CONF-740622--10

FAST-RESPONSE FUEL ROD CALORIMETER FOR 36 INCH FUEL COLUMNS*

by
N. S. Beyer, R. N. Lewis, R. B. Perry
Argonne National Laboratory
Argonne, Illinois

MASTER

June 1974

ABSTRACT

The primary interest in fuel rod calorimeters is due to the high measurement precision attainable with such instrumentation. However, for this interest to be sustained by those who need to make safeguards-type inventory control measurements, it must have a relatively fast measurement-response-time. This report describes the design features and the results of evaluation tests of a new, fast-response, fuel rod calorimeter that can be used to nondestructively measure a 36 inch fuel column (FFTF size) of mixed-oxide fuel. With this instrument measurements can be made in 13 to 23 minutes with an accuracy of ± 0.12 to 0.13% relative.

INTRODUCTION

The purpose of this report is to present a general description of a new, fast-response, fuel-rod calorimeter which can be used to nondestructively assay plutonium-bearing reactor fuel rods which have a fuel column length of 36 inches or less. We have recently designed, constructed, and evaluated such an instrument. The design and the operating characteristics of the instrument are both discussed. However, it is not within the scope of this paper to present a detailed discussion of the electronic circuitry of the control theory applied to the circuit designs and of the construction of the measurement chamber. These details will be presented later in a report now in preparation which will be directed primarily toward specialists with interests in this area.

This new instrument is similar to the fuel rod calorimeters which we have previously built and used for the measurement of short (i.e., 6 in.) ZPPR (Zero Power Plutonium Reactor) fuel rods.[1][2] It consists of a measurement chamber which is held very precisely at a constant temperature. The input power (milliwatts in this case) to maintain this temperature is accurately measured when the chamber is empty and when it contains a fuel rod. Since a plutonium-bearing fuel rod produces heat (due primarily to the alpha particle activity of the plutonium), less power is needed to maintain the constant temperature of the chamber when it contains a fuel rod than when it is empty. The difference between the power measured when the chamber is empty and when it contains a heat-producing fuel rod is equal to the electrical equivalent of the power produced by the plutonium. This power measurement can then be converted to the quantity of plutonium through the use of values of the specific power for each heat-producing constituent (i.e., plutonium isotopic and fraction americium-241), and weight fraction of each constituent (i.e., plutonium isotopic and fraction americium-241). The conversion has been presented in detail in previous fuel calorimetry reports.[1][2][3] Or, the instrument can be used as a direct comparison device by comparison to measurements of standardized fuel rods for which the fuel content has been verified by other means.

* Work performed under the auspices of the U. S. Atomic Energy Commission

DESCRIPTION OF THE INSTRUMENT

General Features. Figure 1 is a picture of the measurement chamber with the preheater chamber attached to one end. The rectangular box contains the measurement or sample chamber which is surrounded by another chamber to provide a reference temperature for it. The remaining space in the box acts as a temperature controlled enclosure for these two interior chambers. The cylindrical tube extending from one end of the box is the preheater unit. It is used to preheat the fuel rods to a temperature very close to that of the sample chamber and thereby shorten the time needed for the sample chamber (i.e., measurement chamber) to stabilize at the measurement temperature after inserting a rod into it. The external dimensions of the box which encloses the measurement chamber are approximately 7" x 12" x 56". The preheater is approximately 39" long by 3" in diameter.

Shown in Figure 2 is the cabinet containing the control circuits, main operating controls, and readout device. It is in the center of the figure in the foreground of the picture. Beside it, to the left, is a group of meters that may be used to monitor operation of the chamber heaters and temperature sensors. However, it is not necessary to monitor these meters while making a measurement. They were installed for use during the evaluation testing of the instrument. Recently we replaced them with smaller horizontal-reading meters which are now located in the upper part of the cabinet. The equipment to the right of the cabinet was used in operating the electrically simulated fuel rod during evaluation testing and calibration. The power supply and control circuit for the preheater can be seen in the rear center of the picture near the preheater. The procedure to be followed when operating the instrument will be described in the next section.

Measurement Components. The instrument consists of four major components which are: (1) the measurement chamber and its heat shield chambers (contained in the rectangular box), (2) the control circuitry, (3) the preheater, and (4) the readout components and operating controls. These are shown in Figures 2 and 3.

The measurement chamber and its heat shield chambers will be briefly described by referring to the simplified diagrammatic sketches included in Figure 3. The sample chamber (or measurement chamber) is centrally located in the upper half of the box and can be located in the diagram by its temperature indication which is designated as T_3. For simplicity, the chambers will be referred to by their temperatures. T_3 is surrounded by a larger cylinder (T_2) which is maintained at temperature T_2 and acts both as a heat shield for T_3 and supplies a reference temperature for its sensor-controller. The remaining space in the box (T_1) acts as a temperature controlled enclosure to provide further heat shielding and is maintained at temperature T_1.

The highly simplified block diagrams of the control circuit are included in the figure to indicate the method of controlling the three chambers at temperatures T_1, T_2, and T_3, and of measuring the electrical power needed to maintain the sample chamber at T_3. The interior of the box is maintained at $T_1 = 30 \pm 1 \times 10^{-2}$°C by circulating air past electrical resistance heaters in the bottom of the box. There are twelve thermistors located along the top of the box above the T_2 chamber which sense the temperature of the circulating air and with the control circuit hold the air at temperature T_1. This provides a heat shield against the room temperature. The large cylinder which surrounds the sample measurement chamber is wrapped with two wire coils which act as heater and temperature sensors. With these a highly controlled reference temperature is provided in the space between the T_2 and T_3 cylinders. As indicated in the figure, this temperature (T_2) is held at

$32 \pm 5 \times 10^{-5}$ °C. The sample chamber (T_3) is maintained at a temperature $T_3 = 33 \pm 2 \times 10^{-5}$ °C in a similar fashion to the T_2 chamber. Also included in the figure is a diagrammatic representation of the power measurement system for T_3 (i.e., sample chamber). This includes a method of digitizing the current (I) and voltage (E) which is applied to the T_3 heater coil and of obtaining the product E x I (power) which is required to maintain the sample chamber and its contents (i.e., a plutonium-bearing fuel rod) at T_3. A programmer circuit permits the power (E x I) to be displayed digitally with light emitting diodes for readout. A crystal controlled clock is also included in the circuit. It is used for automatically timing the period over which the power measurements are made and for controlling the period required for the sample chamber to reach a steady state (i.e., stabilize) at the temperature T_3. The stabilization period can be preset in increments of 5 minutes.

The preheater has been referred to above as part of the general features of the instrument and is included in Figures 2 and 3. As was mentioned above, its primary function is to warm-up a rod that is to be measured so that it is very close to the sample temperature. This substantially shortens the time needed to stabilization after inserting it into the sample chamber. It can also function as a heat shield to guard against heat losses when rods are being measured that are longer than the fuel column they contain. A fuel-rod element (i.e., tubing containing fuel pellets, spacers and other hardware) may be considerably longer than the actual column of mixed-oxide fuel it contains in it. This is the case, for example, of FFTF fuel rods which have the fuel pellet column down near one end of the tubing. When this is the case, a portion of the fuel element tube will extend out of the measurement or sample chamber while the mixed-oxide column is in the sample chamber being measured. This non-fuel-bearing portion of the tube can reside in the preheater during a measurement. Since the preheater is maintained at a temperature very close to T_3, any heat losses due to the element extending out of the sample chamber are reduced to an insignificant minimum. At this point it should be mentioned that the preheater is not the only guard against such losses referred to above. The T_2 chamber is long enough to extend beyond the T_3 measurement chamber approximately one inch on each end for thermal shielding of the sample chamber. In addition, several inches of plastic insulator-spacer are provided at the ends of the T_2 and T_3 cylinders. Specific details of these features are beyond the intended scope of this report and cannot be presented at this time; they are therefore omitted in the interests of maintaining the desired brevity. Such details will be presented in a report now in preparation which was referred to in the introduction to this report. A diagram of the control circuitry for the preheater is not shown in Figure 3; however, it is basically similar to that used for the control system of the box environmental temperature (T_1) which relies on thermistors for temperature sensing, etc.

The power measurement system and its circuitry has been briefly commented upon above. However, some additional discussion concerning it should probably be included at this time while describing the operating controls and the procedure to be followed in using them to make a measurement. As has been mentioned, the readout circuitry provides a measurement of the electrical power (i.e., in this case milliwatts) that is required to maintain the sample chamber at the T_3 temperature. This signal is converted to digital form, which makes possible a digital presentation or readout. It also simplifies the future addition of signal processing equipment requiring a digitized form. Indeed, plans are now underway to add such signal processing equipment to the instrument.

The procedure that is followed in making a measurement is relatively simple because of the automated features built into the instrument. The first step is to insert a cold (i.e., room temperature) fuel rod into the preheater and allow it to warm-up to a temperature very close to T_3. This usually takes about 10 to 15 minutes. After completing this preheating, the rod is slid into the sample chamber (also referred to as the measurement chamber) which is directly in line with it. The sample chamber, which now contains a rod, must now be allowed to stabilize at $T_3 \pm 2 \times 10^{-5}$ °C. For a preheated fuel rod, this usually takes from 3 to 8 minutes. It is possible to select in 5 minute increments a stabilizing period of from 5 to 35 minutes. A thumb-wheel selection switch is provided for this. For a 5-minute stabilization period (usually long enough), the operator sets a thumb-wheel selector at "1" and presses the "start" button. The "start" button is located in the lower left-hand corner of the control cabinet and is visible in Figure 2. It is to the left and below the panel containing the light emitting diodes (LEDs) which read out milliwattage or seconds in digital form. No digits are visible in the picture, but would appear in the black rectangle with the white frame. The thumb-wheel selector for selecting the number of 5-minute stabilization cycles is located to the right of the "start" button; and to the right of it is the "remeasure" button. After pressing the "start" button, the elapsed stabilization time is displayed on the LEDs. After this is completed, a 300-second measurement cycle starts automatically. During this cycle, a power measurement is made every 3 seconds and is displayed on the LEDs for the operator to monitor if he desires. When the 100 measurements (i.e., once every 3 seconds for 300 seconds) are completed, the mean value is automatically computed and displayed by the LEDs as milliwatts to two decimal places. This is the power provided to the sample chamber to hold it at $T_3 \pm 2 \times 10^{-5}$ °C. It is possible to repeat this 300-second measurement cycle (i.e., remeasure) as many times as is desired. To remeasure, the "remeasure" button and "start" button are pressed. We found that three 300-second measurement cycles produced a measurement precision of from ± 0.02 to 0.04%.

Three potentiometers are available for setting the temperatures T_1, T_2, and T_3. They can be seen in Figure 2 below the "start" and "remeasure" buttons. These controls seldom need to be adjusted. They are used to set temperatures to values appropriate for the type of fuel loading being measured. Some other controls are located on the right-hand side of the chassis and consist of an "on/off" switch and of a switch/connector for calibrating the readout system. For normal operation (i.e., one 5-minute measurement cycle), the machine operator only needs to press the "start" button and record the milliwattage displayed by the LEDs. As was stated previously, the milliwattage (i.e., equivalent electrical power) produced by the plutonium contained in a fuel rod is obtained by subtracting the milliwattage provided when the chamber contains a fuel rod from the milliwattage provided when the sample chamber is empty. This difference is equal to the equivalent electrical power produced by the plutonium because the plutonium provides heat to the chamber to stabilize it at T_3 (i.e., the sample chamber heater coils need to provide less power which equals this difference).

OPERATING CHARACTERISTICS

Evaluation testing of this instrument was conducted to determine four basic characteristics which include: (1) measurement capacity, (2) measurement response time, (3) measurement precision, and (4) measurement accuracy. The results of these evaluation tests are summarized in Table I and a short discussion

of each is presented in this section.

Measurement Capacity. As indicated in Table I, the measurement capacity is from 6 to 36 inches of fuel column length containing from one to one hundred grams of plutonium which has a plutonium isotopic and americium composition similar to the FFTF type fuel. The internal diameter of the sample chamber is approximately 3/8 inches in diameter and can handle fuel rods up to this diameter.

Measurement Response Time. Table I indicates that the measurement time is 13 to 23 minutes. This is indicated as a range because the time required is a function of the precision desired and the stabilization time needed. In the previous section it was indicated that the time needed for the sample chamber to reach a stable temperature (i.e., $T_3 \pm 2 \times 10^{-5}$ °C) is from 3 to 8 minutes after inserting a preheated rod into it. Adequate preheating of an FFTF type rod takes from 10 to 15 minutes. The shortest measurement cycle time is 5 minutes. As mentioned previously, this cycle includes 100 measurements taken at 3 second intervals for 300 seconds, and at its conclusion the mean of the 100 measurements is automatically computed and displayed by the LEDs.

If a measurement precision of from ± 0.03 to 0.07% is acceptable, one 5-minute measurement cycle is adequate. Therefore, if an 8-minute stabilization period is necessary after a preheated rod is inserted into the sample chamber, the total measurement time is 5 plus 8 minutes, or a total of 13 minutes which was indicated to be a minimum measurement time in Table I. In some cases, a 3-minute stabilization period is sufficient and therefore the total measurement is sometimes as short as 8 minutes. The time required for preheating a rod has not been included in the above calculations because it only affects the first measurement made during a run. This is because the next rod to be measured can be preheated while its predecessor is being measured. The measurement time for the first rod of a measurement run would require a total of preheat time (10 to 15 minutes), plus stabilization time (3 to 5 minutes) and measurement cycle (5 minutes). This could amount to 18 to 28 minutes. The evaluation test indicated that empty chamber measurements should probably be taken twice daily and would take 5 minutes each. Therefore, a total measurement run of one day would require 10 additional minutes per day. However, the trend of current testing indicates that the number of empty chamber measurements that are needed may be able to be reduced since empty chamber power appears to be approaching a constant value for a particular value of T_3. To obtain measurement precision of ± 0.02 to 0.04% (as indicated in Table I), we found that 3 measurement cycles (15 minutes) were required. Using an 8-minute stabilization period for this case, a total of 23 minutes (indicated as a maximum in Table I) would be required for a measurement.

Measurement Precision. In the process of discussing measurement response time in the previous section, the level of precision to be obtained was discussed in terms of its dependence upon measurement time. The level of precision that is reported (i.e., ± 0.02 to 0.04%) was obtained from repeated measurements of the same fuel rod from day to day during the evaluation testing period which lasted approximately 6 weeks. It refers to the reproducibility of milliwattage measurement. Studies of the precision and accuracy obtainable with this instrument are still being conducted. As more data is collected and/or improvements in the instrument are made, a reevaluation will be made of this characteristic.

Measurement Accuracy. Three techniques were used to assess the measurement accuracy. These included: (1) comparison to measurements of plutonium-bearing fuel rods measured with a high accuracy water-bath calorimeter through the courtesy of Dr. W. W. Rodenburg of Mound Laboratories, (2) comparison with the equivalent power to be expected from the amount of plutonium contained in a group of fuel rods which can be calculated for the rods from knowledge of the composition of the rods and the specific power factors for each constituent, and (3) comparison with measurements of an electrically simulated fuel rod for which the power could be determined through electrical measurements with equipment calibrated against NBS certified electrical standards.

The results of our measurements of plutonium-bearing fuel rods when compared to those obtained by Rodenburg at Mound Laboratories are presented in Table II. The uncertainty of the slope of the linear least squares fit to this data indicates a one sigma uncertainty at the 95% confidence level of ± 0.12%. The amount of equivalent electrical power that would be expected to be produced from these was determined from calculations based upon their composition. These values were in close agreement with the Mound measurements, so a similar accuracy (i.e., ± 0.12%) was obtained from this type of analysis. The mixed-oxide fuel rods used for these tests were well-characterized, 6-inch long, Zero Power Plutonium Reactor (ZPPR) fuel rods. Their composition (which is similar to FFTF fuel) had previously been well established through exhaustive destructive analyses and through other NDA methods which included passive gamma-ray, neutron coincidence, and other calorimetric (1)(2) techniques.

An electrical fuel rod was fabricated by loading a piece of FFTF tubing with a 36-inch long string of resistors, electrically heating the resistor string, and measuring the power supplied. The results of these measurements are shown in Table III. As is indicated in the table, the one sigma uncertainty at the 95% confidence level was ± 0.13%. The fact that it is possible to construct and use an electrically simulated fuel rod for such measurements is a fortunate circumstance, since the determination of the so-called "real" value of power supplied by the rod is in this case independent of the uncertainties associated with mass spectrometric and/or chemical analyses which usually form a basis for determining the accuracy of other nondestructive assay instruments.

CONCLUDING REMARKS

The instrument should be useful for the NDA of plutonium fuel rods either on an absolute basis or on a comparative basis if used for comparing to so-called "standard rods". The latter case would be faster and require less computation but would require reliable "standard rods". The accuracy and precision that can be obtained with this instrument is considerably better than most NDA techniques and although measurement time is longer than many (particularly active assay techniques), it is not intolerable. It is possible that in addition to using this instrument for the usual type of NDA measurements it might find a use in characterizing "standard rods" for other NDA techniques.

As with any calorimetric NDA technique, a potential problem is that the measurements depend upon an accurate knowledge of plutonium isotopic measurements and upon knowledge of the fraction of americium-241 that is present. However, reliable information of this type is often available. It has been suggested that a check of the reliability of the isotopic composition could be made by neutron

coincidence measurements and that of the americium-241 through passive gamma-ray counting.

Although the present instrument would be useful for the control and measurement of the plutonium content of reactor fuel rods, work continues on the improvement of the design. Current effort is directed toward adding data storage and processing circuits to the readout system so that the required isotopic, americium, specific power factors, etc., could be entered and the weight percent plutonium and/or fissile content could be printed out directly following a measurement.

REFERENCES

(1) N. S. Beyer, R. B. Perry, R. W. Brandenburg, and R. N. Lewis, "Four Passive Assay Techniques Applied to Mixed-Oxide Fuel," ANL-7906, Argonne National Laboratory, January 1972.

(2) N. S. Beyer, R. N. Lewis, R. B. Perry, "A Portable Dry Calorimeter for the Nondestructive Assay of Mixed-Oxide Fuel Rods," Nuclear Materials Management, Volume 1, No. 3 (Sept. 1973), pp. 170-196.

(3) F. A. O'Hara, J. D. Nutter, W. W. Rodenburg, M. L. Dinsmore, "Calorimetry for Safeguards Purposes - Determination of Plutonium in Reactor Feed Material," AEC Research and Development Report, MLM-1798, January 1972.

LIST OF FIGURES AND TABLES

Figure 1 Fuel rod calorimeter measurement chamber with preheater.

Figure 2 Fuel rod calorimeter, preheater, control cabinet, and other control circuitry and meters which were used for evaluation testing.

Figure 3 Simplified block diagrams of the calorimeter control circuitry including operating temperatures.

Table I Summary of the main operating characteristics of the calorimeter.

Table II Results of the calibration and evaluation of the measurement accuracy and precision of the calorimeter as based upon a comparison with plutonium-bearing fuel rods.

Table III Results of the calibration and evaluation of the measurement accuracy and precision of the calorimeter as based upon a comparison with an electrically simulated fuel rod.

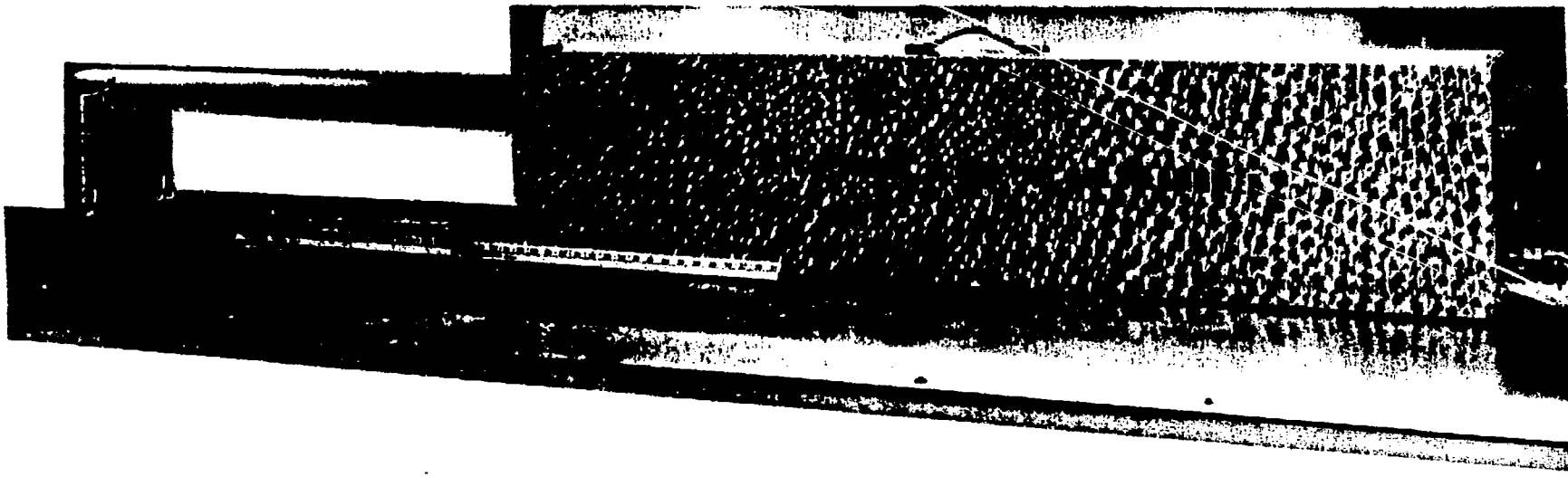

FIG. 1

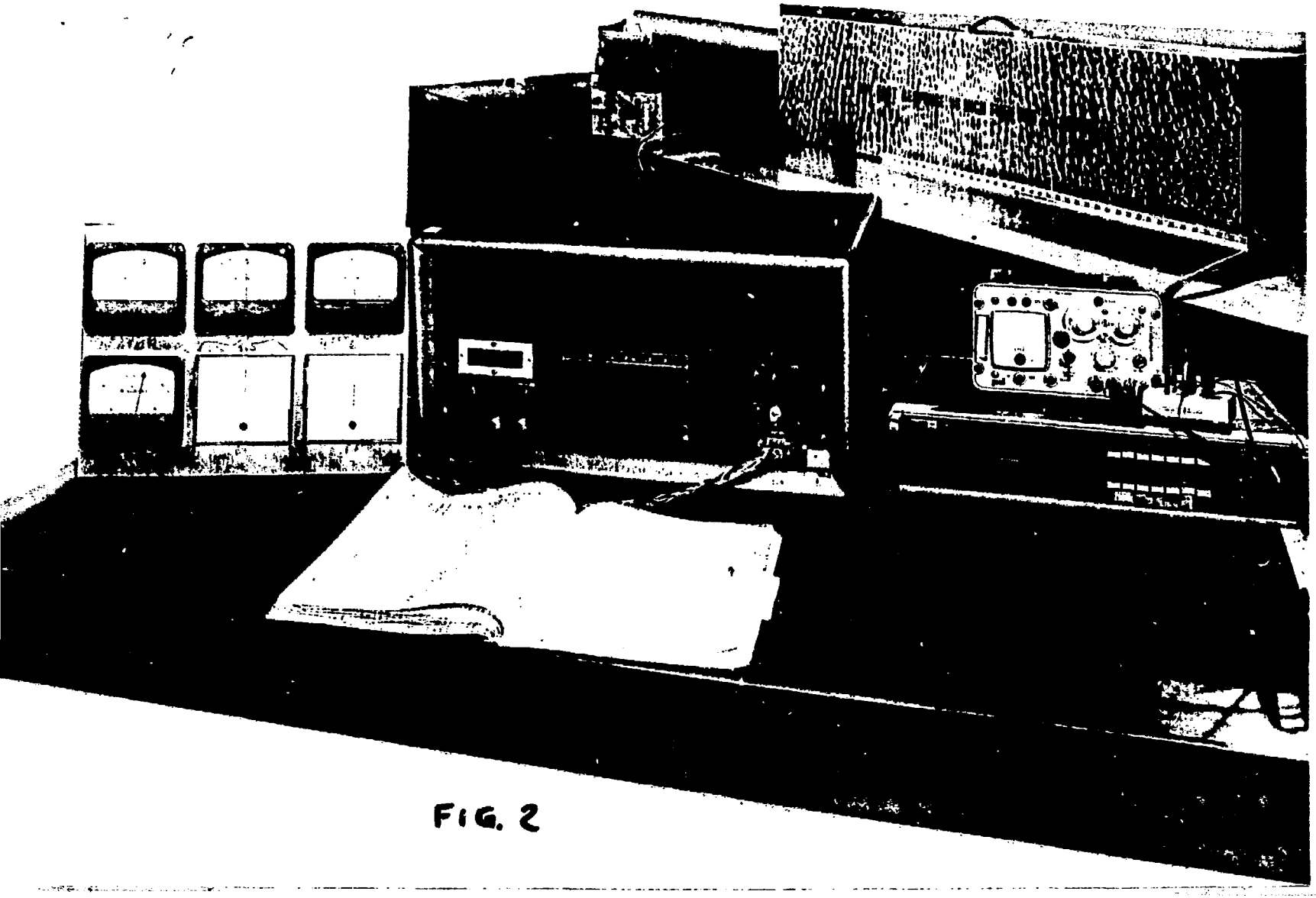

FIG. 2

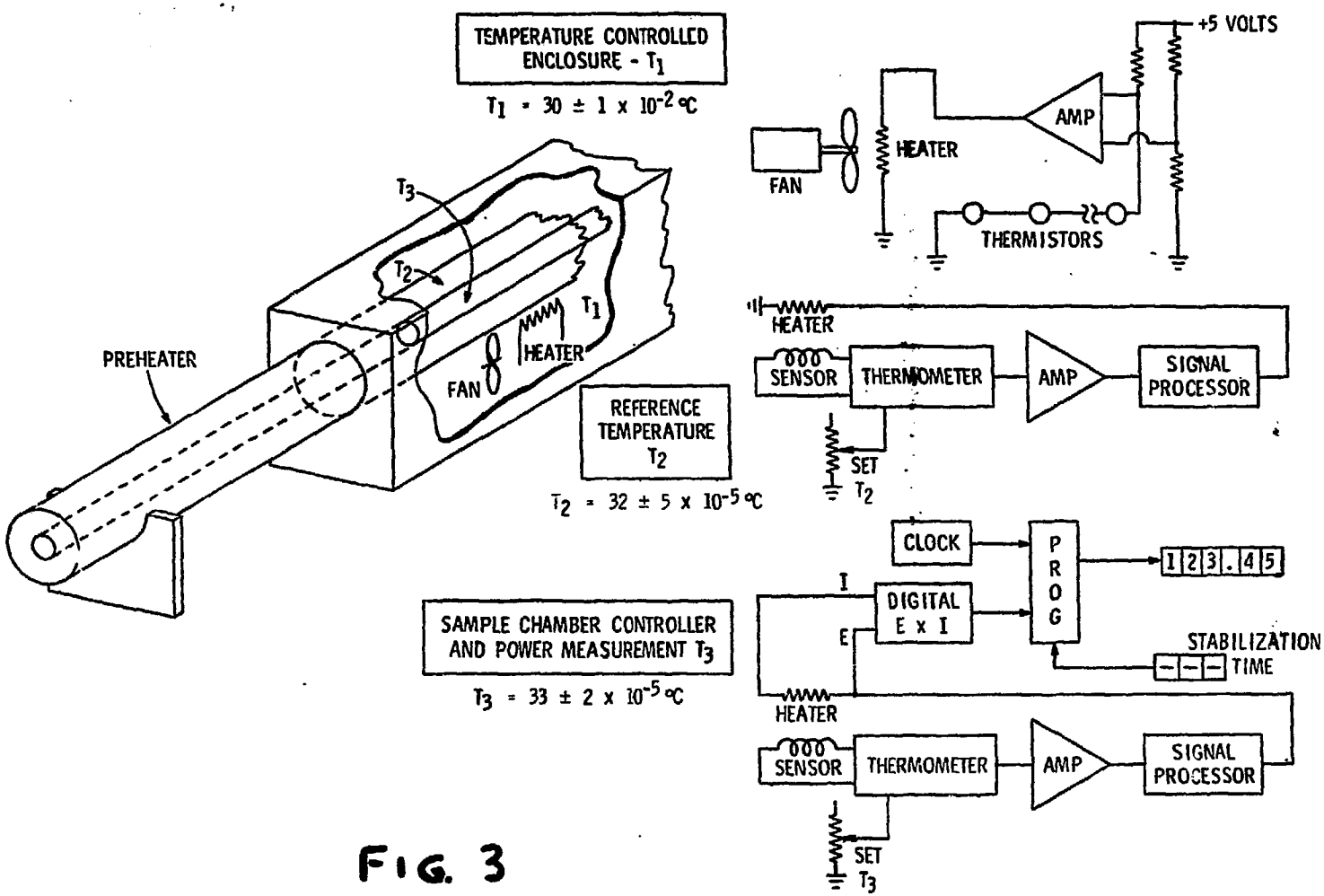
TEMPERATURE CONTROLLED ENCLOSURE - T_1
$T_1 = 30 \pm 1 \times 10^{-2}$ °C
T_3
T_2
T_1
HEATER
FAN
PREHEATER
REFERENCE TEMPERATURE T_2
$T_2 = 32 \pm 5 \times 10^{-5}$ °C
SAMPLE CHAMBER CONTROLLER AND POWER MEASUREMENT T_3
$T_3 = 33 \pm 2 \times 10^{-5}$ °C
+5 VOLTS
AMP
HEATER
FAN
THERMISTORS
HEATER
SENSOR
THERMOMETER
AMP
SIGNAL PROCESSOR
SET T_2
CLOCK
PROG
1 2 3 . 4 5
I
DIGITAL E x I
E
STABILIZATION TIME
HEATER
SENSOR
THERMOMETER
AMP
SIGNAL PROCESSOR
SET T_3

FIG. 3

Tab I

ANL, DRY, FAST RESPONSE, 36 INCH FUEL ROD CALORIMETER

Measurement Capacity:	6 to 36 in. Fuel Column
	1 to 100 gms Pu (FFTF Type)
Measurement Time:	13 to 23 minutes
Measurement Precision:	±0.02 to 0.04%
Measurement Accuracy:	±0.12 to 0.13%

TABLE I

CALIBRATION OF ANL, DRY, FAST RESPONSE 36 INCH FUEL ROD CALORIMETER USING ZPPR MIXED OXIDE FUEL RODS

Number of ZPPR Fuel Rods	Calorimetric Measurement Mound Labs.* (MW)	Calorimetric Measurement ANL QVS Labs. (MW)	Difference Mound Minus ANL QVS Labs. (MW)
2	77.61 ± 0.08	77.83 ± 0.08	-0.22 ± 0.11
3	116.84 ± 0.12	116.92 ± 0.15	-0.08 ± 0.19
4	155.43 ± 0.16	155.21 ± 0.15	+0.22 ± 0.21

Linear least squares fit to this data yields: slope = 0.9944 ± 0.0012 or uncertainty = ±0.12%.

*Also agree to ±0.06% with the mean value of the MW/gm of Pu calculated for this composition.

TABLE II

CALIBRATION OF ANL, DRY, FAST RESPONSE 36 INCH FUEL ROD CALORIMETER USING ELECTRICALLY SIMULATED FFTF FUEL ROD

Input Power to Electrical Fuel Rod (MW)	Measured Power from Calorimeter (MW)	Difference Input - Meas. (MW)
149.98 ± 0.06	149.88 ± 0.11	0.10 ± 0.13
125.01 ± 0.05	124.90 ± 0.14	0.11 ± 0.15
115.00 ± 0.05	114.64 ± 0.08	0.36 ± 0.10
112.01 ± 0.04	111.78 ± 0.05	0.23 ± 0.07
109.98 ± 0.04	109.76 ± 0.07	0.23 ± 0.08
100.04 ± 0.04	100.05 ± 0.12	-0.01 ± 0.13
75.10 ± 0.03	75.05 ± 0.14	0.05 ± 0.14
50.08 ± 0.02	49.62 ± 0.14	0.46 ± 0.14
25.00 ± 0.01	24.97 ± 0.13	0.03 ± 0.13
10.00 ± 0.004	10.09 ± 0.14	-0.09 ± 0.14

Linear least squares fit to this data yields: slope = 0.9990 ± 0.0013 or uncertainty = ±0.13%.

TABLE III