0.8467	0.8317	0.8558	0.8442	0.8550	0.8599
60	0.8469	0.8552	0.8380	0.8230	0.8464	0.8346	0.8489	0.8519
63	0.8405	0.8495	0.8315	0.8144	0.8386	0.8250	0.8382	0.8461

TABLE D-6. Regression Results for Run 11

<u>Data Source</u>	<u>Slope of Best-Fit Line, sec⁻¹</u>	<u>Slope Difference, sec⁻¹</u>	<u>Significant Slope Difference, sec⁻¹</u>	<u>Residual Standard Deviation, sec⁻¹</u>	<u>Adjusted Mean Square for Time, sec²</u>
Cobalt Detector	0.00583	--	--	0.000545	90
TF 1	0.00643	+0.00060	0.00128	0.00187	45
TF 2	0.00607	+0.00024	0.00115	0.00166	45
TF 5	0.00713	+0.00130	0.00135	0.00207	90
TF 6	0.00723	+0.00140	0.00121	0.00191	157.5
TF 9	0.00632	+0.00049	0.00123	0.00180	45
TF 10	0.00683	+0.00100	0.00123	0.00180	45
TF 11	0.00652	+0.00069	0.00130	0.00191	45
TF 12	0.00669	+0.00086	0.00181	0.00273	45

TABLE D-7. Power and Temperature Data for Run 13

Time, sec	Normalized Cobalt Detector Output	Thermocouple No.							
		TF 1	TF 2	TF 5	TF 6	TF 9	TF 10	TF 11	TF 12
0	1.0000	828	1027	671	881	825	1082	855	1108
3	1.0034	829	1029	672	883	827	1083	856	1109
6	1.0075	828	1027	672	882	826	1083	856	1109
9	0.9940	829	1026	672	882	827	1081	856	1109
12	0.9697	824	1020	668	875	821	1075	852	1102
15	0.9508	816	1009	660	862	812	1062	845	1092
18	0.9293	805	993	650	847	801	1043	833	1074
21	0.9070	787	978	639	833	787	1025	816	1053
24	0.8834	777	960	631	821	772	1008	803	1036
27	0.8639	765	945	622	803	762	985	790	1014
30	0.8451	750	926	612	791	748	964	777	994
33	0.8241	739	909	603	776	734	943	763	973
36	0.8093	728	893	594	761	723	925	749	953
39	0.8173	720	883	590	756	716	910	742	940
42	0.8079	714	877	588	752	709	900	735	930
45	0.7902	707	868	582	745	703	889	727	919

TABLE D-8. Normalized Temperature Data for Run 13

Time, Sec	Thermocouple No.							
	TF 1	TF 2	TF 5	TF 6	TF 9	TF 10	TF 11	TF 12
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3	1.0017	1.0025	1.0023	1.0031	1.0034	1.0012	1.0016	1.0012
6	1.0000	1.0000	1.0023	1.0016	1.0017	1.0012	1.0016	1.0012
9	1.0017	0.9988	1.0023	1.0016	1.0034	0.9988	1.0016	1.0012
12	0.9932	0.9911	0.9936	0.9906	0.9932	0.9917	0.9951	0.9931
15	0.9796	0.9771	0.9745	0.9704	0.9778	0.9762	0.9837	0.9816
18	0.9609	0.9568	0.9513	0.9470	0.9590	0.9537	0.9642	0.9608
21	0.9303	0.9377	0.9258	0.9251	0.9350	0.9323	0.9366	0.9366
24	0.9133	0.9149	0.9072	0.9064	0.9094	0.9121	0.9154	0.9171
27	0.8929	0.8958	0.8863	0.8783	0.8923	0.8848	0.8943	0.8917
30	0.8673	0.8717	0.8631	0.8596	0.8684	0.8599	0.8732	0.8687
33	0.8486	0.8501	0.8422	0.8362	0.8444	0.8349	0.8504	0.8445
36	0.8299	0.8297	0.8213	0.8128	0.8256	0.8135	0.8276	0.8214
39	0.8163	0.8170	0.8121	0.8050	0.8137	0.7957	0.8163	0.8065
42	0.8061	0.8094	0.8074	0.7988	0.8017	0.7838	0.8049	0.7949
45	0.7974	0.7980	0.7935	0.7878	0.7915	0.7708	0.7919	0.7823

TABLE D-9. Regression Results for Run 13

Data Source	Slope of Best-Fit Line, sec^{-1}	Slope Difference, sec^{-1}	Significant Slope Difference, sec^{-1}	Residual Standard Deviation, sec^{-1}	Adjusted Mean Square for Time, sec^2
Cobalt Detector	0.00705	--	--	0.00182	540
TF 1	0.00722	+0.00017	0.00138	0.00316	378
TF 2	0.00707	+0.00002	0.00089	0.00138	378
TF 5	0.00725	+0.00020	0.00095	0.00167	378
TF 6	0.00742	+0.00037	0.00094	0.00181	540
TF 9	0.00736	+0.00031	0.00105	0.00205	378
TF 10	0.00784	+0.00079	0.00113	0.00233	378
TF 11	0.00743	+0.00038	0.00096	0.00170	378
TF 12	0.00767	+0.00062	0.00090	0.00145	378

TABLE D-10. Power and Temperature Data for Run 17

Time, sec	Normalized Cobalt Detector Output	Thermocouple No.							
		TF 1	TF 2	TF 5	TF 6	TF 9	TF 10	TF 11	TF 12
0	1.0000	838	1039	679	892	834	1098	864	1127
3	1.0060	837	1040	678	893	835	1099	865	1126
6	1.0089	840	1044	680	895	835	1102	866	1130
9	0.9930	840	1043	681	896	834	1102	866	1128
12	0.9685	832	1033	676	887	827	1092	859	1120
15	0.9399	821	1021	664	872	817	1076	848	1106
18	0.9090	805	999	652	854	803	1054	834	1085
21	0.8757	789	979	638	833	786	1029	817	1061
24	0.8408	771	955	623	813	766	1002	798	1034
27	0.8115	752	930	610	790	747	970	777	1001
30	0.7923	732	904	596	769	728	939	756	970
33	0.7923	720	887	587	755	715	918	742	949
36	0.7923	712	878	584	749	707	904	734	935
39	0.7844	706	871	582	744	703	894	727	925
42	0.7801	699	865	577	740	695	885	719	917

TABLE D-11. Normalized Temperature Data for Run 17

Time, sec	Thermocouple No.							
	TF 1	TF 2	TF 5	TF 6	TF 9	TF 10	TF 11	TF 12
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3	0.9983	1.0013	0.9977	1.0015	1.0017	1.0012	1.0016	0.9989
6	1.0033	1.0063	1.0023	1.0046	1.0017	1.0047	1.0032	1.0034
9	1.0033	1.0050	1.0046	1.0061	1.0000	1.0047	1.0032	1.0011
12	0.9900	0.9925	0.9932	0.9923	0.9882	0.9930	0.9920	0.9921
15	0.9716	0.9775	0.9658	0.9693	0.9714	0.9744	0.9744	0.9763
18	0.9448	0.9499	0.9385	0.9417	0.9478	0.9487	0.9519	0.9526
21	0.9181	0.9249	0.9066	0.9095	0.9192	0.9196	0.9247	0.9256
24	0.8880	0.8949	0.8724	0.8788	0.8855	0.8881	0.8942	0.8952
27	0.8562	0.8636	0.8428	0.8436	0.8535	0.8508	0.8606	0.8575
30	0.8227	0.8310	0.8109	0.8113	0.8215	0.8147	0.8269	0.8230
33	0.8027	0.8098	0.7904	0.7899	0.7997	0.7902	0.8045	0.7993
36	0.7893	0.7985	0.7836	0.7807	0.7862	0.7739	0.7917	0.7835
39	0.7793	0.7897	0.7790	0.7730	0.7795	0.7622	0.7804	0.7723
42	0.7676	0.7822	0.7677	0.7669	0.7660	0.7517	0.7676	0.7632

TABLE D-12. Regression Results for Run 17

Data Source	Slope of Best-Fit Line, sec^{-1}	Slope Difference, sec^{-1}	Significant Slope Difference, sec^{-1}	Residual Standard Deviation, sec^{-1}	Adjusted Mean Square for Time, sec^2
Cobalt Detector	0.01062	--	--	0.00202	157.5
TF 1	0.00986	-0.00076	0.00182	0.00182	45
TF 2	0.00963	-0.00099	0.00197	0.00230	45
TF 5	0.01040	-0.00022	0.00164	0.00201	90
TF 6	0.01048	-0.00014	0.00174	0.00227	90
TF 9	0.01055	-0.00007	0.00176	0.00161	45
TF 10	0.01084	+0.00022	0.00220	0.00295	45
TF 11	0.01015	-0.00047	0.00195	0.00226	45
TF 12	0.01052	-0.00010	0.00256	0.00383	45

TABLE D-13. Power and Temperature Data for Run 21

Time, sec	Normalized Cobalt Detector Output	Thermocouple No.							
		TF 1	TF 2	TF 5	TF 6	TF 9	TF 10	TF 11	TF 12
0	1.0000	884	1126	713	974	878	1211	917	1223
3	0.9717	882	1126	713	974	876	1209	917	1221
6	0.9440	878	1119	709	967	874	1204	913	1215
9	0.9257	872	1107	702	955	867	1193	906	1205
12	0.8949	860	1093	692	941	854	1176	894	1187
15	0.8628	845	1075	681	922	840	1153	881	1167
18	0.8377	832	1055	669	904	825	1132	866	1148
21	0.8075	816	1035	658	885	810	1107	851	1127
24	0.7710	796	1011	645	864	792	1076	832	1099
27	0.7540	779	985	629	841	772	1043	811	1070
30	0.7421	760	963	617	823	753	1013	791	1044
33	0.7421	744	943	607	807	736	986	774	1019
36	0.7400	735	930	601	796	726	968	763	1001

TABLE D-14. Normalized Temperature Data for Run 21

Time, sec	Thermocouple No.							
	TF 1	TF 2	TF 5	TF 6	TF 9	TF 10	TF 11	TF 12
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3	0.9969	1.0000	1.0000	1.0000	0.9969	0.9979	1.0000	0.9980
6	0.9907	0.9921	0.9915	0.9905	0.9937	0.9928	0.9941	0.9919
9	0.9814	0.9786	0.9767	0.9741	0.9828	0.9815	0.9838	0.9817
12	0.9627	0.9628	0.9556	0.9550	0.9624	0.9640	0.9660	0.9634
15	0.9394	0.9424	0.9323	0.9292	0.9404	0.9403	0.9468	0.9430
18	0.9193	0.9199	0.9070	0.9046	0.9169	0.9186	0.9247	0.9237
21	0.8944	0.8973	0.8837	0.8787	0.8934	0.8929	0.9025	0.9023
24	0.8634	0.8702	0.8562	0.8501	0.8652	0.8610	0.8744	0.8739
27	0.8370	0.8409	0.8224	0.8188	0.8339	0.8270	0.8434	0.8444
30	0.8075	0.8160	0.7865	0.7943	0.8041	0.7961	0.8139	0.8179
33	0.7826	0.7935	0.7759	0.7725	0.7774	0.7683	0.7888	0.7925
36	0.7686	0.7768	0.7632	0.7575	0.7618	0.7497	0.7725	0.7742

TABLE D-15. Regression Results for Run 21

<u>Data Source</u>	<u>Slope of Best-Fit Line, sec⁻¹</u>	<u>Slope Difference, sec⁻¹</u>	<u>Significant Slope Difference, sec⁻¹</u>	<u>Residual Standard Deviation, sec⁻¹</u>	<u>Adjusted Mean Square for Time, sec²</u>
Cobalt Detector	0.01010	--	--	0.00288	157.5
TF 1	0.00957	-0.00053	0.00230	0.00133	45
TF 2	0.00911	-0.00099	0.00229	0.00130	45
TF 5	0.01007	-0.00003	0.00316	0.00489	90
TF 6	0.00935	-0.00075	0.00203	0.00185	90
TF 9	0.00997	-0.00013	0.00224	0.00092	45
TF 10	0.01081	+0.00070	0.00224	0.00089	45
TF 11	0.00989	-0.00021	0.00223	0.00085	45
TF 12	0.00942	0.00068	0.00224	0.00093	45

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