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Contract No. W-7405-eng-92

THE DEVELOPMENT OF A THERMAL-NEUTRON-
FLUX MEASURING INSTRUMENT

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Date: 2/11/10

April 12, 1956

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THE DEVELOPMENT OF A THERMAL-NEUTRON- FLUX MEASURING INSTRUMENT

by BM1-1083

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and Sherwood L. Fawcett

An instrument was developed to measure thermal neutron flux directly and automatically in the range from 10^{13} to 10^{14} neutrons/(cm²)(sec) at ambient temperatures up to 600 F. Two prototype tests were conducted. Measurements made with this instrument are independent of gamma flux and, within a small error, independent of ambient temperature. The method depends on balancing the temperatures of an electrically heated balancing element and a fission-heated uranium-fueled sensing element. Thus, the instrument gives a direct measurement of fission-product power, produced by a known amount of uranium.

The flux-detector assembly measures 3/16-in. in OD by about 4 in. in length and is fitted with an extension so that it is movable over a 20-ft length inside a 0.210-in. ID tubular well in the reactor.

Two tests of the prototype instrument were conducted by making vertical traverses of the flux field in the beryllium reflector of the MTR. Measurements were made in 1-in. increments from 16 in. above to 5 in. below the center line of the core. Instrument response time was about 1 min for each measurement. The maximum deviation of a single instrument reading from the average readings at a given point was about 2.5 per cent at a flux of 10^{14} neutrons/(cm²)(sec).

INTRODUCTION

The objective of this research program was to develop an instrument that could be calibrated to measure thermal neutron flux directly and accurately in the range from 10^{13} to 10^{14} neutrons/(cm²)(sec). Desired detector life was about 100 hr at an average flux of 5×10^{13} neutrons/(cm²)(sec) at an ambient temperature of approximately 600 F. In addition, the detector assembly was to be movable over a 20-ft length inside a 0.210-in. -ID tube. The detector was to be operable over the bottom 4 ft of the total travel.

To avoid the use of correction factors and curves and, therefore, make the instrument convenient to use, it was initially decided that the instrument should be self-compensating for ambient-temperature changes and should not include gamma flux in its measurements.

ANALYSIS OF MEASURING METHODS

The two basic methods of measurement that were considered were the usual ion-chamber technique and the use of the fission heat generated by neutrons in a uranium-fueled element. A variation of the latter method was finally chosen, the reasons for this choice being given in the following discussion.

Ion-Chamber Method

Work done previously in the development of small fission chambers was reviewed. The smallest chamber described in the literature with which reasonably accurate measurements could be obtained was about 1/2 in. in OD. Its center electrode was only slightly smaller than the total allowable outside diameter of the instrument to be developed in this program. Furthermore, the materials used in this chamber for measurement in the flux range from 10^{13} to 10^{14} neutrons/(cm²)(sec) would not be satisfactory for operation in a 600 F ambient temperature.

Review of the work by other experimenters and work at Battelle indicated that the problem of reducing the size of an ion chamber to less than 0.210 in. while maintaining the necessary potentials would be extremely difficult. Also, maintaining insulation over a 20-ft length, some of it at 600 F, seemed formidable. For these reasons, and the promise shown by other methods, this system was abandoned.

Fission-Heat Method

The fissioning of uranium in a specimen generates heat and, consequently, provides a method of measuring the neutron flux which induces the fissions. If two identical elements, one containing enriched and the other natural uranium, are placed together in a neutron flux, a temperature difference will exist between the two. Since both are heated equally by the gamma radiation, this temperature difference can be related to the neutron flux. Two methods exist for using this phenomenon as a measuring technique.

Temperature Method

The temperature rise caused by fission in the fueled element above any reference temperature can be measured by using the potential generated in a differential thermocouple between the fueled element and an element at the reference temperature. If the reference element is of exactly the same

shape and composition as the fueled element, except that it contains natural uranium, the temperature difference will be independent of gamma flux. This method has the advantage of having only two leads, from the thermocouple, to take out through the reactor well. However, the elements are at different temperatures and, consequently, the heat losses for the elements are not identical nor are they constant over the complete range of temperatures encountered. Furthermore, the temperature differential between them is not a linear function of the heat generated. Hence, the temperature differential measured by the thermocouple will be a function of the temperature and the instrument will not be self-compensating for temperature changes.

As it would be impractical to attempt to construct an element assembly that would exhibit the required thermal characteristics over the wide range of temperatures necessary for accurate measurement, this method was not further considered for development.

Power Method

If the above method is modified so that the element containing natural uranium is heated electrically to the temperature of the fueled element, both elements will be losing heat at the same rate. The electrical power to accomplish this is proportional to the difference in heat generation between the elements which is proportional to the neutron flux. In any ambient temperature range where the product of the macroscopic fission cross section and the neutron velocity can be considered constant, the electrical power supplied is directly proportional to the thermal-neutron density. Because the thermal flux is defined as the neutron density multiplied by a mean neutron velocity of 2200 m per sec, the electrical power supplied is also directly proportional to this thermal flux.

Since this electrical power could be calibrated directly as a linear function of thermal-neutron flux with very small error, and since the possibility existed that this power could be matched accurately and automatically to the fission power by a reasonably simple controller, this system was chosen for development.

DESIGN CONSIDERATIONS

After choosing the power-measuring method of determining the fission rate, radiation seemed the best method to remove the heat generated in both elements. Conduction would be affected by changes in the thermal conductivity which could occur because of radiation damage. Forced convection is impractical and natural convection is unpredictable.

To insure heat loss by radiation a reasonable gap must exist between the elements and the containing tube. This and the dimensions of the tube required an element size no larger than 3/32 in. OD. Such a small space eliminated the hope of placing the elements side by side, and they were arranged in tandem. This arrangement is better from the standpoint of one element being shielded from the flux but necessitates the use of short elements. It was decided that the total active portion of the device should not exceed 1-1/4 in. Each element will then be about 1/2 in. long and 3/32 in. in diameter.

One of the most important considerations in choosing the element material was the electrical resistivity. To keep the heating current small so that a negligible amount of heating takes place in the No. 20 copper leads, a resistance of 30 to 50 ohms was needed. Furthermore, a resistance of 30 to 50 ohms would keep the heating potential below 20 v, which would simplify the insulation problems.

Initially, several high-temperature alloys were investigated for use in the elements. Wires of uranium-thorium and uranium-zirconium were of interest because of their known radiation-damage stability and their fairly high resistivity. However, to obtain resistances of 30 ohms, several inches of 0.002-in. -diameter wire is required. This wire could be wound on a mandrel 1/2 in. long and 3/32 in. in diameter. However, the difficulties of drawing and winding the wire caused the use of these materials to be considered as an alternate method.

Many ceramic materials can be extruded in the proper size and shape to serve as elements. The resistivity of some of these materials is 1 to 2 ohm-cm, which will give a resistance of 30 to 50 ohms for this size. In addition, materials with specific resistivities of this order have very small temperature coefficients. These materials have the disadvantages of unknown radiation-damage susceptibility and, in many cases, poor mechanical strength.

The feeling that these disadvantages could be overcome by suitable choice of materials and fabrication techniques prompted a first-line effort. A material with very good mechanical strength containing about 62 w/o Al_2O_3 , 36.4 w/o MoSi_2 , and 1.6 w/o UO_2 was developed. It also could be made with the proper resistivity. Later tests showed the radiation damage to be negligible within the required flux and time conditions.

Calculations were made to determine the amount of uranium-235 required in the sensing element to produce 7 w of power. This power level was decided upon primarily as a compromise between element-temperature considerations and the desire to minimize error due to resistance losses in the leads. This power was chosen to correspond to the maximum flux, 5×10^{14} neutrons/(cm²)(sec), since it could be supplied easily electrically

to the balancing element. The fission power in the sensing element is:

$$P_S = \Sigma_{25} \phi V_{25} E, \quad (1)$$

where Σ_{25} = macroscopic fission cross section of uranium-235

ϕ = neutron flux

V_{25} = volume of uranium-235

$E = 2.67 \times 10^{-11}$ w-sec per mev.

From this the required mass of uranium dioxide can be easily calculated as:

$$M_{UO_2} = \frac{P_S A_{UO_2}}{N_0 \sigma_{25} \phi E \psi}, \quad (2)$$

where N_0 = Avogadro's number

A_{UO_2} = molecular weight of UO_2

ψ = enrichment.

The mass of UO_2 required for the experiments in the MTR was calculated to be 2.3×10^{-3} g, or 1.64 w/o. Since the fission cross section decreases with neutron energy, the amount would be larger for reactors operating at higher temperatures.

The power generated by fissions in the balancing element, P_B , is simply P_S times the enrichment ratio. The difference, $P_S - P_B$, is the amount of power which must be supplied electrically.

Assuming the heat loss to be entirely radiant, the surface temperature of the sensing element was calculated from:

$$T = \left[\frac{P_S}{\epsilon \sigma A} + T_o^4 \right]^{1/4},$$

where $\epsilon = 0.50$ (assumed)

$A = 1.27 \text{ cm}^2$

$T_o = 600 \text{ F}$

$\sigma = 5.67 \times 10^{-12} \text{ w}/(\text{cm}^2)(\text{K}^4).$

With the difference $P_S - P_B$ supplied to the balancing element, it will have, of course, the same surface temperature.

Table 1 gives the results of the design calculations for the final element material.

TABLE 1. RESULTS OF DESIGN CALCULATIONS

ϕ , neutrons/(cm ²)(sec)	P_S , w	P_B , w	$P_B - P_S$, w	T, K
5×10^{14}	7	0.045	6.946	1200
1×10^{14}	1.4	0.011	1.389	849
5×10^{13}	0.7	0.005	0.695	755
1×10^{13}	0.14	0.001	0.139	641
5×10^{12}	0.07	—	—	634

DEVELOPMENT OF THE PROTOTYPE INSTRUMENT

Basic-System Design

A schematic diagram of the basic control system is shown in Figure 1.

To analyze this system, suppose that the temperature of the balancing element does not equal that of the sensing element. Because the heat-transfer and gamma-heating characteristics of the two elements are identical, this temperature differential means that the electrical power being supplied to the balancing element is not equal to the power being generated by fission in the sensing element. The potential created in the differential thermocouple by this temperature difference is converted into an a-c signal and amplified by the amplifier. An a-c amplifier is used to avoid the drift often encountered in the use of d-c amplifiers. The output of the amplifier is supplied to the two-phase reversible motor, which adjusts the secondary variable transformer in the direction dictated by the polarity of the thermocouple voltage. This automatic adjustment continues until the thermocouple potential and, therefore, the temperature differential between the elements are zero. When this null point is reached, the equivalent of the net fission power is read directly from the wattmeter.

The manually adjustable primary variable transformer is supplied to provide maximum voltage resolution of the motor-driven transformer.

FIGURE 1. BASIC-SYSTEM DESIGN

Commercially available components were used throughout in the construction of the prototype controller. All thermocouple lead wires were shielded between the amplifier and the junction box on the end of the element assembly tube to eliminate 60-c pickup from surrounding equipment. A 288:1 speed reduction was used between the two-phase reversible motor and the secondary variable transformer.

Element-Assembly Design

A cross-sectional view of the element assembly is shown in Figure 2. It will be noted that the thermocouple beads are located at the midpoint inside each element for maximum measuring accuracy. The bead diameter was less than 1/32 in. and the short piece of 1/32-in.-diameter insulation between the beads was put in place before the beads were formed. All insulators and the spring pad were made of Lavite. These were heat treated after machining.

The change from platinum heating leads and thermocouple wire to copper wire was made immediately above the element assembly. Copper wire was then used for all additional wiring.

Element Fabrication Technique

As there were no commercially available materials from which the sensing and balancing elements could be made, special materials were developed. Both ceramic and metallic materials were investigated for this use. The material finally used in the prototype was extruded ceramic with a composition of 61.96 w/o alumina, 36.40 w/o molybdenum disilicide, and 1.64 w/o uranium dioxide. Natural uranium dioxide was used in the balancing element and highly enriched uranium dioxide was used in the sensing element. See Appendix A for the fabrication procedure.

The machining to size was done between the presintering operation and final sintering since the final material is too hard to be machined using ordinary processes. Shrinkage due to final sintering was about 4 per cent. The electrical resistance of each finished element is about 25 to 50 ohms.

The electrical contacts were added to the balancing element by painting each end with colloidal gold resinate and baking at 650 F. This coating was then painted with high-temperature liquid silver, which was baked on at 650 F. The baking is done in a slightly reducing atmosphere.

The nominal 1/2-in. element length was chosen as the optimum for thermal end losses by conduction while maintaining both elements in essentially the same flux in the reactor.

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FIGURE 2. ELEMENT-ASSEMBLY DESIGN

Other Construction Details

The platinum electrical contacts through which power was supplied to the balancing element were made by forming the end of a 0.010 in. platinum wire into a loop which fitted against the end of the hollow cylindrical element. These contacts were loaded by the spring in the bottom of the assembly. Inconel X was used for this spring material because of the high ambient temperature.

A Chromel-Alumel differential thermocouple made of 36-gage wire was used for the temperature measurements.

EXPERIMENTAL TESTS

Preliminary Tests of Components

Several bench tests were conducted with components identical to those intended for use in the prototype instrument to assure proper operation of the measuring system. Tests were conducted in air at room temperature with the 61.96 w/o Al_2O_3 -36.40 w/o MoSi_2 -1.64 w/o natural UO_2 specimens to provide data regarding element temperature rise as a function of power and the material's temperature coefficient of electrical resistivity. The average experimental values obtained were 150 C per w and minus 0.0004 ohm/(ohm)(C), respectively.

The controller was tested by heating both the sensing and balancing elements electrically. The known power input to the sensing element was compared with the power automatically supplied to the balancing element by the controller. The data showed that the powers were matched within 0.013 w, which, when correlated with the temperature-rise data, yields a maximum temperature difference of about 1 C between the two elements.

Radiation-Damage Tests

Samples of the ceramic materials intended for use in the prototype element assembly were encapsulated in helium-filled 2S aluminum capsules. The samples were irradiated in the MTR to determine their radiation stability in a flux equivalent to the desired assembly life of 100 hr in an average flux of 5×10^{13} neutrons/(cm^2)(sec). Six Al_2O_3 - MoSi_2 -natural UO_2 balancing-element-material samples and two Al_2O_3 - MoSi_2 -enriched UO_2 sensing-element-material samples were tested. In addition, three Al_2O_3 -C- TiO_2 -natural UO_2 alternate-element-material samples and three Lavite insulator-material samples were irradiated.

In the postirradiation examination, all of these samples appeared to be satisfactory for their intended use. The $\text{Al}_2\text{O}_3\text{-MoSi}_2\text{-enriched UO}_2$ specimens, which were expected to suffer the greatest damage, increased in size an average of only 1 per cent in OD.

Because of its superior mechanical properties, the $\text{Al}_2\text{O}_3\text{-MoSi}_2\text{-UO}_2$ material was chosen over the $\text{Al}_2\text{O}_3\text{-C-TiO}_2\text{-UO}_2$ material.

Tests Measuring MTR Thermal Flux

Method of Testing and Calibration

An in-pile test was run inside the beryllium reflector of the MTR. The element assembly was used to make a measuring traverse in 1-in. increments from 16 in. above to 5 in. below the vertical center line of the core. Measurements were then taken at random points in multiples of 1 in. along this length to determine the instrument response time and to establish the reproducibility of the data obtained in the original traverses.

No accurate data were available for direct calibration of the instrument in terms of thermal neutron flux. Therefore, it was necessary to use the conversion curve shown in Figure 3 to convert the measured balancing-element power in watts to thermal neutron flux. This curve was calculated from the power and the element parameters. In the neutron-density calculations, it was assumed that the macroscopic fission cross section varies as the inverse of the neutron velocity.

Test Results

Two tests were conducted with identical element assemblies and the same controller used for both. Each element assembly was continuously evacuated while being used.

Analysis of Experimental Data. The experimental curve shown in Figure 4 was drawn by using the calculated curve from Figure 3 to convert the average balancing-element power at each position to thermal flux. The latest available MTR flux map of the test location, obtained using foil techniques, was for a core of somewhat different geometry. However, this old curve is shown in Figure 4 so that basic comparisons can be made.

Using the calculated calibration of power in terms of flux, the maximum deviation of a single instrument reading from the average of all readings at a point where the flux was about 1.04×10^{14} neutrons/(cm²)(sec) was 2-1/2 per cent, and the corresponding deviation for a flux of about 2.2×10^{13}

FIGURE 3. CALCULATED CONVERSION CURVE—BALANCING ELEMENT POWER TO NEUTRON DENSITY AND MTR FLUX

FIGURE 4. THERMAL-FLUX MAP OF ONE MTR REFLECTOR POSITION DRAWN FROM EXPERIMENTAL DATA

Test conducted January, 1956.

neutrons/(cm²)(sec) was 5-3/4 per cent. If the actual flux at any given point is assumed constant, these represent the maximum instrument errors.

Element-Assembly Life. During the first test, the ambient temperature was 850 F instead of the desired maximum 600 F, due to gamma heating of the surrounding equipment. However, the instrument operated at this extreme temperature with excellent reproducibility of data for approximately 6 hr in an average flux of 5×10^{13} neutrons/(cm²)(sec) before the electrical heating circuit inside the element assembly opened and prevented the recording of additional data.

The second assembly was used for about 70 hr in the same average flux with an ambient temperature of approximately 600 F before its circuit shorted.

Time does not permit an examination of these assemblies at present, but it is believed that deterioration of the silver heating contacts due to the extreme temperature caused the open circuit. It is also believed that crumbling of the solid porcelain insulators in the thermocouple and heating lead tube due to vibration induced by coolant-water flow caused the short circuit.

Instrument Response Time. Response time of the instrument was about 1-1/2 min in going directly from the minimum to the maximum flux region. Measurements in increments up to 3 in. in the test position could be made in less than 1 min. This shows that a complete core traverse in 1-in. increments can be made in about 1 hr.

The response time can be shortened by changing the servo ratio, keeping in mind that hunting may occur if this is continued too far.

CONCLUSIONS

The prototype instrument is capable of measuring the flux distribution at 37 points along a core 3 ft high in a total time of 37 min. This is much less time than that required for comparable measurement using other techniques. The maximum instrument error, as calculated from the maximum deviation of a single reading from the average value of all readings at a given point, is between 3 and 5 per cent.

A number of improvements to make the flux-measuring device a more suitable reactor instrument can be made. First, the tube extension could be removed and replaced by a four-wire ceramic-filled metal-sheathed conductor. These conductors can be manufactured commercially and permit

the leads to be coiled on a fairly small diameter. Second, the response time can be shortened by changing the reduction gear between the motor and transformer, or a variable-speed or cam drive might be used. Finally, minor modifications of the balancing system will permit a reduction in the balancing error.

If all of the proposed improvements are accomplished, this instrument should be capable of making a flux-measuring traverse through a fuel element 3 ft long in less than 10 min if the element assembly were moved continuously and slowly through the fuel element. The accuracy of the measurements obtained would be comparable to, or better than, that obtained with present measuring methods.

The control and measuring system would be contained in one unit with an estimated weight of less than 50 lb. Total maximum power consumption is expected to be about 50 w. Therefore, the instrument would be reasonably portable and could be used in any convenient location where 110-v, 60-c current is available.

Since the instrument measures the power generated in a given amount of uranium, it might be well to relate this to reactor power directly. This can be done quite simply if the ratio of uranium concentrations in the fuel elements and in the measuring device are known. In preparing these components, uranium concentrations can be very accurately determined. The wattmeter could then be calibrated directly in reactor power, the parameter actually needed. This would eliminate the errors associated with cross-section data in calibrating the instrument with foils. The device is an absolute measure of reactor power and could be used to calibrate foils.

FABRICATION OF BALANCING AND SENSING ELEMENTS

The following is an outline of the method used to fabricate these elements, starting with a 100-g total of the three basic constituents.

- (1) Dry mix 61.96 g Al_2O_3 , 36.40 g MoSi_2 , and 1.64 g UO_2 with 2.73 g Unigum binder for 15 hr
- (2) Add 15 cm^3 water to this mixture while mixing with mortar and pestle
- (3) Extrude the wet mixture into rods, using a 1/8-in. die operating with a 5-ton gage pressure
- (4) Place these extruded rods in small round-bottomed boats to keep them straight
- (5) Place the boats in a glass dish, and wrap the dish in waxed paper
- (6) Slightly elevate one end of the dish, and let the rods cure in this manner for 48 hr
- (7) Remove the rods from the dish and dry them for 1 hr in air at 180 F
- (8) Presinter the rods in a hydrogen atmosphere by raising the temperature from room to 2100 F in about 8 min and maintaining the 2100 F for 2 min; cool slowly
- (9) Machine the rods to a 0.096-in. OD, a 0.036-in. ID, and a 0.520-in. length
- (10) Final-sinter the machined rods in a hydrogen atmosphere by raising the temperature from room to 2500 F in about 15 min and shutting the furnace off immediately; cool slowly.