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CONTROL TEMPERATURE ERROR ANALYSIS

I. INTRODUCTION

During the operation of NRX-A2 the control thermocouples at station 32 began reading low during the 73 per cent power hold owing to potting compound degradation, allowing by-pass flow to overcool the thermocouples. The overcooled thermocouple reading caused the temperature loop to operate against its 15 per cent clamp. The Chief Test Operator then began to control the reactor temperature manually by observing the average nozzle chamber thermocouple output. These thermocouples were also reading low which caused the NRX-A2 reactor to be operated about 15 per cent above planned power.

For NRX-A3, the assembly technique for the in-core control thermocouples has been changed to eliminate the potting compound, removing the possibility of overcooling these thermocouples.

The uncertainties with respect to temperature measurements by the nozzle chamber thermocouples still exists. Our knowledge of the temperature distribution in the nozzle chamber, the effects of the increased peripherial flow required for A3 and the effects of the A3 shield is incomplete. As a consequence we can not confidently predict the nozzle chamber thermocouple readings in advance of the A3 power run.

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On the assumption that the in-core thermocouple assembly technique is good, we have performed an analysis of the relative temperature measurement errors expected at various axial locations during the operation of NRX-A3. This analysis has been used

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to guide the choice of the temperature measurements to be used for control of NRX-A3. The two sigma (2 σ) values for station 48 inferred from measurements at the various axial locations are: station 20 ± 78.5°R, station 26 ± 50°R, station 32 ± 67°R. A plausible variation for the nozzel chamber measurement has been estimated at ± 190°R. These values are based on the best available information of all known contributions to thermocouple output uncertainties including data system errors. Barring any systematic errors, which are presently unknown, these are the variations expected from the NRX-A3 operation.

On the basis of this analysis, it is recommended that the station 26 thermocouples be used for the primary control transducer with station 32 thermocouples as the back-up transducers. Capability of switching to the nozzle thermocouples is recommended in the event that sufficient operation at power on either station 26 or 32 will have provided a calibration of the chamber thermocouples. Manual trim of the controller on the basis of computed temperature has also been considered and is recommended in the event that all thermocouple indications are lost and that sufficient operation at power on station 26 or 32 thermocouples will have provided calibration of the computed temperature.

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II. CONTROL TEMPERATURE ERROR ANALYSIS

A. Objective:

The objectives of the endurance run of the NRX-A3 reactor are best achieved by controlling the core temperature to some desired set point. This is so since corrosion phenomena are a very strong function of temperature. Even an ability to set power accurately at 100% cannot assure that temperature goals are met since temperature is also a function of flow.

The objective of this report is to present the results of an analysis of the possible errors in temperature that might accrue depending upon which of several methods of determining temperature for control purposes is used. The possible methods considered are listed below:

1. Station 20 thermocouples
2. Station 26 thermocouples
3. Station 32 thermocouples
4. Nozzle chamber thermocouples
5. Calculated nozzle chamber temperature

B. Results

The results of the analysis of the possible errors in station 48 inferred temperature are summarized in Tables I, II and III. These results will be discussed briefly under the headings of core measurements, nozzle measurements and calculated nozzle mixed mean temperature.

1. Core Thermocouples

The objective of the study is to determine what errors are possible in the inferred temperature at station 48 if the reactor control system held the

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indicated average temperature at some selected station to a desired set point. This set point would be pre-selected to give a desired temperature at station 48 based upon 100% power and 100% flow in the reactor. The sources of error considered were thermocouple variation, data system errors, core temperature variation at the thermocouple station locations, thermocouple installation dimensional variations as they affect gamma heating effects, uncertainty in gamma heating in the thermocouple and the uncertainty in the ability to extrapolate the results at the thermocouple station to station 48. The uncertainties due to control system errors are not included since this would be common to all of the temperature control systems. The analysis is therefore on a comparative basis. The assumptions and data which enter into each of the above contribution to variance are discussed in later sections.

Table I shows the results of the analysis of possible errors using core thermocouples. This shows that using station 26 thermocouples, the temperature at station 48 should be capable of being attained within $\pm 50^{\circ}R$ (with 95% probability) of the desired set point. The corresponding temperature errors using stations 32 and 20 are $\pm 67^{\circ}R$ and $\pm 78.5^{\circ}R$ respectively.

2. Nozzle Thermocouples

The problem of making an error analysis of the system using nozzle thermocouples is much more difficult because of the very limited data available and the extreme difficulty (if not impossibility) of making a meaningful analysis of the gas mixing situation in the nozzle. Therefore, a tentative attempt to obtain a picture of the nozzle chamber temperature measurement errors was made using the NRX-A2 results as a starting point. To these results, there

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TABLE I

VARIANCE OF STATION 48 INFERRED TEMPERATURE USING CORE THERMOCOUPLES FOR CONTROL

Station	20		26		32	
Number of T/C's	9		16		39	
Number for Control	4		14		20	
Contributions to Variance	Value in (Degrees)^2	Relative Contribution %	Value in (Degrees)^2	Relative Contribution %	Value in (Degrees)^2	Relative Contribution %
T/C Variations	54.	3.5	34.3	5.6	589. ✓	52.5
Data System Errors	449.	29.3	88.5	14.3	154.	13.7
Core Temp Variation at T/C Location	676.	44.1	255.0	41.2	202.	18.0
T/C Dimensional Tolerances	67.	4.4	12.1	2.0	6.	0.6
Gamma Heating Uncertainty	174.	11.3	119.5	19.3	90.	8.1
Extrapolation to Sta. 48 Uncertainty	114.	7.4	109.0	17.6	79.	7.1
Total	1534.	100.0%	618.4	100.0%	1120.	100.0%
2 Std. Deviations	78.5°R		50.0°R		67.0°R	

was added an estimate of the effects which arise because of differences between NRX-A2 and NRX-A3. These differences are listed below:*

a. NRX-A3 has overcooled fuel elements along the core periphery from $\theta = 30^o$ around the core to $\theta = 360^o$. This overcooling exists in those elements that are in contact with the filler strips. The extent of the overcooling is to make the nominal fuel temperature at station 48 run about 318°R cooler than in NRX-A2. This results in an average reduction in effluent temperature of 230°R in the outer 0.75" of the core periphery and 160°R in the outer 1.15" of the periphery.

b. NRX-A3 will have a shield around 135° of the pressure vessel periphery on the side of the reactor facing the test cell wall. This causes a power tilt such that the core periphery will tend to run hotter near the shield and colder opposite the shield than if the shield were not present. On the shield center line these effects are as follows:

   (1) Near shield; +80°R average for a depth of 2.5" into core

   (2) Opposite shield; - 45°R average for a depth of 2.5" into core.

c. The NRX-A3 will run 15 minutes on its first endurance run as compared to approximately 30 seconds near full power for NRX-A2. During this time period there will be drum motion required to compensate for reactivity loss due to corrosion. It is expected that the peripheral modules will rise in temperature 100°R over the 15 minute test duration. This drum motion

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* - Because the core thermocouples used for control are not in the periphery of the reactor, no account was taken of these effects in analyzing the core thermocouple errors.

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effect is not present in the G row of modules and only slightly present at the core center.

Since NRX-A2 gave evidence of incomplete mixing in the nozzle and since the above three items do affect the peripheral effluent temperature of the reactor, they will have some effect on the nozzle thermocouple indications. Table II shows a possible range of effects which the first two items above could plausibly have. It is not really possible to critically evaluate these effects since the nozzle mixing phenomenon is not very well understood. This table leads to an average nozzle thermocouple indication of 3676°R plus or minus approximately 190°R. Of the total range of 380°R, 315°R was observed among the thermocouples on NRX-A2. To the constant 3676°R demand it would be necessary to add a slowly increasing temperature demand from beginning to end of run as a consequence of drum swing. This change in temperature might be in the order of 35°R to 65°R. If the nozzle thermocouples were used for automatic control, the set point would be fixed and the beginning of run to end of run drum swing would cause a slight reduction in total reactor thermal power and a slight reduction of core material temperatures in the center of the core.

If nozzle thermocouples are used for automatic control, it is necessary to have, beforehand, a desired set point to which to control them. The value of 3676°R of Table II could be used as such a value, with manual temperature trim available to correct the set point on the basis of actual nozzle thermocouple calibration at the full power hold.

3. Temperature Calculated from Nozzle Pressure and Weight Flow

The mixed mean nozzle chamber temperature will be calculated from chamber pressure and reactor weight flow and displayed to the CTO. The error in this computed temperature and its display has the following contributions:

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TABLE II

NOZZLE THERMOCOUPLE VARIATION

Nozzle Thermocouple Designation	T-138	T-139	T-140
Location R, θ	11.8", 330°	11.8", 150°	11.8", 210°
Based on NRX-A2*			
Possible Max Indication	3945°R	3945°R	3945°R
Expected Indication	3760°R	3760°R	3760°R
Possible Min. Indication	3630°R	3630°R	3630°R
Over Cooling Periphery			
Assumed Plausible Max Effect	-160°R	-160°R	-160°R
Assumed Plausible Min. Effect	- 80°R	- 80°R	- 80°R
Effect of Shield			
Assumed Plausible Max. Effect	0	+ 70°R	- 40°R
Assumed Plausible Min. Effect	0	+ 50°R	- 30°R
Net Effect of Over Cooling and Shield			
Plausible Max. Effect	-160°R	- 90°R	-200°R
Plausible Min. Effect	- 80°R	- 30°R	-110°R
Net Thermocouple Indications			
Plausible Range (Max. Effects)	3470° to 3785°	3540° to 3865°	3430° to 3745°
Plausible Range (Min. Effects)	3550° to 3865°	3600° to 3915°	3520° to 3835°
Plausible Expected Indication	3665°R	3730°R	3633°R
Possible Ave. Nozzle Thermocouple Indication	3676^{+196}_{-186}		

*This does not take into account shield, peripheral cooling effects.

[redacted]

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a) Uncertainty in nozzle coefficient

b) Uncertainty in pressure measurement

c) Uncertainty in weight flow measurement

d) Uncertainty in computations

e) Uncertainty in display

f) Uncertainty in data system

Table III shows the results for the displayed chamber temperature computed from pressure and flow, based on assumed 4090°R chamber temperature at 100 per cent power and 100 per cent flow. The two sigma values of possible error in display is 552°R. This error translated to station 48 and including an additional error due to uncertainty in tie rod flow and heat transfer characteristics results in a 2σ value of approximately 615°R for station 48 inferred temperature.

TABLE III

Variance of Computed Chamber Temperature

Contributing Factor	Test Cell "As Is"		
	Error in Degrees	Variance (Degrees)^2	Relative Contribution
Nozzle Coefficient	147.2°R	21,700	28.4%
Pressure Measurement	98.3°R	9,600	12.6
Weight Flow Measurement	159.5°R	25,400	33.2
Computer Uncertainty	114.5°R	13,100	17.0
Display Errors	81.8°R	6,700	8.8
Total		76,500	100.0%

$\sigma = 276°R$

$2\sigma = 552°R$

[redacted]

C. Analysis

The method of analysis is briefly described below in two parts. The first deals with the core thermocouples and the second with the calculated temperature. No attempt is made to justify the analysis of the nozzle thermocouple since Table II in the previous section is self-explanatory.

1. Core Thermocouples

Figure 1 is a block diagram of the system which is analyzed. This block diagram applies to any one of the three possible thermocouple stations (20, 26, and 32). The output of each thermocouple is a voltage (e_{1i}) which is dependent on the temperature the thermocouple is measuring. This voltage is amplified in the preamplifier, the output of which is a double ended signal which is transmitted approximately 2 miles to the control room. This double ended signal is converted to a single ended signal at the averaging amplifier which averages the outputs of all thermocouples of any one station. The output of this amplifier (e_{av}) is conditioned by the thermocouple calibration curve to give the average temperature (T_{av}) at a particular thermocouple station. This average temperature is then multiplied by a constant obtained from Reactor Analysis to give the calculated average temperature (T_{C48}) at station 48.

In the block diagram of Figure 1, the thermocouple voltages (e_{1i}) are random variables because the temperature the thermocouples are measuring and the thermocouple characteristics are random. The preamplifiers, double to single ended converter, and averaging amplifier introduce an error which is described by the random voltages e_{2i} shown at the

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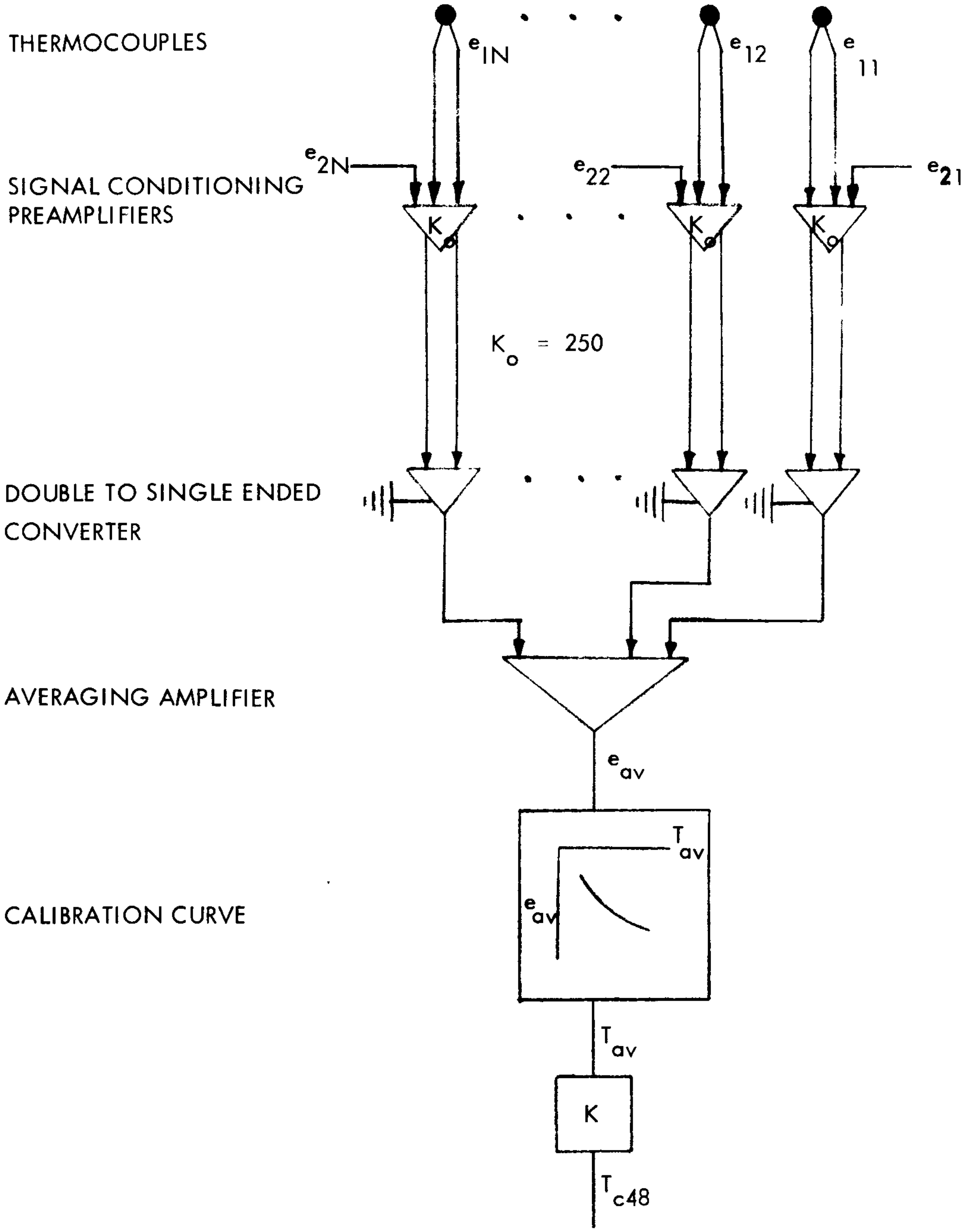

FIGURE 1

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preamplifier inputs. The constant K which multiplies the average temperature at the thermocouple station to obtain the calculated average temperature at station 48 is also a random variable. All of these factors contribute to the error in calculating the average temperature at station 48. Also contributing to error is the gamma heating effect on the core thermocouples. The analytically expected effect of gamma heating upon the thermocouple indications can be taken out as a fixed bias on the indication. However, there are random effects due to dimensional tolerances of the installation and uncertainties in the value of heat deposition.

Taking into account all of these contributions to error, the variance of the calculated average temperature at station 48 can be determined from the following equations*:

$$\sigma^2(T/c) = \frac{\bar{K}^2 K_3^2 K_o^2}{N^2} \sum_{i=1}^{N} \sigma^2(E_i) \qquad (1)$$

$$\sigma^2\,(\text{Data System}) = \frac{\bar{K}^2 K_3^2 K_o^2\, \sigma^2\,(e_{2i})}{N} \qquad (2)$$

$$\sigma^2\,(\text{Core Temp.}) = \frac{\bar{K}^2 K_3^2 K_o^2}{N^2} \sum_{i=1}^{N} K_{2i}\, \sigma^2\,(T_i) \qquad (3)$$

$$\sigma^2\,(\text{Dimen.}) = \frac{\bar{K}^2 K_3^2 K_o^2}{N^2} \sum_{i=1}^{N} \left| K_{2_i}^2\, \bar{\gamma}^2 \sigma^2(D) + K_{2i}^2\, \sigma^2\,(D)\, \sigma^2(\gamma) \right| \qquad (4)$$

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*A derivation of these equations is in Laboratory Notebook 117992.

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$$\sigma^2\,(\text{Gamma}) = \bar{K}^2 K_3^2 K_o^2\, \bar{D}^2\, \sigma^2(\gamma) \sum_{i=1}^{N} K_{2i} \qquad (5)$$

$$\sigma^2\,(\text{Extrap.}) = \bar{T}_{av}^{\;2}\, \sigma^2(K) + \sigma^2\,(K)\,\sigma^2\,(T_{av}) \qquad (6)$$

$$\sigma^2\,(T_{c48}) = \sigma^2\,(T/c) + \sigma^2\,(\text{Data System}) + \sigma^2\,(\text{Core Temp.}) + \sigma^2\,(\text{Dimen.}) + \sigma^2\,(\text{Extrap.}) + \sigma^2\,(\text{gamma}) \qquad (7)$$

where

σ^2 (T/c) ~ $(^oR)^2$ ~ contribution to total variance due to thermocouples

σ^2 (Data System) ~ $(^oR)^2$ ~ contribution to total variance due to data system

σ^2 (Core Temp.) ~ $(^oR)^2$ ~ contribution to total variance due to core temp

σ^2 (Dimen) ~ $(^oR)^2$ ~ contribution to total variance due to thermocouple dimensions

σ^2 (Gamma) ~ $(^oR)^2$ ~ contribution to total variance due to gamma heating

σ^2 (Extrap.) ~ $(^oR)^2$ ~ contribution to total variance due to extrapolation to station 48 temperature

σ^2 (T_{c48}) ~ $(^oR)^2$ ~ total variance of the calculated average temperature at station 48

σ^2 (e_{3i}) ~ $(\text{volts})^2$ variance of the output of the i^{th} preamplifier

K_o ~ $\frac{\text{volts}}{\text{volt}}$ ~ preamplifier and double to single ended converter gain

σ^2 (E_i) ~ $(\text{volts})^2$ ~ variance of the i^{th} thermocouple characteristics

σ^2 (e_{2i}) ~ $(\text{volts})^2$ ~ variance of the error introduced by the preamplifier and averaging amplifier

K_{2i} ~ volts/^oR ~ slope of thermocouple characteristics at the expected thermocouple temperature

[redacted]

$\sigma^2(T_i) \sim (^\circ R)^2$ $\sim$ variance of temperature the i^{th} thermocouple is sensing

N $\sim$ number of thermocouples at a particular station

$\sigma^2(e_{av})$ $\sim$ $(\text{volts})^2$ $\sim$ variance of the output voltage of the averaging amplifier

K_3 $\sim$ $^\circ R/\text{volt}$ $\sim$ slope of calibration curve at the expected value of e_{av}

$\sigma^2(T_{av})$ $\sim$ $(^\circ R)^2$ $\sim$ variance of the measured average temperature at a particular thermocouple station

$\bar{K}$ $\sim$ units $\sim$ expected value of the multiplier K relating T/c station temperature to station 48 temperature

$\sigma^2(K)$ $\sim$ units $\sim$ variance of the multiplier K

$\bar{T}_{av}$ $\sim$ expected value of the calculated average temperature at a thermocouple station

$\bar{\gamma}$ $\sim$ $\frac{BTU}{IN\text{-}SEC}$ $\sim$ expected value of normalized gamma heating

$\sigma^2(\gamma)$ $\sim$ $\left(\frac{BTU}{IN\text{-}SEC}\right)^2$ $\sim$ variance of normalized gamma heating

$\bar{D}$ $\sim$ $\frac{^\circ R\ IN\text{-}SEC}{BTU}$ $\sim$ expected value of a function of thermocouple dimensions and heat transfer coefficients

$\sigma^2(D)$ $\sim$ $\left(\frac{^\circ R\ IN\text{-}SEC}{BTU}\right)^2$ $\sim$ variance of a function of thermocouple dimensions and heat transfer coefficients

These equations are arranged in such a manner as to correspond to the entries under "Contributions to Variance" of Table I.

The data required to compute the variance of the temperature at station 48 falls into six categories which are discussed at length below. This data and the above equations were used to compute the entries in Table I.

a. Temperatures Measured by Thermocouples

The core temperature at each thermocouple location has a variance associated with it. This variance depends on the axial core station and whether the thermocouple is in the periphery or the central region of the core. The distinction between the central and peripheral regions of the core depends on whether the thermocouple is located at a radius less than or greater than 15 inches. From an analysis of the thermal capsule data from the A2 tests by Reactor Analysis it has been determined that, at station 45, the standard deviation of the core temperatures are

$$\sigma_{c45} = 54.7\ ^{\circ}R \text{ in the central region}$$

and

$$\sigma_{p45} = 89.6\ ^{\circ}R \text{ in the peripheral region.}$$

These results are reported in RA 2013. The standard deviation at other core stations are related to those at station 45 by the equations

$$\sigma_{cx} = \sigma_{c45} \left(\frac{T_x - T_{ci}}{T_{45} - T_{ci}} \right)$$

and

$$\sigma_{px} = \sigma_{p45} \left(\frac{T_x - T_{ci}}{T_{45} - T_{ci}} \right)$$

where

[redacted]

T_x ~ average temperature of station where standard deviation is desired

T_{45} ~ average temperature of station 45

x ~ axial station of interest

T_{ci} ~ core inlet temperature

Figure 2 is a plot of $\sigma(T_i)$ for the central and peripheral region of the core as a function of the axial station from core inlet.

b. <u>Thermocouple Characteristics</u>

The variance of the thermocouple characteristics was calculated from experimental data obtained from a test simulation of the temperature conditions and the thermocouples which will be used during the NRX-A3 tests. These tests were performed for 3 thermocouples at station 26 and 32 and for 2 thermocouples at station 20. The expected thermocouple characteristics are taken as the average of the experimental data. The variance about this average was calculated using the equation:

$$\sigma^2(E_i) = \frac{\sum_{r=1}^{k} (\bar{e} - e_r)^2}{k - 1}$$

where

$\bar{e}$ ~ the expected thermocouple voltage at a given temperature

r ~ measured voltage of the r^{th} thermocouple at given temperature

k ~ number of thermocouples in test

$\sigma^2(E_i)$ ~ variance of thermocouple output voltage

The variance of the thermocouple characteristics depends on the temperature the thermocouple is sensing.

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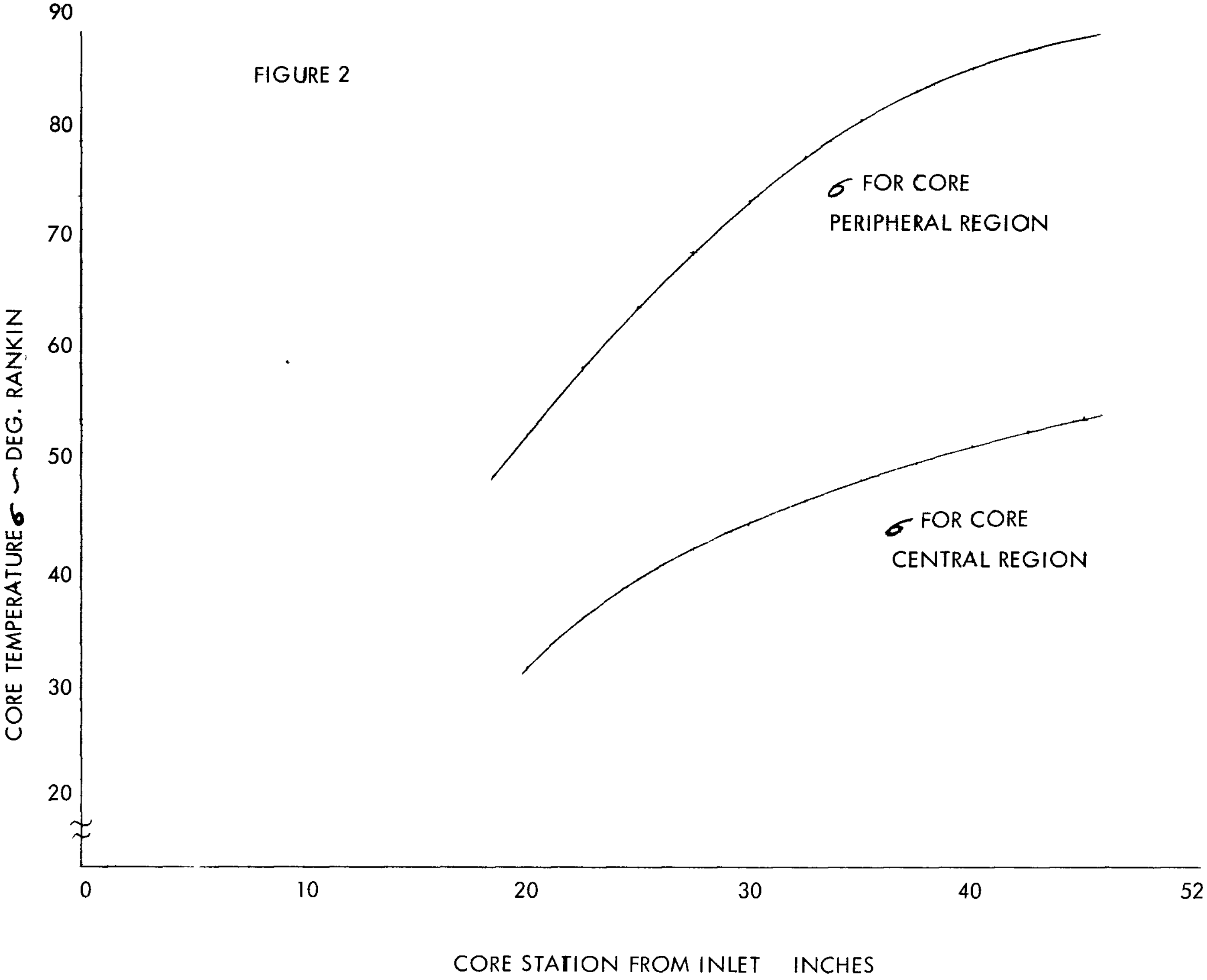

FIGURE 2

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Figure 3 presents the results of this analysis showing the average or expected thermocouple characteristics along with the variance of the thermocouple characteristics. The variance is shown for thermocouples at three axial stations (20, 26, and 32) in the temperature range of interest for each of these stations.

c. Data System

The thermocouple output is amplified by a preamplifier, the output of which is a double ended signal. This voltage is transmitted approximately 2 miles where it is converted to a single ended signal and averaged with other thermocouple signals in the averaging amplifier. Each of these amplifiers introduce some error in the signal. The preamplifier has an accuracy of 1%, the double to single ended converter has an accuracy of 1/2%, and the averaging amplifier has a worst case accuracy of 2%. These accuracies mean the output of the amplifier can be in error by the stated percentage of full scale output. All of these error voltages can be referred to the input (e_{2i} of figure 1) of the preamplifier. These error voltages are not correlated and add in a random manner. In addition, each of the error voltages is assumed to be 3 standard deviation errors.

Referring the error voltages to the preamplifier input and combining them as uncorrelated random signals we obtain the variance of a single equivalent random input as

$$\sigma(e_2 i) = 3.05 \times 10^{-4} \text{ volts}$$

The expected value of this voltage is zero since the error voltages are equally likely to be positive or negative.

σ
.333 .111
.667 .444

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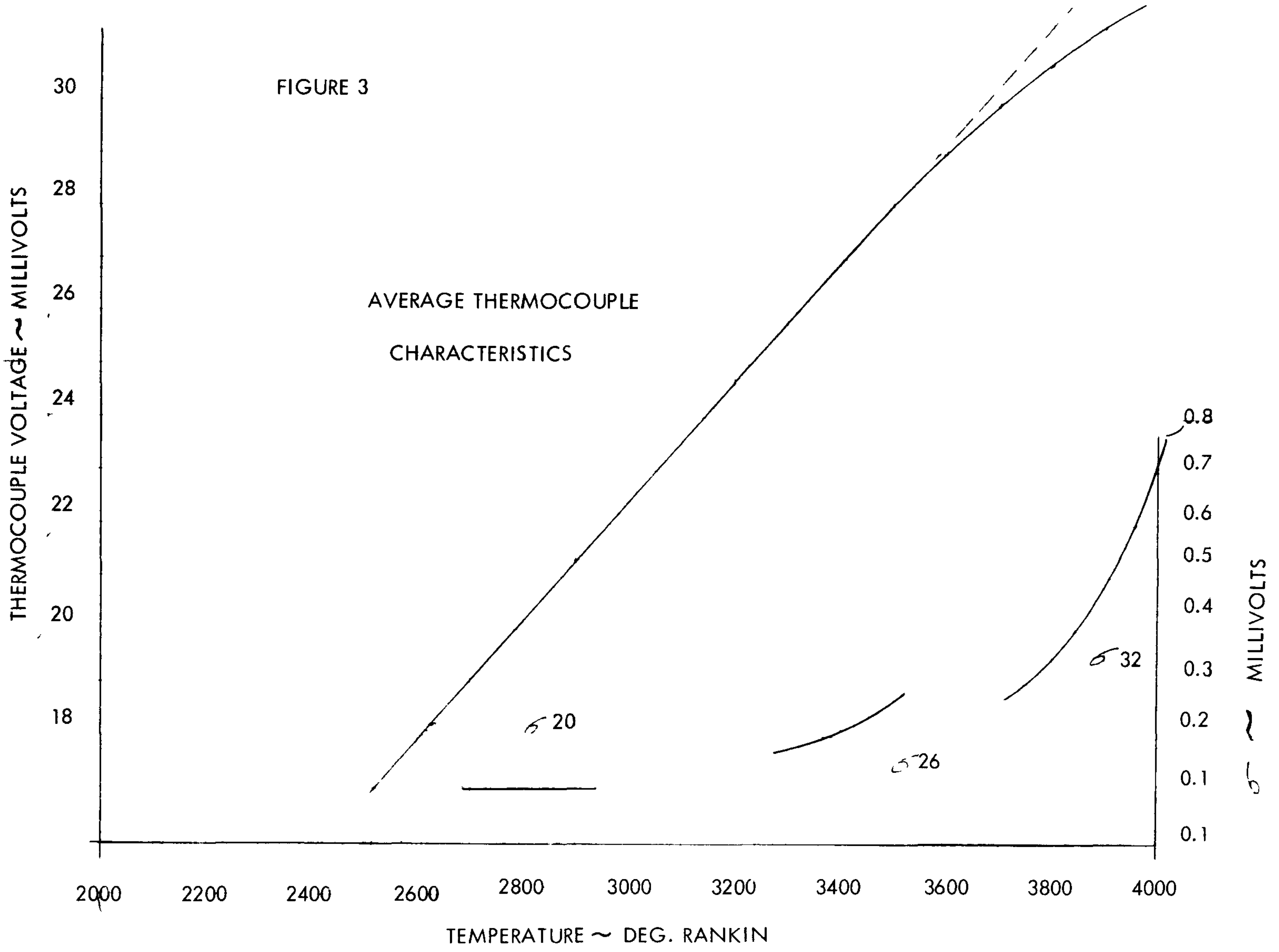
FIGURE 3



AVERAGE THERMOCOUPLE CHARACTERISTICS

d. Constant K Relating Average Temperature at a Thermocouple Station to the Average Temperature at Station 48

In order to make an estimate of the variance of K the calcomp data from the A2 test was analyzed. At four times (13785, 13790, 13795, and 13800 CRT during the 581 MW power hold) the output of the three thermocouples at station 20 which were functioning properly were averaged. At these same times the output of four thermocouples at station 45 were averaged. The four thermocouples chosen at station 45 were those which were located nearest the same radius and angular position as the thermocouples at station 20. From these averages, four values of K (the ratio of T_{45} to T_{20}) were determined.

The expected value of K ($\bar{K}$) was taken to be the ratio of the average value of the unfueled graphite temperature at station 45 to the average value of the unfueled graphite temperature at station 20. These temperatures were calculated by Reactor Analysis from data obtained during the A2 tests. They were calculated using the reactor power, flow, and core inlet temperature as measured during this same power hold.

The variance of K was calculated by the equation

$$\sigma^2 (K) = \frac{\sum\limits_{i=1}^{N} (\bar{K} - K_i)}{N - 1}$$

where

$\bar{K}$ = expected value of K (calculated by Reactor Analysis)

Ki = value of K as calculated from the calcomp data

N = number of times K was calculated from the calcomp data

[redacted]

The results of this analysis was a standard deviation of

$$\sigma(K) = 0.00354 \text{ units}$$

This is the standard deviation of the K relating station 20 to station 45 at approximately 50% power. It is required for this analysis to know $\sigma(K)$ for each of the three thermocouple stations (20, 26, and 32) at full power. It is assumed $\sigma(K)$ does not depend on power or flow and that it is a linear function of the distance between the station where the thermocouples are located and the station at which the temperature is being calculated. Figure 4 is a plot of the expected value of K and $\sigma(K)$ as a function of the thermocouple station. 7

e. Gamma Heating and Thermocouple Dimensional Effects

The actual temperature the thermocouple senses is affected by gamma heating of the molybdenum plug and the graphite thimble used in the installation of the thermocouple in the core. The temperature sensed by the thermocouple is higher than the temperature of the unfueled graphite in which it is mounted. In steady state heat is conducted away from the thermocouple to the unfueled graphite. The ability of the thermocouple to conduct this heat away to the unfueled graphite is affected by the dimensional tolerances of the molybdenum plug and the graphite thimble.

Since the amount of gamma heating and the dimensions of the thermocouple are both random variables, these effects cause the temperature of the thermocouple to be a random variable.

These effects have been analyzed and are reported in TME-1019 "Effects of NRX-A3 Installation on In-Core Thermocouple Accuracy and Response Time." In this report it is shown that the differential temperature of the thermocouple and the unfueled graphite is a function of the dimensions of the thermocouple (D) and the gamma heating rate (γ) i.e.

[redacted]

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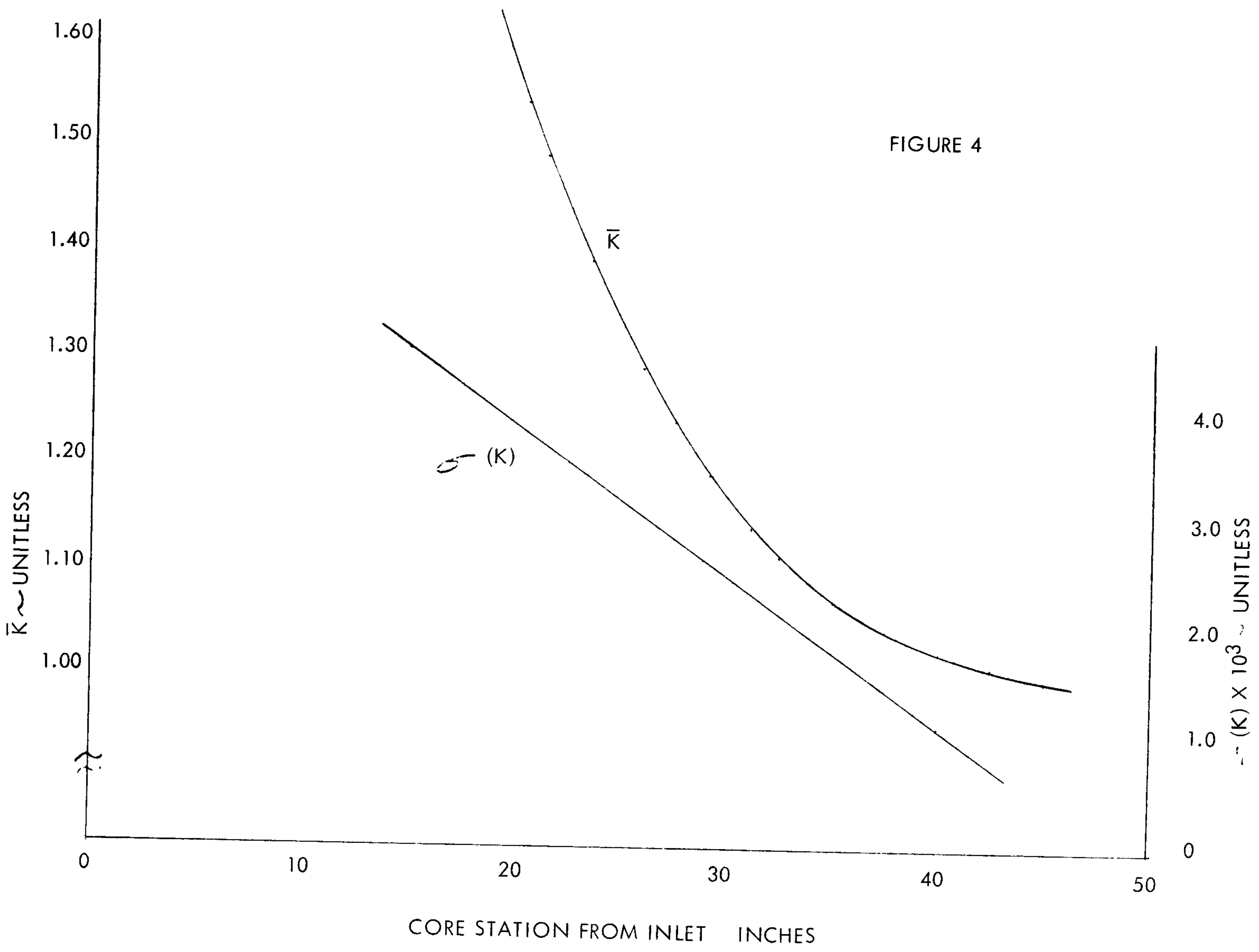
FIGURE 4



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$$\Delta T = D\gamma$$

From the data of TME-1019 and from TME-840 "Reactor Analysis Data Book" (page F-21) the expected value and the variance of D and γ can be calculated. For this analysis the expected value of gamma heating has been normalized to unity. The results are

$$\bar{D} = 28 \frac{{}^{o}\text{R in-sec}}{\text{BTU}}$$

$$\bar{\gamma} = 1 \frac{\text{BTU}}{\text{in-sec}}$$

$$\sigma^2(D) = 100 \left(\frac{{}^{o}\text{R in-sec}}{\text{BTU}}\right)^2$$

$$\sigma^2(\gamma) = 0.09 \left(\frac{\text{BTU}}{\text{in-sec}}\right)^2$$

The number of thermocouples which are usable for control is less than the total number of thermocouples installed at each of the three core stations. The reason for this is that at each core station some of the thermocouples are located near the extreme peripheral core elements which will be overcooled during the NRX-A3 tests. In addition, the temperature of these thermocouples will be affected by the presence of the shield. Since the effects of the overcooling and the shield are uncertain, the thermocouples affected will not be used for control. This reduces the number of thermocouples for control at each core station to the number listed in Table I.

With the data listed above, equations 1 through 6 and the number of thermocouples at each core station, the entries in Table I can be calculated.

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2. Calculated Chamber Temperature

The chamber temperature is computed from flow and pressure from the following equation. Figure 5 is a block diagram of the implementation used to perform this computation.

$$T_c = K_\eta^2 \frac{P_c^2}{\dot{W}^2} \qquad (8)$$

where:

T_c - computer chamber temperature

K_η - nozzle coefficient

P_c - measured chamber pressure

$\dot{W}$ - measured weight flow

The variance from expected calculated chamber temperature is given by

$$\sigma^2(T_c) = 4\left\{\sigma^2(K_N) + \sigma^2(P_c) + \sigma^2(\dot{W})\right\} + \sigma^2(\text{Comp.}) + \sigma^2(\text{Displ.}) \qquad (9)$$

where:

$\sigma^2(K_N)$ is variance of nozzle coefficient in $(\%)^2$

$\sigma^2(P_c)$ is variance of pressure measurement in $(\%)^2$

$\sigma^2(\dot{W})$ is variance of weight flow measurement in $(\%)^2$

$\sigma^2(\text{Comp})$ is variance due to inaccuracies in $(\%)^2$ computer

$\sigma^2(\text{Displ})$ is variance due to inaccuracies in display in $(\%)^2$

$\sigma^2(T_c)$ is variance due to inaccuracies of T_c in $(\%)^2$

[redacted]

[redacted]

SKETCH SHEET
FORM 28577

WESTINGHOUSE ELECTRIC CORPORATION

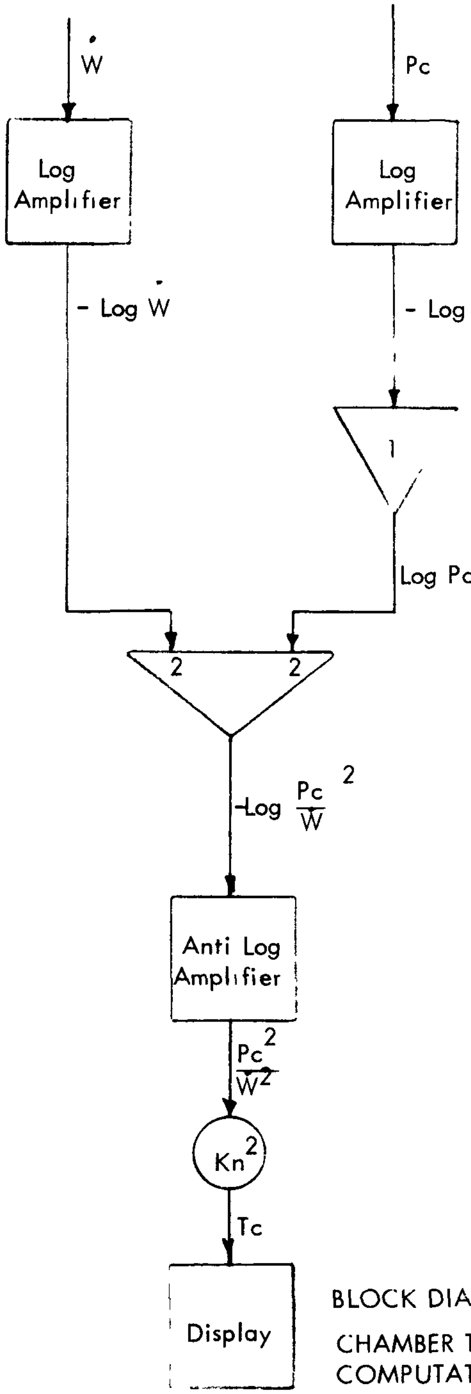

FIGURE 5

BLOCK DIAGRAM -----
CHAMBER TEMPERATURE
COMPUTATION

[redacted]

[redacted]

The factor 4 appears before the bracketed term because of the fact that the three variables in equation 8 are squared.

The data required to evaluate the variance of the calculated chamber temperature has been developed by Reactor Analysis. This data is presented in Table IV. Included in this table are the data for the test cell equipment "as is" and for the "improved" test cell equipment.

TABLE IV

Data for Evaluating Computed Chamber Temperature

	Test Cell "As Is"	Test Cell "Improved"
$\sigma(K_N)$	1.8% at full power	0.75% at full power
$\sigma(P_c)$	1.2% at full power	1.2% at full power
$\sigma(\dot{W})$	1.95% at full power	1.7% at full power
σ(Comp.)	1.4% at full power	1.4% at full power
σ(Disp.)	1.0% at full power	1.0% at full power

The uncertainty in the weight flow measurement includes a 1% computational error in the weight flow computer. The reduced error for the nozzle coefficient listed under the "improved" test cell is based on an accurate experimental determination of this coefficient during the gas flow tests. The improvement in the weight flow measurement is the result of averaging two pressure signals in the weight flow computer.

The data listed in Table IV was used to calculate the entries in Table III which presented the errors of the computed chamber temperature.

[redacted]