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Portable Active Neutron Interrogation System for Light-Water Reactor Fuel Assemblies

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PORTABLE ACTIVE NEUTRON INTERROGATION SYSTEM FOR LIGHT-WATER REACTOR FUEL ASSEMBLIES

by

J. D. Brandenberger, H. O. Menlove,
and E. Medina

ABSTRACT

The portable active interrogation assay system for light water reactor fuel assemblies is described. Methods for its calibration and use are given and results of several tests are presented that indicate the results to be expected from the instrument.

I. INTRODUCTION

The portable active neutron interrogation system for light-water reactor (LWR) fuel assemblies, hereafter called the collar, was designed to assay pressurized-water reactor (PWR) and boiling-water reactor (BWR) fuel assemblies. A $^{241}\text{AmO}_2\text{-Li}$ neutron source, with spectrum moderated by the polyethylene frame of the assay system, actively interrogates a fuel assembly for fissile content with subthreshold thermal and epithermal neutrons. A large fraction of the thermal and epithermal neutrons entering the fuel assembly cause fissions to occur in the fissile material. A fission neutron spectrum is thus induced, which has a yield that is a function of the fissile mass in the fuel assembly and which has an average neutron energy higher than that from the moderated

Fig. 1. Portable assay system for LWR fuel assemblies. The components are discussed in Section II. Counting electronics are not shown.

$^{241}\text{AmO}_2\text{-Li}$ source. Two ^4He detectors are used and measure the relative fluence of the induced fission neutrons from the fuel assembly. The assay system is shown in Fig. 1 and its characteristics are given in Table I.

II. DETAILED DESCRIPTION OF THE ASSAY SYSTEM.

A. Introduction

The principal components of the assay system are the polyethylene main frame, the interrogating neutron source, the ^4He neutron detectors, and the electronic counting system for the neutron detectors.

B. Polyethylene Moderating Assembly

Figure 2 shows that the bulk of the assay system consists of the polyethylene main frame. There are two arms whose span is adjustable to fit around a fuel assembly, a back-piece which supports the arms and the source holder, and the source holder. In the top cutaway view of Fig. 2, channels formed between the source and the fuel element position can be seen. This design, with the polyethylene arms, causes the interrogating thermal neutron source to appear more diffuse to an LWR fuel assembly and thus results

TABLE I

Characteristics of the Assay System

Dimensions

Height: 0.400 m
 Width: 0.305 m
 Depth: 0.255 m

Weight: 18 Kg

Arm Span Adjustment: Steps from 0.10 m to 0.23 m

Driving Neutron Source: $^{241}\text{AmO}_2\text{-Li}$, about 10 Ci
 5.5×10^5 neutrons - s^{-1} .

Neutron Detectors: Reuter-Stokes ^4He ,
 Diameter 0.05 m, active length 0.30 m, pressure 18 atm
 Maximum voltage: 3500 v
 Operating voltage: 1900 v

Preamplifier: Canberra Model 806

Counting Electronics: Supplied by User

in significantly better interrogation of the side and interior region of the fuel assemblies. To reduce effects from nearby SNM, the main frame is clad with sheet cadmium on the outside.

C. Interrogating Source

The neutron source is $^{241}\text{AmO}_2$ in powdered form mixed with lithium, which produces neutrons by the $^7\text{Li}(\alpha, n)^{10}\text{B}$ reaction. Because alpha particles of various energies participate in the (α, n) reaction, and because the neutrons are emitted at various angles with respect to the alpha-particle trajectories, the source has a continuum of neutron energies. This continuum peaks at ≈ 0.3 MeV; there are few neutrons with more than 1.5 MeV. Details for the $^{241}\text{AmO}_2\text{-Li}$ sources are given on the manufacturer's technical information sheet, Table II. To reduce the intensity of the gamma rays, the sources for use with the assay system are encapsulated in a 5.0 cm by 13.4 cm tungsten cylinder with

Fig. 2. Drawing of the collar showing dimensions, assembly details, and details of the source holder.

0.88 cm walls as shown in Fig. 3. The dose rates are 1) less than 1 mR for gamma rays 10 cm from the collar and 2) less than 1 mR/h for neutrons 35 cm from the collar.

D. Detectors

The fission neutrons resulting from thermal and epithermal interrogation of a fuel assembly are detected by two 5 cm diam by 30 cm long ^4He proportional counters. These tubes, containing helium at 18 atm, should be operated at 1900 V. Table III gives the specifications of the Reuter-Stokes detectors.

E. Electronics

Use of the assay system requires counting electronics for the ^4He detectors. A Salina BS 27/N multichannel pulse height

analyzer (PHA) with a Canberra 806 preamplifier is a suitable electronic counting system for the ^4He detectors. High voltage for the detectors and preamplifier power are both provided by the PHA. Alternate electronic packages might consist of 1) a preamplifier, amplifier, pulse height discriminator, scaler, and power supplies, or 2) a Sam II unit which provides the above functions in a single package. The Canberra 806 charge sensitive preamplifier provides pulses of appropriate shape and amplitude for the Salina BS 27/N. Characteristics of the Canberra 806 included with the assay system are given in the manufacturer's manual.

The Salina PHA has a variable gain at the signal input so that signal amplitudes can be adjusted for collection in 256, 512, or 1024 channel sections of the memory. Computing capability exists for integrating the number of counts above a predetermined channel number (discrimination level). Spectra from the PHA can be stored on magnetic tape for later analysis or reanalysis of a fuel assembly assay. The user

Fig. 3. Cylindrical tungsten γ -ray shield for the 10 curie $^{241}\text{AmO}_2\text{-Li}$ source.

TABLE II

Characteristics of $^{241}\text{AmO}_2\text{-Li}$ Neutron Sources

Technical Information				SHIPPING CONTAINER DESCRIPTION	
Type of Source:	neutron	Chemical Form: AmO_2		10 gallon drum	6M-1023
Isotope:	Am-241				
Target (if any):	lithium				
				USA DOT Spec. 6m, Type B	
Source No.	Am't of Isotope	Wt. of Target	Particle Energy	Emission Rate-Rate	
MRC-AmLi-72	9.94 Ci or 2.901 g	17.5 g	n.m.	6.2×10^5 n/s	
MRC-AmLi-73	8.51 Ci or 2.481 g	17.5 g	n.m.	5.3×10^5 n/s	
MRC-AmLi-74	9.94 Ci or 2.901 g	17.5 g	n.m.	6.2×10^5 n/s	

Source(s) Container Description: MRC Model 24132
Stainless Steel, 1.250" O.D. X 4.25" O.L

is expected to provide the Salina PHA and have access to its instruction manual.

III. OPERATION OF THE ASSAY SYSTEM

A. Detailed Steps for Calibration

The measured response of the assay system corresponds to all of the pulses (counts) in the Salina PHA above a predetermined discrimination level (channel number in the PHA). A suitable discrimination level (DL) should be experimentally determined to give good statistical results in a reasonable time. Calibration of the assay system is done by counting a known or standard fuel assembly, and also the $^{241}\text{AmO}_2\text{-Li}$ source in its calibration position (see Fig. 4). During field operation, the calibration is done by again placing the $^{241}\text{AmO}_2\text{-Li}$ neutron source between the two ^4He detectors to establish the previous DL. Figure 5 gives the response to the $^{241}\text{AmO}_2\text{-Li}$ source as a function of DL. For good sensitivity to fissile material in the interior region of a PWR fuel

TABLE III

⁴He Neutron Detector Characteristic

Model Number RS-PS-1612-201
Serial Number V-2972

TEST RESULTS

Resistance: $10 \times 10^{+13}$ ohms

Capacitance: 8.0 pf

Tested for Voltage Breakdown to 3500 volts.

assembly, a DL similar to B in Fig. 5 is recommended. A single 1000s spectrum of the source in this position can be used to determine the DL with a statistical precision of $\approx 0.5\%$. Any room background component should be subtracted from this source count. Since the response for an assay is linear for small changes in the calibration DL as shown in Fig. 6, a renormalization is possible for small changes from the original calibration with $^{241}\text{AmO}_2\text{-Li}$.

B. Detailed Steps for Assay

After the assay system has been calibrated, it is ready for use in a verification. The working standard for a verification of a fuel assembly may be a previous equivalent measurement on either 1) the fuel assembly being assayed or 2) a fuel assembly considered to be identical for practical purposes. If the latter is used as a standard, one must have confidence that the fuel loading, presence of burnable poisons, etc., is the same in both the "standard" and the fuel assembly being verified.

For an assay, the $^{241}\text{AmO}_2\text{-Li}$ driving source is placed in the source housing shown in Fig. 2. The polyethylene arms must be in the same position used for the calibration, and the assay system is placed next to the fuel assembly to be assayed as shown in Fig. 7. A spectrum of the neutron counts from the ⁴He detectors

Fig. 4. Neutron collar with Am-Li neutron source in position for field calibration.

Fig. 5. The response of the neutron collar as a function of discrimination level (DL) with the $^{241}\text{AmO}_2\text{-Li}$ neutron source in the calibration position. The gain is adjusted so that 10 corresponds to channel 1000 on the Salina PHA, the B corresponds to a DL at channel 125.

Fig. 6. Response of the neutron collar to an interrogation of a PWR fuel assembly as a function of discrimination level (DL) near the DL noted in Fig. 5 by B. On Salina PHA, the response is nearly linear for 10 channels on either side of B.

is collected in the Salina PHA for a time, e.g., 1000s, appropriate to the assay precision required. This spectrum will ordinarily be recorded on magnetic tape for future reference or analysis, and the counts above the calibration DL are computed by the PHA for a real-time assay. A background count, corresponding to the detector response with the fuel assembly removed, is taken before the verification measurements. After counts in the background spectrum are subtracted, the response is then compared to a similar measurement on the working standard.

An assay of a PWR fuel assembly is quantitatively different from that of a BWR fuel assembly. PWR fuel assemblies are generally physically larger than the BWR fuel assemblies. This larger size makes it much more difficult for the thermal neutrons to penetrate into the interior of the assembly; an assay of a PWR is much more sensitive to the fuel rods near the outside of the assembly than to SNM in the interior. This sensitivity to fissile material for various regions of the assembly is discussed in detail

Fig. 7. Neutron collar next to PWR fuel assembly in assay position. The small circles represent individual fuel rods in part of a 15-by-15-rod assembly. The numbers are used to designate regions of the assembly for sensitivity tests.

in Sec. IV. For BWR fuel assemblies, on the other hand, Menlove et al., have succeeded in making the relative response of the different rod locations approximately uniform.¹

It is important to note that an assay of a LWR fuel assembly verifies an expected loading rather than achieves a quantitative assay of an unknown assembly.

IV. PERFORMANCE CHARACTERISTICS

A. Introduction

Section IV discusses the results of measurements using the assay system which gives quantitative information on 1) the geometrical effects of locating the assay system near the end of a fuel assembly or in the close vicinity of an adjacent fuel assembly, 2) the sensitivity for fissile material in various regions of a fuel assembly, and 3) relative assay uncertainties. Finally, other possible uses of the assay system are mentioned.

B. End Effects and Cross Talk

Tests were made to determine the effects on a measurement as 1) the assay system approached the end of a fuel assembly, 2) the assay system approached a concrete wall and 3) the assay system approached a neighboring fuel assembly. The results of these tests are shown in Figs. 7 and 8, which may be used to determine the environment suitable for an assay. The conclusions of these tests are that the instrument should be used at positions at least 30 cm away from the ends of the fuel elements, and that neighboring fuel assemblies or reflecting walls should be at least 20 cm away from the instrument. When there is a significant effect from walls or other assemblies, the same geometry should be used for the background (no element) measurement and then the net result will be free from the interference.

C. Precision of the Assay System

For maximum sensitivity (precision), the calibration DL is set to count the maximum number of fission neutrons while still excluding counts from electronic noise and most of the counts from the driving $^{241}\text{AmO}_2$ -Li source. Figure 5 shows such a DL. The

Fig. 8. Response of the assay system as a function of proximity to a concrete wall (Δ) and a nearby fuel assembly ($\circ$). The line represents the constant background of an assay system far from a wall or fuel assembly.

Fig. 9. Response of an axial scan of a fuel assembly. The asymmetry is probably caused by neutron reflection from the floor. The collar should be ≥ 30 cm from either end for an assay.

PWR test case represents a difficult but typical assay problem in which a 15-rod-by-15-rod fuel assembly was assayed. The results of the sensitivity test are summarized in Table IV.

In a similar sensitivity test of a 6-rod-by-6-rod BWR fuel assembly with 1000s measurements it was possible to detect the substitution of four 1.77% ^{235}U rods for the normal 2.34% rods in the center of the assembly¹ or the removal of a single rod from any part of the assembly. For the BWR fuel assembly, however, the response and hence the sensitivity was almost uniform throughout the entire fuel assembly as shown in Fig. 10.¹

TABLE IV

Sensitivity for Fissile Content Verification
of 15- by 15-Rod Fuel Assembly

Region From Fig. 7

Number of Rods Missing for Detecta-
 bility with 95% Confidence in 1000s
 Verification Assay

	Rods	Percentage of PWR Rods
1	0.8	0.4
2	1.3	0.6
3	1.1	0.6
4	2.7	1.1
5	2.2	1.0
6	1.4	0.6
7	4.2	2.0
8	3.3	1.5
9	2.4	1.1
10	7.7	3.4
11	5.8	2.1
12	2.7	1.1

D. Uncertainties of the Assays

Significant sources of uncertainty in an assay can be identified as 1) statistical uncertainty, 2) uncertainty from the precision of the calibration and 3) electronic instability. Electronic instability should be a small effect which can be further reduced by frequent calibration of the assay system with the Am-Li neutron source. With stable electronics it can be made small compared to statistical uncertainties, σ_{st} . In a careful calibration, the resulting uncertainty σ_{cal} can be made as small as the change

Fig. 10. Source and detector configuration for the assay of a 6-rod-by-6-rod BWR fuel assembly. The numbers correspond to the relative decrease in counting rate caused by the removal of the various rods.

in counts in the assay corresponding to a change of one channel in the DL. Since σ_{cal} is to some extent systematic,

$$\left| \sigma_{st}^2 + \sigma_{cal}^2 \right|^{1/2} \leq \sigma_{net} \leq \sigma_{st} + \sigma_{cal} .$$

The precision of an assay at the 95% confidence level is then simply $2 \sigma_{net}$.

E. Other Uses

The assay system can be used to perform assays of other types of fuel assemblies, such as those used for heavy-water reactors of the Candu type. In principle, the assay system can be used to verify an expected configuration that contains SNM in quantities and sizes similar to LWR fuel assemblies.

¹ H. O. Menlove, S. Siebelist, M. DeCarolus, and A. Kaddar, Los Alamos Scientific Laboratory report LA-6530-PR, (October 1976) p 12.