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RRFC Hardware Operation Manual

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by

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ABSTRACT

This manual describes the design features, hardware specifications, and performance characteristics of the Research Reactor Fuel Counter (RRFC) system. The system is an active mode neutron coincidence counter intended to assay Material Test Reactor (MTR) fuel assemblies underwater. The RRFC contains 12 ^{3}He tubes with 1 preamplifier per tube and 1 ion chamber. The neutron counting electronics are based on the Los Alamos Portable Shift Register (PSR) and the gamma readout is a manual range pico-ammeter of Los Alamos design. The RRFC is connected to the surface by a 20-m-long cable bundle. The PSR is controlled by a portable IBM computer running a modified version of the Los Alamos NCC code called RRFC. A description of the software can be found in the RRFC Windows NCC Software Users Manual.

GENERAL

The Research Reactor Fuel Counter (RRFC) system was developed to assay the ^{235}U content in spent Material Test Reactor (MTR) type fuel elements underwater in a spent fuel pool. The RRFC assays the ^{235}U content using active neutron coincidence counting, and also incorporates an ion chamber for gross gamma-ray measurements.

This manual describes the RRFC hardware, including detectors, electronics, and performance characteristics.

GENERAL

The RRFC contains 12 ^{3}He tubes, each with its own separate preamplifier, polyethylene neutron moderator, lead gamma shielding, 2 Am-Li interrogation sources, and an ion chamber in a sealed stainless steel housing. A schematic diagram of the RRFC is shown in Fig. 1. MTR elements are loaded from the top with a funnel to aid in the loading process. A grappling tool can be inserted into the topmost section of the central cavity of the counter, which has been enlarged to allow easy access for insertion and withdrawal. The fuel element to be measured is centered within the central cavity of the detector by a basket which is designed to fit each specific type of MTR assembly, as shown in Fig. 2.

Figure 3 shows a photograph of the body of the detector, and Fig. 4 shows a photograph of the polyethylene insert with the preamplifiers installed.

^{3}He TUBES

The RRFC contains 12 ^{3}He tubes that efficiently count neutrons emitted from the fuel assembly. Each tube has a 2.5-cm diameter and 61-cm active length. The fill-pressure is four atmospheres of ^{3}He with a nitrogen quench-gas additive. The tubes are made of aluminum with an internal carbon coating for gamma resistance. Table I gives the specifications of the ^{3}He tubes. Figure 5 shows two photographs of a ^{3}He tube with a preamplifier attached.

The ^{3}He tubes are arranged in a semicircle around the central cavity. This arrangement was selected to limit the total neutron count rate coming from the interrogation sources while maintaining acceptable counting efficiency for neutrons coming from the fuel. Each ^{3}He tube has its own preamplifier in order to maximize gamma rejection. The signals from six preamplifiers are "daisy chained," forming two symmetric banks of six tubes each with a separate signal cable going to the surface from each bank. The signals from the two banks are combined in an adder circuit at the surface for normal operation, or each bank can be counted independently for diagnostic purposes.

The preamplifiers are powered by a 5-V cable from the Portable Shift Register (PSR) at the surface. The 5-V supply is "daisy chained" to all 12 preamplifiers.

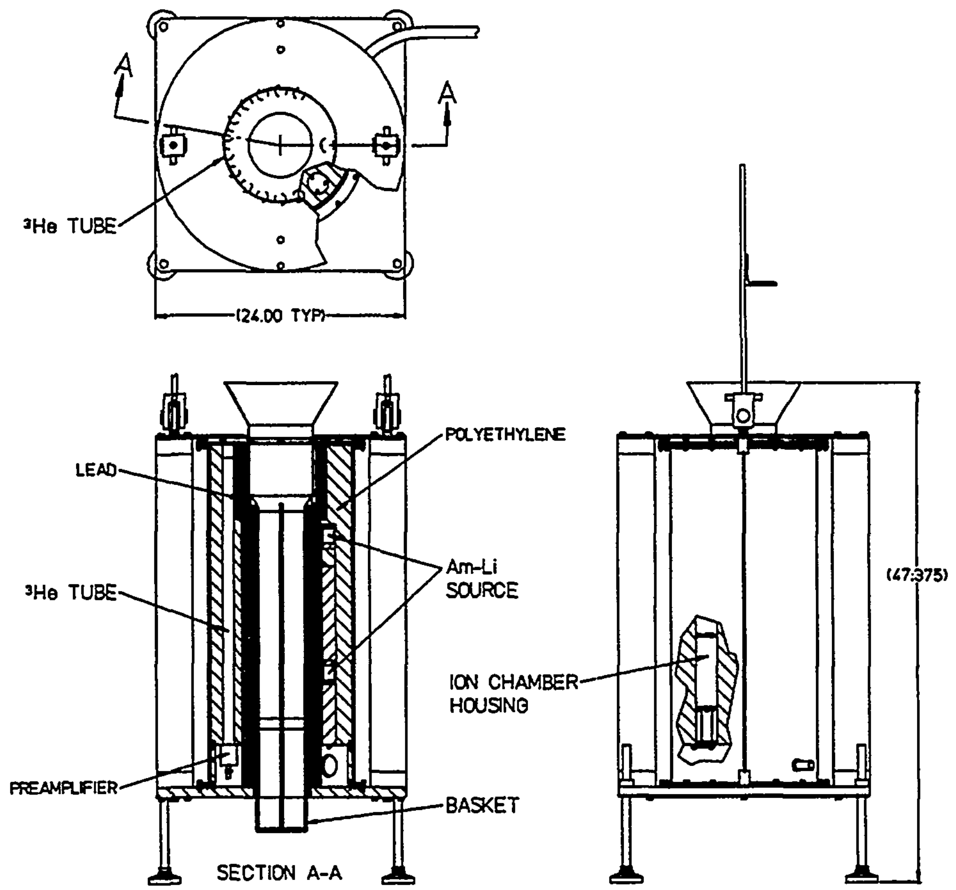


Fig. 1. Schematic diagram of the RRFC detector showing the location of the ^{3}He tubes, the Am-Li neutron sources, the ion chamber, and the preamplifiers.

ION CHAMBER

The ion chamber is a high-efficiency gamma detector containing Xenon gas. The ion chamber is placed inside a 25-mm-diameter sealed brass holder that is surrounded by a tungsten collimator. The brass holder is hermetically sealed to prevent water vapor from contacting the ion chamber. The tungsten collimator reduces the gamma sensitivity from all angles except in the direction of the central cavity, making the ion chamber insensitive to gamma sources outside of the RRFC. The specifications of the ion chamber are shown in Table 1. Figure 6 shows a schematic drawing of the ion chamber in the tungsten collimator.

The ion chamber is read out using a manual range digital picoammeter. A 300-V bias for the ion chamber is provided by a cable from the ion chamber readout at the surface.

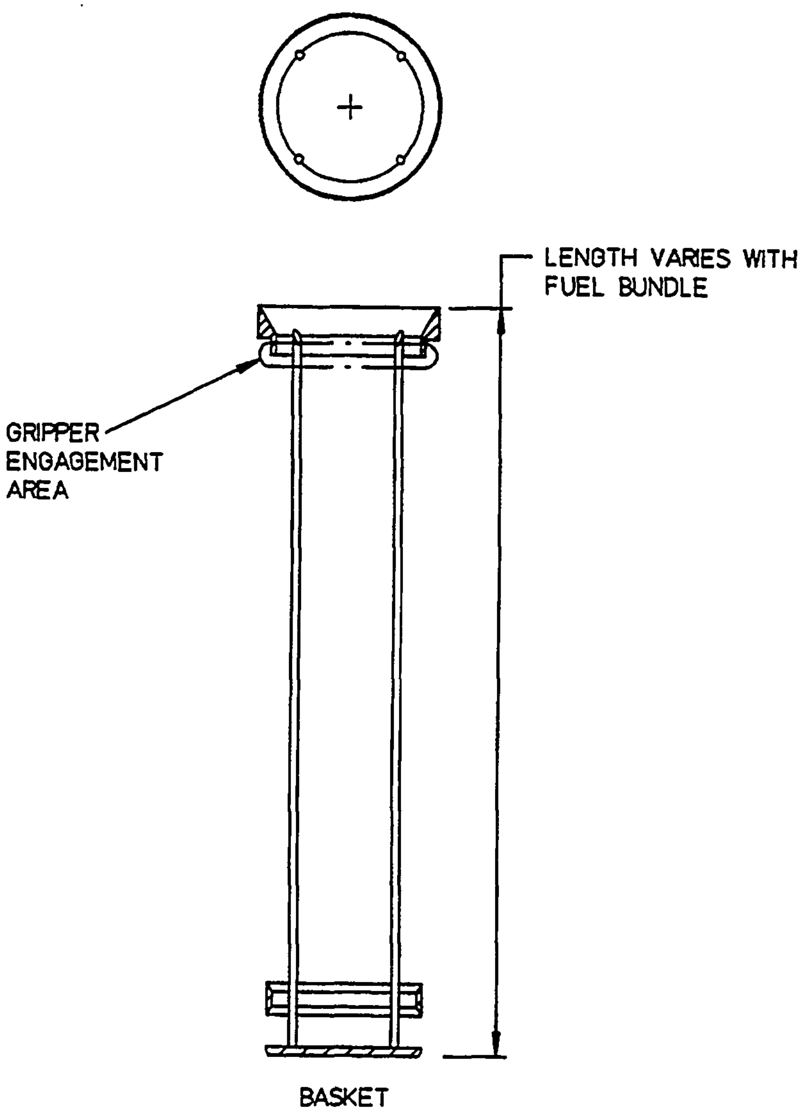


Fig. 2. Centering basket

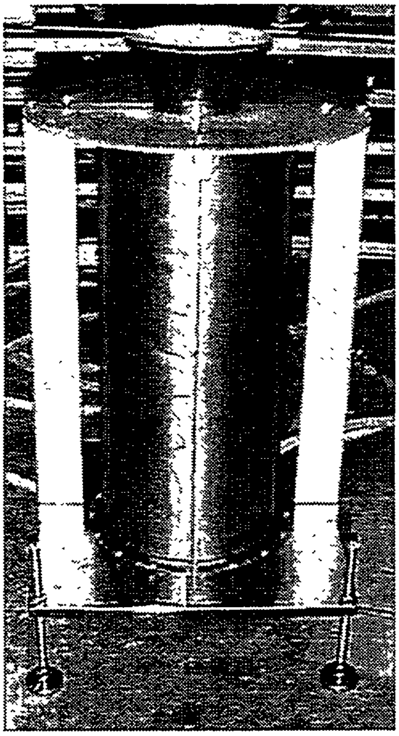


Fig. 3. Photograph of the RRFC detector body.

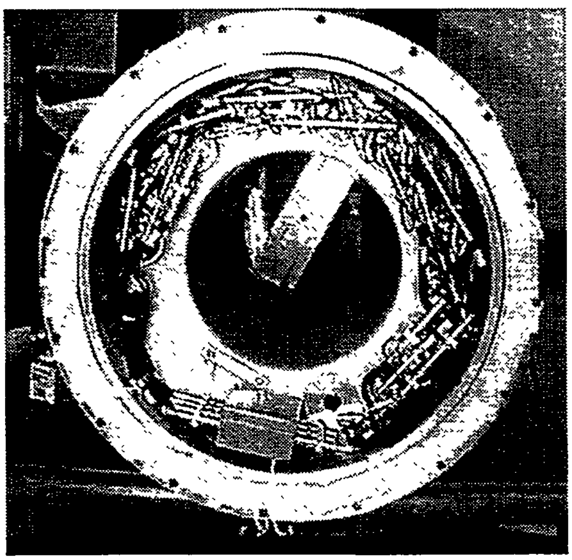


Fig. 4. Photograph of the polyethylene moderator and preamplifiers.

NEUTRON INTERROGATION SOURCES

The RRFC contains two 1.2-Ci Am-Li neutron sources. Each source supplies approximately 5.5 x 10^4 uncorrelated neutrons per second that induce fission in the fuel assembly. The sources effectively interrogate roughly 16 cm of fuel each. The two sources are separated axially along the fuel to minimize the sensitivity of the RRFC to the burnup profile of the fuel, and also to minimize the sensitivity to the fuel assembly axial placement.

TABLE I. Parameters for the ^{3}He Tubes, Ion Chamber, and Neutron Sources	
Parameter Description	Value
He-3 Tubes	
Manufacturer	Reuter-Stokes
Model	RS-P4-0824-104
Diameter	1.0 inch
Active Length	60.96 cm
Gas Pressure	4 atm
Gas Mixture	He-3 / Nitrogen
Wall Coating Material	Carbon
Nominal Operating Bias	1680 Volts
Preamplifiers	
Manufacturer	Precision Data Technologies
Model	110-A
Shaping Time	50 ns
Ion Chamber	
Manufacturer	LND
Model	52110
Diameter	16 mm
Sensitive Length	1153.9 mm
Fill Gas	Xenon
Fill Pressure	10 atm
Nominal Operating Bias	300 Volts

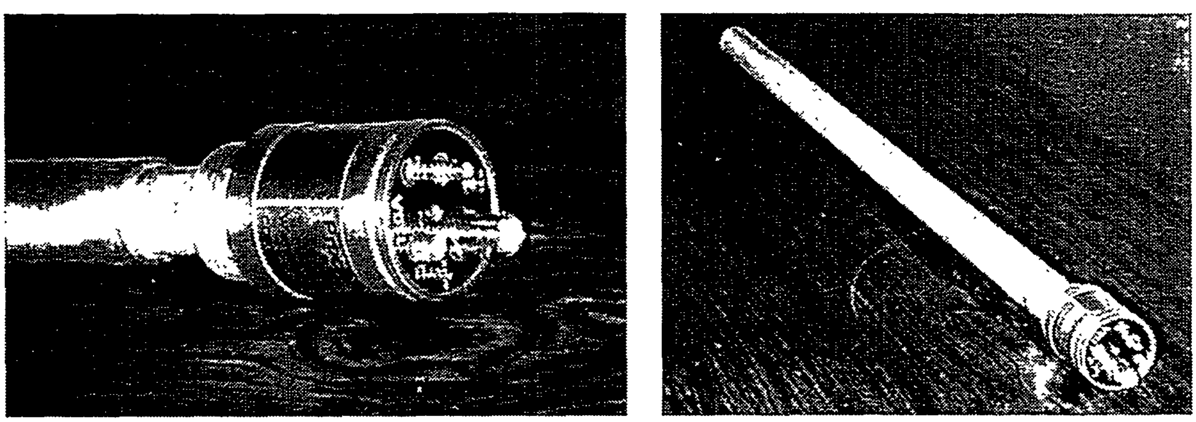


Fig. 5. Photographs of a ^{3}He tube with attached preamplifier.

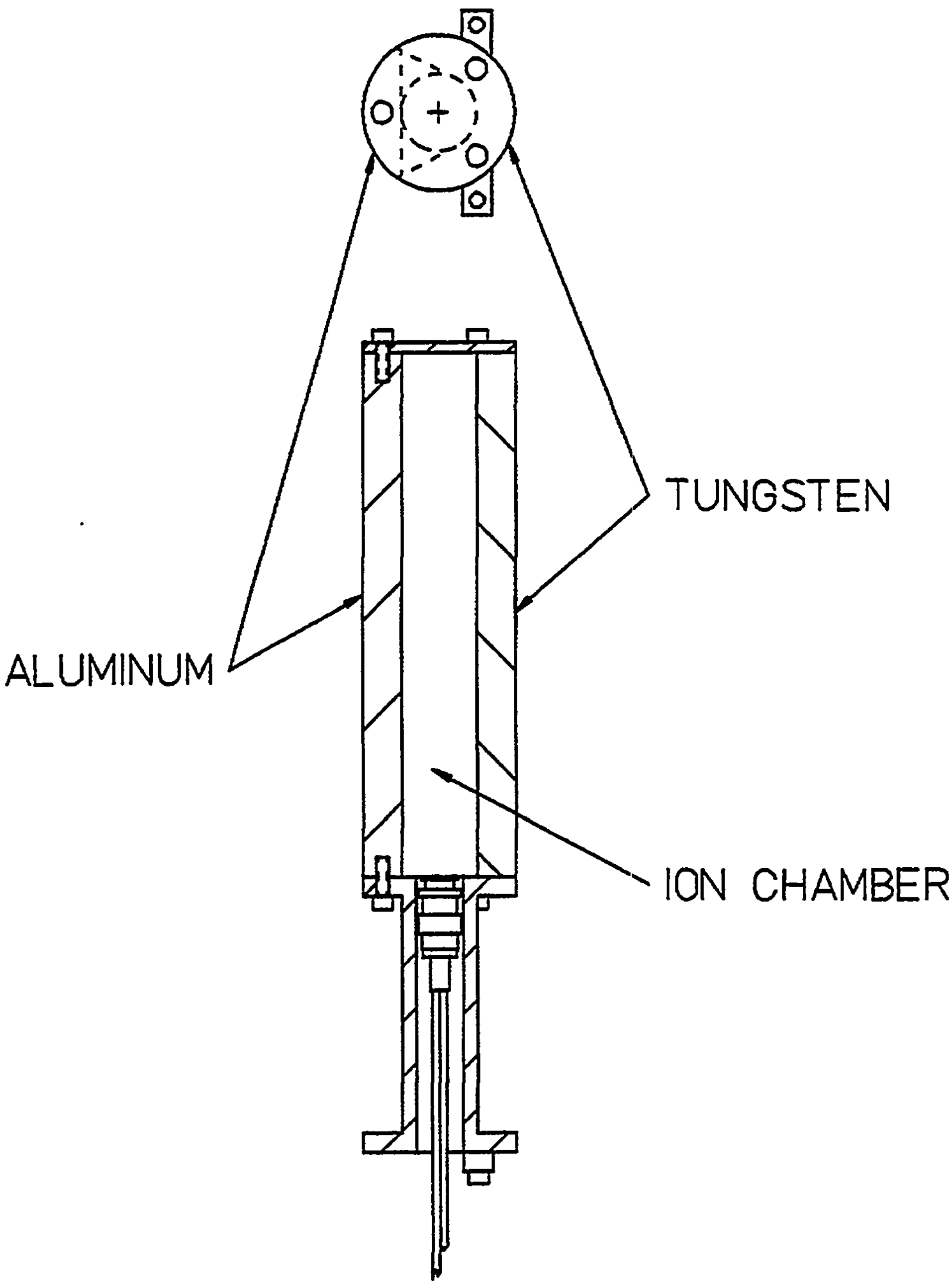


Fig. 6. Schematic of the ion chamber assembly.

INSTALLATION

The RRFC is intended to be installed on the floor of a spent fuel pool. The RRFC is shipped with the neutron sources, all detectors, and all the associated electronics in place.

To assemble the RRFC, use the following steps:

1. Open the shipping container, check for Am contamination.

2. Attach lifting cables to the eyebolts on the top lid. The RRFC weighs approximately 750 lb.

3. Lift the RRFC from the shipping container. WARNING - the RRFC must remain vertical at all times. Placing it in a horizontal position may compromise the o-ring water seals.

4. Attach the support legs to the baseplate and adjust their length.

5. Place the RRFC on a solid surface next to the fuel pool.

6. Attach the transfer bar using the pins and retaining rings provided.

7. Fasten the free end of the polyethylene cable tubing to a convenient attachment point to prevent the open end of the cable from falling into the pool.

8. Connect the cable leads to the PSR, the Ion Chamber Readout, and the adder box.

9. Perform a count of the calibration assembly L-107 in air. The nominal singles rate should be in the vicinity of 7100 counts/s, the doubles rate 115 counts/s.

10. Place the unit into the pool.

11. Perform a count of the calibration assembly L-107 underwater. The nominal doubles rate should be in the vicinity of 344 counts/s.

CABLE CONNECTIONS

Five RG-174/U type coaxial cables and one high voltage cable are bundled inside the polyethylene cable tubing. Table II identifies each cable, connector, and its label.

CABLE CONNECTIONS (cont.)

Fig. 7 shows the cable connections from the RRFC to the electronics.

TABLE II. RRFC Cable Identification

ID Label	Cable Type	Description	Connector Type
Signal 1	RG-174/U	Signal from Bank 1	BNC
Signal 2	RG-174/U	Signal from Bank 2	BNC
+5 Volt Preamp Power	RG-223/U	+5V Preamp Power	BNC
HV Bias	RG-71	^{3}He High Voltage Bias	SHV
IC Signal	RG-174/U	Ion Chamber Signal	LEMO (Coax)
IC Bias	RG-174/U	Ion Chamber Bias	LEMO (4 pin)

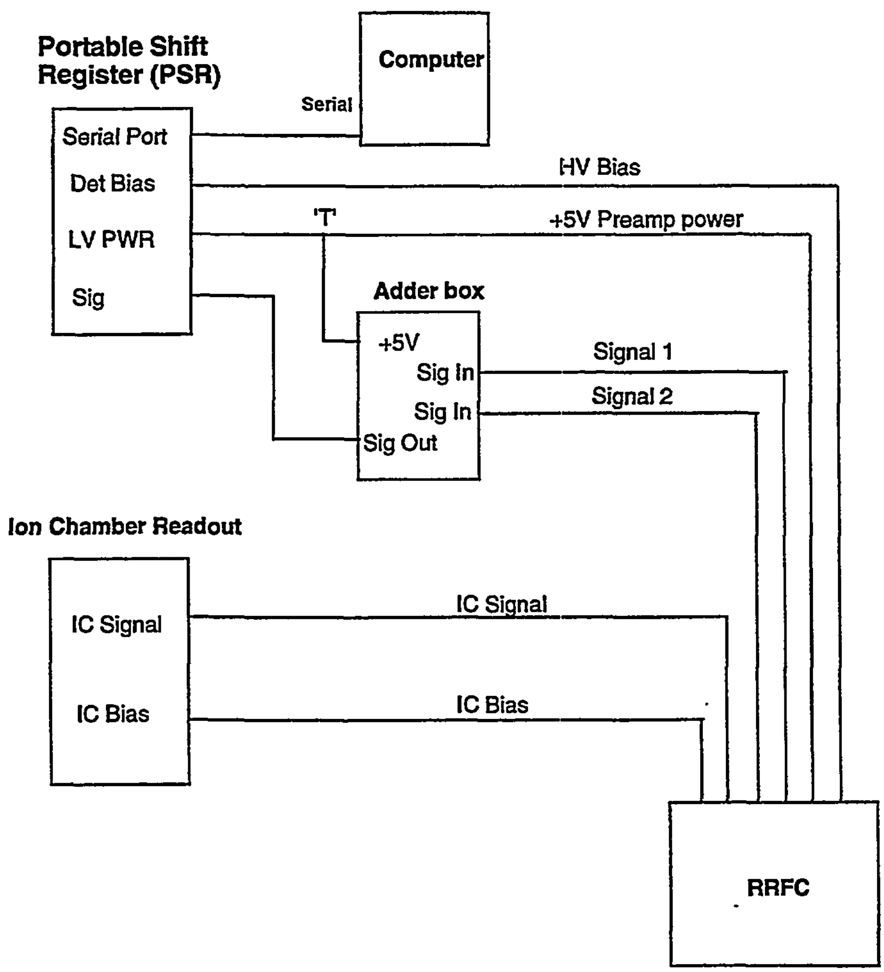


Fig. 7. Diagram of the cable connections between the RRFC and the electronics.

DETECTOR PERFORMANCE CHARACTERISTICS

Prior to assembly, the performance of the ^{3}He tubes and the ion chamber was measured using a 4.5-Ci, ^{226}Ra gamma-ray source, an Am-Li source, and ^{252}Cf neutron sources.

^{3}He Tube Tests

The counting efficiency for each tube/preamplifier was measured in a fixed geometry with a ^{252}Cf source, and the preamplifier gain was then adjusted to match the count rate across all the tubes. One tube was then taken into the hot cell for gamma pileup testing with an Am-Li neutron source and a ^{226}Ra gamma source. The measured detector bias plateau and the gamma pileup behavior for the one tube is shown in Fig. 8.

Gamma pileup was observed at 50 rad/hr at 1700 V. Therefore, to reduce the sensitivity to the gamma flux, the operating voltage was set at 1680 V. At 1680 V, gamma pileup is not observed at 50 rad/hr, and only minimal pileup is observed at 100 rad/hr.

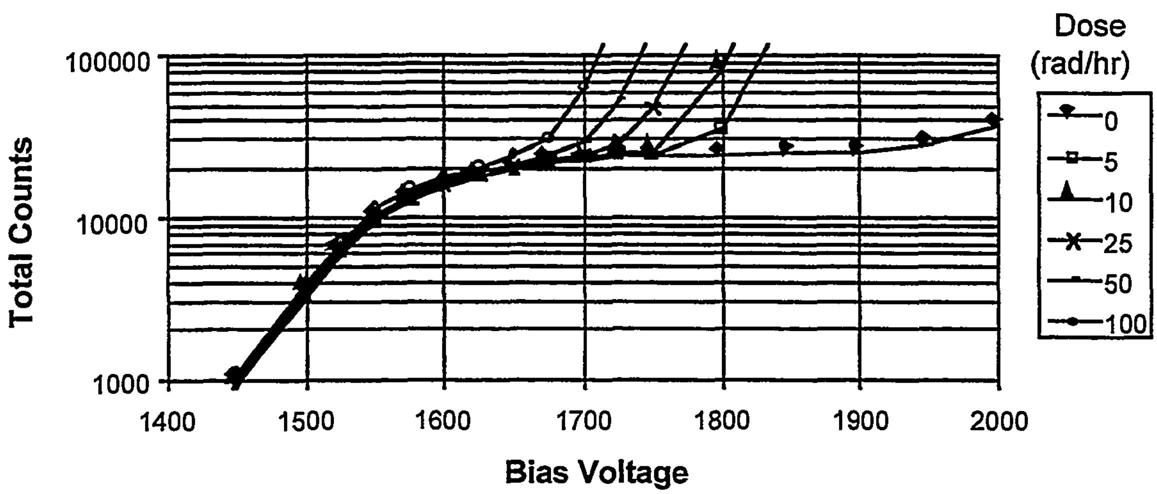


Fig. 8. Detector bias plateau and gamma pileup behavior for the ^{3}He Tube and PDT preamplifier.

Ion Chamber Tests

The ion chamber, installed in only the brass shield, was tested for functionality over the dose rate range from 0.1 to 100 rad/hr using an intense ^{226}Ra source in LANL hotcell facilities. This range covers the dose rates expected to be seen by the ion chamber as it is installed in the RRFC (behind the one-inch central cavity lead shield). The ion chamber is only intended to give a qualitative indication of the gamma dose rate; therefore, it was not calibrated for absolute dose measurements while placed inside the RRFC. However, calculations were performed to relate the dose rate seen by the ion chamber inside the RRFC to the surface dose rate at the assembly. Figure 9 shows the measured ion chamber (unshielded) response as a function of dose rate. Figure 10 shows a calculated estimate of the ion chamber readout vs. the surface dose rate of the MTR assembly. Figure 10 gives only an approximate indication (within about 50%) of the surface dose rate of the assembly; factors such as the burnup profile, the location of the assembly in the detector, and the geometry of the assembly all impact the calibration.

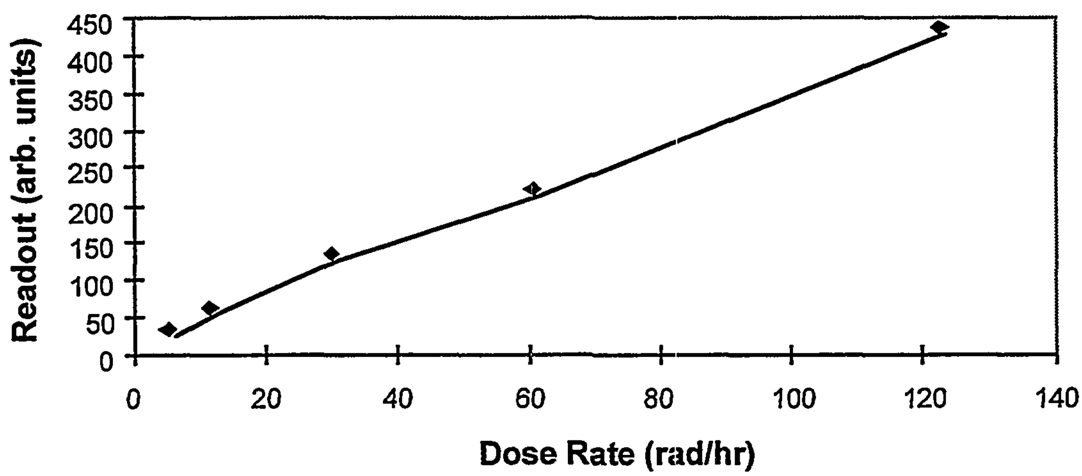


Fig. 9. Measured ion chamber readout vs gamma dose rate (unshielded ion chamber).

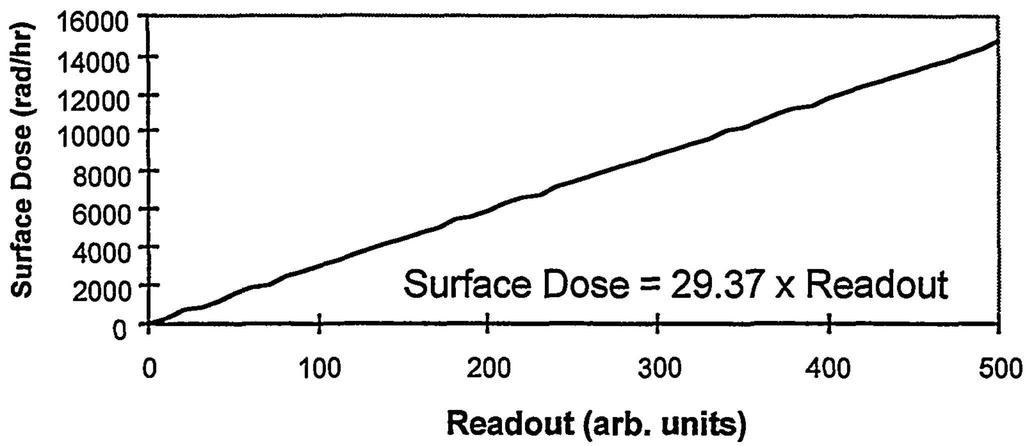


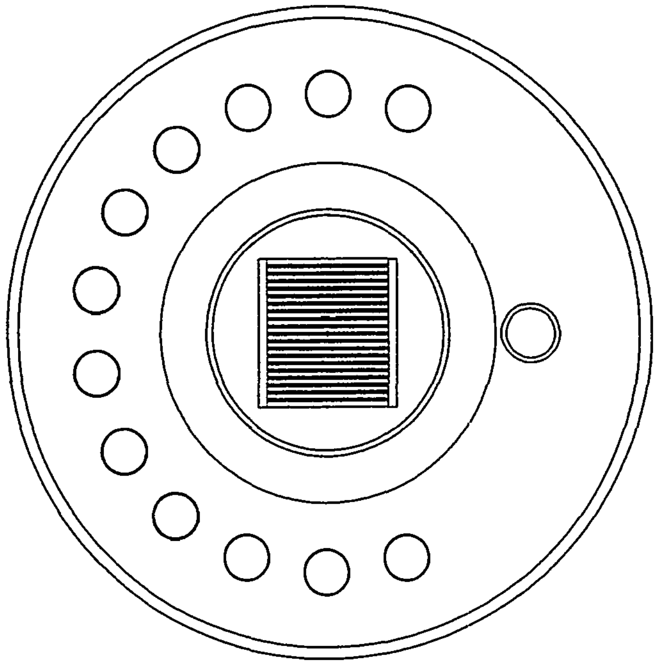
Fig. 10. Ion Chamber readout vs. surface dose rate of the MTR Assembly (calculated).

RRFC CALIBRATION FOR FRESH FUEL

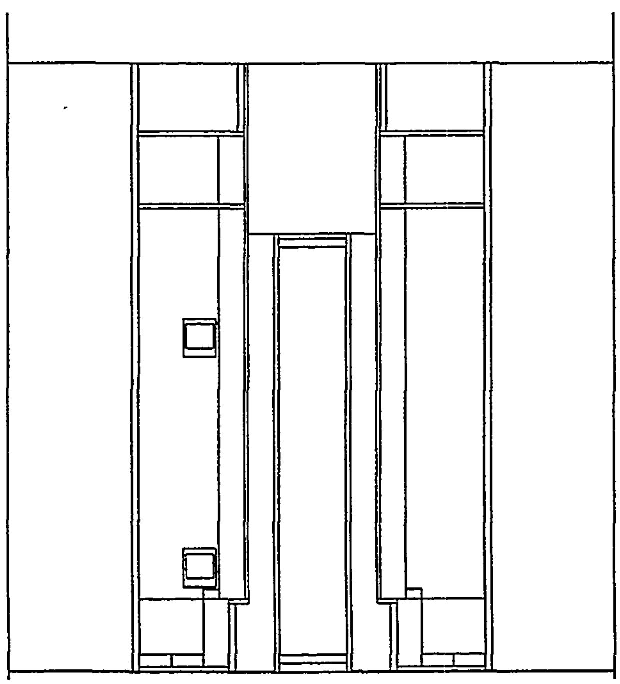
Calibration parameters for the RRFC will be derived by calculation for each separate type of spent fuel assembly. Calibration by calculation, rather than by measurement, is necessary because of the lack of suitably characterized MTR-type spent fuel assembly standards. Calibration of the RRFC for fresh fuel is possible by measuring adequately characterized fresh fuel assemblies. For code validation purposes, a calibration for fresh fuel was performed by calculation and then compared to the measured calibration using a fresh MTR test assembly.

The calculations were performed using the three-dimensional neutron transport code MCNP.[1] An MCNP model was constructed containing the dimensions, compositions, and densities of all materials used in the RRFC. Figure 11 shows the MCNP model of the RRFC with a fuel assembly positioned inside.

The model allows the code to predict the reaction rates in the ^{3}He tubes per source Am-Li neutron, the fission and radiative capture rates in the assembly, and other necessary parameters. The output of the MCNP code, along with information from the measured ^{3}He tube voltage response curve, was then entered into an Excel spreadsheet that calculated the doubles rate and other parameters. This process was repeated for several ^{235}U masses, with the



(a) Top view showing ^{3}He Tubes



(b) Side view showing Am-Li sources

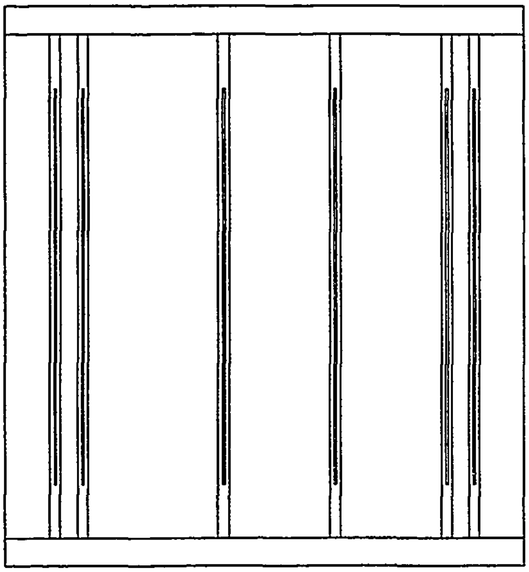
Fig. 11. MCNP model of the RRFC with a fuel assembly positioned inside.

RRFC CALIBRATION FOR FRESH FUEL (cont.)

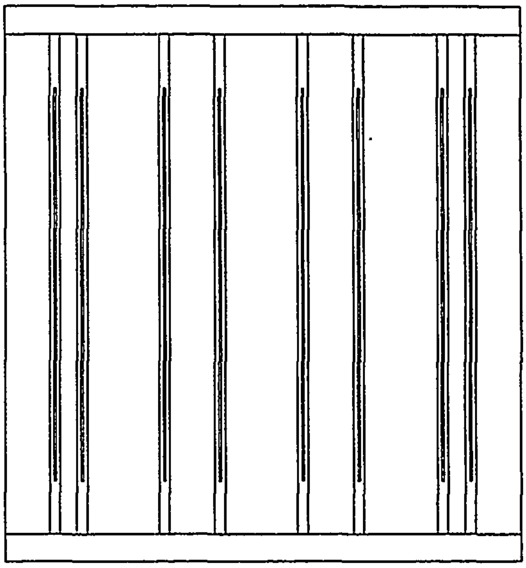
curve through the mass vs doubles rate forming the calibration for that type of MTR assembly. It is important that the MTR fuel assembly model be as accurate as the neutron multiplication, and hence the doubles rate is very sensitive to the geometry of the assembly. Also, as the RRFC is only able to interrogate a portion of the fuel, the length of the assembly must be accurately modeled.

VALIDATION OF THE CALCULATIONAL MODEL FOR FRESH FUEL

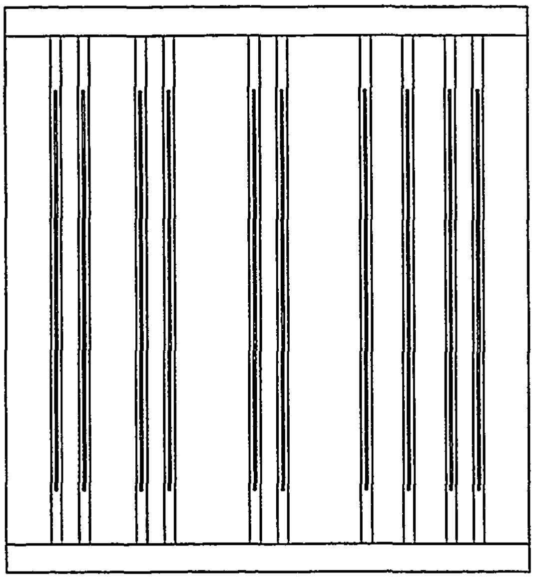
The calculational model was validated by comparison to measurements made on a fresh MTR test assembly that can be disassembled and configured with varying numbers of plates in various geometries. Figure 12 shows the geometries used in the comparison.



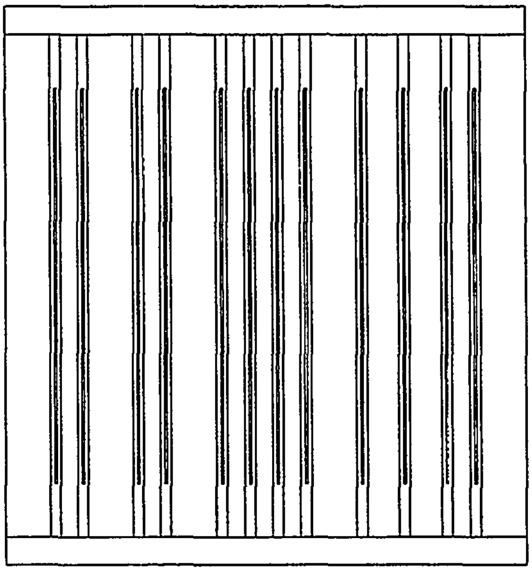
(a) 84.924 g geometry



(b) 113.23 g geometry

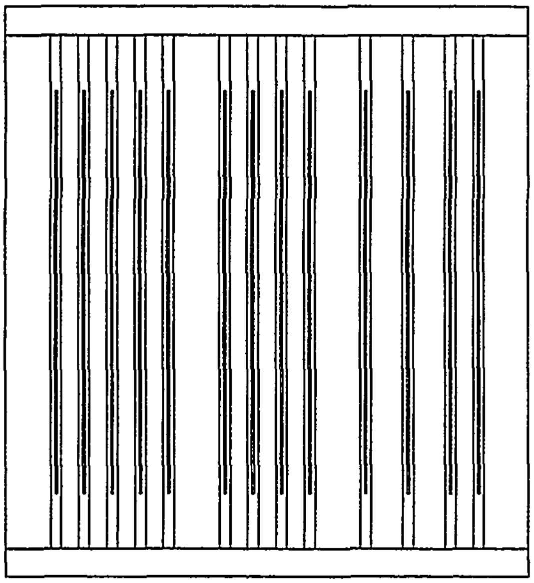


(c) 141.54 g geometry



(d) 169.84 g geometry

Fig. 12. MTR test assembly geometries used in the comparison.



(e) 184.002 g geometry

Fig. 12 (cont). MTR test assembly geometries used in the comparison.

VALIDATION OF THE CALCULATIONAL MODEL FOR FRESH FUEL
(cont.)

Figure 13 shows the result of the comparison. All of the calculated doubles (reals) rates agree quite well with the measured values. The largest difference between the calculation and the measurement was 4.4% for the 85-g case, and the average (signed) error was 0.4%. The differences can be accounted for by the statistical error inherent in the measurement (approximately 2%) and by the statistical error of the Monte Carlo calculation (also approximately 2%).

Another set of measurements was taken to determine the die-away time of the counter. The measured value was then compared with the calculated die-away time of the counter, providing another means to validate the calculational model. The measured value was 111 μs, the calculated value was 112 μs.

The close agreement between the calculations and the measurements demonstrates that the calculational approach is valid for determining calibration parameters for fresh fuel.

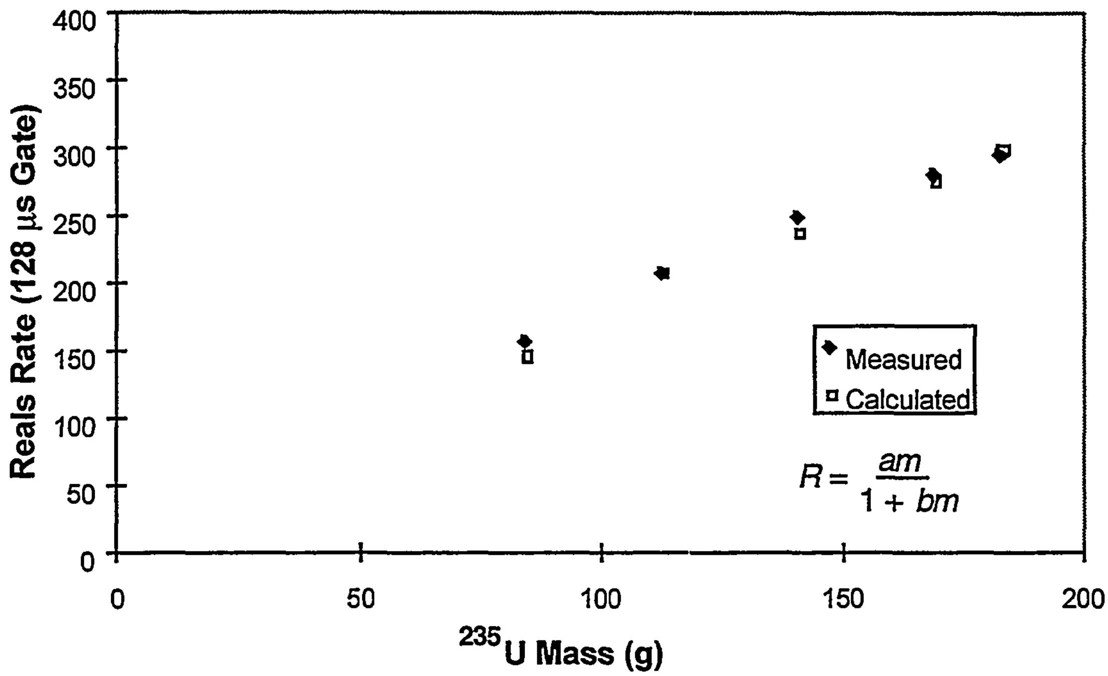


Fig. 13. RRFC measured vs calculated reals rate for various test assembly geometries.

RRFC PERFORMANCE WITH FRESH FUEL

A series of tests was performed to determine the precision of the RRFC. A calibration curve was determined by 1-hr measurements using the test assembly, and then a series of 10 5-min measurements were made on various configurations of the test assembly. The test assembly was removed and then reinserted between each measurement. The series of measurements was made at a 64-µs gate setting, measurements made at the final 128-µs gate setting will show some improvement in precision. The results are presented in Table III.

TABLE III. Measured Precision of the RRFC (5-Min Measurements Made With 64-µs Gate).

^{235}U Mass (g)	RMS Deviation From True Value %	Precision (Std. Deviation) %
84.924	3.5	2.8
141.54	2.3	2.1
231.74	4.1	2.6

RRFC PERFORMANCE WITH FRESH FUEL (cont.)

The RMS deviation shown in Table III results from a combination of measurement precision and bias. The bias in this set of measurements is caused by the calibration curve fit not passing exactly through each calibration point. The bias can be improved by a more careful calibration curve fit. The measurement precision is limited by nuclear counting statistics and is a function of the counting efficiency of the detector.

RRFC SENSITIVITY TO ANGULAR DISPLACEMENTS

A set of measurements were performed to determine the RRFC sensitivity to MTR assembly orientation using a full MTR assembly. The nominal placement is with the fuel plates oriented parallel to the line from the Am-Li source to the center of the assembly. The sensitivity to the angle of placement was determined by rotating the assembly through angles ranging from 0 to 315 degrees from the nominal placement. Results are shown in Fig. 14. Figure 14 demonstrates that the RRFC is relatively insensitive to the orientation of a full assembly, with the largest difference between any two angles being less than 2.5%. The RRFC is especially insensitive to rotations of less than 45 degrees from nominal, the maximum difference in this range is less than 0.2%.

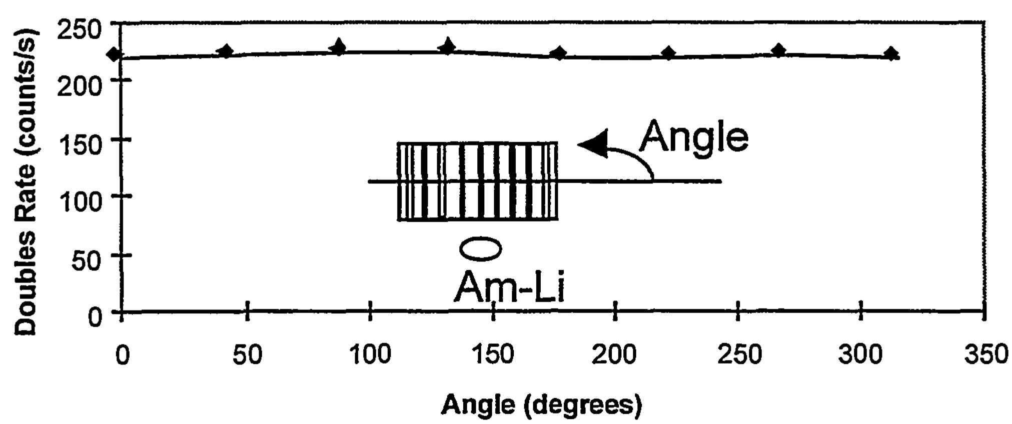


Fig. 14. RRFC sensitivity to angular displacements.

RRFC SENSITIVITY TO AXIAL DISPLACEMENTS

Finally, measurements were performed to determine the sensitivity to off-axis placements of the fuel. The fuel was purposely loaded in the axial position closest to the interrogation source, then repositioned to be as far from the interrogation source as the basket would allow. The difference between the two sets of measurements was less than 0.5%.

CALIBRATION FOR FRESH MTR FUEL

The RRFC is similar in operation to the AWCC[2] that has been used for the active assay of fresh MTR elements. Figure 15 from Ref. 3 shows the measured response of the AWCC to both rectangular and cylindrical MTR type fuel assemblies. Both type of fuel assemblies can use the same basic calibration curve. In general, the fuel plate configuration is less important in the measurement than the difference between low and high burnup fuel.

For fresh fuel assemblies, the cause of the nonlinear calibration curve is the self-shielding of the thermal neutrons in the ^{235}U. The calibration data can be fit by a function of the form.

$$R = \frac{am}{1 + bm}$$

However, for spent fuel there are additional contributions to the calibration shape, including fission product absorption and self-interrogation from the ^{238}Pu (α,n) Al neutrons. These can perturb the shape of the calibration curve for spent fuel.

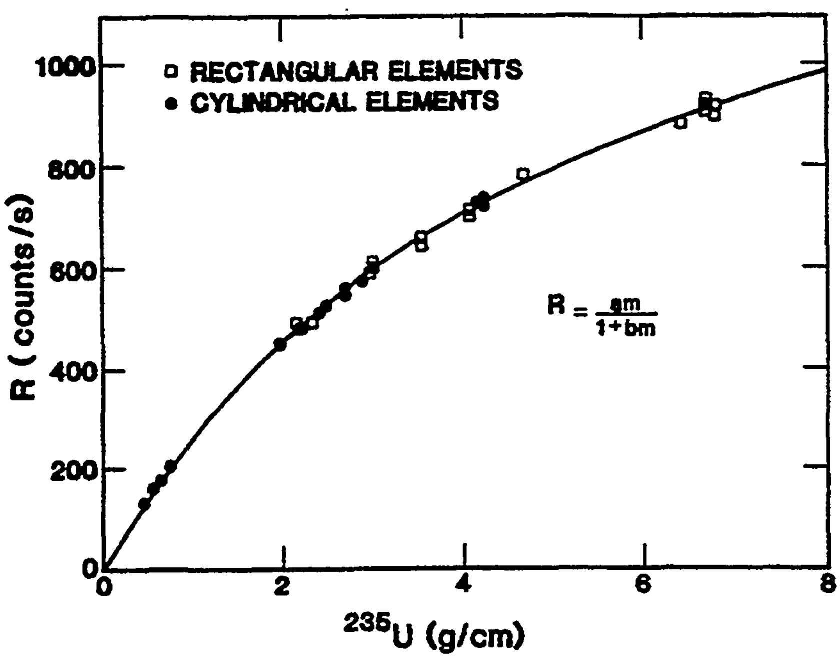


Fig. 15. Fresh MTR fuel element calibration for rectangular and cylindrical elements. Calibration performed in air in a modified AWCC counter.

RRFC CALIBRATION FOR SPENT FUEL

Fission products build up in the MTR fuel assembly as it is irradiated in a reactor. Some of these fission products are effective neutron absorbers. Transuranic elements also build up (principally ^{238}Pu), causing alpha-n reactions in the aluminum that provide an additional source of neutrons. These two effects are partially compensating: the neutron absorbers reduce the number of neutrons that are counted per gram of fissile material, and the alpha-n reactions increase the number counted. However, as the burnup is increased beyond about 50%, the alpha-n production starts to overcome the fission product neutron absorption and a greater number of neutrons are emitted from the fuel per gram than for fresh fuel. Therefore, high burnup spent fuel requires a separate calibration curve from fresh fuel.

Currently, adequately characterized calibration standards for spent MTR fuel are not available. Therefore, the same basic calculational method described above for fresh fuel must be used to obtain the calibration for spent fuel. In addition to the basic calculation, additional calculations must be performed to predict the amount and isotopic composition of the fission products, as well as the alpha-n neutron production rate.

RRFC CALIBRATION FOR SPENT FUEL
(cont.)

An example calibration curve for spent fuel was calculated for Rhode Island Nuclear Science Center specification MTR fuel[4] with 18 plates containing 220 g of ^{235}U. Calculations of the fission product inventory were performed using the ORNL burnup code for a PC called ORIGEN2[5,6] and the alpha-n neutron production rate was taken from previous calculations performed using the Los Alamos CINDER-2 code.[7] Calculations were performed for fresh fuel as well as spent fuel with approximately 44% and 63% burnup. The calculated calibration curve is presented in Fig. 16. The ^{235}U mass range in Fig. 16 is restricted by the total mass in a fully loaded fresh assembly multiplied by (1 - % burnup). For example, the highest ^{235}U content that can possibly remain in 63% burnup fuel is 37% of the initial maximum loading or, in this case, approximately 82 g.

From this figure it can be seen that fuel with burnup lower than 44% can be assayed with the same calibration curve as that used for fresh fuel. In this range, which is expected to extend to about 55% burnup, the additional alpha-n neutrons are compensated by the neutron absorption in the fission products. However, the calibration curve for the 63% burnup fuel is substantially different than that for fresh fuel. If fuel with this burnup were to be assayed using the calibration curve for fresh fuel, the resulting assay value would be off by up to about 16%. Therefore, for burnup greater than roughly 55%, it is necessary to use a specific calibration curve developed for the high burnup.

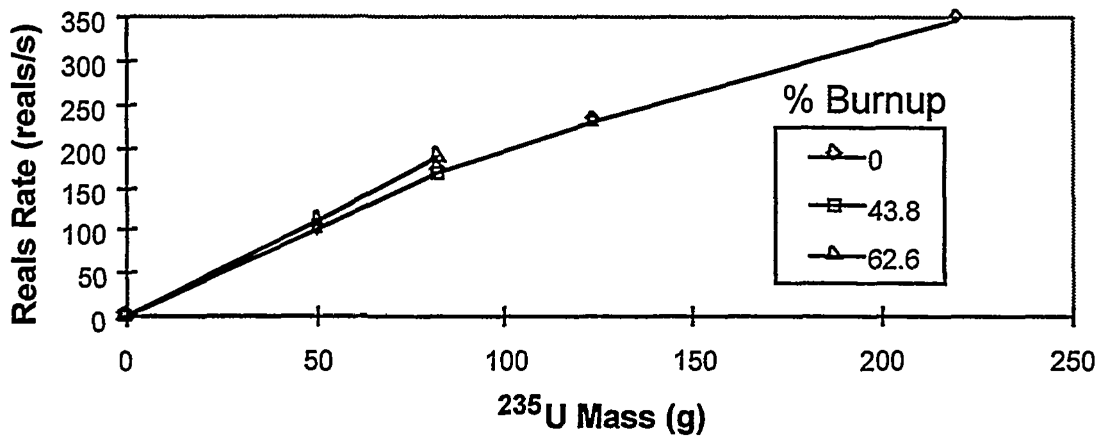


Fig. 16. Example calibration curve for spent fuel.

RRFC SYSTEM PERFORMANCE SUMMARY

The performance and important parameters of the RRFC are summarized in Table IV.

TABLE IV. RRFC System Performance and Important Parameters

Parameter Description	Value
Efficiency	13%
Die-away Time	111 μs
Doubles Gate Length	128 μs
Precision (5-min count, > 80 g ^{235}U)	< 3%
Am-Li Source Strength	1.1 x 10^5 n/s (total)
Gamma Rejection Capability	12,000 rad/hr (surface)
Unit Weight	750 lb.

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