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A LOW-POWER THERMAL TEST REACTOR ADAPTABLE TO NUCLEAR
PHYSICS RESEARCH

H. B. Stewart, F. G. LaViolette, C. L. McClelland,
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ABSTRACT

A low-power thermal test reactor has been in operation at the Knolls Atomic Power Laboratory for approximately two years. A primary objective in the design of the thermal test reactor was the utilization of the reactor as a sensitive and reliable detector of danger coefficient samples. To achieve this sensitivity the sample is introduced in a graphite thermal column located inside the active lattice. The neutron flux in the sample position is approximately 2.3 times the average flux in the active lattice, and the cadmium ratio of indium activation is 5.9.

The critical U-235 mass of the TTR is 2.7 kg. Experience with the TTR indicates that a reactivity change of 5×10^{-7} in K can be detected by normal danger coefficient procedures. A cross section of 10^{-3} cm^2 can be measured by routine danger coefficient methods.

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A LOW-POWER THERMAL TEST REACTOR ADAPTABLE TO NUCLEAR PHYSICS RESEARCH

H. B. Stewart, F. G. LaViolette, C. L. McClelland,*
G. B. Gavin, T. M. Snyder

INTRODUCTION

The two basic requirements for neutron physics experiments are (1) a source of neutrons and (2) a detector. The source of neutrons might be a natural radioactive source such as a radium-beryllium source, a particle accelerator, or a nuclear reactor. The more popular detectors include ion chambers, photographic films, scintillation detectors, or detectors which measure some induced change in a target element, for example, the induced radioactivity or the change in isotopic composition.

The value of a nuclear reactor as a source of neutrons has been generally recognized. The application of the reactor as a detector has received somewhat less attention but has been discussed by several authors.**,** The latter application involves the measurement of pile reactivity changes resulting from the introduction of sample materials into the active lattice region of a reactor. The measurement may take the form of danger coefficient experiments or pile oscillator experiments. In a danger coefficient experiment the magnitude of the reactivity change is measured by the displacement of a calibrated control rod which compensates for the poison effect of the sample. In the pile oscillator experiment the amplitude of the reactor neutron flux variation is measured while the sample is oscillated in and out of the reactor. Although ion chambers are necessary to measure the change of reactor power level or the modulation of the neutron flux in these experiments, the basic detector is the reactor itself.

Much attention has been given to the design of reactors to provide a neutron flux which might be desirable for research or production purposes. Little attention, however, has been accorded the optimum reactor design for detection. One of the primary objectives in the design of the KAPL Thermal Test Reactor was the exploitation of the detection utility of the reactor.

In order to compete with other detectors involving counting techniques, the accuracy of the reactivity experiment must be comparable to the errors inherent in particle counting. These errors arise from poor counting statistics, counting geometry, or limitations of counting equipment. Depending

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**H. L. Anderson, E. Fermi, A. Wattenberg, G. Weil, and W. H. Zinn, "Method for Measuring Neutron-Absorption Cross Sections by the Effect on the Reactivity of a Chain-Reacting Pile," Phys. Rev., 72, 16 (1947).

***J. I. Hoover, W. H. Jordan, C. D. Mosk, L. Pardue, H. Pomerance, J. D. Strong, and E. O. Wollan, "Measurement of Neutron Absorption Cross Sections with a Pile Oscillator," Phys. Rev., 74, 864 (1948).

on the type of experiment, the error may range from 10% to 0.1%. Increasing the size of the sample has no appreciable effect on the accuracy of a counting experiment. The increase in counting rate which might be gained by increasing the sample size can also be achieved by increasing the neutron flux. In contrast to experiments which use counting techniques for detection, the accuracy of the reactivity experiment can be improved by choosing larger samples.

The criteria for a reactor to be a good detector are as follows:

1. The control system must be sensitive and reproducible.
2. The neutron flux intensity per watt at the sample position must be large.
3. The spectrum of the neutron flux should have characteristics such that the detection experiments are interpretable.
4. The critical mass of the reactor should be small.
5. The sample should be located in some position of the reactor to ensure that the neutrons absorbed by the sample are very effective in maintaining the pile reactivity.

It is noted that the sensitivity of the reactor as a detector is independent of the absolute neutron flux falling on the sample; consequently the reactor can be operated at relatively low power levels. By designing the reactor so that it can be operated at a higher power level, the reactor can also serve as a good source of neutrons. In addition to its versatility, the Thermal Test Reactor (TTR) has the advantages of being a relatively inexpensive reactor and of being very safe to operate.

GENERAL DESCRIPTION OF THE TTR

The structure of the TTR can be divided into four regions:

1. An internal graphite thermal column located in the interior of the active lattice region.
2. An active lattice region in an annular aluminum container surrounding the thermal column.
3. A graphite reflector surrounding the active lattice.
4. An external thermal column extending horizontally away from one of the reflector faces.

A unique feature of the TTR is its internal thermal column. In the KAPL model the internal thermal column consists of a cylinder of graphite 12 inches in diameter and 18 inches high. A test hole is located in the center of this thermal column at the point that:

1. The neutron flux available at a given reactor power level is relatively large.
2. A large ratio of thermal flux to epithermal flux is achieved.
3. The neutrons which are absorbed or created in a test sample in the test hole have a large effect on reactivity, thereby making the TTR an exceptionally sensitive instrument for the measurement of relative thermal absorption or fission cross sections.

The floor plan for the reactor room, shielding walls, and control room is indicated in Figure 1. The TTR is located in a cell which has a floor area 15 x 10 feet. The cell has a 6-ft poured concrete wall on all four sides except for a door 3 x 7 feet and a hole 4 x 4 feet which contains the external thermal column. The ceiling consists of a 1-foot thick slab of concrete. The attenuation of the neutron flux and gamma radiation through the shielding wall is more than adequate to operate the TTR at a power level of 100 watts.

The reactor which is indicated at one corner of the reactor room is approximately a cube 5 feet on each side. The reactor is operated by remote controls which are located on the control panel in the control room. Relay racks are mounted beside the external thermal column in order to accommodate equipment to be used for the neutron beam experiments.

The details of the TTR design are illustrated in the cutaway section shown in Figure 2. The active lattice region contains 20 fuel slug tubes, each 2 inches in diameter and 24 inches long, arranged in a cylindrical array in an aluminum tank having a 12-inch ID and an 18-inch OD. The enriched uranium is contained in U-Al alloy disks which are about 2 inches in diameter and have a 3/16-inch diameter hole through the center. A fuel slug consists of fuel disks separated by polyethylene spacers located on an aluminum rod about 18 inches long. The slugs are immersed in a light paraffin base oil in the slug tubes, and the interstices between the slug tubes and the walls of the aluminum container are filled with water.

The central hole in the reactor container is filled with the 12-inch diameter graphite plug which functions as an internal thermal column. This graphite cylinder has a central slot approximately 2 inches by 1/2 inch which accommodates the experimental samples.

CONTROL AND SAFETY MECHANISMS

Coarse Control

Six channels at the periphery of the aluminum container accommodate iron-clad cadmium sheets which are 4 inches wide and about 18 inches long. These sheets are withdrawn from the reactor individually by remote controls located on the control panel. The total reactivity change effected by the six coarse control sheets is about 6.5%. The minimum withdrawal time for all six sheets is about 3 minutes. Interlocks on the control sheet drive mechanism prevent the sheets from being withdrawn before the automatic safety rods are cocked, and before the fine control rods are completely in the reactor core.

Fine Control

Two cadmium rods, each 18 inches long and about 1/2 inch in diameter, are used for the fine control of the reactor. These rods move into aluminum guide tubes which are located in the reactor container between the fuel slug tubes. The reactivity value for each of the fine controls is approximately 0.5%. The control rods are driven by motors mounted on a plate above the reactor core. Selsyn systems coupled to the control drives indicate the control rod position on the control panel.

Automatic Safety Rods

Four 1/2-inch diameter cadmium rods, each 18 inches long, are used as automatic safety rods. These rods move in aluminum guide tubes similar to the control guide tubes. The rods are suspended above the reactor core by solenoids which automatically release the rods in case the power level of the reactor exceeds a predetermined magnitude. The rods and magnetic release mechanism are designed to release the rod in less than 0.005 second; the rod requires a total of 0.4 second to drop completely into place after the initial signal. The total reactivity value of the four automatic safety rods is approximately 2.5%.

RADIATION DETECTION INSTRUMENTS

Neutron Flux and Level Trip Circuits

Two neutron-sensitive, paraffin-moderated, boron-trifluoride-filled ionization chambers which are located outside the graphite reflector give signal currents of about 0.03 μ a/watt of reactor power. Feedback stabilized electronic d-c amplifiers operate from these chambers to drive fast-response continuous-writing recorders and high-speed trip circuits. The trip circuit relays control the power to the safety rod solenoids and coarse control sheet drive motors. The trip circuits are set to operate at about full-scale on the indicating recorders. The sensitivity of the electronic amplifiers may be varied by a factor of 10^5 so that the trip circuit is operable down to flux levels produced by the neutron source alone.

Neutron-Counting Instruments

Two neutron counter circuits are used for measuring multiplications during initial loading and for operating an audible indicator. These consist of boron-lined proportional counters driving pulse amplifiers and scalars.

Health Instruments

The neutron flux in the assembly room is continuously monitored and recorded by a BF_3 -filled proportional counter and scaler.

The gamma flux in the assembly room and in the control room is continuously monitored and recorded by an air ionization chamber and electronic amplifier units.

REACTOR PERFORMANCE

Theory of TTR

The performance characteristics of the TTR can be described conveniently by applying the danger coefficient theory as developed by Dr. H. Hurwitz, Jr. at the Knolls Atomic Power Laboratory. The reactivity change observed in a reactor due to the addition of a danger coefficient sample is indicated by:

$$\frac{\Delta K}{K} = \nu \frac{\Delta f}{\Sigma f} F_H - \frac{\Delta a}{\Sigma f} F_L$$

where

Δf = rate of fissions in the danger coefficient sample,

Δa = rate of neutron absorption in the danger coefficient sample,

Σf = total fission rate in the entire reactor,

F_H = favorableness of high energy neutrons (fission energy spectrum) toward maintaining the chain reaction,

F_L = favorableness of low energy neutrons (absorption energy spectrum) toward maintaining the chain reaction.

If absolute units of reactivity are used, then the favorableness $F(r, E)$ has the significance of an "iterated fission probability" for a neutron of energy E at position r in the reactor. The iterated fission probability is a geometric average of fission probabilities for succeeding generations over an infinite number of generations. The average value of F_H for the entire reactor must be $1/\nu$ (0.4 for U-235) in order for the reactor to be critical. Since fast neutrons have a greater probability for escape from a reactor, the iterated fission probability for low energy neutrons is usually greater than that for fission energy neutrons in the active lattice region of a small reactor. Hence F_L is usually larger than F_H in a reactor core. F_H and F_L are sensitive functions of the position in the reactor.

If the sample consists of U-235, then

$$\frac{\Delta K}{K} = \frac{\Delta f}{\Sigma f} \left[v F_H - (1 + \alpha) F_L \right]$$

where

$$\alpha = \frac{\Delta c}{\Delta f} = \text{parasitic capture rate per fission rate.}$$

If the sample is a nonfissionsable absorber, then

$$\frac{\Delta K}{K} = - \frac{\Delta a}{\Sigma f} F_L.$$

The more complete expression contains a term describing the effect of scattering on the reactivity. If the sample is located at the center of the reactor, then scattering has no effect on the reactivity. If we write

$$\frac{\Delta a}{\Sigma f} = \frac{nv_0 \sigma_a (w_a/A_a)}{\overline{nv} \sigma_f (w_f/235)}$$

where

nv_0 = thermal flux at the center of the internal thermal column,

$\overline{nv}$ = the average thermal flux in the active lattice region,

σ_a = atomic cross section of absorber,

$\frac{w_a}{A_a}$ = moles of absorber,

σ_f = effective fission cross section of the fuel disks,

$\frac{w_f}{235}$ = total moles of U-235 in the reactor,

then the reactivity change due to an absorber placed in the sample hole is

$$\frac{\Delta K}{K} = - R \frac{\sigma_a w_a 235}{\sigma_f w_f A_a} F_L$$

where

R = the ratio of thermal neutron flux in the sample hole to that in the active lattice region.

It is noted that the reactivity change is proportional to R and F_L , and inversely proportional to w_f . Hence for a given sample absorber, the maximum reactor sensitivity is obtained by designing the reactor such that the flux augmentation factor R and favorableness factor F_L are as large as possible and the critical mass is as small as possible. The values of F_H , F_L , and R can be determined from the results of some activation and danger coefficient experiments.

EVALUATION OF REACTOR PARAMETERS

Critical Mass

The mass of U-235 which was required to achieve criticality in the KAPL TTR was approximately 2.7 kg. An extra 0.1 kg was added for experimental flexibility which provides about 0.6% in K excess reactivity.

Power Distribution

The fission product activity induced in the TTR fuel disks was measured to determine the power distribution in the active lattice region. The ratio of maximum to average fission rate in the slug is 1.12. A fuel disk which was placed in the sample hole of the internal thermal column showed an induced specific fission rate which was 2.3 times the average specific fission rate in the active lattice region. Hence the augmentation of the neutron flux as measured by U-235 is $R = 2.3$.

Neutron Flux

The thermal neutron flux at the TTR sample hole was obtained from activation experiments with manganese foils. The thermal flux was found to be

$$nv_{th} = 3.4 \times 10^7 \frac{\text{neuts}}{\text{cm}^2 \text{ sec watt}}$$

The cadmium ratio of the activation induced in a 0.005-inch indium foil was found to be

$$CR = \frac{A_{bare}}{A_{Cd}} = 5.9$$

at the sample hole.

Figure 3 shows the thermal neutron flux intensities per watt along a radius from the center of the internal thermal column through the active lattice, the reflector, and the central axis of the external thermal column. The cadmium ratio for indium foils varies from 100 to greater than 1,000 in the external thermal column.

The epithermal neutron flux intensity at the sample hole in the internal thermal column has been measured by the self-absorption of strong resonances in indium, gold, and manganese detectors. The foils were calibrated in a graphite sigma pile using a 3-gram radium-beryllium source. The results of the TTR measurements indicate that at 1.44 ev,

$$Nv = 1.80 \times 10^6 \frac{\text{neuts}}{\text{cm}^2 \text{ sec watt } \Delta \ln E}$$

at 4.9 ev,

$$Nv = 1.95 \times 10^6$$

and at 300 ev,

$$Nv = 2.08 \times 10^6.$$

The probable absolute error in these measurements is estimated to be 10%, while the probable relative error is 3%.

Neutron Favorableness

The favorableness of thermal neutrons at the sample hole was measured with indium, gold, and manganese foils. The reactivity change, $\Delta K/K$, was measured by the control rod shift necessary to compensate for the sample, while the absorption per watt, $\Delta a/\Sigma f$, was determined from the activations of the sample foil and monitor disks. The results with the three different foils indicated

$$F_L = 0.45$$

The probable absolute error, due largely to inaccurate absolute reactivity calibrations, is 10%, while the probable relative error between the different foil determinations is 2%.

The average value of F_L in the active lattice region is approximately

$$(F_L)_{\text{avg}} = 0.6$$

Although there is an appreciable augmentation of the neutron flux, there is some loss in F_L at the sample position. However, the net effect is an augmentation of the reactivity change resulting from a sample located at the sample hole position.

Danger coefficient and reactivity measurements of U-235 at the sample hole position indicate that

$$F_H = 0.42$$

Since F_H is approximately the same as the average value in the active lattice while F_L is somewhat smaller, the sample hole in the TTR is particularly sensitive to fissionable samples.

Sensitivity

The value of the reactor as a detector depends not only upon the magnitude of the reactivity change caused by the sample, but also upon the reliability of the reactor control system and the associated instruments for measuring the reactor power level. Experience with the TTR indicates that a reactivity change of 5×10^{-7} in K can be detected by normal danger coefficient procedures. With some improvement in the instrumentation it should not be difficult to detect a reactivity change of 10^{-7} . A 1.5-gram gold foil having a macroscopic absorption cross section of approximately 0.4 cm^2 causes a reactivity change of $\Delta K/K = 2 \times 10^{-4}$ in the TTR. Hence a cross section of 10^{-3} cm^2 can be measured by routine danger coefficient methods. Improvements in the instrumentation might decrease the minimum detectable cross section by a factor of 5. The use of a pile oscillator might result in greater sensitivity. The limit to detection sensitivity appears to be instability of the reactor due to temperature changes. A temperature change of $10^{-3} \text{ }^\circ\text{C}$ causes a reactivity change of $\Delta K/K = 10^{-7}$. Consequently, it is important to maintain good temperature control in the reactor cell.

A convenient size for danger coefficient samples in the TTR is one which causes a reactivity change of $\Delta K/K = 10^{-4}$ to 10^{-3} . Hence it should be practical to measure relative thermal absorption cross sections with an accuracy better than 1%.

SAFETY ASPECTS OF TTR

Although the experimental versatility and the cost of construction were major considerations in the choice of the TTR design, considerable emphasis was placed on safe operational characteristics. The safety is achieved by:

1. Interlocks to prevent an incorrect sequence of operations which might lead to a hazardous condition.
2. Automatic safety rods which poison the reactor if the power level unexpectedly exceeds some predetermined power level.
3. A strong negative temperature coefficient of reactivity, so that the reactor will shut down automatically in case all other safety measures should fail.

Interlocks

The following interlocks are provided in the TTR control system:

1. The approach to criticality cannot be commenced until the reactor cell is evacuated and the cell door is locked.
2. The coarse control sheets cannot be withdrawn unless:
 - a. Power is supplied to the instruments.

- b. The fine control rods are in the most poisonous position.
- c. The safety rods are cocked.
- d. The neutron source is located in the active lattice region.

3. The control rods cannot be moved prior to the complete withdrawal of the control sheets.

Automatic Safety Rods

The four automatic safety rods, which are suspended by solenoids above the active lattice region, drop into the reactor within 0.4 second following the trip signal. If the reactor should suddenly be brought to prompt criticality, that is, an excess reactivity of approximately 0.8% (it is difficult to imagine how this could be accomplished), then the power level would increase exponentially within a period of approximately 0.5 second. If it is assumed that at least one of the two trip circuits functions properly, the peak power level would not exceed twice the predetermined trip level for safety rod release.

Negative Temperature Coefficient

The fuel disks in the slug tubes are surrounded by a light paraffin base oil which serves as a moderator. The choice of oil for a moderator was based on the following reasons:

- 1. The large bulk modulus of oil.
- 2. The noncorrosive characteristics of oil.

Since oil has a large bulk modulus, a small reactor temperature increase causes a large change in the moderator density, which in turn decreases the pile reactivity. If it is assumed that all of the safety mechanisms should fail completely during an accident when the reactor becomes prompt critical (this is an extremely improbable combination of events), then the strong negative temperature coefficient of the TTR would limit the energy release so that the integrated radiation outside the shield would be less than daily tolerance.

The authors wish to acknowledge the contributions of E. E. Haslund and P. L. Clairmont in the design and the assembly of the reactor.

TTR FLOOR PLAN

Fig.1

Fig. 2

Fig. 3