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METHOD FOR NEUTRON-FLUX STUDIES IN AN OPERATING POWER REACTOR USING BARE AND CADMIUM-COVERED RADIOACTIVANTS

by

W. G. Knapp

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ANL-7011
Reactor Technology
(TID-4500, 43rd Ed.)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60440

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Reactor Physics Division

March 1965

Operated by The University of Chicago
under
Contract W-31-109-eng-38
with the
U. S. Atomic Energy Commission

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ABSTRACT

A method of study of neutron-flux distributions and energy spectra in the core of an operating nuclear power reactor has been developed. The foil-activation technique, including the use of cadmium absorber covers, has been adapted in a way that overcomes the access limitations of most power reactors. Small spherical foils are inserted through the tube irradiation facilities having a 3/16-in. OD into selected locations in the core without affecting the reactor operation. Both insertion and removal are performed with pneumatic transfer methods.

The small (1/16-in.-diameter) spherical foils can be fabricated from a variety of detector materials and are particularly adapted to automatic analysis techniques. An automatic sample changer is described that was used extensively during the initial demonstration of the method in the Experimental Boiling Water Reactor (EBWR).

Modifications and recommendations based on actual experience with the method in the EBWR are given.

1. INTRODUCTION

The increasing complexity in nuclear reactor design has brought about an ever-increasing need to evaluate the ambient neutronic conditions in and about the reactor core. Information is needed on core power distribution and fuel burnup, for the advanced-concepts reactor design engineer and the reactor fuel specialist; on the effects of control mechanisms, for the physicist; and on the neutron spectrum and flux in the vicinity of critical construction items, for the metallurgist and reactor safety engineer.

In the power reactor, one encounters on one hand the desire for extensive information (all the more of interest because of the complexity of the reactor), while on the other hand one is limited in obtaining this information because of this complexity. The need for access to power reactors

for use by experimentalists has been generally ignored by groups charged with a specific power reactor design project, so that invariably the problem of making in-core measurements is encumbered with a variety of after-the-fact experiment-design exercises. This is the situation that was encountered in neutron-flux studies made in the EBWR.

1.1 Objectives

The object of this project was to devise a method for extensive study of the neutron-flux distribution in the operating reactor. The method for making these studies could not interfere with normal operation of the facility.

The evaluation of the soluble-poison shim control in the EBWR was the primary interest that lead to the need for neutron-flux distribution information. When it became apparent that a variety of detector foils could be used, it became the further objective to provide for obtaining neutron spectral information as well.

A final objective was the demonstration of the method,⁽¹⁾ with modifications to be designed as the need was encountered for future, more-detailed application.

1.2 Background

Neutron flux is measured in power reactors for a variety of reasons, ranging from power-level determinations^(2,3) to radiation-damage studies.⁽⁴⁾ Because of the high flux density and the power-reactor environmental conditions (600 psi and 250°C in EBWR), studies are limited to the radioactivation technique in a variety of forms. Most common is the irradiation of foil material in a given in-core or near-core location, occasionally with both bare and cadmium-covered foils being used. This usually requires that the foils be positioned in the reactor during a down period. After being "buttoned up," the reactor vessel is hydrostatically tested, preheated, and brought to power. This usually requires at least one day. Following operation at given parameters for foil activation, the reactor is shut down, cooled at a slow rate, and opened for retrieval of the foils, again requiring at least one day. Not only is this technique frequently impractical, it is impossible to make short-term irradiations or to use radioactivants with fairly short-lived products. This was the only procedure available, however, in which cadmium covers could be used. Cadmium covers are required for most resonance detector materials.

An in-core irradiation provision in the Vallecitos BWR has been mentioned⁽⁵⁾ that would allow insertion, irradiation, and removal of radioactivant wires from the reactor core during power operation. Such a procedure would be a definite advantage if wires could be so manipulated in small, necessarily-long tubes. No published results have appeared on this technique. The use of cadmium covers would be most difficult, if not impossible.

1.3 Brief Description of EBWR Facility

The EBWR has been extensively described in the literature;⁽⁵⁻¹²⁾ however, a brief description is given here. The EBWR, originally designed for 20 MWt, has now been modified for a heat dissipation capacity of 100 MWt. The reactor is of the direct-cycle, boiling-water type, in which the coolant-moderator water circulates upwards through the core with consequent steam formation, and downwards around the core periphery in the downcomer region. The operating conditions of 600 psi, 250°C, places considerable emphasis on structural design requirements so that nozzles for experimental use must be placed in conformance to structural requirements rather than the experimenter's desires. The only nozzle location available in EBWR for this project was one originally provided for a superheat experiment. Modifications of the nozzle are described in Section 2.2.

Since the reactor is located in a containment shell, there was access to the experimental area during normal reactor power operation.

The reactor fuel loading was fairly complex (see Fig. 1) and included plate-type fuel assemblies of two dimensions and two enrichments, and spike assemblies.⁽¹⁰⁾ The fuel assembly dimensions and configurations place important limitations on the irradiation facility design from the standpoint of physical size.

2. METHOD FOR IN-CORE NEUTRON-FLUX STUDIES DURING POWER REACTOR OPERATIONS

It was early determined that the foil activation technique was the only neutron detection method suitable for application to this study. It was desired to provide for cadmium absorbers. It then became necessary to design the irradiation equipment to be compatible with the power reactor. A schematic diagram of the method developed is shown in Fig. 2.

2.1 Design Criteria

The design criteria were determined by the reactor facility as a whole, the fuel element configuration, experiment access limitations, and the radioactivant foil configuration. These are discussed below.

The experimental nozzle, a short stub of 3-in. schedule 80 stainless-steel pipe,⁽¹⁰⁾ projected from the vessel at 63° to the vertical axis. No penetrations could be made in the reactor head, or elsewhere in the vessel.

EXPERIMENT DEVICE CODE

BURNABLE POISON STRIPS

PREFIX LETTER CODE

N NATURAL "U" THICK PLATES
 T NATURAL "U" THIN PLATES
 EH ENRICHED "U" THICK PLATES
 ET ENRICHED "U" THIN PLATES
 S ENRICHED "U" RODS (SPIKES)
 SDS DUMMY W/SOURCE
 SD DUMMY STAINLESS STEEL

Fig. 1. EBWR Fuel-loading Diagram Showing Foil Irradiation Facility Locations

Fig. 2. Schematic Diagram of Irradiation-analysis Procedure Used in Study of Neutron Flux in a Power Reactor

The maximum diameter of tubing that could be run through plate-type fuel assemblies was $3/16$ in. Previous experience had shown Inconel to be most suitable for experimental and instrument uses in the reactor vessel, so that use of this material was specified. Since foil material would be manipulated through the tubing to in-core locations, with the tube being at atmospheric pressure inside and reactor conditions on the outside, the tube wall thickness was designed with an adequate safety provision.

The foils had to be inserted and accurately positioned in-core for irradiation with a minimum of transit time. Removal from the core had to be accomplished with the same high speed. Provision was to be made for complete axial traverse irradiations in a given fuel assembly at one time. These could be done at selected intervals, rather than continuous, if desired. If absorber was used, such as cadmium covers, the quantity of this material had to be held sufficiently low so as to not affect reactor operation, nor to significantly perturbate the flux in the area under study.

A plane through one quadrant of the reactor was of interest and was to include a comparable location in the downcomer and also one external to the reactor pressure vessel. Irradiation facilities were to be provided accordingly.

As for the design of the foils, lengths of wire could not be manipulated with sufficient accuracy and without danger of high radioactivity levels where portions of the manipulation cable might be in in-core locations for long times. Individual foil detectors coupled into flexible lengths suitable for axial traverse irradiations were necessary.

The design requirement for fast insertion and removal rates led to the choice of pneumatic transport and seating of the foil assemblies, making necessary a loop that offered several design possibilities.

Finally, in the case of the EBWR, the irradiation facilities had to be installed in existing fuel assemblies in the reactor vessel. The fuel assemblies were already highly radioactive, and remote handling tools with 25-ft handles were necessary to manipulate the facilities into place. Provision for attaching the facilities to the individual fuel assemblies was necessary. There could be no interference with flow of cooling water through the fuel assembly during power operation.

2.2 EBWR Modifications

In the final design, as used, the only modification of the EBWR to allow neutron-flux studies was the extension of the 3-in. nozzle to an accessible location on the main floor of the reactor building, as shown in Fig. 3. The nozzle was enlarged to 6-in. pipe and terminated in a 6-in. flange. This flange was fitted with an extra thick ($2\frac{1}{2}$ -in.), blind flange through which 16 penetrations, each fitted with Conax lava pressure sealant fittings, were provided. Twelve of these penetrations, each with $3/8$ -in.-diameter fittings, were used for the neutron-flux studies (see Fig. 7).

2.3 Irradiation Facilities in EBWR

Six continuous lengths of Inconel tubing, each 70 ft long, were formed into a U with a $1\frac{1}{2}$ -in. saddle radius and equal-length legs. (Fabrication difficulties by the supplier made it necessary to use two 35 ft lengths, joined with a precision-welded coupling.) Sleeves were welded onto the tubing about 3 ft from each end so that the Conax fittings (shown in Fig. 7) would form a pressure seal without deforming the tubing. The tubing had a $3/16$ -in. OD and 0.140- to 0.145-in. ID. The sleeves were $3/8$ -in. OD.

Installation in the reactor vessel was fairly simple, fixtures as shown in Figs. 4 and 5 being used to hold the tube with reference to the fuel assembly. Tubes installed only in plate-type assemblies were attached for support to a cross brace in the reactor steam dome, as shown in Fig. 6. Much care was necessary to prevent bending or deforming of the tubes, since such deformation would have prevented use of the loop. One of the six loops was located in the downcomer region, as seen in Fig. 3. In addition, a loop was located outside the pressure vessel in the vacuum shield vessel. The outer termination of the nozzle is shown in Fig. 7; the two tubes of the loop located in the vacuum vessel are also shown. Since air pressure and vacuum were used in the manipulation of the foils, the individual tube ends terminated in a glovebox, which was kept at atmospheric or negative pressure by exhausting to the plant stack, using a small centrifugal pump. In this manner, radioactive dust from the tubes would not contaminate the work area.

Fig. 3. Scale Drawing of Reactor and East Instrument Nozzle, Showing Typical Irradiation Facility

112-2413

Fig. 4. Fixture for Holding Irradiation Loop
in a Fuel Assembly

112-2407

Fig. 5. Tool for Positioning Irradiation Loop
and Fixture in Fuel Assembly

112-1845

Fig. 6. Open EBWR Vessel, Showing East Instrument Nozzle Opening and Irradiation Loop Tubes

112-2423

Fig. 7

East Instrument Nozzle Flange. Note tubes at upper right which connect to loop in vacuum shield vessel.

In connection with the irradiation facilities, compressed gas (dry, bottled, nitrogen gas in most cases) was used to effect fast removal of the detector assemblies, while vacuum was used for fast insertion and positive positioning of the detector assemblies. The vacuum pump

exhausted to the plant stack. Lead-shielded storage facilities were used for temporary or long-term storage of the samples (see Fig. 8).

112-2420

Fig. 8. Pneumatic Removal of Sample Chain to Shielded Storage Cave (Foreground, Partially Disassembled)

2.4 Preparation of Radioactivant Foils

Since many detector foils were required for the study program, individual weighing of foils and consequent individual calculation corrections for foil weights were impractical. Both for the neutronic advantage and for the handling and calculational simplicity, a small spherical foil shape with the diameter held to precision tolerances was chosen. High-purity, uniform alloys of the desired materials were fabricated into 0.075-in. wire, from which spherical foils were fabricated to a 0.0625 ± 0.0002 -in. diameter. No fabrication difficulty has been experienced with ten aluminum-radioactivant alloys (including a suspension of tungsten in aluminum) prepared to date, and consideration has been given to preparation of metal-fissile alloys and fissile glass or ceramic, cermet,

or high-temperature plastic preparations, and to pure metals such as nickel, to further extend the scope of the neutron-flux studies. These could all be readily prepared in the small spherical configuration that has many advantages, as will be shown. The cost of fabrication of the spherical foils from the alloy wire averaged less than five cents each, with much greater savings in weighing and computation time.

The very small spherical foil, with sufficiently low radioactivant concentration to keep self-shielding low, approaches the ideal point detector for isotropic flux irradiation, in that this shape eliminates obliquity variations. Small size and low radioactivant content result in insignificant flux-depression and perturbation factors.

The foils were encapsulated in small pieces of stainless-steel tubing of 0.096-in. ID and 0.008-in. wall thickness by forming the tubing ends over end beads of 3/32-in. commercial stainless-steel bead chain, as shown in Fig. 9. Cadmium covers were fashioned from 15-mil wall-thickness tubing

Fig. 9. Sample Assembly (A) Partially Assembled, Bare Foil; (B) Partially Assembled, Cadmium-covered Foil; (C) Completed Assembly (Note Bead-chain Connector at Right End)

with an ID of 0.065 in., and from 15-mil cadmium sheets. The pieces were sized to cover the foil adequately, and to seat together accurately during the forming of the capsule tubing over the bead chain. Figure 9c shows the parts ready for final assembly.

112-2411

Fig. 10

Complete Sample
Assembly for Flux
Traverse through
EBWR Fuel Assembly

The capsules could have been enlarged to hold several different bare foils, or two or three cadmium-covered foils, either with individual absorber covers or one cover for several foils. Since there is nothing by which to distinguish different aluminum alloy foils visually, some color identification would be necessary in such a multifoil arrangement. Therefore a capsule, sized to hold only one foil, was assembled as shown in Fig. 10. Six-inch spacing was used, except for the lower 12 in., which had 2-in. spacing between detector foils.

Since positioning of the sample foils was controlled from the glove box (see Fig. 11), long lengths of bead chain were used with measured stops that seated on the tube ends. This required a long preparation time and was not an entirely satisfactory method.

There is considerable latitude in preparation, spacing, intermixing, and handling of the foils in preparation for irradiation. Further diversity can be realized through use of the common bead-chain connectors (one is shown in Fig. 9c) to assemble a variety of samples from prefabricated encapsulated sections. Care must be taken to prevent deformation or expansion of these connectors, and specially-made pliers were used to correct this when it occurred. Alternately, sections of bead chain can be joined with special pliers available commercially* and shown in Fig. 12.

Encapsulation could be improved by using soft aluminum tubing in place of the stainless steel for encapsulation. The capsule could be joined to the bead chain by crimping rather than spinning.

*The Bead Chain Manufacturing Company, 110 Mountain Grove Street, Bridgeport 5, Connecticut.

112-2421

Fig. 11. Loading Sample Chain into Irradiation Tube before Activation

Fig. 12

Hand Tool for Assembling Continuous Lengths of Bead Chain

112-2408

2.5 Foil Irradiation

Sample chain assemblies were inserted into the selected tubes to a point about 8 ft from fully in. Vacuum was used to fully insert the chain at the beginning of the irradiation time, 4 to 5 sec being required for this operation. Only one assembly was fully inserted at a time.

Tape recorders were used in connection with the irradiation procedure. One recorder served as an audioclock with prerecorded time signals and information helpful in keeping track of which assembly was to be inserted or withdrawn. The second tape recorder was operated with a foot control and was particularly convenient for noting information concerning an irradiation such as what sample assembly number was inserted into what reactor location, etc. This was made necessary because glove-box manipulation and insertion of samples, as shown in Fig. 11, did not allow time for written notes.

At the end of the irradiation time, the sample assembly was blown from the reactor core directly to the lead-shielded storage facility (see Fig. 8). The personnel received a short exposure to moderately high activity levels but did not receive an excessive total exposure. When there was sufficient time, sample assemblies would be first removed to the approximate preirradiation position above the reactor core and allowed to decay radioactively for about 30 min before transfer to the storage facility.

2.6 Recovery of the Activated Foils

After sufficient radioactive "cooling," determined by the half-life of the radioactivant product, the foils were recovered from the irradiated sample assemblies. Since stainless-steel tubing was used for encapsulating the foils, the capsules were machine-opened, using a small Unimat lathe and hollow collet chuck, as shown in Fig. 13. A glovebox was used to prevent contamination of the work area.

If soft aluminum tubing were used for encapsulation, as previously suggested, the bead chain could be pulled from the tubing by hand or, alternately, the capsule could be cut with a specially designed knife, eliminating the necessity to chuck up and machine-open a large number of capsules. Certain high-temperature plastics might be equally suitable for this application. Construction of the entire assembly chain from aluminum or plastic would reduce the personnel exposure problem.

112-2422

Fig. 13. Disencapsulation of Irradiated Foils .

2.7. Analysis of Foil Activity

The spherical foil was ideally suited for automatic analysis with gamma-sensitive detectors and associated instrumentation. The sample changer, shown in Fig. 14, was designed so that individual foils could be pneumatically transferred to the detector assembly for analysis and then returned to the same indexed location in the changer. The sample-changer disc (which was interchangeable) was loaded as the foils were recovered, eliminating the possibility of mixing of foils. Saran tubing connecting the sample-changer pickup head to the detector assembly was used for transferring foils.

The samples were positioned above, between, or in a NaI(Tl) gamma scintillation crystal with the device shown in Fig. 15. The inset shows details of the sample holder. Normal analyses with a wide range of detector geometry (to about 30 in.) were possible, while coincident counting could be done with two crystals, one on either side of the sample holder. A 6 x 6-in. crystal with a 3/8-in.-diameter by 3-in.-deep well could be used for sum peak counting.

A multichannel analyzer was used for the routine analyses because it was the only instrument available that had a completely automatic read-out feature necessary for overnight runs. The analyzer timer controlled both analyzer live time and elapsed time while the cycle timer (shown in Fig. 14) controlled the changer and the pneumatic valve (returning one sample, advancing the sample changer, and introducing the next sample) between each analysis. The equipment was fully interlocked to prevent erratic operation (see Fig. 16). The variac controlled the sample-changer advance solenoid for smooth operation.

The calculation of thermal and resonance neutron-flux levels from bare and cadmium-covered foil data was straightforward. One advantage here, as mentioned earlier, was the lack of necessity for individually weighing the sample foils and for individual weight adjustments in the calculations.

112-2588

Fig. 14. Automatic Sample Changer with Concentric Row Selector Mounted on Top. Shown also are the advance solenoid variac, cycle timer, and pneumatic control system (pump and automatic three-way valve).

112-2416

Fig. 15. Sample Positioning Device with Conventional NaI(Tl) Scintillation Detector and Preamplifier with Inset Showing Details of Sample Positioning Probe

Fig. 16. Schematic Diagram of Automatic Sample Changer and Auxiliary Equipment

3. EXPERIMENTAL DATA

One-percent cobalt-aluminum alloy spherical foils, each weighing $0.0571 \text{ g} \pm 1\%$, were used in a demonstration of the method in the EBWR. Other than for the time consumed by the various operations (fabricating the foils, inserting and removing samples from the reactor, recovering the foils, analysis, and computation) all of which could be speeded up considerably with the proposed modifications given in the following section, no factor was encountered that would indicate a need for a change in the basic procedure. The data obtained in the demonstration study are reported in ANL-6751.

Different spherical detector foils are now on hand for use in the Plutonium Recycle Experiment. These materials will give an extended range of data necessary for characterization of the neutron energy spectra in and about the core with different operating parameters. Some interest exists for the possible use of fissile detectors in alloy form, or as glass, ceramic, or cermet detector foils. All could be prepared in spherical shape for this application. Sulfur has been considered as part of a high-temperature plastic, or as a compounded inorganic preparation, while nickel and certain other low-cross-section materials may be used as pure metal foils.

4. PROPOSED MODIFICATIONS FOR FUTURE APPLICATION OF METHOD

From the experience at the EBWR reported in Ref. 1, certain modifications have been found desirable. Contemplation of similar studies to be made in connection with the Plutonium Recycle Experiment has suggested other improvements, as discussed in the following paragraphs.

4.1 Modifications of Irradiation Facilities

The long length of chain necessary to manipulate and position the short foil-containing chain in the core was difficult to handle. An alternate method has been tested using a mock-up of an irradiation facility. All the existing restrictions of the EBWR have been considered in the design of the modified facility.

In the alternate design, the upper end of the foil-containing sample chain would terminate in a larger link of about $1/4$ -in. OD. Total lengths of the chain would be 4 to 6 ft, depending on length of fuel assemblies, etc. The irradiation tubes could still be of the U-design, so that samples could be alternately activated in one or the other leg of the U. A simple probe design, with provision for pneumatic transfer, could also be used. In any event, a larger-diameter tube (about 0.27 ± 0.01 -in. ID) would run from the

glovebox through the nozzle and suitable pressure seals, down in the reactor vessel to a point above the core. An adapter (see inset, Fig. 3), affixed to the fuel assembly of interest, would be fitted to the lower end of the larger tubing, connecting it to smaller tubing, such as used in previous EBWR studies (3/16-in. OD, 0.142 ± 0.002 in. ID). The adapter would have an internal taper so that sample chains would not lodge at this point. The enlarged link on the upper end of a sample chain would seat in this tapered adapter during irradiation, the samples being precisely located relative to this adapter.

Since the pneumatic driving force for removal of the chain works on the enlarged bead, alternate designs are possible. If two irradiation locations are desired, and if (in the case of spike-type fuel assemblies) the loops can be installed before the assemblies become highly radioactive, the U-design might be preferred. The adapters could be permanently fastened to the assembly. Samples would be irradiated in one leg at a time, the other leg being used to manipulate the samples pneumatically.

Alternately, if only one irradiation location is needed per facility, and particularly if it is necessary to install or remove the equipment from other than plate-type assemblies in-core, a probe with a second tube connection made at the adapter just below the tapered portion may be preferred. The second tube could be used for air or vacuum to drive the enlarged link, thus manipulating the entire sample chain. Both designs have worked well in mock-up tests.

In connection with modification of the in-reactor design, it is proposed that a large dip or loop be formed in the larger-diameter tubes in the steam-dome area of the reactor vessel. These dips or loops would provide temporary storage of sample chains immediately before and after activation. If the loops were manifolded properly, sample chains could be dropped into their respective tubes before a run, and by application of pressure and/or vacuum, all samples could be transferred to their in-core locations at one time. Subsequently, removal from the core could be accomplished in reverse fashion, and the samples could radioactively decay until they could be transferred to the glovebox or storage containers. This modification has been tried in a mock-up and is recommended for use.

4.2 Modifications of Foil Analysis Equipment

The equipment used in the previous studies was limited to analysis of one sample at a time. With the large number of samples used in a single irradiation, the analysis was a bottleneck in the study. A multiple-position sample changer, as shown in Fig. 17, with several analyzing stations is proposed. Further savings of time could be realized with computer analysis off-line or shared-time on-line. A typical off-line facility and a computer data reduction program are described in the literature.⁽¹⁵⁾

Fig. 17. Proposed Design for Six-bank Automatic Sample Changer

5. CONCLUSIONS

The method described here for the study of neutron flux in the operating power reactor makes available for the first time a convenient, reliable way for obtaining neutron-flux distribution and spectral data without affecting the reactor operation. The method is an adaptation of the foil-activation technique and retains all but the most exotic of the possibilities of data accumulation of that technique. This method uses small spherical foils only 1/16-in. in diameter, which are ideally suited for activation analysis where many foils must be used. The fabrication cost is insignificant in comparison with the time savings and automatic analysis advantages. A broad range of detector materials is available. Cadmium covers or other absorber covers can be used.

The system described here would be directly applicable to several existing power reactors, and by specific design

of selected fuel assemblies (as is being done for the Plutonium Recycle Experiment), could be adapted to practically all such reactors.

Analysis can be performed automatically, with computer off-line or shared-time on-line computation being desirable for large quantities of data.

The method has been demonstrated in the EBWR, yielding much data on the effects of various reactor parameters on the neutron-flux distribution and energy.

ACKNOWLEDGMENTS

The author wishes to acknowledge the valuable assistance provided by the following persons: R. E. Grajek and D. K. Hannaman, for their assistance throughout the project and particularly in the design and construction of the sample handling equipment; D. L. Vetter and his associates, for preparation and installation of the irradiation loops in the reactor; and the Reactor Engineering Division and Reactor Operations Division EBWR staff, for help in conduct of the studies.

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