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Nondestructive Assay of Sphere-Pac Fuel Rods

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NONDESTRUCTIVE ASSAY OF SPHERE-PAC FUEL RODS

E. J. Allen,* P. Angelini, S. P. Baker,† J. L. Heck,‡ and J. E. Mack

ABSTRACT

Sphere-pac fuel, which contains several sizes of high-density spheres loaded into tubes and vibratorily compacted to high smear densities, appears to have several advantages over conventional pellet fuel and is especially suited for remote fuel fabrication. In addition, sphere-pac rods appear to be more resistant to radiation damage because fuel-cladding interactions are not as severe. For these reasons, the sphere-pac process is a promising alternative fuel fabrication method, especially for ^{233}U -fuels, spiked fuels, or any fuel with a high gamma ray background.

Nondestructive assay (NDA) methods were studied for application to sphere-pac fuel with a high gamma ray background. It was decided that the NDA method selected should be capable of measuring total fissile content of each fuel rod as well as determining the axial fissile distribution because assay techniques that employ detection of spontaneous or induced gamma ray emission are not practicable because of the high gamma ray background of candidate fuels. Therefore, methods employing neutron detection were studied for use with sphere-pac fuel rods.

Sphere-pac fuel is a viable alternative for either light-water reactor (LWR) or fast breeder reactor (FBR) fuel, and thus methods were studied for application to either fuel type. A technique employing thermal-neutron irradiation and fast fission-neutron detection appears to be practicable for assay and fissile homogeneity inspection of LWR-type fuel rods. Various experiments were conducted to investigate this method for use with LWR sphere-pac fuel. However, this method does not appear useful for assay of FBR fuel rods because of the higher absorption and self-shielding of the thermal neutrons in the higher fissile density FBR fuel. A method using ^{124}Sb -Be 26-keV neutrons and fast fission-neutron detection was identified as being potentially capable of providing assay and fissile homogeneity inspection of FBR fuel rods that have a high gamma ray background.

An existing experimental assay device using thermal-neutron irradiation and fast fission-neutron detection was studied for application to LWR sphere-pac fuel rods. The device was modified such that the tube through which the fuel rods were

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translated was covered with cadmium except for a small region near the detectors. The thermal neutrons, from a ^{252}Cf neutron source in a moderator assembly, could not penetrate the cadmium and, therefore, fissions occurred only in the small cadmium-free region of the fuel rod. Thus, the axial fissile distribution of the fuel rod could be measured. Various cadmium gap sizes were experimentally studied, and sphere-pac fuel rods with intentional small axial voids were assayed. Analysis procedures were identified for use with this assay technique. Fissile homogeneity inspection criteria for LWR sphere-pac fuel were assumed to be the same as for LWR pellet fuel, and the criteria could be satisfied by using assay speeds of 100 to 200 mm/min and a 1-mg ^{252}Cf neutron source. A two-channel fuel-rod assay device was designed.

INTRODUCTION

Sphere-pac nuclear fuel is composed of a specific mixture of two to four sizes of high-density spheres. The sphere mixture is loaded into Zircaloy or stainless steel tubes and compacted by low-energy vibration to achieve smear densities 83 to 88% of theoretical. The sphere-pac fabrication process is more adaptable to remote handling and fabrication than conventional pellet-type fuel fabrication and therefore is a promising alternative for fabricating ^{233}U -containing fuel or spiked fuel. Also, irradiation tests indicate that sphere-pac fuel is more resistant to irradiation damage than pellet fuel.

Inspection of the loaded fuel rods for fissile material and density homogeneity is necessary to satisfy quality control requirements. Total fissile material measurement of each rod is necessary to satisfy material accountability requirements. For moderately to highly radioactive fuel (e.g., ^{233}U fuel and spiked fuel) the fissile material measurement technique must be relatively insensitive to gamma radiation. Nondestructive assay (NDA) techniques employing detection of spontaneous or induced gamma ray emission do not appear useful because of the high gamma ray background of such fuels. Also the NDA technique selected should be spatially sensitive to the axial fissile material distribution in the fuel rod.

SPHERE-PAC FUEL DESCRIPTION

The major steps in the sphere-pac process are shown in Fig. 1. The major steps in producing the spheres are sphere forming and gelation and sphere calcination and sintering. Details on these steps in the process have been reported.^{1,2}

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Fig. 1. Major Steps in the Gel-Sphere-Pac Process.

The spheres are loaded into fuel rods and compacted by low-energy vibration to high densities. Packing studies have shown that at least three particle sizes are needed in fuel rod loading to achieve acceptable densities. When spheres with diameters of 30, 300, and 1200 μm , designated as fine, medium, and coarse, respectively, are used smear densities of 87% of theoretical are achieved. The mixture of the three sizes for high-density packing is approximately 17 wt % fine, 20 wt % medium, and 63 wt % coarse. In certain fuel concepts, the fine spheres are composed primarily

of fertile material while the medium and coarse spheres contain the fissile material. Usually, however, all three sphere types are considered to have the same composition.

ASSAY TECHNIQUES

The methods selected to measure the fissile material content of sphere-pac fuel rods must be relatively insensitive to a possibly high gamma ray background from the fuel and be spatially sensitive to the axial fissile material distribution. In addition, the NDA method must be adaptable to LWR-type fuel as well as to FBR-type fuel or separate NDA methods for the two fuel types must be identified.

The above requirements cannot be simultaneously satisfied with currently used nondestructive assay devices if the fuel has a high gamma activity. Nondestructive assay methods employing detection of spontaneous or induced gamma ray emission are not practicable for fuels that have high levels of gamma radiation. Assay methods insensitive to the high gamma ray background may not be particularly sensitive to the fissile material axial distribution. In addition, certain assay techniques that work well for LWR fuel may not be satisfactory for assay of FBR fuel because of its higher fissile material density.

Three NDA methods were identified as being capable of satisfying the above requirements for assay of sphere-pac fuel rods. All three methods use neutron interrogation and fast fission-neutron detection. Two techniques use intermediate-energy interrogating neutrons and are suitable for LWR fuel as well as for FBR fuel. The third technique uses thermal neutron interrogation suitable for LWR fuel but probably is not suitable for FBR fuel because of its greater self-shielding of the interrogating thermal neutrons. However, assay of LWR fuel can be more rapid with thermal rather than intermediate-energy neutron irradiation. These techniques are described in the following sections for assay of LWR and FBR fuel.

A calculational study was undertaken to determine whether an assay technique employing thermal-neutron irradiation and fast fission-neutron detection could also be used with fast reactor fuel. A one-dimensional

cylindrical model of an FBR fuel rod being irradiated with neutrons from a ^{252}Cf neutron source in a moderator assembly of polyethylene and heavy water was developed. The discrete-ordinates transport computer code³ XSDRNPM was used to calculate fission rates in the FBR fuel rod. The fuel rod was modeled to have a diameter of 6 mm and a ^{239}Pu axial fissile content of 40 or 44 g/m. Four computations were made with various radial fissile distributions in the fuel rod as described in Table 1.

Table 1. Thermal-Neutron Irradiation Calculations
of FBR Fuel Rods

Calculation	^{239}Pu Linear Density, g/m			Relative Fission Rate
	Inner Half Volume	Outer Half Volume	Total Volume	
1	20	20	40	10.319
2	22	18	40	10.263
3	18	22	40	10.387
4	22	22	44	10.615

The first three computations are for a fuel rod containing on the average 40 g $^{239}\text{Pu}/\text{m}$, although the radial fissile density varies $\pm 10\%$ from the average. For these cases, the fission rate or ultimately the count rate only changes by about 0.6%, although the radial fissile distribution changes $\pm 10\%$. In the fourth computation, the fissile content throughout the rod is increased by 10% to 44 g $^{239}\text{Pu}/\text{m}$. The calculated increase in fission rate for a 10% increase in fissile content is only 2.9%. In other words, a 2.9% increase in count rate or fission rate indicates a 10% increase in fissile content. A 0.6% increase, obtained by radial fissile density variations, would therefore indicate a 2.1% increase in fissile density. Because of the low sensitivity of fission rate to fissile content for thermal irradiation of FBR fuel rods, we recommend that thermal-neutron irradiation assay techniques not be used for FBR fuel rods. This conclusion agrees with that reached by other investigators.⁴

For assay and fissile homogeneity inspection of FBR fuel rods that have a high gamma-ray background, an NDA technique developed at Los Alamos Scientific Laboratory for assay of reactor fuel rods and small samples^{5,6} appears promising. In this method, a ^{124}Sb -Be 26-keV neutron source and ^4He fast-neutron detectors are placed in an assembly similar to that shown in Fig. 2. The fuel rod is exposed to intermediate-energy neutrons and the fuel rod is moved next to the source. As lead shielding is already present between the ^4He detectors and the fuel rod to prevent interference from the ^{124}Sb gamma rays, the response of the device is insensitive to

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Fig. 2. Schematic Diagram Showing a Cross Section of the LASL ^{124}Sb -Be Fuel Rod Assay Device.

gamma radiation from the fuel. Also, since the interrogating neutrons have intermediate energy and are therefore penetrating, the high fissile density of FBR fuel rods does not present a self-shielding problem. However, the source and reflector design needs to be modified to obtain a spatially small irradiation region at the fuel rod for measurement of the axial fissile distribution. High-intensity neutron sources ($\sim 10^8/\text{s}$) can be obtained by using 100 to 200 Ci of ^{124}Sb positioned in a beryllium piece about 40 mm in length.⁷ With a suitable nickel reflector assembly, an axial fuel region about 80 mm in length will be under the most intense neutron irradiation. This is sufficient that inhomogeneities in the fissile distribution can be detected. We estimate that approximately 400 counts/s can be obtained per gram ^{239}Pu by using 100 to 200 Ci of ^{124}Sb .

This method has several disadvantages. The ^{124}Sb sources will have to be routinely replaced because the half-life of ^{124}Sb is only 60.9 d. In addition, the lead shielding of the ^{124}Sb -Be device described by Menlove et al.⁵ will have to be increased for a 100 to 200 Ci source to limit the dose rate at the detectors to less than 10 rd/h. Also, even by using a $10^8/\text{s}$ neutron source and local intense irradiation of the fuel rod, the assay speed to satisfy the fissile homogeneity inspection criteria may be so low that several such devices would be needed in a fuel fabrication facility. In this case, perhaps such a device can be used for total fissile material measurement only, and other techniques (e.g., gamma-ray densitometry) can be used for axial fuel homogeneity inspection.

A second NDA technique that looked promising for assay and fissile homogeneity inspection of FBR fuel rods was developed by National Nuclear Corporation.⁸ This method uses a ^{238}Pu -Li (α, n) neutron source and a doughnut-shaped ZnS fast neutron detector (Hornyak button). The intermediate-energy neutrons from the ^{238}Pu -Li source have good penetration in the FBR fuel rods and the ZnS detector has a geometry suitable for good spatial sensitivity of the axial fissile content. However, this method has two serious disadvantages. The neutron source is limited to about $10^6/\text{s}$, restricting the assay speed for fissile homogeneity

inspection. The ZnS detectors are more sensitive to gamma-ray radiation than are ^4He detectors⁹ and would therefore have to be moved back further from the fuel rod and shielded with lead.

EXPERIMENTAL ASSAY DEVICE

The NDA method that appears most promising for LWR sphere-pac fuel rod assay and fissile homogeneity inspection uses thermal-neutron irradiation and fast fission-neutron detection. The method considered was originally developed at Los Alamos Scientific Laboratory (LASL) for assay of LWR fuel rods.¹⁰ The method later appeared attractive for assay of high-temperature gas-cooled reactor (HTGR) fuel rods and was evaluated for this purpose.¹¹ The neutron source is ^{252}Cf , and the neutrons are thermalized in an arrangement of heavy water and polyethylene, as shown in Fig. 3.

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Fig. 3. Cross-Sectional View of Fuel Rod Nondestructive Assay Device.

The fast-neutron detectors are ^4He proportional counters, which are relatively insensitive to gamma radiation. Basically the device operates as follows: thermal neutrons from the source cause fissions in the fissile material of the fuel rod, and the fast neutrons from the fission events are detected by the ^4He detectors. The count rate is therefore proportional to the fissile content of the fuel rod. By wrapping cadmium, which is a strong neutron absorber, around the tube in which the fuel rod travels except for a small region near the detectors, the thermal source neutrons are prevented from interacting with the fuel rod except in this small cadmium-free region. Spatial sensitivity is thus achieved, and the fissile axial distribution in the fuel rod can be measured by this method. This technique was experimentally studied for application to assay of sphere-pac fuel rods, and the main body of this report is addressed to describing this method and the experimental evaluations.

The experimental assay device is a modification of the device used for investigation of HTGR fuel rods.¹¹ It is shown in Fig. 4. A ^{252}Cf neutron source is positioned in the center of a cylindrical drum about 0.6 m in diameter and 0.6 m in length. Surrounding the neutron source are annular regions of 18.3 mm tungsten, 23.4 mm polyethylene, and 250 mm heavy water, in order. The tungsten shields source gammas and moderates through inelastic scattering the high-energy source neutrons. The polyethylene and heavy water further moderate the source neutrons.

A polyethylene shell at the drum surface contains holes for the detector tubes and fuel rod samples. In the experimental assay device only one hole is used, but a production device will have a series of such channels at equal angular spacings around the drum for multiple fuel rod assays. According to results of simultaneous multiple fuel-rod assay experiments,¹¹ we estimate that 10 to 12 fuel rods could be assayed simultaneously with only small corrections to be applied for interference between adjacent channels. Thus, channels will be spaced 30 to 36° apart on the production assay device.

The counting instrumentation is located outside the hot cell, and a block diagram of the instrumentation is given in Fig. 5. The signals

Fig. 4. Experimental Assay Device.

Fig. 5. Block Diagram of Neutron Detection Instrumentation for the Nondestructive Assay System.

from the discriminator can be sent to a Tracor Northern (TN-1700) multi-channel analyzer. A Data General Corporation NOVA computer operates the TN-1700 and can be programmed to analyze the counting data.

The detectors were manufactured by Reuter-Stokes. The detectors contain ^4He gas at 203 kPa (15,200 torr), have an active length of 152.4 mm,

and have a diameter of 38.1 mm. The anode diameter is 50 μm . Rushton et al.¹¹ determined the gamma sensitivity of the detectors at various gamma ray dose levels. The detectors are relatively insensitive in a 10 rd/h gamma ray background, but the sensitivity increased appreciably in a 25 rd/h gamma ray background.

Operation of the experimental assay device is relatively simple. A fuel rod sample is loaded into a grooved track that leads to the sample hole. A threaded rod driven by a stepping motor advances the sample at a constant speed between the detectors. After the fuel rod has moved through the assay device, it is removed and the next fuel rod sample is loaded onto the track.

The assay device is located in the Thorium-Uranium Recycle Facility (TURF) at Oak Ridge National Laboratory. To facilitate design changes and to protect personnel from the unshielded ^{252}Cf neutron source when experiments are being conducted, the device is situated in an uncontaminated shielded hot cell (Hot Cell B). When not in use, the source can be removed from either assay device and stored in a biologically shielded tank, allowing safe entrance to the cell.

The ^{252}Cf neutron source is contained within a 15.9-mm-OD by 375-mm-long stainless steel tube, which can be positioned into the assay device. The source is sealed in a small metal capsule, which is screwed to the end of a polyethylene rod. The rod is sealed in the stainless steel source tube. As of July 1, 1978, the source had an activity of about 1.4×10^9 neutrons/s. The half-life of ^{252}Cf is 2.63 years and its specific activity is about 2.3×10^{15} neutrons/(s $\cdot$ kg).

ANALYSIS PROCEDURES

A summary of statistical considerations in the design and utilization of high-speed rod scanners has been published.¹² A simplified statistical treatment is presented in this section, but the notation is similar to that used by Costello and Gozani.¹²

For application of this method, a sphere-pac fuel rod is considered as being composed of a number of equally long segments. The analysis

procedure using the count rate data determines whether the fissile content of each segment is within or outside the fissile content specifications. This analysis procedure assumes that the frequency of off-specification segments is so low that the probability of two off-specification segments being next to each other would be very low. Several definitions are presented first:

M_i = the detector response for the i th segment,

B_i = the detector response for the i th background,

L = effective size of the detector in terms of number of segment lengths,

A_j = detector spatial response function; namely the relative contribution of the j th section of the detector, where

$$\sum_{j=1}^{L+1} A_j = 1 ,$$

and

C_i = count in the i th time interval for the time required for a segment to pass its own length.

Using the above definitions, Eq. (1) can be readily written as follows:

$$C_i = \sum_{j=1}^{L+1} A_j M_{i-j+1} + B_i . \quad (1)$$

Now, let a particular (k th) segment pass $L + 1$ lengths through the detector. During this time interval, the total number of counts accumulated is given by Eq. (2):

$$C_T = \sum_{m=0}^L C_{i+m} = \sum_{m=0}^L \sum_{j=1}^L A_j M_{i+m-j+1} + \sum_{m=0}^L B_{i+m} . \quad (2)$$

If all $L + 1$ segments have the nominal loading except for the k th segment, one has $M_i = M$ for $i, i + 1, \dots, i + L, i \neq k$, and $M_k = M + \Delta M$, where M is the basic detector response for a nominal segment and ΔM is the amount an off-specification segment deviates from the nominal one.

Then Eq. (2) becomes for the off-specification pellet Eq. (3):

$$C_T = (L + 1)M + \Delta M + (L + 1)B . \quad (3)$$

The standard deviation of C_T , by Poisson counting statistics, is just $\sqrt{C_T}$. The standard deviation of C_T is given as Eq. (4):

$$\sigma_{C_T} = C_T^{1/2} = (L + 1)^{1/2}(M + B)^{1/2} . \quad (4)$$

The number of standard deviations indicated by an off-specification segment for the total count during the time the off-specification segment passes through the detector region is given by Eq. (5):

$$N_s = \frac{\Delta M}{\sigma_{C_T}} = \frac{\Delta M}{(L + 1)^{1/2}(M + B)^{1/2}} = \frac{C_T - C_T'}{C_T^{1/2}} , \quad (5)$$

where

N_s = number of standard deviations indicated by off-specification segment,

C_T = counts obtained for off-specification segment, and

C_T' = counts obtained for within-specification segments.

Note that the number of standard deviations indicated by an off-specification segment can possibly be increased by summing only those counts for which the off-specification segment passes through the detector region in which the A_j are greatest. An analysis of the count data obtained with the experimental assay device revealed that N_s was greatest for the sum of the counts for the total time the off-specification segment contributed to the detector response.

As an example, assume that the segment length is 10 mm, the effective detector length is 50 mm, M and B are each equal to 1000, and ΔM is 500. L is readily calculated to be equal to 5. By Eq. (3), C_T' and C_T are 12,000 and 12,500, respectively. By Eq. (4), $\sigma_{C_T} = 110$. From Eq. (5), N_g is 4.6. Therefore, a deviation of 4.6 standard deviations in the total count is obtained during the time a segment off specification by 50% passes through the detector region in this example.

SPECIFICATIONS ON FISSILE MATERIAL DISTRIBUTION

The specifications on fissile material distribution have not been developed for sphere-pac fuel rods. However, it appears that current specifications for pellet fuel can be conservatively used for sphere-pac fuel. Specifications on fissile material distribution in pellet fuel rods were developed in conjunction with suitable hot-spot factors to limit the probability of hot spots occurring in the fuel during reactor power operation. In pellet fuel, the heat flow is restricted in the axial direction by contact resistances between fuel pellets and in the radial direction by a gas gap. In sphere-pac fuel, neither of these restrictions to heat flow is present and as a result the fuel is more resistant to hot-spot formation due to nonhomogeneous fissile distributions. Therefore, it appears that specifications for fissile material distributions in pellet fuel can be conservatively used for sphere-pac fuel.

On the basis of current LWR pellet-fuel inspection criteria, two specifications have been postulated for fissile homogeneity inspection of sphere-pac fuel. They are (1) a 99% probability of detecting a 25% deviation in average fissile content in a 13-mm fuel segment and a 1% false reject probability of a good rod and (2) a 95% probability of detecting a 12.5% deviation in average fissile content in a 13-mm fuel segment and a 5% false reject probability of a good rod.

A LWR fuel rod may contain 280 of these 13-mm fuel segments. The fuel rod is rejected if the measured fissile content of any of these segments deviates by more than 25 or 12.5%, depending on the specification

used, from the desired fissile content. In order to detect an off-specification segment with the probability specified by the inspection criteria, the off-specification segment must deviate from the average by a certain number of standard deviations. This number of standard deviations can be determined as described below:

Let P_R = rejection probability of a good segment,

Then $(1 - P_R)$ = acceptance probability of a good segment.

As there are 280 segments in a fuel rod,

$$\begin{aligned} 1 - (1 - P_R)^{280} &= \text{rejection probability of a good fuel rod,} \\ &= 0.01 \text{ (first specification),} \\ &= 0.05 \text{ (second specification).} \end{aligned}$$

Therefore,

$$\begin{aligned} P_R &= 2.59 \times 10^{-5} \text{ (first specification),} \\ &= 1.83 \times 10^{-4} \text{ (second specification).} \end{aligned}$$

If the distribution of measured fissile content about the average is normal, rejecting no more than 1 or 5% of the good fuel rods requires control limits of $\pm 4.13\sigma$ or $\pm 3.74\sigma$, respectively, where σ is the standard deviation in measured fissile content for each segment.

In addition, a bad segment must be identified with a 99 or 95% probability for the first or second specification, respectively. Therefore, the measured fissile content of these segments must lie 2.33σ or 1.64σ , respectively, beyond the control limits. The measured fissile content of an off-specification fuel segment must therefore lie beyond the desired fissile content by the following total number of standard deviations:

$$\begin{aligned} N_g &= 6.46 \text{ [for fissile homogeneity inspection specification (1)];} \\ N_g &= 5.38 \text{ [for fissile homogeneity inspection specification (2)].} \end{aligned}$$

Therefore, N_g given in Eq. (5) must be at least 6.46 or 5.38 to satisfy specification 1 or 2, respectively.

EXPERIMENTAL ANALYSIS

Several experiments were performed on the experimental assay machine modified for assay of sphere-pac fuel rods. An experiment to determine spatial response functions for various cadmium widths was performed. Background-corrected counts for a capsule containing 93 mg ^{235}U , approximately 3 mm in length, were measured and are plotted vs position in Fig. 6.

Fig. 6. Detector Spatial Responses for 25- and 50-mm Cd Gaps.

For a given fuel rod scanning speed, the number of counts accumulated with the 50-mm Cd gap would be about twice that with the 25-mm gap. At any time, however, a larger region of the fuel rod is being interrogated when the wider gap is used. The data in Fig. 6 were fit with main straight line segments since this greatly simplified the theoretical calculations performed to compare the experimental and calculated response. The deviation of the straight-line fit from the experimental points at positions distant from the maxima are of minor consequence since the counts obtained at those positions are such a small fraction of the total.

The second experiment used two sphere-pac fuel rods. Each was loaded with one size range of UO_2 spheres (1150 to 1410 μm in diameter) to lengths of 530 mm. One rod contained fuel with a ^{235}U enrichment of 2.53% and the other of 10.95%. The inside diameter of each cladding tube was 9.6 mm and the axial ^{235}U densities in the fuel rods were 10.5 and 45.6 g/m, simulating LWR fuel rods. Each fuel rod had two aluminum spacers, 3 and 6 mm in length, loaded at specified positions to represent voids in the fissile distribution. The rods were then scanned at 25.7 mm/min on the prompt-neutron assay machine with a 500- μg ^{252}Cf source and cadmium gap sizes of 25 and 50 mm. The count rate data using a 50-mm Cd gap are plotted in Fig. 7 for the 2.5%-enriched fuel rod. For comparison, a densitometer scan of the same fuel rod is presented in Fig. 8. This densitometer scan verified the gap locations indicated by the prompt-neutron assay system. The assay count rate data indicate that, even for detecting small heterogeneities, a 50-mm Cd gap is more efficient than a 25-mm Cd gap. An analysis of this experiment is presented next.

The numbers of counts accumulated when the spacers passed the cadmium gap are given in Table 2. Table 2 also indicates the decrease in numbers of counts due to the spacers in terms of the number of standard deviations. It appears from the data that use of a 50-mm Cd gap gives better results than use of a 25-mm Cd gap.

It is worthwhile to estimate the assay speed required to satisfy the fissile homogeneity specifications given earlier. Since a 3-mm spacer represents a 23% change in fissile content in a 13-mm fuel segment, the

Fig. 7. Fissile Assay Scan of 2.5%-Enriched Sphere-Pac Fuel Rod Using 50 mm Cd Gap. Fissile gaps were resolved by the experimental assay device.

Fig. 8. Gamma-Ray Densitometer Scan of 2.5%-Enriched Sphere-Pac Fuel Rod.

Table 2. Counts Obtained in Assay of Sphere-Pac Fuel Rods^a

Counts	Counts for 25-mm Cd Gap (Count time 128 s)		Counts for 50-mm Cd Gap (Count time 224 s)	
	10.5 g ²³⁵ U/m	45.6 g ²³⁵ U/m	10.5 g ²³⁵ U/m	45.6 g ²³⁵ U/m
Average Background	121,666	123,269	213,033	213,812
Average Fuel	157,404	226,409	361,455	628,519
3-mm Spacer	155,253	221,801	357,313	621,788
6-mm Spacer	153,553	217,606	351,945	606,558
Background-Corrected Average Fuel	35,738	103,140	148,422	414,707
N_g (3-mm Spacer)	5.42	9.68	6.89	8.49
N_g (6-mm Spacer)	9.71	18.50	15.82	27.70

^aFuel cladding had an inside diameter of 9.6 mm, simulating LWR fuel rods.

data indicate (a deviation of 6.89 standard deviations in counts was obtained) that the first fissile homogeneity specification can be readily satisfied by using a scan speed of 25.7 mm/min and a 500- μ g ²⁵²Cf source. However, the second specification specifies detection of a 12.5% change in fissile content in a 13-mm fuel segment. The estimated number of standard deviations, N_g , that a 12.5% fissile content change in a 13-mm segment gives according to the data given on Table 2 is 3.5 for a speed of 25.7 mm/min. To satisfy the specification, N_g needs to be at least 5.38. To obtain this, a reduction in speed by a factor of 2.4 is required because N_g is proportional to the square root of the number of counts or to the inverse of the square root of the assay speed. Thus, a speed of about 11 mm/min is required to satisfy the second fissile homogeneity inspection specification.

For the prototype assay device, described in the next section and having twice the number of detectors and a 1.0-mg ²⁵²Cf source, the speed can be 4 times those given above and still satisfy the fissile homogeneity inspection specifications. In addition, LWR fuel contains about 20 g/m

rather than 10 g/m, so the estimated assay speeds to satisfy specifications 1 and 2 are approximately 200 and 100 mm/min, respectively.

To estimate the sensitivity of the count rate response to changes in fissile content, the background-corrected number of counts for the 50-mm Cd gap were fit to a calibration equation, Eq. (6). This form of calibration equation fits the count data well, as mentioned by Rushton et al.¹¹

$$C = a(1 - e^{-bU}) , \quad (6)$$

where

a and b = calibration constants,

U = ^{235}U fissile axial density (g/mm), and

C = count rate (counts/224 s).

The calibration constants, a and b , were calculated to be 566,409 and 28.896, respectively. For a ^{235}U density of 20 g/m, nominal LWR fuel rod fissile content, a 10% change in fissile content produces a 7.2% change in count rate. For 10 g/m, a 10% change in count rate produces an 8.5% change in count rate. At high ^{235}U densities (e.g., 50 g/m), the count rate becomes less sensitive to fissile density changes. For 50 g/m, a 10% change in fissile content produces a 4.2% change in count rate to fissile density. Thus, we do not recommend that this device be used for assay of FBR-type fuel rods, which have a much higher fissile density than LWR-type fuel rods.

DESIGN OF PROTOTYPE TWO-CHANNEL DEVICE

A conceptual design for a density and assay device for inspection of 4-m LWR sphere-pac fuel rods was made. The engineering drawing numbers and description are presented in the appendix. The device would determine axial density profiles, total density, axial fissile profiles, and total fissile assay. Shielding calculations for the assay and fissile homogeneity inspection portion of the 4-m sphere-pac fuel-rod inspection device have been completed by using the computer code XSDRNPM.³ The calculations

indicate that the dimensions of the device should be 1.36 by 1.21 m to reduce the surface dose to 2.5 mrd/h when a 1-mg ^{252}Cf neutron source is used. A diagram of one face of the device, showing the various shielding materials and relative thicknesses, is given in Fig. 9. Notice that a scale is given in the lower right-hand corner of the figure. If the D_2O leaks from the tank, the calculated surface dose is 4.2 mrd/h, and the device can still be handled safely. The total mass of the device is roughly 4 Mg.

Fig. 9. Shielding Design of Sphere-Pac Fuel Rod Assay Device.

Fuel rods will be moved through a cadmium-covered tube centered between ^4He detectors, as shown in Fig. 10. A short cadmium-free section of the tube located at the centerline of the detectors allows low-energy neutrons to penetrate the fuel rod. These low-energy neutrons cause fissions in the fissile material of the rod, and fast neutrons released in the fissioning events are detected by the ^4He detectors. The count rate is therefore proportional to the fissile content of the fuel rod. Only a

small section of the fuel rod is inspected at any one time because the cadmium, which is a very good low-energy neutron absorber, restricts source neutrons from most of the fuel rod. The ^4He detectors were selected as they are relatively insensitive to gamma rays released by the fuel. Other fast-neutron detector types, such as ZnS detectors or "Hornyak buttons," are also being investigated. Several motor-drive options for translating fuel rods through the device have been investigated. One concept being considered uses a friction drive wheel.

Fig. 10. Detector Fuel-Rod Arrangement.

FUTURE WORK

Future work should include studying the effect on assay speed of modifications to the assay device that are necessary for assay of highly spiked fuel rods. The device is currently capable of assay of ^{233}U fuels, but highly spiked fuels can introduce considerable gamma-ray interference. A highly spiked fuel element can give¹³ a radiation level of 27,000 rd/h

at 0.3 m, so one unshielded fuel rod can produce a dose of 1500 rd/h at 25 mm. If the detectors are placed in a lead assembly and moved back about 50 mm from the fuel rod, the dose rate at the detectors can be kept below 10 rd/h, which would be acceptable. The effect on assay speed for such as modification needs to be determined.

The effect on assay accuracy due to changes in the particle distribution in sphere-pac fuel rods also needs to be studied. For LWR sphere-pac fuel, the ^{235}U density in the spheres is about 0.3 Mg/m^3 . If the distribution of the fine, medium, and coarse spheres varies, variations in self-shielding change the count rate, although the fissile axial density is constant. For example, assume that the weight percentages of the various sphere sizes are the following:

Particle Size	Diameter (μm)	Weight Percent	
		Distribution 1	Distribution 2
Fine	30	17	23
Medium	300	20	20
Coarse	1200	63	57

Using a relationship developed by Rushton et al.¹¹ for HTGR-type fuel,

$$C = A - B\rho d, \quad (7)$$

where

$$A = 78,315,$$

$$B = 5.1812,$$

$$C = \text{counts},$$

$$\rho = ^{235}\text{U} \text{ density (Mg/m}^3\text{)}, \text{ and}$$

$$d = \text{diameter } (\mu\text{m}).$$

We can estimate the relative count rate for the above two distributions. For distribution 1, $C = 77,039$, and for distribution 2, $C = 77,148$.

Therefore, even for a relatively large distributional variation, the effect on assay accuracy is less than 0.2%. However, this effect needs to be studied for expected process variations in fissile particle distributions for sphere-pac LWR-type fuel.

A third area for future work involves development of computer programs for analysis of the count rate data. In addition, procedures for determination of the axial fissile content in the ends of the fuel rods need to be studied.

Faster techniques need to be identified and developed for assay and fissile homogeneity inspection of FBR sphere-pac fuel rods that have a high gamma ray background. The importance of fissile material homogeneity inspection should be studied to determine whether alternative techniques such as gamma-ray densitometry can satisfy the axial homogeneity inspection criteria.

SUMMARY AND CONCLUSIONS

Techniques for assay and fissile homogeneity inspection of sphere-pac fuel rods have been studied. A method employing thermal-neutron irradiation and fast fission-neutron detection was experimentally investigated for assay and fissile homogeneity inspection of light-water reactor fuel. A localized irradiation zone is created by surrounding with cadmium the hole through which the fuel pin travels except for a space at the detectors 50 mm in length, which is left free of cadmium. The method appears capable of satisfying specifications on fissile material homogeneity inspection using a 1-mg ^{252}Cf neutron source and assay speeds of 100 to 200 mm/min. As many as 12 fuel rods can be assayed simultaneously at equal angular intervals around the periphery of the heavy-water tank with only about 1% correction to be applied for interference between adjacent fuel rods.

For assay and fissile homogeneity inspection of fast breeder reactor sphere-pac fuel, a promising NDA method uses intermediate-energy neutron irradiation and fission-neutron detection. Employing a ^{124}Sb -Be (γ, n) neutron source in a nickel reflector arrangement, a localized irradiation

zone at the fuel pin about 80 mm in length can probably be obtained. We estimate that approximately 400 counts/s can be obtained per gram ^{239}Pu by using 100 to 200 Ci of ^{124}Sb . However, because the fuel rod passes through the center of the device, only one fuel rod can be assayed at a time.

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APPENDIX

A conceptual design for a density and assay device for inspection of sphere-pac loaded 4-m LWR fuel rods was made. In this appendix, the titles and identification numbers of the engineering drawings are listed.

<u>Drawing Description</u>	<u>Drawing</u>
Sphere-Pac Cold Development Density and Assay Device	
Main Assembly Sheet 1	X3E-11765-A150
Main Assembly Sheet 2	X3E-11765-A151
Main Assembly Sheet 3	X3E-11765-A152
Main Assembly Sheet 4	X3E-11765-A153
Main Assembly Sheet 5	X3E-11765-A154
Main Assembly Sheet 6	X3E-11765-A155
Main Assembly Sheet 7	X3E-11765-A156
Main Assembly Sheet 8	X3E-11765-A157
General Notes, Items List, Vendor Notes, Assembly Procedures	X3E-11765-A158
Sphere-Pac Cold Development Density and Assay Device	
Main Assembly Detail Sheet 1	X3E-11765-A159
Main Assembly Detail Sheet 2	X3E-11765-A160
Main Assembly Detail Sheet 3	X3E-11765-A161
Main Assembly Detail Sheet 4	X3E-11765-A162
Main Assembly Detail Sheet 5	X3E-11765-A163
Main Assembly Detail Sheet 6	X3E-11765-A164
Main Assembly Detail Sheet 7	X3E-11765-A165
Main Assembly Detail Sheet 8	X3E-11765-A166
Main Assembly Detail Sheet 9	X3E-11765-A167
Main Assembly Detail Sheet 10	X3E-11765-A168
Main Assembly Detail Sheet 11	X3E-11765-A169
Main Assembly Detail Sheet 12	X3E-11765-A170
Main Assembly Detail Sheet 13	X3E-11765-A171
Main Assembly Detail Sheet 14	X3E-11765-A172

<u>Drawing Description</u>	<u>Drawing</u>
Main Assembly Detail Sheet 15	X3E-11765-A173
Main Assembly Detail Sheet 16	X3E-11765-A174
Main Assembly Detail Sheet 17	X3E-11765-A175
Main Assembly Detail Sheet 18	X3E-11765-A176
Top Plug Sub-Assembly	X3E-11765-A177
Top Plug Sub-Assembly Detail Sheet 1	X3E-11765-A178
Top Plug Sub-Assembly Detail Sheet 2	X3E-11765-A179
Top Plug Sub-Assembly Detail Sheet 3	X3E-11765-A180
Front and Rear Plugs Sub-Assembly	X3E-11765-A181
Front and Rear Plugs Sub-Assembly Detail Sheet 1	X3E-11765-A182
Front and Rear Plugs Sub-Assembly Detail Sheet 2	X3E-11765-A183
Front and Rear Plugs Sub-Assembly Detail Sheet 2	X3E-11765-A184
Shielding Box Sub-Assembly	X3E-11765-A185
Shielding Box Sub-Assembly Detail Sheet 1	X3E-11765-A186
Shielding Box Sub-Assembly Detail Sheet 2	X3E-11765-A187
Shielding Box Sub-Assembly Detail Sheet 3	X3E-11765-A188
Shielding Box Sub-Assembly Detail Sheet 4	X3E-11765-A189
Shielding Box Sub-Assembly Detail Sheet 5	X3E-11765-A190
Fuel Pin Drive Assembly	X3E-11765-A191
Fuel Pin Drive Assembly Detail Sheet 1	X3E-11765-A192
Fuel Pin Drive Assembly Detail Sheet 1	X3E-11765-A193
Fuel Pin Drive Assembly Detail Sheet 2	X3E-11765-A194
Fuel Pin Drive Assembly Detail Sheet 3	X3E-11765-A195
Fuel Pin Drive Assembly Detail Sheet 4	X3E-11765-A196
Fuel Pin Drive Assembly Detail Sheet 5	X3E-11765-A197

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