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*Research Reactor Fork
Users Manual*

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Los Alamos

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RESEARCH REACTOR FORK USERS MANUAL

by

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ABSTRACT

This manual describes the design features and operating characteristics of the research reactor fork. The system includes an ion chamber for gross gamma-ray counting, fission chambers for neutron counting, and a collimated high-resolution spectroscopy system for gamma-ray measurements. The neutron and ion chamber measurements are designed to be made underwater in spent-fuel cooling ponds. The neutron and gamma-ray detectors have been designed with high efficiencies to accommodate the relatively low emission rates of neutrons and gamma rays from low-burnup, research-type reactor fuel. This manual presents the design, performance, and test results for the system.

INTRODUCTION

The International Atomic Energy Agency (IAEA) inspectors need the capability to conduct independent on-site verification of reactors, including light water reactors (LWR), fast breeder reactors, and various types of heavy water and graphite moderated reactors. Spent LWR fuel is currently verified using the Fork detector¹ and the GRAND electronics.² The measurements are based on gross gamma-ray counting using ion chambers and neutron counting using fission chambers. However, for low-power research reactor fuel, the irradiation level and signal rates are much lower and a standard Fork detector is too inefficient.

The research reactor fork (RRF) detector was developed to measure spent-fuel elements from research reactors that are under IAEA inspection. We designed the RRF and performed basic research on it under the Department of Energy safeguards research program. The Program of Technical Assistance to IAEA Safeguards funded RRF fabrication.

The RRF can be used to determine several important signatures of spent fuel. It can be used to determine the following: the burnup profile of fuel rods by scanning, the plutonium content of fuel rods, the cooling time, and limited information on the consistency of irradiation.

This manual describes the RRF including the detectors, electronics, and performance characteristics. The RRF contains an ion chamber for gross gamma-ray measurements, ²³⁵U fission chambers for gross neutron measurements, and an HpGe-based high-resolution gamma system (HRGS).

GENERAL

The RRF contains a collimated ion chamber and fission chambers in a sealed polyethylene body that operates underwater in the spent-fuel cooling pond. A collimator tube connected to the polyethylene body extends to the surface of the water where the HpGe-based HRGS system is located. A diagram of the polyethylene body is shown in Fig. 1, where fuel rods enter through the 66.1-mm-diam hole in the top of the detector body. Figure 2 is a photograph of the detector head and collimator pipe.

ION CHAMBER

The ion chamber is a small-volume (2.5-cm-diam by 2.5-cm-long) high-efficiency detector containing xenon gas. The ion chamber is enclosed in a tungsten collimator and positioned near the top of the detector body to allow scanning the rods for a gamma-ray profile. Figure 3 shows the ion chamber in the tungsten collimator and Fig. 4 is a photograph of the ion chamber assembly. The GRAND supplies the -100-V bias for the ion chamber and it records the current output from the detector.

FISSION CHAMBERS

The RRF detector contains seven ^{235}U fission chambers with a 2.5-cm diam and an active length of 50.8 cm. Table I gives the fission chamber's specifications.

The fission chambers are connected to two AMPTEK amplifiers of the design used in the Fork detector. Four fission chambers route to one amplifier and three fission chambers route to the other amplifier with two signal lines to the GRAND that is used for data collection. The dual neutron-detector electronic channels are used to provide redundancy for reliability and diagnostic information. The fission chambers are sealed in the polyethylene detector body so that they surround the fuel rod as shown in Fig. 1. These detectors

Fig. 1. Schematic diagram of the RRF polyethylene detector body showing the locations of the seven fission chambers, the ion chamber, and the AMPTEK amplifier. This unit is sealed to operate underwater.

Fig. 2. Photograph of the RRF detector body and HRGS collimator pipe.

Fig. 3. Diagram of the ion chamber and its tungsten shield and collimator.

Fig. 4. Photograph of the ion chamber and shield assembly for insertion into the RRF.

TABLE I. Parameters for Fission Chamber, Ion Chamber, and HpGe Detectors

Item	Value
Fission chamber model	RS-P6-0820-101
Diameter	25.4 mm
Active length	508 mm
Gas pressure	1 atm
Uranium-235 deposit thickness	2 mg/cm ²
Uranium-235 deposit	1.12 g
Operating bias	+500 V
AMPTEK discrimination level	~0.07 counts/s per tube
Ion chamber model	LND
Diameter	25.4 mm
Active length	25 mm
Gas fill	Xenon
Operating bias (outer shell)	-100 V
HpGe ORTEC (Pop Top) - 1	
Model	GEM-15180-P
Serial number	33-TP20775A
Bias	+2500 V
HpGe ORTEC (Pop Top) - 2	
Model	GEM-15180-P
Serial number	33-TP10894B
Bias	+3000 V

FISSION CHAMBERS

(cont.)

give an integral measurement of the neutron emission rate from the entire rod.

HRGS SYSTEM

An entry hole in the side of the polyethylene detector body is used to align the collimator tube with the center of the fuel rod. The collimator pipe has a diameter of 5 cm for the lower 85 cm and a diameter of 7.6 cm for the remainder of the pipe length extending to the germanium detector.

The two HpGe detectors are ORTEC Model GEM-15180-P with relative efficiencies of 15%. There is a 16-mm-thick tungsten shield around the germanium detector with an opening for the collimator tube. Shields and filters of various thicknesses can be inserted between the germanium detector and the collimator tube.

GENERAL

The RRF can be installed at the side of a spent-fuel pool. A front view of the system at the pool side is shown in Fig. 5. The top view of the system is shown in Fig. 6 and the side view in Fig. 7.

Fig. 5. Diagram of the RRF assembly on the wall of the spent-fuel pool (front view).

Fig. 6. Diagram of the RRF assembly on the wall of the spent-fuel pool (top view).

Fig. 7. Diagram of the RRF assembly on the wall of the spent-fuel pool (side view).

GENERAL

(cont.)

The RRF setup consists of two parts: the RRF detector head and the HRGS detector.

To assemble the RRF, assemble the components for hanging the detector adjacent to the pool area in the following order:

DETECTOR HEAD

1. Bolt the detector seat plate to the lower 1-m-long channel.
2. Bolt the middle and top 1-m-long channel to the lower channel, as shown in Fig. 8, and stand the combined sections up so that the seat is on the ground.
3. Bolt the aluminum support plate to the top 1-m-long channel.

DETECTOR HEAD
(cont.)

Fig. 8. Channels for hanging the RRF underwater and for the collimator pipes.

4. Place the polyethylene detector on the seat after raising the seat 3–5 cm above the floor using a spacer to give access to the bottom nuts.
5. Attach the four nuts on the bottom of the four legs of the detector plate.
6. Rotate the detector about 5° so that the collimator tube will line up with the edge of the concrete wall when the unit is in the pool.
7. Attach a safety rope through the eyebolts on each side of the support channel and coil the plastic cable tube on top of the detector.
8. The partially assembled unit is now ready to lift over the rail and into the water. Lift manually using two or three persons or use an overhead crane. Make sure that the safety ropes are attached to the rail or the crane.

DETECTOR HEAD

(cont.)

9. After the detector has been lowered about 1-3 m into the water, rest the top support plate on the safety rail.
10. Lift up the plastic cable tube (connect the safety cable to the rail) and lower the entire unit until the top support plate rests on the concrete floor.
11. Bolt the tie-bracket from the top aluminum plate to the back of the concrete if appropriate.
12. Connect the cable leads from the detector to the decoupling box and from the decoupling box to the GRAND.

The ion chambers and fission chambers are now installed.

HRGS

1. Bolt the sections of the collimator tube together to give the appropriate length tube.
2. Place the aluminum floor plate at a distance of ~2.5 m (center line to center line) from the detector support plate. This separation distance assumes a 4-m hanging depth for the RRF. A greater depth will require a larger separation than the 2.5 m because the angle between the fuel axis and the collimator pipe is ~36°.
3. Lower the closed end of the collimator pipe into the water, insert it into the steel funnel on the side of the polyethylene body, and tie the pipe to the rail using the safety cable that is attached to the top section of the collimator pipe.
4. Place the top of the collimator tube into the open channel of the aluminum floor plate.

HRGS

(cont.)

5. Secure the collimator pipe with the adjustable aluminum plate and bolt into place.
6. Place the tungsten shield on its cradle and clamp into place.
7. Place the germanium detector into the shield and rest it on the support platform.
8. Connect the cables from the germanium preamplifier to the portable multichannel analyzer (PMCA) and from the PMCA to the minicomputer.
9. After a fuel rod is in the measurement position, adjust the HpGe detector to give the maximum counting rate.
10. Use the additional collimators and filters to obtain the desired counting rate.

GENERAL

The GRAND is used to provide bias high voltage to the fission detectors and the ion chamber and to provide the AMPTEK amplifier³ power (+5 V). The GRAND also collects the signal and calculates the statistical errors for the two neutron channels and the ion chamber current. The data are displayed on the LCD window and printed on the small tape printer.

The GRAND is normally powered by the ac power line with an internal ac/dc converter. It can operate from its internal batteries for approximately 10 h with limited printer use.

The cable connections between the GRAND and the detector head are shown in Fig. 9. The cables run from the detector head through 5 to 7 m of plastic tubing to the decoupling box and from the decoupling box to the GRAND.

Fig. 9. Diagram of the cable connections to the GRAND electronics.

GENERAL

(cont.)

Signals from the two neutron channels are recorded separately for redundancy and diagnostics but are added together for the final results.

The operation of the GRAND is described in the GRAND operating procedures.

FISSION COUNTER SETUP

The seven fission chambers are split with three chambers to amplifier channel A and four chambers to amplifier channel B. The separate channels are used to reduce alpha-particle pileup and to provide redundancy. The ratio of the counts in channel B to the counts in channel A should be fixed (~1.2).

Figure 10 shows the pulse-height distribution from a single fission counter. The bottom curve with no neutron source present shows the alpha-particle pileup distribution. We

Fig. 10. Pulse-height spectrum from a fission chamber with a ^{252}Cf neutron source (top curve) and the alpha-particle background (bottom curve). With a high gamma-ray dose, the alpha-particle background shifts deeper into the neutron distribution.

FISSION COUNTER SETUP

(cont.)

normally set the discrimination level just above the point at which the alpha-particle counting rate becomes zero. When three or four fission chambers are connected to the same amplifier, the alpha-particle pileup extends deeper into the neutron fission distribution.

Table I lists the fission chamber and ion chamber setup parameters. The amplitude of the output signal from the fission chamber is very dependent on the number of tubes and the cable lengths between the fission chambers and the AMPTEK amplifier. The AMPTEK gain is preset with the screw pot located on the side of the amplifier case shown in Fig. 11.

Fig. 11. The dual channel AMPTEK amplifier showing the screwdriver holes for the gain adjustment.

FISSION COUNTER SETUP

(cont.)

Table II lists the fission chamber serial numbers, their relative efficiency for neutron counting, and their alpha-particle backgrounds for the same amplifier and discriminator settings.

The output of the AMPTEK amplifier is the integral of all pulses above the discrimination level. Table III gives the integral neutron counts and alpha background counts as a function of signal discriminator level. The integral counts as a function of discrimination energy level are shown in Fig. 12.

The fission chamber efficiency is relatively insensitive to the high-voltage bias in the range of 200 to 800 V. Figure 13 shows the relative counting rate as a function of high-voltage bias. We operate the fission chambers at 500 V.

ION CHAMBER SETUP

The ion chamber has a 9-mm-thick tungsten shield with a 9.5-mm-wide collimation slit for scanning the fuel rod. The collimator opening is covered by a 0.4-mm-thick tungsten filter. The outer shell of the ion chamber is operated at 100 V and it is isolated from the tungsten shield by a thin layer of insulation.

Figure 9 shows the cable connections from the GRAND to the ion chamber.

To test the operation of the ion chamber, a 500-mR/h ^{241}Am source was placed adjacent to the collimator slit. The resulting current was 1 to 2 orders of magnitude above the background noise level. The ion chamber is designed for fuel rods in the range of 0.5 to 10^6 R/h on contact.

The ion chamber is collimated to facilitate the measurement of the gamma-ray profile of an individual fuel rod. To test the spatial resolution of the ion chamber, we moved an intense

TABLE II. Fission Chamber Relative Efficiency
(RS-P6-0820-101)

Chamber S/N	Relative Neutron Efficiency (counts/s)	Cosmic-Ray and Alpha Bkgd ^a (counts/s)	AMPTEK Channel
1154	1.02	0.06	B
1155	1.00	0.07	A
1156	0.92	0.06	A
1157	0.99	0.06	B
1158	0.97	0.07	B
1159	1.12	0.07	A
1160	0.98	0.06	B
$A_v = 1.00 \pm 0.06$			

^aThe alpha decay background is dependent on the discriminator level and cosmic-ray dose. For field use underwater, the alpha background rate should be ~0.032 counts/s per tube or about 0.224 counts/s for the sum of all seven tubes.

TABLE III. Amplifier Integral Fission
Chamber Rates and Alpha Background

Channel	Bkgd (counts/s)	Neutrons (counts/s)
17	2.60	419
18	1.10	406
19	0.45	395
20	0.18	383
21	0.07	367
22	0.03	350
23	0.01	332
24	0	312

Fig. 12. The integral response of the fission chamber above the discrimination level for a neutron source (top curve) and the alpha background (bottom curve).

Fig. 13. The fission counter rate as a function of high-voltage bias.

ION CHAMBER SETUP

(cont.)

^{241}Am source (60 keV) in 1-cm steps along the axis of the fuel-rod channel. Figure 14 shows the relative ion chamber current as a function of position from the top of the polyethylene detector. The measured full width at half maximum (FWHM) was 4.8 cm for the ^{241}Am source. We also measured the profile using a high-energy (1–2.7 MeV) ^{226}Ra source and the response is shown in Fig. 14 (top curve). The average gamma-ray energy from spent fuel is about halfway between these two extremes, so the FWHM should be ~ 10 cm for spent fuel.

HRGS

The cabling for the HRGS system is shown in Fig. 15. The germanium detectors are 15% efficient and have an energy resolution of ~ 1.75 keV for ^{60}Co . The dewar can hold enough LN2 to last 3 days, but it is good practice to fill it every day. The amplifiers of the PMCAs are designed for high counting rates and have been tested by measuring spectra

Fig. 14. Axial scan profile of a collimated ion chamber for a small gamma-ray source (^{241}Am) and a high-energy ^{226}Ra source positioned along the sample axis. The zero position is the top (below funnel) of the polyethylene detector body.

Fig. 15. Diagram of the cable connections to the HRGS system.

HRGS

(cont.)

with rates up to 100 000 counts/s with little peak-shape degradation. Each detector-PMCA pair has been optimized in terms of pileup rejection, so it is desirable to use matching pairs.

The matching hardware pairs are as follows:

PMCA	Detector	Bias Voltage (V)	PPRT	Gain
C346	TP10894B	3000	220	500
C345	TP20775A	2500	240	1040

There are several considerations in setting up the HRGS system. The time constant of the amplifier is 2 μ s. The gain of the system should be adjusted so that the 4-k channels cover up to 2.5 MeV. The pole-zero adjustment should be performed.

Rate Loss

The spent-fuel rods have varying counting rates. To determine the relative ^{137}Cs activity, it is necessary to make a rate-loss correction between different rods. For both systems, the rate-loss corrections are relatively small and less than 12% for counting rates up to 80 000 counts/s. The live-time correction for both PMCAs does correct for the dead time of the MCA; however, the correction may not be accurate. For PMCA C345, the dead-time correction is undercorrected, reaching a maximum of 6% at a counting rate of 50 000 counts/s. For PMCA C346, there is no rate-loss correction up to 40 000 counts/s. Above 40 000 counts/s, the dead-time correction is overcorrected, reaching a maximum of 12% at 85 000 counts/s. The rate-loss correction curves are shown in Appendix B and the ^{137}Cs counts should be divided by the correction.

Count Rate

The most important adjustment for the HRGS is the count rate. It is crucial to use the same collimator and absorbers for the entire measurement campaign. Choose the fuel rod with the highest declared burnup and load it in the RRF. There is a set of three tungsten collimators; each one added will reduce the count rate by a factor of ~ 4 . There is also a set of absorbers: 6.4 mm of tungsten, 3.2 mm of tungsten, 0.9 mm of tin, and 0.25 mm of copper. The transmission properties of these absorbers are shown in Table IV. The proper sequence of

TABLE IV. Attenuation of Gamma Rays Through Absorbers

Energy (keV)	W 6.4 mm	W 3.2 mm	Sn 0.9 mm	Cu 0.25 mm
400	0.11	0.34	0.92	0.980
700	0.34	0.58	0.95	0.985
1000	0.46	0.68	0.96	0.987

Count Rate

(cont.)

absorbers is as follows: tungsten nearest the spent fuel, next the cadmium, and finally the copper. It is desirable to adjust the count rate first by selecting the collimators and absorbers and installing the 16-mm-thick tungsten shield around the detector last.

The highest count rate for this system for reasonable peak shape is ~70 000 counts/s. A spent-fuel spectrum taken with this system at 45 000 counts/s is shown in Appendix B.

It is good practice to get the peak area for the 605- and 662-keV peaks during the measurement. It is also desirable to determine the resolution of one peak for all the runs during the campaign for quality control purposes.

Short Cooling Time

The gamma-spectrum measurements of spent fuel with a short cooling time are more challenging. They are dominated by the short-lived fission products such as ^{99}Mo (66 h), $^{132}\text{Te-I}$ (78.2 h), and $^{140}\text{Ba-La}$ (12.8 d). A fission product spectrum from irradiated ^{235}U is shown in Appendix B. The peaks from ^{134}Cs are buried under the Compton continuum of the short-lived fission products. It is desirable to have a minimum cooling time for measuring fission product gamma rays of 1 month and preferably 2 months. Two months cooling would allow the $^{140}\text{Ba-La}$ to decay by a factor of ~30.

BURNUP PROFILE MEASUREMENT

The burnup profile can be determined by the RRF. The most straightforward method is using the data from the ion chamber. The ion chamber detects the gross gamma radiation from the spent fuel, which is dominated by the direct fission products.

Another possibility is the signal from the total counting rate from the germanium detector obtained from the PMCA. A typical burnup profile is shown in Fig. 16.

In this figure, fuel rod 1 has a declared burnup of 873 MWD/tU and fuel rod 2 has a declared burnup of 652 MWD/tU. The two burnups differ by 30%. The two burnup profiles do have similar shapes although the magnitudes of the activity are quite different.

The burnup profile from neutron measurement is more peaked than either profile from the ion chamber or the total germanium counting because total neutron response is approximately proportional to the second, third, or fourth power of the burnup.

Fig. 16. Burnup profile of typical spent fuel from a research reactor.

BURNUP MEASUREMENT

The burnup of the fuel rods can be verified with the RRF by two gamma-ray methods: counting the ^{137}Cs and the cesium ratio method. The isotope ratios can be related to the absolute burnup using reactor calculations.

Cesium-137 is the most widely accepted indicator of burnup because its yields from both ^{235}U and ^{239}Pu are approximately the same, and its 30-yr half-life makes a correction for irradiation history unnecessary. To measure the relative ^{137}Cs activity, it is crucial that the positions of the fuel and detector be reproducible. Figure 17 shows the correlation between the measured ^{137}Cs activity and the declared burnup for typical research reactor fuel.⁴ To determine the ^{137}Cs activities, it is important to account for the rate loss resulting from counting rate differences.

This rate-loss measurement is a small correction when using the new PMCA with the high-performance amplifier and can be done with the figures in Appendix B.

Fig. 17. The ^{137}Cs relative activity vs fuel-rod burnup.

BURNUP MEASUREMENT

(cont.)

Cesium-134 is produced by neutron capture of ^{133}Cs , which is a direct fission product. The concentration of ^{134}Cs is approximately proportional to the square of the integrated neutron flux. The concentration of ^{134}Cs divided by the concentration of ^{137}Cs , which is proportional to the integrated flux, is approximately proportional to the burnup. Cesium-134 has a decay half-life of 2.6 yr. Therefore any removal of the fuel from the reactor may require an irradiation history correction. For example, during a 3-month removal, the ^{134}Cs in a fuel rod will decay by a factor of 0.919. Figure 18 shows the correlation between the measured $^{134}\text{Cs}/^{137}\text{Cs}$ ratio for research reactor fuel. This set of data⁴ was not corrected for irradiation history because most of the fuel rods examined were in the reactor core for the whole duration and therefore have similar irradiation histories.

In determining the cesium ratio, the rate-loss correction is not necessary but the relative detection efficiency needs to be considered. This can be done by using several gamma peaks from the same isotope. A typical relative efficiency curve is

Fig. 18. The $^{134}\text{Cs}/^{137}\text{Cs}$ activity ratio vs fuel-rod burnup.

BURNUP MEASUREMENT

(cont.)

shown in Fig. 19. Gamma radiations from ^{134}Cs (622, 873, 1050, 1128, and 1562 keV), ^{144}Pr (696 and 1489 keV), and ^{106}Rh (604, 796, 1038, 1167, and 1365 keV) were used to construct the relative efficiency curve. For research reactor fuels, the assemblies have the same physical characteristics (geometry, density). The relative efficiency curve is essentially the same for all assemblies. To improve the counting statistics of some of the weaker peaks, it is desirable to use data from many assemblies to construct the relative efficiency curve. Because the same relative efficiency curve is used for all assemblies, the inspector can plot the ratio of 795/662 as a function of the declared burnup during the data collection.

Fig. 19. The gamma-ray counting efficiency vs gamma-ray energy of an ^{11}pGe detector.

GENERAL

For low-burnup fuel (<400 MWd/tU), the ^{240}Pu isotope is the dominant source of neutrons. As the burnup increases, the ^{242}Cm isotope contributes an increasing fraction of the total neutrons. The ^{242}Cm decays with a 163-d half-life, so its neutron contribution decreases with cooling time; after several years of cooling, its contribution is negligible. For fuel burnup <1000 MWd/tU, the neutron contribution from ^{244}Cm is negligible.

The ratios of the ^{240}Pu and the ^{242}Cm to the total plutonium are determined using reactor burnup calculations.

Table V lists the primary neutron sources for low-burnup metallic fuel.

TABLE V. Neutron Sources for Low-Burnup Fuel		
Isotope	Half-Life	Spontaneous-Fission Yield [n/(s•g)]
^{238}U	$4.47 \times 10^9 \text{ yr}$	1.36×10^{-2}
^{240}Pu	$6.56 \times 10^3 \text{ yr}$	1.02×10^3
^{242}Cm	163 d	2.10×10^7
^{244}Cm	18.1 yr	1.08×10^7

PLUTONIUM CALIBRATION

The fission chambers are used to detect neutrons because they are insensitive to high gamma-ray levels. The fission chambers have an absolute counting efficiency of 0.7–1.0%, depending on the alpha-particle discrimination level, for a fuel rod positioned in the central sample cavity shown in Fig. 1.

The amount of water surrounding the fuel rod influences the detection efficiency. Figure 20 shows the relative efficiency vs the water thickness in the sample cavity. For calibration,

Fig. 20. The relative neutron counting efficiency vs the radial thickness of water surrounding the fuel rod.

PLUTONIUM CALIBRATION

(cont.)

the same water thickness should be used with the standards and unknowns. For example, if a ^{252}Cf source is used for absolute calibration, it should be contained in a steel rod or pipe with the same water displacement as the fuel rod.

The absolute calibration is performed using a plutonium mixed-oxide fuel rod or a uranium fuel rod or both. The linear neutron emission rate is known for the standards with units of neutrons/s per cm of rod. Calibration curves can be measured for both ^{238}U and ^{240}Pu in fuel rods.

Table VI lists the calibration data for uranium and plutonium rods and Figs. 21 and 22 show plots of the data for uranium and plutonium, respectively. The fission chamber alpha-particle background has been subtracted to give an intercept at zero and corrections have been made for any (α, n) -reaction neutrons in the oxide.

TABLE VI. Neutron Calibration Data for the RRF:

Sample Rods ^a	g U/cm	g ²⁴⁰ Pu/cm	Δt (s)	A (s ⁻¹)	B (s ⁻¹)	A + B (s ⁻¹)	σ (%)	Net A + B	Top Corr. ^c (s ⁻¹)	U Corr. ^d (s ⁻¹)	Rate ^e /1 + α (s ⁻¹)
Bkgd	0	0	10 ⁴	0.10	0.13	0.23	2.0	0	0	N/A	0
7 DU + 0 Pu	41.7	0	2000	0.174	0.282	0.456	3.3	0.232	0.213	N/A	0.209
9 DU + 0 Pu	53.6	0	5700	0.215	0.316	0.531	1.8	0.307	0.282	N/A	0.276
7 DU + 1 Pu	52.1	0.052	300	16.13	19.60	35.73	1.0	35.51	32.6	32.32	17.31
6 DU + 2 Pu	56.7	0.104	300	32.2	38.1	70.3	0.7	70.08	64.4	64.1	34.33
5 DU + 3 Pu	61.1	0.155	300	47.3	56.7	104.0	0.6	103.8	95.4	95.1	50.94
1 DU + 5 Pu	58.1	0.259	300	82.6	97.3	179.8	0.4	179.6	165.1	164.8	88.27
5 DU + 3 Pu ^b	61.1	0.155	300	46.6	54.3	100.9	0.6	100.7	95.7	95.4	51.10

^aThe designation 7 DU + 1 Pu, for example, corresponds to seven depleted uranium oxide plus two plutonium MOX rods in a tight bundle on the sample axis.

^bThis rod bundle was measured at 4 cm above the other bundles.

^cThe calibration rods extended above the top of the RRF, so a correction was made to give the equivalent count rate for a rod that stopped at the top of the polyethylene body.

^dThe uranium metal correction removes the ²³⁸U spontaneous fission neutrons from the yield.

^eThe correction for (α, n) reaction neutrons in the oxide is $1/(1 + \alpha)$, where $\alpha = 0.867$ for plutonium.

Fig. 21. Uranium metal calibration curve for underwater measurements.

Fig. 22. Plutonium calibration in a uranium metal rod for underwater measurements.

CALIFORNIUM-252 CROSS REFERENCE

The efficiency of the RRF under field conditions can be checked using a small ^{252}Cf source. At the time of the calibration listed in Table VI, a standard reference ^{252}Cf source CR-5 was counted in the water-tight bottle that is supplied with the RRF. For the reference count, the bottle was lowered with a string until it rested on top of the 12.5-cm-high polyethylene plug in the bottom of the RRF sample hole. The resulting reference rate was

$$T(\text{CR-5}) = 39.7 \text{ counts/s (on 5-27-93).}$$

As can be seen in Fig. 23, any change in the height of the neutron source will change the counting rate. The reference source and fuel rods should always be counted in the same position.

Fig. 23. Neutron counting profile for a point source of ^{252}Cf scanned along the axis of the RRF.

FISSION PRODUCTS

If the irradiation history of the fuel rod is assumed, it is possible to calculate the activity ratios of fission product isotopes at the end of the irradiation. From the calculated activity ratios and the measured ratios, it is possible to determine the cooling time of the fuels. The different activity ratios can also be used to verify the irradiation history in an indirect way. The isotopes used in determining the activity ratios have half-lives ranging from 64 d (^{95}Zr) to 366 d ($^{106}\text{Ru-Rh}$); these isotopes decay by different amounts during a shutdown of the reactor or the removal of the fuel from the reactor core. Possible activity ratios are $^{95}\text{Zr}/^{137}\text{Cs}$, $^{144}\text{Pr}/^{137}\text{Cs}$, $^{106}\text{Rh}/^{137}\text{Cs}$, and $^{95}\text{Zr}/^{95}\text{Nb}$. The half-lives and gamma-ray energies associated with these isotopes are listed in Appendix B.

ACTINIDES

The neutron measurements can be used to determine the ^{240}Pu content, and if two measurements are made for the same sample with a time separation of 3 to 6 months, the ^{242}Cm component can be separated from the ^{240}Pu component in the data analysis. Because of its long half-life, the ^{240}Pu gives an integral of the fuel burnup with no specific irradiation time information. However, the ^{242}Cm has a half-life of 163 d and it is created through a multiple neutron capture chain that includes ^{241}Pu and ^{241}Am , so the ratio of $^{242}\text{Cm}/^{240}\text{Pu}$ is sensitive to irradiation history and cooling time.

1. P. M. Rinard and G. E. Bosler, "Safeguarding LWR Spent Fuel with the Fork Detector," Los Alamos National Laboratory report LA-11096-MS (March 1988).
2. J. K. Halbig, S. F. Klosterbuer, R. H. Augustson, G. E. Bosler, H. O. Menlove, and M. C. Miller, "Applications for Unattended, Remote NDA Instrumentation," IEEE Nuclear Science Symposium and Medical Imaging Conference, Santa Fe, New Mexico, November 2-9, 1991.
3. J. E. Swansen, "Deadtime Reduction in Thermal Neutron Coincidence Counter," Los Alamos National Laboratory report LA-9936-MS (March 1984).
4. J. R. Phillips, T. R. Bement, C. R. Hatcher, S. T. Hsue, and D. M. Lee, "Nondestructive Verification of the Exposure of Heavy-Water Reactor Fuel Elements," Los Alamos National Laboratory report LA-9432-MS (June 1992).

By S.-T. Hsue and S. F. Klosterbuer

GENERAL

The DISPLAY program is a computer code to display spectral data and transfer spectra from the PMCA. It is written for DOS. The data are recorded in the Canberra Industries S100 format with the same header block and spectral data format. There is a trailer block to store information specific to the Los Alamos National Laboratory Safeguards Assay Group; this trailer block does not interfere with the plotting or peak-area-analysis programs from Canberra Industries. The program DISPLAY is stored in the subdirectory \RRF\.

Two files are associated with the DISPLAY program: GRAPH.CFG and ROI.CFG, also stored in the subdirectory. These are text files and can be edited by any text editor.

GENERAL
(cont.)

When DISPLAY is typed, the following dialog box will be shown on the screen:

LOS ALAMOS NATIONAL LABORATORY
Copyright, 1993, Regents of University of California.

PMCA Spectral Transfer and Display

Version 0.01
Release April 20, 1993

Enter date (MM/DD/YY) 04/04/93

Enter time (HH:MM:SS) 06:37:42

Adjust the System Date if necessary
[↑, ↓] to parameters [F10] to save [Esc] to cancel/exit

Move through the date and time with the ← and → keys.
Move between date and time with the ↓ and ↑ keys.

If the date and time are correct, push the F10 button to proceed.

MAIN MENU

After the date and time are verified, the following main menu will be shown:

Main Menu
T Transfer Spectrum from PMCA
G Graph Spectrum from File
Z Adjust Spectrum
Q Quit

To select the different options in the main menu, use the ↓ and ↑ keys and [enter] or type the first letter of the option.

TRANSFER SPECTRUM

When the transfer spectrum option is selected, the following dialog box will be shown:

Transfer Spectrum Parameters	
Spectrum Filename=	Spfuel
Drive, path, and extension=	\specdata*.dat
Channels to transfer=	4096

When transferring data for the first time, it is necessary to check the PMCA to see if it is ready to transfer data. This can be done by pushing the END button on the PMCA. At this point, the display of the PMCA will show [Push Command Key]. Push the I/O button on the PMCA. The display will show [Output all Channels?]. If the answer is YES, then the display will show [Serial Port Active]. Now the system is ready for spectral transfer. This only needs to be done at the beginning of the transfer.

TRANSFER SPECTRUM

(cont.)

Push the F10 button on the computer to start the actual data transfer. If all the settings are correct, the following screen will be shown:

Transfer spectrum from PMCA
into file. Please wait.
This takes 10-60 sec
depending on spectrum size.

If the filename already exists on the disk, the following dialog box will be shown:

File:\SPECDATA\spfuel.dat already exists.
Overwrite the existing file?
Yes
No

A YES answer will allow the transfer to proceed. A NO answer will abort the data transfer. After the transfer is complete, the spectrum will be displayed on the screen of the computer.

DISPLAY

In displaying the spectrum, a set of commands can change the display. The following is a discussion of these commands. On the upper left hand corner of the graph, two lines are displayed: x = channel, energy and y = counts. The first x number is the channel number of the cursor, the second x number is the energy corresponding to this channel. In case the system is not calibrated, the energy and channel are the same number.

Help	The commands can be displayed by typing h for help. Pressing the [h] key repeatedly will display the possible display commands sequentially on the line at the bottom of the screen.
Q, F10	Return to main menu
[Arrows]	Move cursor on graph
[alt+Arrows]	Fast move of cursor on graph
X n	Expand <i>n</i> times around cursor. Expansion is limited to [<i>n</i> = 2 to 9]
U	Unexpand to full spectrum
M	Mark channel numbers and counts
V	Vertical scale VL = log VA = auto VM = manual
R	Under the region-of-interest (ROI) options, there are four selections: RC = clear all ROIs RI = integral of all ROIs RN = net counts in the peak ROIs RS = set ROI
RS	When RS is selected, a question will be asked whether the ROI is for peak or background. If the ROI is for peak, then a selected number of channels above and below the ROI will be used for background determination. The number of channels used is specified in the file ROI.CFG. Position the cursor at the ROI star channel and press [enter]. Next move the cursor to the end channel and press [enter].

- RI** When RI is selected, the integral sum of the first ROI will be shown on the screen. Press any key to advance to the next ROI. The final display is of the gross spectral counts of the entire spectrum. Pressing any key again will return the screen to displaying the R options.
- RN** When RN is selected, the net peak area of the first ROI will be shown on the screen. Press any key to advance to the next ROI. The background is calculated by three channels beyond the peak ROI. The number of skip channels between the ROI and background is specified in the ROI.CFG file.
- E** This option allows you to perform energy calibrations. There are two options:
- EC = energy calibration
EE = examine energy calibration
- EC** This option performs the energy calibration. When this option is selected, the program asks the user to move the cursor to the low-energy channel. It is important that the display has both peaks in it. When the cursor is at the correct peak channel, press [enter]. At this point, the screen will show [Low energy = 0.0, Type new energy, and Enter]. Next move the cursor to the high-energy channel and enter the energy. The code will perform a linear fit to these two points and return with the slope and intercept in the equation
- $$\text{Energy} = \text{Slope} \times \text{Channel} + \text{Intercept}$$
- You can verify the energy calibration by moving the cursor to the low and high peaks and check the energy calibration by reading the *x* and *y* display at the upper left hand corner.

F

This option determines FWHM and centroid of a peak in an ROI. If the cursor is positioned in an ROI with a peak in it, the F option will calculate the FWHM and centroid channels and display the results next to the peak. The results are in units of channels.

If the cursor is not positioned in an ROI, the following message will be shown:

[Cursor not positioned in valid peak ROI, strike any key]

P PRINT GRAPH

This option provides a hard copy of the spectral data.

**GRAPH SPECTRUM
FROM FILE**

This option displays a spectrum recorded on disk. The following dialog box is shown:

Plot Spectra Parameters	
Spectrum Filename=	Spfuel
Overlay a spectrum (Y/N)=	N
Overlay Spectrum filename=	
Drive, path and extension=	\specdata*.dat

If the information is correct, then press the F10 key. If the spectrum is successfully read from the file, it will be displayed on screen. If the answer to overlay spectrum is YES, then enter the filename of the overlay spectrum. Then the overlay spectrum will be displayed on screen. Pressing Q or the F10 key will return the display to the main menu.

ADJUST SPECTRUM

This option allows the user to adjust the spectrum energy or normalize the spectrum height. The following dialog box will be shown:

Adjust Menu	
E	Adjust Spectrum Energy
N	Normalize Spectrum Height
Q	Return to Main Menu

Adjust Spectrum Energy

This option changes the gain of the original spectrum and creates a new spectrum with the desired gain and intercept. When this option is selected, the following dialog box will be shown:

SPECTRAL RECALIBRATION PARAMETERS	
Spectrum Filename:	
Drive, path and extension =	\specdata*.dat
Original slope (keV/chan):	
Original intercept (keV):	
Desired slope (keV/chan):	
Desired intercept (keV):	
New Spectrum filename=	
Drive, path, and extension =	\specdata*.adj

Normalize Spectrum Height This option adjusts the counts in one ROI to a desired number of counts and multiplies the entire spectrum with the constant. When this option is selected, the following dialog box will be shown:

COUNT NORMALIZATION PARAMETERS	
Spectrum Filename:	
Drive, path and extension =	\specdata*.dat
Original ROI cts:	
Desired ROI cts:	
New Spectrum filename=	
Drive, path, and extension =	\specdata*.nrm

ROI.CFG

The ROI can be set on the computer screen using the RS option. However, to retain the same ROI after the computer has powered off, modify the ROI.CFG file. This is done by entering EDIT ROI.CFG on the keyboard. The following typical file will be shown on screen:

```

3 /*    numbers of rois in file*/
3 /*    number of channels in assumed backgrounds */
0 /*    number of channels bet. roi and assumed
backgrounds */
1 244 344 0 /* roi number, beg. chan, end chan. type:0=pk,
1=bk */
2 235 240 0 /* roi number, beg. chan, end chan. type:0=pk,
1=bk */
3 346 351 0 /* roi number, beg. chan, end chan. type:0=pk,
1=bk */

```

ROI.CFG

(cont.)

The content of the file can be modified by using the left and right cursor and the insert and delete keys. The comments at the end of the data entry are necessary to remind the operator of the meaning of the numbers. Channels are 4-digit integers. There should be a space between any two numbers and between the number and the beginning of the comment.

At the end of editing, press the Alt key to activate the menus and move the cursor by the up, down, left, and right arrow keys. Similarly using the mouse can also activate the options. The ROI.CFG file will be saved when exiting the edit.

GRAPH.CFG

The GRAPH.CFG file controls the display parameters. Most of the time this file need not be modified. This file can be modified in a fashion similar to the ROI.CFG file.

**FISSION PRODUCTS
FROM SPENT FUEL**

The following table gives the fission product gamma rays normally observed in spent fuel. This table lists the isotopes normally observed after several months of cooling time. All the information in this appendix is obtained from *Table of Isotopes*, Seventh Edition, by C. M. Lederer and V. S. Shirley.

FISSION PRODUCTS
FROM SPENT FUEL

(cont.)

Isotopes	Half-Life	Gamma-Ray Energy (keV)	Branching Ratio (%)
⁹⁵ Zr	64 d	724.18	43.08
		756.72	54.60
⁹⁵ Nb	35 d	765.71	99.82
¹⁰³ Ru	39.4 d	497.08	86.40
		610.41	5.39
¹⁰⁶ Ru-Rh	366.5 d	511.80	19.00
		622.20	9.78
		873.73	0.45
		1050.47	1.60
		1128.21	0.42
¹³⁴ Cs	2.062 y	569.29	15.43
		604.66	97.56
		795.76	85.44
		801.84	8.73
		1038.50	1.00
		1365.13	3.04
¹³⁷ Cs	30.17 y	661.65	85.00
¹⁴⁴ Ce-Pr	284.5 d	696.43	1.34
		1489.15	0.27
		2185.60	0.66
¹⁵⁴ Eu	8.5 y	591.78	4.83
		723.30	19.53
		873.19	11.50
		996.32	10.30
		1274.39	35.50

FISSION PRODUCTS
FROM SPENT FUEL

(cont.)

If the cooling time is less than a few months, then some of the shorter-lived fission products may be observed. The following table lists some of these fission products:

Isotopes	Half-Life	Gamma-Ray Energy (keV)	Branching Ratio (%)
⁹⁹ Mo	66.02 h	739.40	12.60
		777.80	4.40
¹³² Tc-I	78.2 h	667.69	98.70
		669.80	4.94
		772.61	16.20
		954.55	18.06
		1398.57	7.11
¹⁴⁰ Ba-La	12.79 d	328.75	18.53
		487.3	42.98
		537.25	23.60
		815.85	22.44
		867.82	5.35
		925.24	6.78
		1596.49	95.50

Figure B-1 is a spent-fuel spectrum recorded with one of the germanium detectors of the RRF.

The manual mentions that ¹³⁷Cs can be used to monitor burnup. This is the case if the rate-loss correction of the amplifier and MCA combination is corrected. This can be done by applying a rate-loss correction with respect to the PMCA. Figures B-2 and B-3 show the rate-loss correction for PMCA's C345 and C346, respectively. The ¹³⁷Cs count rate should be divided by this correction factor.

Fig. B-1. Spectrum from research reactor fuel after several months of cooling.

Fig. B-2. Count-rate correction curve for PMCA C345.

Fig. B-3. Count-rate correction curve for PMCA C346.

FISSION PRODUCTS
FROM SPENT FUEL

(cont.)

Figure B-4 is a spectrum from irradiated ^{235}U with a relatively short cooling time of 24 days. This sample was irradiated for in a reactor. If the sample is irradiated a few hours for an extended time, the short-lived isotope will come to equilibrium, whereas the long-lived fission products such as ^{137}Cs will continue to build up.

Fig. B-4. Spectrum from ^{235}U sample irradiated for a few hours and then cooled for 24 days.

END

DATE

FILMED

2/17/94