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TITLE: A PORTABLE NEUTRON MEASUREMENT TECHNIQUE FOR THE ASSAY OF ^{235}U IN LWR FUEL ASSEMBLIES

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A Portable Neutron Measurement Technique for the Assay of ^{235}U in LWR Fuel Assemblies

Contribution from Los Alamos National Laboratory, Los Alamos, NM

An active neutron interrogation technique has been developed for the measurement of the ^{235}U content in fresh fuel assemblies. The method employs an AmLi neutron source to induce fission reactions in the fuel assembly and coincidence counting of the resulting fission reaction neutrons. When no interrogation source is present, the passive neutron coincidence rate gives a measure of the ^{238}U via the spontaneous fission reactions. The system can be applied to the fissile content determination in HWR, BWR, and LWR fuel assemblies for accountability, criticality control, and safeguards purposes.

Eine aktive Neutronenabfragetechnik wurde zur Messung vom Uran-235 Gehalt in frischen Brennelementen entwickelt. Die Technik benutzt eine AmLi-Neutronenquelle zum Induzieren von Spaltungsreaktionen in der Brennstoffkassette und eine Koinzidenzzahlung der entstandenen Spaltungsreaktionneutronen. In der Abwesenheit einer Abfragequelle gibt die passive Neutronenkoinzidenzrate eine Messung von Uran-238 ueber die spontanen Spaltungsreaktionen. Das System kann auf die Ermittlung des spaltbaren Gehalts in Brennelementen fuer HWRs, BWRs, and PWRs angewandt werden, fuer Zwecke der Verantwortlichkeit, der Kritikalitatskontrolle und des Schutzes.

INTRODUCTION

The verification of the ^{235}U loading in reactor fuel assemblies is an important measurement problem for international safeguards and reactor fuel quality control. The Coincidence Collar[1] has been developed to help satisfy this requirement. This instrument uses neutron interrogation with an AmLi neutron source, and the neutrons from the induced fission reactions are counted with ^{3}He detectors operated in the coincidence mode. This coincidence counting eliminates the undesired neutron counts from the random AmLi interrogation source and room background neutrons.

Several technical approaches have been tried for the verification of fresh fuel assemblies. These include passive gamma-ray measurements, x-ray autoradiography,[2] and neutron irradiation.[3-5]

The Coincidence Collar has several advantages over presently available methods for the verification of ^{235}U content in fuel assemblies. The performance characteristics of the Coincidence Collar for LWR fuel will be described in the present paper.

SYSTEM DESCRIPTION

The Coincidence Collar consists of three banks of ^{3}He tubes and an AmLi source imbedded in a high-density polyethylene (CH_2) body as shown in Fig. 1. The 18 ^{3}He neutron detector tubes (4 atm pressure) are 2.54 cm in diameter and 33 cm long (active length).

The CH_2 body performs three basic functions in the system: 1) general mechanical support, 2) interrogation source neutron moderation, and 3) slowing down of induced fission neutrons prior to their detection in the ^{3}He tubes. The configuration of the source and detectors shown in Fig. 1 was a result of a series of calculations and experiments to obtain the minimum statistical measurement error and a uniform spatial response in the assembly. For inspection applications, it is desirable to make the system portable. The weight of the present detector system is ~24 kg.

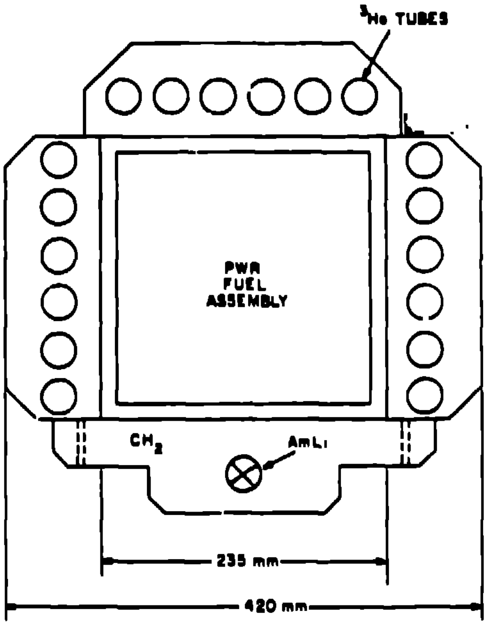


Fig. 1.
Schematic diagram of Coincidence Collar showing the AmLi neutron source, the ^{3}He detector banks and the CH_2 moderator material. The detector bank opposite the neutron source pivots open on the hinge to accommodate PWR, BWR, or HWR fuel assemblies.

The AmLi interrogation source produces random neutrons (not time correlated) with an average energy of ~300 keV. The statistical accuracy of the coincidence counting is independent of the neutron source yield for intensities $\geq 5 \times 10^4$ n/s because of accidental neutron counting in the coincidence circuitry.[6] The present Coincidence Collar uses a source fabricated by Monsanto Research Corp. (model 2724-BT) with a yield of 4.5×10^4 n/s.

The electronics used with the Coincidence Collar are the same as that used with the High-Level Neutron Coincidence Counter.[7] This unit contains the HV and low voltage power supplies, 6 amplifier-discriminator lines, a microprocessor, and the shift-register[8] coincidence logic. The electronic unit is directly interfaced to an HP-97 programmable calculator. The microprocessor is used to read out the run time, total counts, reals plus accidental counts, and accidental counts to the HP-97. The HP-97 is used to reduce the data using the software program selected by the operator.

The complete assay system is shown in Fig. 2 including the detector body, the electronic unit, the HP-97 calculator, and a support cart. For applications, the cart is moved next to a fuel assembly as shown in Fig. 2. The back detector bank of the unit is hinged (see Fig. 1) to aid in positioning the system around the fuel assembly.

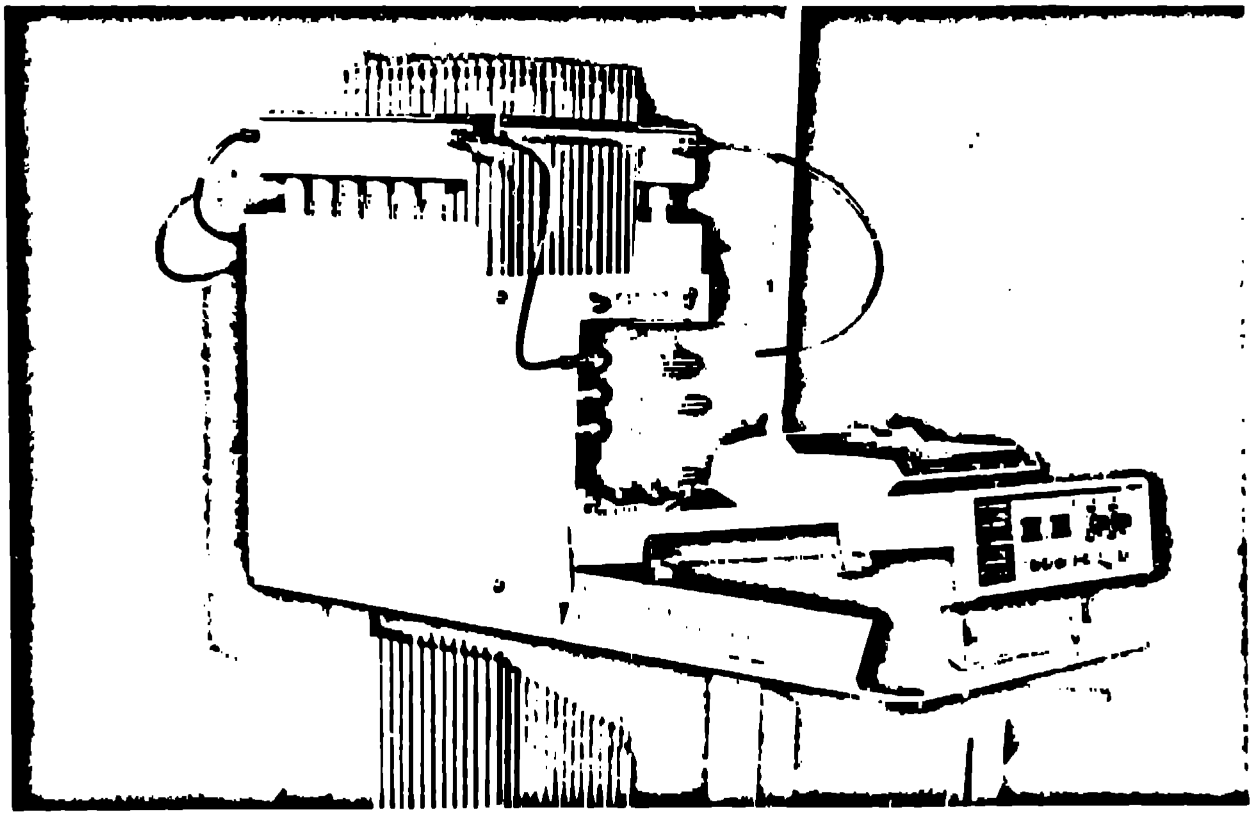


Fig. 2.
Coincidence Collar system positioned around a mockup PWR fuel assembly.

PERFORMANCE CHARACTERISTICS

Active neutron systems using thermal neutron interrogation, such as the Collar,[5] have neutron self-shielding problems that limit the sensitivity in the interior of the assembly, but the present Coincidence Collar gets around this limitation by fast neutron multiplication which is higher in the central region. The multiplication effect is enchanced by the coincidence counting because of the increase in the effective number of time-correlated neutrons emitted by the sample when multiplication occurs. The spatial uniformity of response is achieved by a balancing of three different mechanisms as follows:

a. The front of the assembly near the AmLi interrogation source gets more direct source neutrons than other regions.
b. The back and side regions have higher counting efficiency for the induced fission neutrons because of their close proximity to the ^{3}He detector banks.
c. The central region gets a greater contribution from fast neutron multiplication than the perimeter regions.

The measured coincidence response corresponds to the combination of these components resulting in a rather uniform sensitivity.

In effect, the system works like a reactivity gage for the fuel assembly, and the removal of fissile material from the assembly lowers the neutron reactivity and thus the coincidence response.

1. Rod Positioning Sensitivity

Initial tests have been performed on a mockup fuel assembly. The assembly is a 15 by 15 array of PWR fuel rods enriched to 3.19 percent in ^{235}U and 1.2 m long. The rods in the assembly can be removed for test purposes.

A series of experiments were performed where rods from different sections of the assembly were removed to determine the position sensitivity to rod substitution. The regions selected for the measurements are shown in Fig. 3 which is a cross-section of the rod positions in the PWR array. For each rod configuration, several 1000-s measurements were performed and the coincidence rate was compared with the full array count rate to determine the perturbation caused by the substitution. The measured perturbation was then divided by the number of rods in the substitution region to obtain the perturbation per rod.

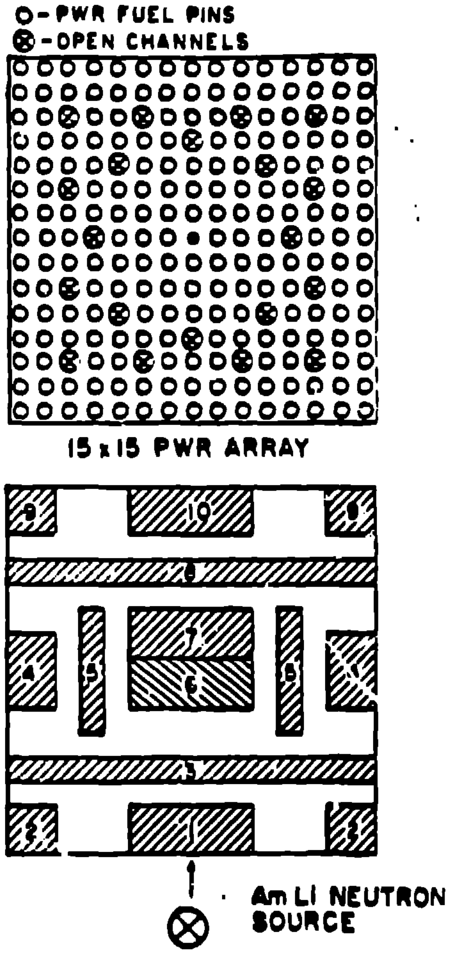


Fig. 3.
Cross-section of the mockup PWR fuel assembly showing rod locations and regions selected for rod substitutions.

Table I gives the results of the sensitivity measurements for the empty rod and iron rod substitution cases. The sensitivity limit is defined as the minimum number of rod substitutions that can be detected in a 1000-s measurement time at the 95 percent (2σ) confidence level. The detection limit for empty rod substitution has an average value of 2.8 rods and is rather uniform at all rod positions including the central region. The iron rod substitution sensitivity is somewhat better (2.2 rod average) and there is high sensitivity on the frontrows because of thermal-neutron absorption.

Preliminary measurements with depleted uranium rods substituted for the enriched uranium rods indicated an average detection limit roughly a factor 1.6 higher than for the empty pin substitution. This is to be expected because the ^{238}U in the depleted rod contributes to the fast neutron multiplication.

By removing the AmLi interrogation source from the coincidence collar, passive measurements give the ^{238}U content by coincidence counting the ^{238}U spontaneous fission neutrons. The combination of the ^{235}U and ^{238}U results gives a high level of verification for the fuel assembly.

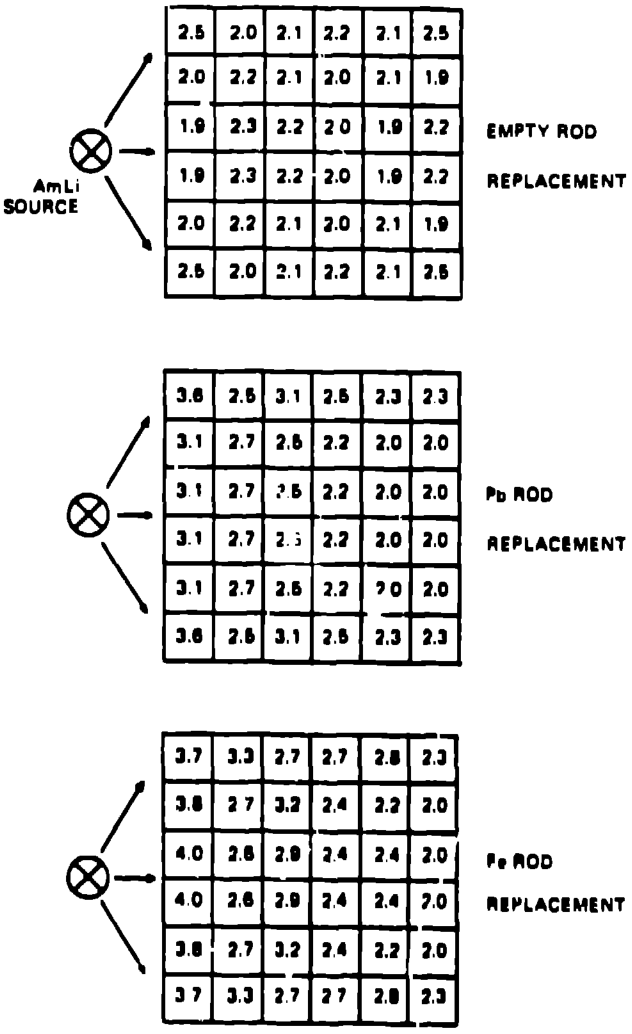
Experiments were performed with a mockup BWR fuel assembly to determine the sensitivity to rod substitution and spatial uniformity of the response. The available BWR assembly has rods enriched to 2.34 percent in ^{235}U. There are 36 rods in the 6 by 6 array which is smaller than the more typical 8 by 8 arrays. Rods were removed from different positions in the array to measure the response as a function of position. In additional measurements, rods filled with lead or iron were substituted into the array to determine the effect of materials with a density similar to UO_2 (10 g/cm^3) on the coincidence counting rate.

The results of the measurements are shown in Fig. 4 where the array represents the 36 fuel rod locations. The number in each array position corresponds to the percent decrease in the coincidence rate when one fuel rod is removed from that position. The top array in Fig. 3 corresponds to the empty rod substitution and shows that the response is very uniform with an average decrease of 2.1 percent for the removal of one pin. The statistical precision of a 1000-s count is 1.1 percent (1σ) compared with 0.63 percent (1σ) for the PWR assembly. The removal of one BWR rod causes a 2.1 percent change in the rate and can be detected at the 95 percent (2σ) confidence level.

The two lower arrays shown in Fig. 4 correspond to lead (cast in steel tubing) and iron rod substitutions. In general these materials give slightly larger changes than the empty substitution case and thus are easier to detect. The changes are considerably larger on the front face of the assembly because the thermal neutron flux is higher there and the absorption of the neutrons by the iron has a large effect. In general, the substitution of iron or lead to obtain the correct assembly weight can be easily detected by both the active and passive counts.

2. <u>Response versus Loading</u>

When fuel rods are removed from a fuel assembly, the measured response decreases. To observe the shape of this response curve, rods were uniformly removed from a mock-



2.5	2.0	2.1	2.2	2.1	2.5
2.0	2.2	2.1	2.0	2.1	1.9
1.9	2.3	2.2	2.0	1.9	2.2
1.9	2.3	2.2	2.0	1.9	2.2
2.0	2.2	2.1	2.0	2.1	1.9
2.6	2.0	2.1	2.2	2.1	2.6

3.6	2.5	3.1	2.6	2.3	2.3
3.1	2.7	2.6	2.2	2.0	2.0
3.1	2.7	2.6	2.2	2.0	2.0
3.1	2.7	2.6	2.2	2.0	2.0
3.1	2.7	2.6	2.2	2.0	2.0
3.6	2.6	3.1	2.6	2.3	2.3

3.7	3.3	2.7	2.7	2.8	2.3
3.8	2.7	3.2	2.4	2.2	2.0
4.0	2.8	2.9	2.4	2.4	2.0
4.0	2.8	2.9	2.4	2.4	2.0
3.8	2.7	3.2	2.4	2.2	2.0
3.7	3.3	2.7	2.7	2.8	2.3

Fig. 4.
Schematic diagram of 3 BWR arrays (6 by 6) showing fuel rod locations relative to the neutron interrogation source in the Coincidence Collar. The numbers in the array are the percent reduction in coincidence count rate caused by the substitution of one rod in the corresponding location

TABLE I

FUEL ROD REMOVAL DETECTION SENSITIVITY FOR A 15 BY 15 PWR ASSEMBLY

Rod Location[a]	Percent Change/Rod		Rod Detection Limit (2σ)[b]	
	Empty	Iron	Empty	Iron
1	.35	1.68	3.6	1.0
2	.64	1.25	2.0	1.0
3	.41	.71	3.1	1.8
4	.41	.62	3.1	2.0
5	.55	.53	2.3	2.4
6	.57	.51	2.2	2.5
7	.53	.44	2.4	2.9
8	.36	.38	3.5	3.3
9	.48	.60	2.6	2.1
10	.46	.47	2.7	2.7
Average =	.48	.71	2.8 Rods	2.2 Rods

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[a] Rod removal locations are shown in Fig. 1.

[b] Rod detection limit corresponds to the perturbation per rod removal being equal to twice the standard deviation for a 1000-s measurement.

measurements are shown in Fig. 5 where the percent decrease in the coincidence response (active mode) is plotted as a function of the percent decrease in the uranium mass. The relationship is linear over the range tested (0-30 percent fuel rod removal) because of the cancellation of compensating nonlinear effects. That is, as the uranium mass decreases, the interrogation neutron self-shielding decreases, which increases the coincidence response per gram uranium. However, as the mass decreases, the neutron multiplication decreases, which decreases the coincidence response per gram and the two effects nearly cancel each other.

In addition to the active neutron measurements, the AmLi source was removed and passive measurements were made to determine the ^{238}U spontaneous fission rate. The results are shown in Fig. 6 where the percent decrease in passive coincidence rate is plotted as a function of the percent decrease in uranium mass.

3. Response Versus Enrichment

A series of measurements were performed[9] using full-size (17 by 17 rods) PWR assemblies with enrichments ranging from 1.8 to 3.4 percent ^{235}U. The thermal-neutron interrogation is saturated for all of the fuel assemblies; however, the measured response continues to increase as a function of enrichment because the fast neutron multiplication increases with increasing enrichment.

4. BWR Assay and Poison Rods

The application of the Coincidence Collar to BWR fuel assemblies is more complicated than for PWR assemblies because of the mixed uranium enrichments in the rods and the possibility of rods containing gadolinium

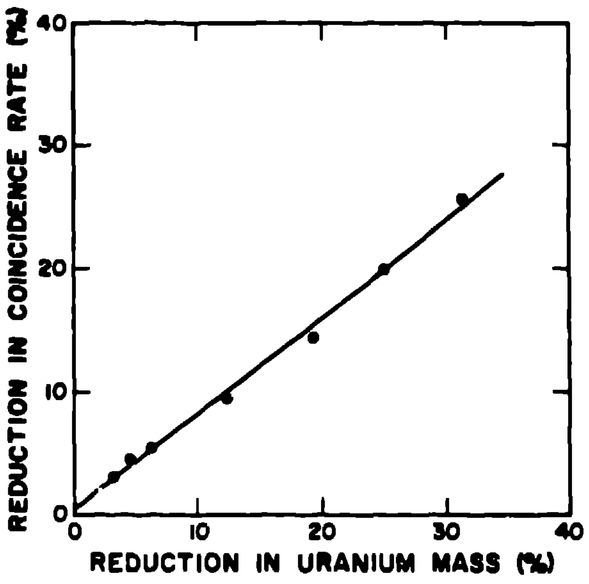

Fig. 5.
Active neutron coincidence response as a function reduction in ^{235}U mass for a uniform distribution of rod removals from a full PWR assembly.

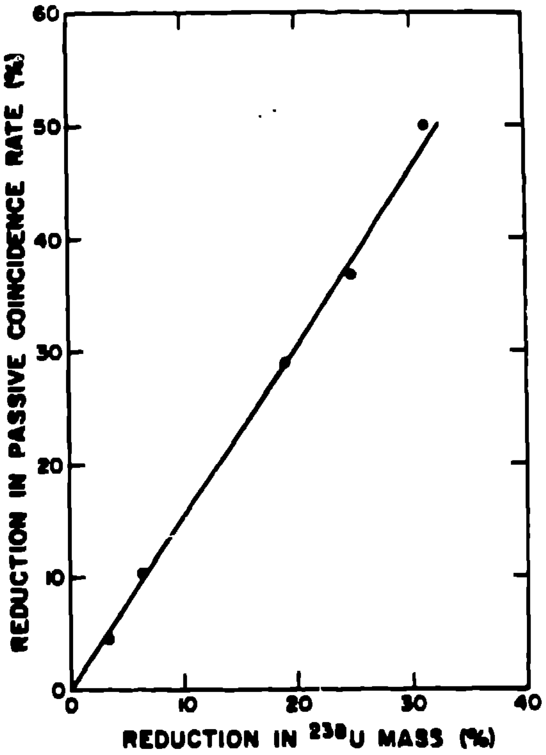

Fig. 6.
Passive neutron coincidence response as a function reduction in ^{238}U mass for a uniform distribution of rod removals from a full PWR assembly.

or other burnable neutron poisons. In effect, the active neutron interrogation gives the reactivity of the assembly and both the enrichment and neutron poisons affect the reactivity.

Measurements were performed using the mockup BWR assembly and inserting fuel rods loaded with 2.0 w/o Gd_2O_3 to determine the effect of the burnable poison on the measurements. A rod loaded with Gd_2O_3 decreases the active coincidence response by approximately 4 percent.

CONCLUSIONS

There are three separate variables in the fuel assembly that can be checked with the Coincidence Collar.

1. The active interrogation coincidence rate is primarily a function of the ^{235}U content.
2. The passive coincidence rate is primarily a function of the ^{238}U content (via spontaneous fission).
3. The passive singles rate is a function of the enrichment (via ^{234}U), but this can only be checked for low room background conditions.

For most applications, only the active measurement of the reactivthe other parameters if there is reason for more thorough verification. The uniform response of all fuel rod locations is important both for interior rod sensitivity and to make the measurement independent of the orientation of the fuel assembly in the Coincidence Collar.

The results indicated a 1000-s detection limit (95 percent confidence) for rod removal of approximately 3 rods or 1.3 percent of the uranium for PWR assemblies. The corresponding rod removal sensitivity is approximately 1 rod for BWR assemblies. The change in coincidence response varies almost linearly with the change in uranium content.

Measurements have been performed at a reactor fuel fabrication facility on full LWR assemblies with ^{235}U enrichments up to 3.5 percent. The response curve is not saturated and continues to increase as the enrichment increases through the normal range of LWR fuel. Relative loadings variations as small as 2.0 percent can be detected in a measurement time of 1000 s.

The system can be applied to the fissile content determination in HWR, BWR, and LWR fuel assemblies as well as HEU fuel assemblies for accountability, criticality control, and safeguards purposes.

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