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**PWR RESEARCH AND
DEVELOPMENT PROGRAM
TEST REPORT
GAMMA SCANNING SPENT
SM-1 CORE I FUEL ELEMENTS
TEST 318**

ALCO PRODUCTS, INC.
NUCLEAR POWER ENGINEERING DEPARTMENT
P. O. BOX 414, SCHENECTADY 1, N. Y.

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GAMMA SCANNING SPENT SM-1 CORE I FUEL ELEMENTS
TEST 318**

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ABSTRACT

This test was designed and performed to experimentally determine fuel burnup distribution in the SM-1 Core I spent fuel elements. This was believed feasible if the spatial distribution of the gamma rays emitted from a long-lived, unsaturated fission product could be measured. However, scintillation spectra indicated an intense peak between 0.7 - 0.8 mev, primarily attributed to the 63-day Zr^{95} fission product and 35-day Nb^{95} . The magnitude of this peak nullified the possibility of distinguishing a long-lived fission product that could be used for scanning purposes. The stationary elements of one quadrant of the core were scanned using the Zr^{95} - Nb^{95} peak as the energy interval; results represent a fair approximation of the power distribution in SM-1 Core I during the latter portion of operating history. Results of the experiment are presented with a description of the techniques and test equipment used.

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1.0 SUMMARY

Because of high average burnup of SM-1 Core I over three years' operating life, a measurement of fuel burnup distribution was of considerable interest to serve as a check on calculated distributions and locate regions of high burnup for subsequent hot cell examination.

Initially, the investigation involved taking scintillation spectra of the gamma energy from spent fuel pit water, fuel element materials, and fuel element-contained fission products to determine a suitable energy range for measurements. Scintillation spectra indicated an intense peak between 0.7-0.8 mev, attributed to the 63-day Zr^{95} and 35-day daughter, Nb^{95} . The magnitude of this peak nullified the possibility of selecting a long-lived fission product to be used for scanning purposes.

The stationary fuel elements from one quadrant of the spent SM-1 Core I were scanned to obtain the gamma ray intensity in the energy interval of 0.7 to 0.8 mev as a function of location on the fuel element. Each element was scanned along the centerline of both of the outside fuel plates and transversely at three axial locations. The fuel element orientation in the reactor core and gamma scanner carriage was established.

Gamma scanning the spent fuel elements using this strong Zr^{95} - Nb^{95} pair scintillation peak as the energy interval provides no direct information on fuel burnup distribution. However, it does give a representation of power distribution in the core, integrated throughout the latter portion of core history. In addition, the radial scans indicate burnup has considerably flattened the intercell peaking that is present in a new core.

In view of the results of this experiment, it is recommended that scintillation spectra be taken periodically in conjunction with decay data of the Zr^{95} - Nb^{95} pair on reference element S-52, which could lead to the selection and scanning of a long-lived fission product in the future. In addition, a comparison should be made between the results of the radiochemistry fission product distribution and the data from this report.

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2.0 INTRODUCTION

SM-1 Core I is one of the first power reactor cores to be burned out. (2) This core operated from April 1957, to April 1960, with an energy release of 16.4 MWYR. (2) Because of the high average burnup of this core (Fig. 3.3.1) (average 36% total a/o U-235), a measurement of fuel burnup distribution is of considerable interest to serve as a check on calculated distributions and locate regions of high burnup for subsequent hot cell examination.

The fuel burnup distribution in reactor fuel elements may be obtained by measuring the spatial distribution of gamma rays emitted by long-lived, unsaturated fission products. This experiment, Test 318, was designed and performed with this objective in mind.

In order to identify the origin of each gamma ray present in intensities adequate to produce a unique scintillation peak, several gamma energy distribution measurements were made. These measurements consisted of scintillation spectra of the spent fuel pit water, fuel element structural materials, and fuel element-contained fission products. The fission product spectrum indicated a strong scintillation peak between 0.7 and 0.8 mev, which was attributed primarily to the Zr^{95} - Nb^{95} pair.

Because of this scintillation peak this energy range was selected for use in scanning the stationary elements of one quadrant of SM-1 Core I. Because Zr^{95} exhibits a relatively short half-life of 63 days, the gamma scans performed at this energy range do not give a representation of the fuel burnup. The 0.7-0.8 mev scintillation peak was so strong that it completely masked all possible peaks that could have been identified and interpreted as resulting from long-lived fission products.

Previous experiments (3), (4), (5) of this nature give differing results between distributions from chemical analysis of specific fission products and from gamma intensity measurements.

Two experiments employed a measurement of the gross gamma activity (3, 4,) while one employed a measurement of the gamma activity between 150 and 200 Kev. (5) It is significant, however, that the burnup for the SM-1 Core I averaged approximately 36% total a/o U-235, which is a factor of 10 higher than the average a/o for reference (5) and 300 times higher than the average a/o for reference (3). In addition, many of the short-lived fission products have reached saturation in the SM-1 Core I fuel elements and it is conceivable that this was not the case in previous experimental work referenced, since the burnups were quite low.

It was believed that more qualitative results could be obtained if the spatial gamma ray intensity could be measured using the energy range of a

distinct scintillation peak associated with the activity of a totally unsaturated, long-lived, fission product. This would alleviate the contribution of the short-lived fission products and afford direct correlation to the results of chemical analysis.

The work performed on this experiment was done as a part of Task 2 of the Program for Engineering Support and Development of Army PWR Plants.

3.0 EXPERIMENTAL METHOD

3.1 GAMMA SCANNING EQUIPMENT

The scanner located in the SM-1 spent fuel pit is a long, shielded collimator tube equipped with removable lead or stainless steel inserts on each end. The inserts have a range of aperture openings which permit regulation of gamma ray intensity and fuel element surface area seen by the detector. Details of the scanner design are shown in Dwg. AEL-558 and AEL-563 (Fig. 3.1.2 and 3.1.3). A more general schematic of the scanning mechanism in the spent fuel pit is shown in Fig. 3.1.1. The fuel element is held horizontally in the carriage and driven past the lower end of the collimator by hand-driven cranks from the support. This carriage had two degrees of freedom so that both radial and axial gamma scans could be made.

The detection equipment consisted of a Baird Atomic model 815 BL probe, containing a 1 3/4 in. x 2 in. cylindrical NaI crystal optically sealed to a Dumont 6192 photo-multiplier tube followed by a cathode follower-type preamplifier. The signal from the preamplifier was fed through a linear amplifier to a motor-driven, single channel, differential pulse height analyzer. The output from the pulse height analyzer was fed to both a scaler and a logarithmic countrate meter; the latter fed a strip chart recorder. A block diagram of the electronic circuitry is shown in Fig. 3.1.4.

3.2 ASSEMBLY AND CALIBRATION OF EQUIPMENT

The gamma scanner components were received and assembled at the SM-1 site. Several slight modifications of the carriage and drive mechanisms were required to accommodate the fuel elements during assembly. The spent fuel pit housing was modified slightly to place the scanner in the pit. Final assembly, testing and scanner calibration were completed.

Energy calibration of the spectrometer was done by gamma ray sources of known energy (Cs^{137} and Co^{60}). The calibration source was attached to the upper insert by means of hollow tube and inserted into the collimator tube. An energy calibration was obtained. Figure 3.2.1 illustrates the scintillation spectrum obtained from the 0.661 mev Cs^{137} source. It should be noted that the crystal was detecting gamma rays both from the Cs^{137} calibration source and from contaminated water in the spent fuel pit. The major peak shown in Fig. 3.2.1 is due to total absorption of the 0.661 mev isomeric transition gamma ray from Ba^{137} , the daughter product of the parent beta emitter Cs^{137} . The location of this peak was utilized to provide a conversion factor between the spectrometer base line voltage reading and the gamma ray energy. Several such calibration spectra were taken during the course of the experiment as verifying checks on the overall gain stability of the counting system. As a comparison, Fig. 3.2.2 illustrates the scintillation spectra for the Cs^{137} source plus spent fuel pit water (Fig. 3.2.1) and the spectrum of the spent fuel pit water (Fig. 4.1.1). Both these spectra were taken under identical instrument settings.

GAMMA SCANNING APPARATUS IN THE SM-1 SPENT FUEL STORAGE PIT

Figure 3. 1. 1 Gamma Scanning Apparatus, SM-1 Spent Fuel Storage Pit

BLOCK DIAGRAM OF ELECTRONICS

FIGURE 3.1.4

Figure 3.2.1 Scintillation Spectrum for Cs^{137} Source and Spent Fuel Pit Water

FIGURE 3.2.2

COMPARISON OF SCINTILLATION SPECTRA FOR Cs-137 SOURCE
PLUS THE SPENT FUEL PIT WATER (FIG. 3.2.1) AND
THE SPENT FUEL PIT WATER (FIG. 4.1.1)

3.3 GAMMA SCANNING TECHNIQUE

Initial identification of the origin of each gamma ray energy adequate to produce a unique scintillation peak was made by observing the scintillation spectra of the spent fuel pit water, the spent fuel pit water plus the fuel element structural materials, and the fission products plus the fuel element structural material and spent fuel pit and water. Using the scintillation spectra from these sources, the predominant scintillation peak due to a specific fission product activity was selected.

Element S-52 from core position #15 was used as the reference element and was scanned periodically throughout the experiment in order to establish a decay curve. The stationary elements from one quadrant of the spent SM-1 Core I were scanned on both of the fuel plate sides. Axial measurements were taken every half-inch starting at the top of the fuel boundary for the first 2 in. and then every inch to the 20-in. reading, from which point measurements were taken again every half-inch to the end of the fuel region. Radial measurements were taken at $+1\frac{1}{4}$, $+1\frac{1}{8}$, $+1$, $+1/2$, 0 , $-1/2$, -1 , $-1\frac{1}{8}$ and $1\frac{1}{4}$ in. where 0 was the radial center of the fuel plate, at axial position of 5 in., 10 in. and 15 in. measured from the top of fuel boundary. The positive dimension of the radial scans indicates that side of the fuel plate closest to reference plane A-A in Fig. 3.3.1. One-minute counts were taken with the scaler at each point.

Figure 3.3.1 illustrates the spent Core I arrangement and the stationary elements scanned for this experiment. Dowel pin locations are represented as arrows pointing in the direction in which they protruded from the end box fitting. These elements were withdrawn individually from the core, transferred to the spent fuel pit, placed in the scanner, scanned on one side, rotated 180° and scanned on the other side, and returned to their respective core positions. The control rod fuel elements were not scanned because of difficulties with the control rod caps.

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FIGURE 3.3.1
SM-1 CORE I SPENT CORE
ARRANGEMENT

*Stationary Elements Scanned.

(1) No Dowel Pin Reference

↑ ↓ Dowel Pin Locations

○ -- ○ Scan References (Fig. 4.4.52 & 4.4.53)

A — A Reference Plane

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4.0 GAMMA RAY ENERGY DISTRIBUTION MEASUREMENTS

4.1 GAMMA SPECTRUM MEASUREMENTS AND ANALYSIS

Several gamma energy distribution measurements were made to identify the origin of each gamma ray present in intensities adequate to produce a unique scintillation peak. These measurements include scintillation spectra of the fuel pit water, fuel element structural materials, and fission products.

The spent fuel pit water spectrum illustrated in Fig. 4.1.1 was obtained without a fuel element in the scanner carriage. Although the relative intensities do not justify quantitative analysis, significant peaks are apparent at energies of 0.2, 0.8, 1.1 and 1.3 mev. These energies are probably indicative of Fe^{59} , Co^{58} , and Co^{60} contaminants in the spent fuel pit water. These isotopes result from activation and subsequent corrosion of the fuel element structural materials and the Haines metal flux suppressors on the top of the control rod fuel elements.

An energy distribution of the gamma rays emitted by fuel element structural materials was obtained from the steel just below the fuel boundary of SM-1 element #79 (Fig. 4.1.2). The significant peaks in the structural materials spectrum are identical to those found in the spent fuel pit water, and as background radiation in the energy calibration data presented in Fig. 4.1.1.

After the predominant peaks due to structural materials were established, the scintillation spectrum for fission products plus structural materials was obtained. Figure 4.1.3 illustrates this spectrum with predominant peaks at 1.55, 0.75, and 0.50 mev. A less significant peak was found at 0.15 mev. Only the 1.55 and the 0.75 new peaks were considered to have adequate intensity for purposes of scanning and subsequent analysis. A review of the literature (1) indicated that the Zr^{95} - Nb^{95} and Ba^{140} - La^{140} pairs would account for the predominant peaks in the scintillation spectrum. The Zr^{95} - Nb^{95} pair is the source of the very strong 0.7 - 0.8 mev peak. The parent product Zr^{95} of 63.3-day half-life emits gamma rays of 0.754 and 0.722, followed by the Nb^{95} daughter, of 35-day half-life, which emits a 0.764 mev gamma ray. Since the fission product yield of the Zr^{95} is very high, the net effect is an extremely potent source of 0.7-0.8 mev gamma rays for several months following reactor shutdown.

The Ba^{140} - La^{140} pair emits a multitude of gamma rays. The predominant energies emitted by the 12.8-day half-life Ba^{140} parent product are 0.53, 0.42, 0.16, and 0.03 mev while the 40.2-hr half-life daughter product La^{140} emits 1.6, 0.82, and 0.486 mev gamma rays. In composite, the Ba^{140} and Zr^{95} spectra should show strong peaks in the regions of 1.6, 0.7-0.8 and 0.5 mev and less significant peaks at 0.42, 0.16, and 0.03 mev.

Figure 4. 1. 1 Scintillation Spectrum for Spent Fuel Pit Water

Figure 4.1.2 Scintillation Spectrum, SM-1 Fuel Element Structural Materials Plus Spent Fuel Pit Water

Figure 4. 1. 3 Scintillation Spectrum for Fission Products Plus SM-1 Fuel Element Structural Materials and Spent Fuel Pit Water, 0-2 Mev

SM-1 ELEMENT #58

↓
□ X = OY = 10 6/27/60

BAIRD ATOMIC MODEL 815B1 SCINTILLATION
PROBE $1\frac{3}{4}$ x 2" NA1 CRYSTAL 6192 DUMONT
PHOTO TUBE HV = 750 AMP GAIN = 2X 74 SCAN
0.4 MEV WINDOW WIDTH 200 KEV

Figure 4.1.4 Scintillation Spectrum for Fission Products Plus SM-1
Fuel Element Structural Materials and Spent Fuel Pit Water,
0-4 Mev

The identification established from Fig. 4. 1. 1 through 4. 1. 3 and other similar curves were considered adequate and the approximate energy interval 0. 7 to 0. 8 mev was selected for scanning purposes for reasons of relative intensity. The fact that the La^{140} peak appeared at 1. 55 mev rather than 1. 60 indicates a slight shift in the system gain in the time interval between energy calibration and scanning or a small error in the calibration factor. Considering the cumulative uncertainties in gain stability, low energy calibration factors applied to high energy gamma rays, and constancy of strip chart drive speeds, the error was not considered excessive.

Figure 4. 1. 4 illustrates the scintillation spectrum over the 0-4 mev range. This scan was made with a window width of 0. 2 mev in order to improve the counting statistics at the higher energy levels. The consequence of the increased window width, however, is some loss of resolution as evidenced by the near disappearance of the La^{140} peak. There were no significant new peaks found at the higher energies.

4. 2 GAMMA SCANNING MEASUREMENTS

The stationary elements from one quadrant of the spent SM-1 Core I were scanned to obtain the gamma ray intensity in the energy interval of 0. 7 to 0. 8 mev as a function of location on the fuel element. Since there was a very strong single peak in this interval, the spectrometer energy calibration was checked periodically by making small adjustments in the amplifier fine gain control to obtain a maximum count rate on the count rate meter. This insured that the discriminator window remained centered about the chosen scintillation peak. Each fuel element was scanned along the centerline of both of the outside fuel plates and transversely at three axial elevations on the outside of fuel plates. The fuel element orientation in the reactor core and gamma scanner carriage was established by periscope observations made on the elements when removed from the reactor core and again as the elements were mounted in the scanner carriage. The point of reference chosen for these observations was the dowel pin protruding from the lower fuel element end box.

The readout dial for the scanner carriage was adjusted to read zero when the upper nominal meat edge passed under the scanner collimator; hence, the axial location shown in Fig. 4. 2. 1 indicates the distance below the top of the active reactor core.

Two scanning operations were performed on fuel element No. 52 from the SM-1 lattice position No. 15. These scans were made approximately one week apart in order to provide correction factors for time behavior of gamma ray activity.

Figure 4. 2. 1 presents gross activity level in the approximate energy interval 0. 7-0. 8 mev vs. location along element No. 52. It should be emphasized that these data are presented for illustrative purposes only and for use in establishing the decay curve shown in Fig. 4. 2. 2.

Figure 4.2.1 Relative Gamma Ray Intensity vs. Axial Location

FIG. 4.2.2

4.3 DATA ANALYSIS

The prominent gamma peaks were from Zr^{95} and Nb^{95} . The decay scheme of both of these isotopes is shown below:

The activity of the 0.75, 0.72, and 0.77 mev gammas at any time t after shutdown will be given by three processes:

- that from the Zr^{95} atoms present at shutdown ($t = 0$)
- that from the Nb^{95} atoms present at shutdown ($t = 0$)
- that from the Nb^{95} atoms build-up from the decay of Zr^{95} after shutdown.

These processes may be expressed as equations (1), (2), and (3) respectively.

At any time, t after shutdown:

$$N^A = N_0^A e^{-\lambda_A t} \quad (1)$$

$$N^B = N_0^B e^{-\lambda_B t} \quad (2)$$

$$N^{B'} = \frac{N_0^A \lambda_A}{\lambda_B - \lambda_A} \left(e^{-\lambda_A t} - e^{-\lambda_B t} \right) \quad (3)$$

where:

N^A = the number of Zr^{95} atoms at any time, t after shutdown,

N_0^A = the number of Zr^{95} atoms at time, $t = 0$

λ_A = decay constant for Zr^{95}

N^B = the number of Nb^{95} atoms at any time, t after shutdown.

N_0^B = the number of Nb^{95} atoms at time $t = 0$

λ_B = decay constant for Nb^{95}

$N^{B'}$ = the number of Nb^{95} atoms resulting from the decay of Zr^{95} atoms at any time, t after shutdown.

In addition, the individual decay rates may be expressed as:

$$(1)' \quad D_A = \lambda_A N^A$$

$$(2)' \quad D_B = \lambda_B N^B$$

$$(3)' \quad D_{B'} = \lambda_B N^{B'}$$

where D_A , D_B and $D_{B'}$ are the individual decay rates for processes

(a), (b), and (c) respectively. The individual gamma emission intensity for these three processes that contributes to the 0.7 - 0.8 mev energy group may be expressed as:

$$(1)'' \quad I_A = \Gamma_A D_A$$

$$(2)'' \quad I_B = \Gamma_B D_B$$

$$(3)'' \quad I_{B'} = \Gamma_B D_{B'}$$

respectively.

where:

Γ_A = probability of gamma photon emission (photons/disintegration) for Zr^{95} - given as 0.97.

Γ_B = probability of gamma photon emission for Nb^{95} given as 1.00.

Therefore, the gross 0.7-0.8 mev gamma emission rate from the Zr^{95} - Nb^{95} pair can be expressed as the sum of equations (1)", (2)", and (3)" and is given as equation (4)

$$I = I_A + I_B + I_B' = \lambda_A \Gamma_A N^A + \lambda_B \Gamma_B N^B + \lambda_B \Gamma_B N^{B'} \quad (4)$$

Using equations (1), (2), (3) and the relationship

$$N_O^B = \frac{\lambda_A N_O^A}{\lambda_B},$$

equation (4) takes the form

$$I(t) = N_O^A \left[\lambda_A \Gamma_A e^{-\lambda_A t} + \lambda_A \Gamma_B e^{-\lambda_B t} + \frac{\lambda_A \lambda_B \Gamma_B}{\lambda_B - \lambda_A} (e^{\lambda_A t} - e^{-\lambda_B t}) \right] \quad (5)$$

and becomes a time dependent equation.

It is wished to determine an effective half-life for the Zr^{95} - Nb^{95} pair at 60-66 days after shutdown. The procedure for this follows:

The observable decay rate that can be seen by the emission of 0.7-0.8 mev gammas from the Zr^{95} - Nb^{95} pair is expressed as

$$I(t) = \lambda_e N_O^e e^{-\lambda_e t} \quad (6)$$

where:

λ_e = effective decay constant

N_O^e = effective number of nuclei of decay constant λ_e .

This holds no real significance in this evolution as may be seen in equation (7).

It follows that

$$\frac{I(t_2)}{I(t_1)} = e^{-\lambda_e (t_2 - t_1)} \quad (7)$$

Evaluating equation (5) for t_1 and t_2 , and using their ratio in equation (7), λ_e is evaluated as 0.00825 and by conversion to half-life,

$$T_e = \frac{0.693}{\lambda_e}$$

$$T_e = 84 \text{ days}$$

Gamma scanning of the spent fuel elements indicated a fall-off in observable activity equivalent to a half-life of approximately 30 days in the period of 60-66 days after shutdown. The calculations using equations (5) and (7) predict a half-life of 84 days, 60-66 days after shutdown. This is indicative of either or both of the following taking place: Some shorter lived fission product or products are emitting a gamma in the 0.7-0.8 mev energy range, and possible scattering from higher than 0.8 mev gammas with short half-lives is contributing to the measured activity.

Of primary consequence is the wait time required to allow the intermediate lived Zr^{95} - Nb^{95} pair intensity to reduce to a point where they no longer mask the Cs^{137} , 0.661 mev gamma which exhibits a 30-year half-life and would be directly representative of the fuel burnup distribution.

The following equation

$$I = \lambda Y F \Gamma (1 - e^{-\lambda T}) e^{-\lambda t} \quad (8)$$

represents the emission rate in photons per hour when: (1)

λ = decay constant (disintegrations/atom-hr)

Y = yield (atoms/fission)

F = number of fissions

Γ = probability of gamma photon emission (photons/disintegration)

T = hours of fission

t = hours after fission

Based on Fig. 3.7.1 of AP Note 291, (2) the SM-1 was operated continuously at practically 100% load factor for approximately the last three months of Core I life, and was operated at an average load factor of 60% for the preceding 2-3/4 years. To account for these facts, equation (8) must be modified as follows:

$$I = \lambda Y F \Gamma \left[L_1 (1 - e^{-\lambda T_1}) + L_2 (1 - e^{-\lambda T_2}) e^{-\lambda T_1} \right] e^{-\lambda t} \quad (9)$$

where:

L_1 = load factor for last three months of operation

T_1 = last three months of operation

T_2 = first 2 3/4 years of operation

L_2 = load factor for period T_2

Assuming the passage of time after fission has allowed the Zr^{95} - Nb^{95} pair to approach equilibrium, (a decay of Zr^{95} is accompanied by the associated decay of Nb^{95}), the decay constant for Zr^{95} establishes the decay of the Zr^{95} - Nb^{95} pair. In addition, the Zr^{95} emits 0.722 and 0.754 Mev photons with probabilities of 0.43 and 0.54, respectively. ⁽¹⁾ The Nb^{95} emits a 0.77 mev photon with a probability of 1.00. ⁽¹⁾ The Cs^{137} emits a 0.661 mev photon with a probability of 0.92. ⁽¹⁾ Based on this, the Zr^{95} - Nb^{95} pair produces photons between 0.722 and 0.77 mev with a probability of 1.97. This establishes a possible ratio between the photon intensities attributed to Zr^{95} - Nb^{95} pair and Cs^{137} . The equation for this is taken from equation (9) evaluated for Zr^{95} and Cs^{137} and taking the ratio of them.

$$R = \frac{I_{Zr}}{I_{Cs}} = \frac{\lambda_{Zr} Y_{95} \Gamma_{Zr} \left[\frac{L_1 (1 - e^{-\lambda_{Zr} T_1})}{1} \div \frac{L_2 (1 - e^{-\lambda_{Zr} T_2})}{e^{-\lambda_{Zr} T_1}} \right] e^{-\lambda_{Zr} t}}{\lambda_{Cs} Y_{137} \Gamma_{Cs} \left[\frac{L_1 (1 - e^{-\lambda_{Cs} T_1})}{1} \div \frac{L_2 (1 - e^{-\lambda_{Cs} T_2})}{e^{-\lambda_{Cs} T_1}} \right] e^{-\lambda_{Cs} t}}$$

For t , time after fission, the Ratio R must be 0.25 or less in order to differentiate the Cs^{137} , 0.661 mev photons. Therefore using equation (10) and the following values, time after fission, t , is computed as 2 years 8 months.

$$R = 0.25$$

$$\lambda_{Zr} = 4.4 \times 10^{-4} \text{ hr}^{-1}$$

$$Y_{95} = 0.064$$

$$\lambda_{Cs} = 2.64 \times 10^{-6} \text{ hr}^{-1}$$

$$Y_{137} = 0.062$$

$$\Gamma_{Zr} = 1.97$$

$$\Gamma_{Cs} = 0.92$$

$$L_1 = 1.00$$

$$T_1 = 2.16 \times 10^3 \text{ hr}$$

$$L_2 = 0.60$$

$$T_2 = 2.4 \times 10^4 \text{ hr}$$

Therefore utilization of the fission product Cs^{137} to determine fuel burnup distribution within a short period after shutdown is unrealistic since it would require a long delay time. However, a delay time of approximately three years is not excessive in comparison to the wait time required for radiochemical analysis, and it would be very worthwhile to scan the spent fuel elements using the Cs^{137} scintillation peak as the energy interval.

4.4 EXPERIMENTAL RESULTS

The SM-1 reached the defined end of Core I life on April 28, 1960, after approximately 16.4 MWYR of energy release. SM-1 Core I was shut-down and operated only at reduced temperatures and low powers for core physics measurements after that date. Gamma scanning of the spent fuel elements was started on June 24, 1960. This corresponds to 57 days wait time between reactor shutdown and gamma scanning.

The results of the axial and radial gamma scans for the 12 fixed elements in one quadrant of the core at 0.7 to 0.8 meV, gain 4×74 , high voltage 750 volts, and upper and lower aperture openings 1/4 in. and 1/4 in. respectively, are illustrated as Fig. 4.4.1 through 4.4.49. These curves were corrected for decay to 1400 hr, June 24, 1960 and are presented as count rates vs. radial or axial position. The fuel element is represented as a box with an arrow pointing down to the fuel plate scanned and a horizontal line extending either from the left or right side of the box representing the dowel pin protrusion. There are essentially four figures for each fuel element inspected; two represent axial scans, one for each side plate, and their corresponding radial traverses at axial locations of 5 in., 10 in., and 15 in. measured from the top of the fuel region. The positive dimensions for the radial scans represent that side of the fuel plate that is closest to the center plane (reference plane A-A, Fig. 3.3.1) of the core.

Figure 4.4.50 presents the centerline axial scans on fuel elements in positions 43, 53, 63, and 73 on reference plane (1)-(1) Fig. 3.3.1. Figure 4.4.51 presents the centerline axial scans on fuel elements in positions 43, 53, 63, and 73 on reference plane (2)-(2), Fig. 3.3.1. Figures 4.4.52 and 4.4.53 present the radial scans at axial location of 5 in., 10 in. and 15 in. for positions 43, 53, 63 and 73 along the reference planes (1)-(1) and (2)-(2) respectively of Fig. 3.3.1. Figure 4.4.54 presents the centerline axial scans for positions 51, 52, 53, and 54.

FIG. 4.4.1

FIG. 4.4.2

FIG. 4.4.3

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

FIG. 4.4.4

FIG. 4.4.5

FIG. 4.4.6

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

20

15

10

Dowel Pin Reference

○ Y = 5 Inches

□ Y = 10 Inches

▽ Y = 15 Inches

Relative Gamma Ray Intensity
Vs. Radial Location for
Element Number 79 from SM-1,
Core 1 Core Lattice Position
43. Applied Correction Factor of
1.032.
Energy Interval 0.7-0.8 Mev.

± 1-1/2 ± 1 ± 1/2 0 -1/2 -1 -1-1/2
DISTANCE FROM FUEL ELEMENT ϕ

FIG. 4.4.7

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

20

15

10

Note:

The jump in this curve is thought to be due to the carriage slipping.

Dowel Pin Reference

Relative Gamma Ray Intensity
vs. Axial Location of
Element Number 79 from SM-1
Core I Core Lattice position
43. Applied Correction
Factor of 1.045
Energy Interval 0.7-0.8
MeV.

FIG. 4.4.8

DISTANCE FROM TOP OF ACTIVE CORE(INCHES)

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

20

15

10

Dowel Pin Reference

○ Y = 5 Inches

□ Y = 10 Inches

▽ Y = 15 Inches

Relative Gamma Ray Intensity
Vs. Radial Location for
Element Number 79 from SM-1,
Core 1 Core Lattice Position
A3. Applied Correction Factor
of 1.045.
Energy Interval 0.7-0.8 Mev.

-1 1/2   -1   -1/2   0   1/2   1   1 1/2

DISTANCE FROM FUEL ELEMENT 4

FIG. 4.4.9

FIG. 4.4.10

FIG. 4.4.11

FIG. 4.4.12

RELATIVE GAMMA RAY INTENSITY $\text{CPM} \times 10^{-3}$

10

FIG. 4.4.13

FIG. 4.4.14

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

20

15

10

Distance from Element ϕ

$\pm 1-1/2$ ± 1 $\pm 1/2$ 0 $-1/2$ -1 $-1-1/2$

Dowel Pin Reference

○ Y = 5 Inches

□ Y = 10 Inches

▽ Y = 15 Inches

Relative Gamma Ray
Intensity vs Radial
Location for Element
Number 48 from SM-1,
Core 1, Core Lattice
Position 52
Applied correction factor
of 1.049.

FIG. 4.4.15

FIG. 4.4.16

FIG. 4.4.17

FIG. 4.4.18

FIG. 4.4.19

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

FIG. 4.4.20

FIG. 4.4.21

FIG. 4.4.22

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

15

20

25

$1-1/2$

1

$1/2$

0

$-1/2$

-1

$-1-1/2$

DISTANCE FROM FUEL ELEMENT

Bowel Pin Reference

○ $r = 5$ Inches

□ $r = 10$ Inches

▽ $r = 15$ Inches

Relative Gamma Ray Intensity
Vs. Radial Location for
Element Number 65 from SM-1
Core I Core Lattice Position
54. Applied Correction
Factor of 1.059.
Energy Interval 0.7-0.8 Mev.

FIG. 4.4.23

FIG. 4.4.25

FIG. 4.4.26

FIG. 4.4.27

FIG. 4.4.28

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

20

15

10

5

Dowel Pin Reference

○ $Y = 5$ Inches

□ $Y = 10$ Inches

▽ $Y = 15$ Inches

Relative Gamma Ray Intensity
Vs. Radial Location for Element
Number 44 from SM-1, Core I
Core Lattice Position 61.
Applied Correction Factor of
1.069.
Energy Interval 0.7-0.8 Mev

-1-1/2   -1   -1/2   0   +1/2   +1   +1-1/2
DISTANCE FROM FUEL ELEMENT ϕ

FIG. 4.4.29

FIG. 4.4.30

FIG. 4.4.31

FIG. 4.4.32

RELATIVE GAMMA RAY INTENSITY $\text{CMP} \times 10^{-3}$

FIG. 4.4.33

FIG. 4.4.34

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

25

20

15

Devel Pin Reference

○ Y = 5 inches

□ Y = 10 inches

▽ Y = 15 inches

Relative Gamma Ray
Intensity vs Radial
Location for Element
Number 49 from S4-1 Core 1
Core Lattice Position 63.
Applied Correction Factor
of 1.106
Energy Interval 0.2-0.8 Mev

Distance from Fuel Element ϕ

FIG. 4.4.35

FIG. 4-4-36

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

15

20

25

Dowel Pin Reference

○ $r = 5$ Inches

□ $r = 10$ Inches

▽ $r = 15$ Inches

Relative Gamma Ray Intensity Vs.
Radial Location for Element Number
49 from SW-1, Core I Core Lattice
Position 63. Applied Correction
Factor of 1.106.
Energy Interval 0.7-0.8 Mev.

-1-1/2   -1   -1/2   0   +1/2   +1   +1-1/2

DISTANCE FROM FUEL ELEMENT ϵ

FIG. 4.4.37

FIG. 4.4.38

RELATIVE GAMMA RAY INTENSITY $\text{cm} \times 10^{-3}$

20

15

10

Dowel Pin Reference

○Y = 5 Inches

□Y = 10 Inches

▽Y = 15 Inches

Relative Gamma Ray Intensity
Vs. Radial Location for
Element Number 58 from SM-1,
Core I Lattice Position 72.
Applied Correction Factor of
1.109.
Energy Interval 0.7-0.8 Mev

$\pm 1-1/2$ ± 1 $\pm 1/2$ 0 $-1/2$ -1 $-1-1/2$

DISTANCE FROM FUEL ELEMENT ϕ

FIG. 4.4.39

FIG. 4.4.4.0

RELATIVE GAMMA RAY INTENSITY $\text{CPM} \times 10^{-3}$

5

10

15

-1-1/2

DISTANCE FROM FUEL ELEMENT ϕ

-1

-1/2

0

+ 1/2

+ 1

+ 1-1/2

Dowel Pin Reference

○ $Y = 5$ Inches

□ $Y = 10$ Inches

▽ $Y = 15$ Inches

Relative Gamma Ray Intensity
Vs. Radial Location for Element
Number 58 from SM-1, Core I
Lattice Position 72.
Applied Correction Factor of
1.117.
Energy Interval 0.7-0.8 Mev.

FIG. 4.4.4.1

FIG. 4.4.42

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

20

15

10

Dowel Pin Reference

- Y = 5 Inches
- Y = 10 Inches
- ▽ Y = 15 Inches

Relative Gamma Ray Intensity
Vs. Radial Location for Element
Number 78 from SM-1 Core I
Lattice Position 73.
Applied Correction Factor of
1.123
Energy Interval 0.7 - 0.8 Mev.

$\pm 1-1/2$ ± 1 $\pm 1/2$ 0 $-1/2$ -1 $-1-1/2$
DISTANCE FROM FUEL ELEMENT ϕ

FIG. 4.4.4.3

FIG. 4.4.44

RELATIVE GAMMA RAY INTENSITY $\text{CPM} \times 10^{-3}$

10

15

-1-1/2   -1   -1/2   0   1/2   1   1-1/2
DISTANCE FROM FUEL ELEMENT ϕ

Dowd Pin Reference

○ $r = 8$ Inches
□ $r = 10$ Inches
▽ $r = 15$ Inches

Relative Gamma Ray Intensity
Vs. Radial Location for Element
Number 75 from SM-1 Core I
Lattice Position 75. Applied
Correction Factor of 1.125
Energy Interval 0.7-0.8 Mev.

FIG. 4.4.45

FIG. 4.4.4b

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

10

15

20

∇ 1-1/2 ∇ 1 ∇ 1/2   0   -1/2   -1   -1-1/2
 DISTANCE FROM FUEL ELEMENT ϕ

Dowel Pin Reference

○ Y = 5 inches

□ Y = 10 inches

▽ Y = 15 inches

Relative Gamma Ray Intensity
 Vs. Radial Location for
 Element Number 77 from SM-1,
 Core I Core Lattice Position 74.
 Applied Correction Factor of 1.125.

FIG. 4.4.47

FIG. 4.4.48

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

FIG. 4.4.49

FIG. 4.4.50

FIG. 4.4.51

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

15

20

25

Element 79,
Position 43

Element 66,
Position 53

Element 49,
Position 63

Element 78,
Position 73

DISTANCE FROM CORE CENTER PLANE(INCHES)

○ = 5 inches
□ = 10 inches
▽ = 15 inches

Relative Gamma Ray Intensity
Vs. Radial Location for
Element 79, 66, 49, and 78,
from 3M-1 Lattice Positions
43, 53, 63 and 73
respectively; dowel pin right.

FIG. 4.4.52

FIG. 4.4.53

RELATIVE GAMMA RAY INTENSITY CPM X 10-3

FIG. 4.4.54

5.0 CONCLUSIONS AND RECOMMENDATIONS

The major conclusions drawn from this experiment are:

1. Gamma scanning the spent fuel elements, using the strong Zr^{95} - Nb^{95} pair scintillation peak as the energy interval, gave a representation of power distribution in the core integrated throughout the latter portion of core history. Approximations based on the operating history of the SM-1 indicate over 70% of the activity of the Zr^{95} - Nb^{95} pair was due to the last three months of operation and the contribution of the previous 2 3/4 years of operation accounted for less than 30% of the activity. The activity percentage was arrived at by using equation (9) from section 4.3.
2. Gamma scanning the spent fuel elements, using the strong Zr^{95} - Nb^{95} pair scintillation peak as the energy interval provides no direct information on fuel burnup distribution.
3. The radial gamma scans indicate burnup has considerably flattened the intercell peaking that is present in a new core. This may be seen by comparing the radial power distribution in Fig. 4.4.55 with Fig. 4.4.52 and 4.4.53.
4. A wait time of approximately three years would be required before the selection of a 0.66 mev gamma peak attributed to the fission product Cs^{137} could be used as the energy interval for gamma scanning.
5. Based on the results of this experiment, gamma scanning spent fuel elements within one year after removal from an operating reactor with large burnup fractions and with several years of fission history yields no direct method of determining fuel burn-up distribution.

In substantiation, the following reasons are given:

- a. Peaks that could be identified as long-lived fission products are masked by the high yield intermediate half-lived fission products and this nullifies the possibility of fission product selection as a means in determining relative burnup distribution.
- b. Selection of a low gamma energy interval, such as 0.2 to 0.3 mev, which might well be attributed to longer lived fission products is rendered useless by the spectral tail associated with the Zr^{95} - Nb^{95} scintillation peak. (6), (7), (8)
- c. Scanning the fuel elements using the entire scintillation spectrum as the energy interval would not yield the relative burnup distribution because of the large activity of the intermediate half-life isotopes and the activity of the fuel element structural material, the distribution of which is due to the neutron flux distribution, known to have changed considerably throughout core life.

The following recommendations are made:

1. Additional scintillation spectra and scans should be taken periodically of reference element S-52, using an abbreviated test procedure TP 318.
2. Test elements, such as the SM-2 elements and the PM-1-M element, if removed prematurely, should be gamma scanned.
3. The methods reported in reference (6) should be reviewed to see if the collimator geometry can be improved and the scintillation spectra of this crystal better understood.
4. Upon unloading SM-1 Core I, scan once the elements from positions 43, 53, 63, 73 (element numbers 57, 78, 44 and 43, respectively) to provide radial power distribution.
5. A comparison should be made between the results of the radio-chemistry fission product distribution and the data from this report.

Figure 4.4.55

6.0 REFERENCES

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7.0 APPENDIX A - ADDITIONAL GAMMA SCANNING RESULTS

Additional gamma scanning data was taken on SM-1 Core I elements No's. S-52 and S-79 during the months of December 1960, and January, 1961, after a decay time of approximately eight months. The results of these data are incorporated in this Appendix.

Scintillation spectra were made of the spent fuel pit water; the spent fuel pit water plus SM-1 fuel element structural material; and the fission products plus the spent fuel pit water and SM-1 fuel element structural material. These are presented as Fig. A.1, A.2, and A.3, respectively. No significant changes were noted in these spectra when compared to the original scintillation spectra reported in the body of this report as Fig. 4.1.1, 4.1.2, and 4.1.3.

The results of the axial and radial gamma scans for elements No's. S-52, January 1960, and S-79, December 1960 and January 1961, are illustrated as Fig. A.1 through A.11. Since the collimator and electronics setups were not similar to all scans, they are given individually on each figure. Also, since the parameters for these scans were not identical to those for the original scans, the data could not be corrected based on a decay curve. However, the data was increased by a multiplication factor so as to match the maximum count rates with the original data for June 24, 1960. These data are presented as relative count rates vs. radial or axial positions. The curves using the gamma energy intervals of 0.65 - 0.85 and 0.7 - 0.8 mev show no significant change when compared to the original curves presented in the body of this report. To illustrate, relative gamma ray intensity was plotted vs. axial location of fuel element S-79 for the original data, June 1960 (from Fig. 4.4.6, of this report), and recent data, January 1961 (from Fig. A.8), and presented as Fig. A.12. In order to provide a comparison, the recent data was corrected to the maximum count rate.

Figures A.10 and A.11 are curves using the gamma energy interval of 0.48 - 0.68 mev. Figure A.13, a comparison of these plots, using the 0.7 - 0.8 mev and 0.48 - 0.68 mev energy intervals, shows a tendency of the 0.48 - 0.68 mev scans to increase the maximum-to-minimum ratio, broaden the peak, and shift the peak towards the lower end of the fuel element. No conclusions are drawn from this, but as it is of interest, we recommend that additional data be taken on the reference element S-52, at the lower energy intervals.

Of note is the fact that scans were attempted during this experimental period utilizing the 1.33 and 1.17 mev Co^{60} peaks as the energy interval. This attempt to measure an integrated neutron flux distribution throughout core life from the fuel element structural material resulted in such low count rates that the statistics were very bad.

Conclusions of the additional testing are:

The recent gamma scans in December 1960 and January 1961 indicated little change in spectra and relative gamma intensity distribution for the 0.7 to 0.8 mev energy interval. The gamma intensity distribution for the 0.48 to 0.68 mev energy interval indicates a slightly broader distribution which may be slightly more representative of the total fission product distribution.

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FIGURE A.1
SCINTILLATION SPECTRUM FOR SPENT
FUEL PIT WATER
January, 1961

Baird Atomic Model 815 BL Scintillation Probe,
1-3/4 x 2 NaI Crystal, 6192 Dumont Photo Tube
H.V. 750, Gain 4 x 71, Scan 0-2 Mev
Window Width 200 Kev

FIGURE A.2

SCINTILLATION SPECTRUM FOR SM-1
FUEL ELEMENT STRUCTURAL MATERIAL
PLUS SPENT FUEL PIT WATER - JANUARY, 1961

Baird Atomic Model 815 BL Scintillation Probe,
1-3/4 x 2 NaI Crystal, 6192 Dumont Photo Tube
H.V. 750, Gain 4 x 71, Scan 0-2 Mev
Window Width 200 Kev

FIGURE A.3

SCINTILLATION SPECTRUM FOR FISSION PRODUCTS
PLUS SM-1 FUEL ELEMENT STRUCTURAL MATERIAL
AND SPENT FUEL PIT WATER - January, 1961

Baird Atomic Model 815 BL Scintillation Probe
1-3/4 x 2 NaI Crystal 6192 Dumont Photo Tube
H.V. 750, Gain 4 x 71, Scan 0-2 Mev
100 Kev Window Width

RELATIVE GAMMA RAY INTENSITY CPM x 10⁻³

FIG. A.4

FIG. A.5

FIG. A.6

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

FIG. A.7

FIG. A.8

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

Relative Gamma Ray Intensity
 Vs. Radial Location of Element
 Number 79, Davel Pin Right,
 0.7-0.8 Mev. Energy Range,
 January 19, 1961

○ $Y = 5$ Inches
 □ $Y = 10$ Inches
 ∇ $Y = 15$ Inches

H. V. 750 Volts
 Gain 4×71
 100 Kev Window Width
 Bottom Aperture Open
 Top Aperture 1/4 Inch Lead
 Applied Correction Factor 2.67

-1 1/2   -1   -1/2   0   1/2   1   1 1/2
 DISTANCE FROM FUEL ELEMENT ϕ

FIG. A.9

FIG. A.10

RELATIVE GAMMA RAY INTENSITY CPM $\times 10^{-3}$

Relative Gamma Ray Intensity
Vs. Radial Location at Y = 10
Inches of Element Number 79,
Dowel Pin Right,
0.48-0.68 Mev Energy Range,
December 29, 1960

H.V. 750 Volts
Gain $\times 71$
200 Kev Window Width
Bottom Aperture 1/2 Inch Lead
Top Aperture 1/4 Inch S.S.

-1 1/2   -1   -1/2   0   1/2   1   1 1/2
DISTANCE FROM FUEL ELEMENT ϕ

FIG. A.11

FIG. A.12

RELATIVE GAMMA RAY INTENSITY $\text{CPM} \times 10^{-3}$

FIG. A.13