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A COMPARISON OF SPENT FUEL ASSEMBLY CONTROL INSTRUMENTS: THE CADARACHE PYTHON AND THE LOS ALAMOS FORK

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ABSTRACT

Devices to monitor spent fuel assemblies while stored under water, with nondestructive assay methods, have been developed in France and in the United States.

Both devices are designed to verify operator's declared values of exposures and cooling-time but the applications and thus the designs of the systems differ.

A study, whose results are presented in this paper, has been conducted to compare the features and the performances of the two instruments.[1]

INTRODUCTION

The use of nondestructive methods (total gamma counting, passive and active neutron counting) for spent fuel monitoring presents some varied applications, which lead to different designs.

In France, the need for a spent fuel control device comes from criticality-safety concerns during domestic transportation and reprocessing. However, in the United States, the work is in support of the international nuclear safeguards effort.

Nevertheless, the two devices presented here (Cadarache PYTHON and Los Alamos FORK) are sufficiently similar to compare and correlate.

After a brief presentation of these two devices, experimental results of the comparison and interpretation are presented.

PYTHON INSTRUMENT

The PYTHON device[2] consists of two detection heads placed in two pond racks and a spent fuel assembly is brought to it (Fig. 1).

Acquisitions are being made while the assembly is moved past the detectors (the counting time for one assembly control is about 600 seconds).

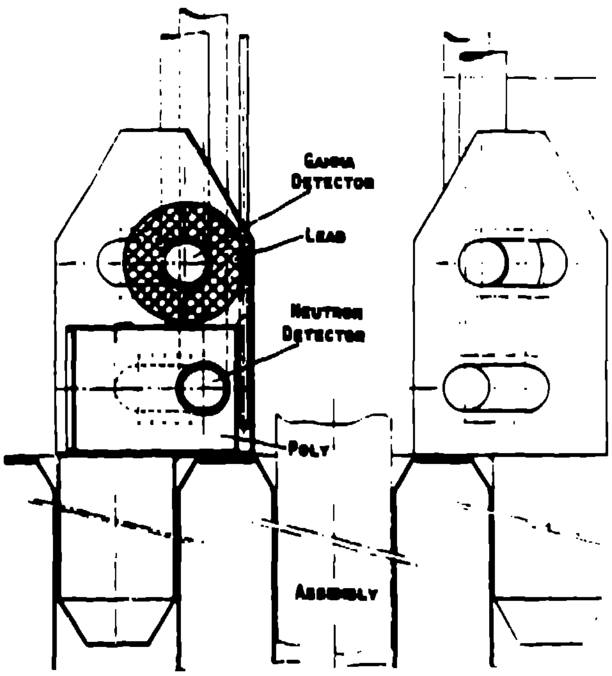

Fig. 1. The two detection heads of the PYTHON instrument are shown from the side, with the inner components indicated on the left head. An assembly is brought to the detector and moved vertically between the heads while neutrons and gamma rays are counted.

Three nondestructive assay (NDA) techniques are available with PYTHON:

- total gamma counting, which leads to the cooling time of the irradiated assembly;
- passive neutron counting, which leads to the burnup of the irradiated assembly; and

- active neutron counting, which leads to the effective multiplying factor (k_{eff}) of the assembly.[3]

The external ^{252}Cf neutron source necessary for the active method is modulated to obtain passive and active acquisitions at the same time (Fig. 2).

The neutron detectors are fission chambers with 22 cm active length inside polyethylene wrapped in cadmium and boron carbide.

The gamma detectors are ionization chambers surrounded by lead collimators that pass radiation from only a very short axial section of an assembly to obtain a profile.

Note: Due to the fact that an active interrogation is not available with the FORK device, this feature was not used during the comparison of the two instruments.

FORK INSTRUMENT

Safeguards require a transportable system and rapid measurements, so the FORK detector[4] mounts on a pond's bridge and is placed by the user around a partially raised assembly (Fig. 3).

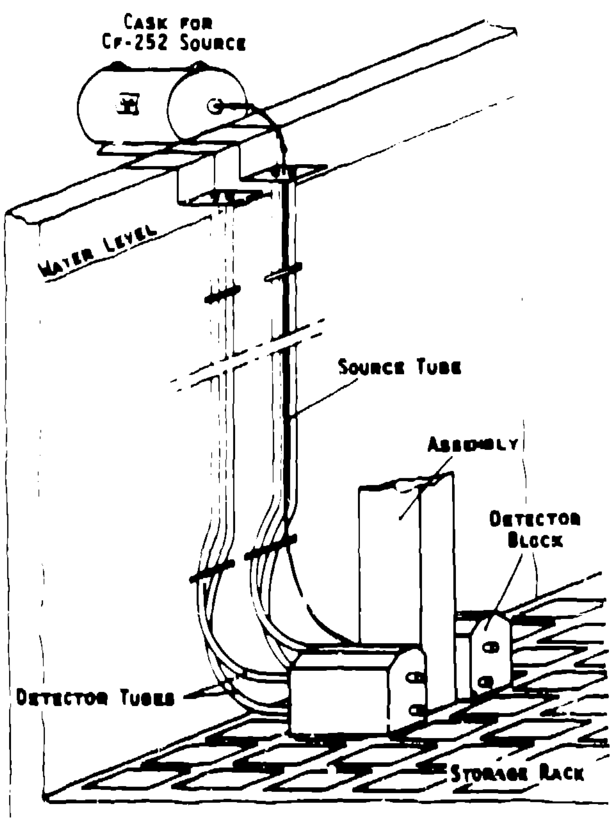

Fig. 2. The complete PYTHON instrument is shown in this drawing. Electrical cables connect the detector heads to the electronics outside the pond. A ^{252}Cf source can be positioned near the assembly for an active neutron measurement.

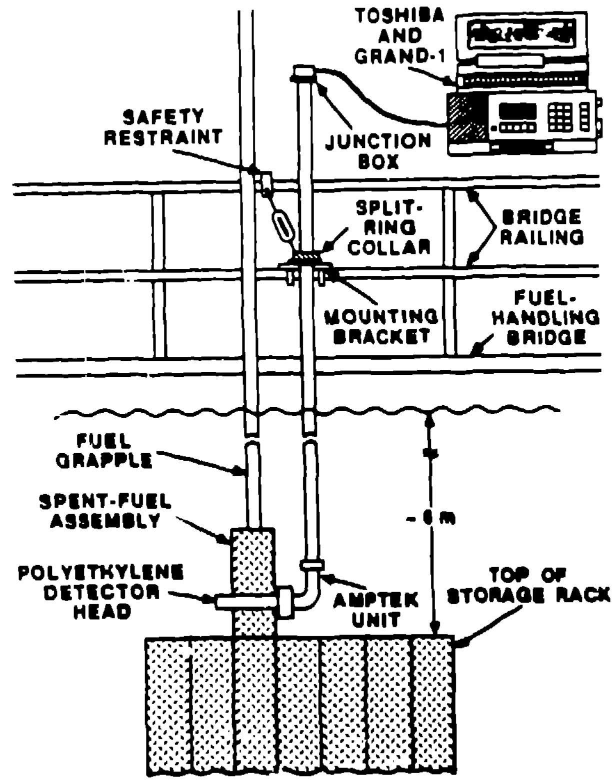

Fig. 3. The head of the FORK instrument is placed around a partially-raised assembly and passive neutrons and gamma rays are counted by the GRAND-1 electronics unit. A computer can be used for real-time analysis of the data. The FORK is supported by the pond's bridge and is moved to an assembly's position for a measurement.

A pressurized-water reactor assembly is usually examined at only one point along its axis; if the result is anomalous, further measurements can be taken along the assembly's length.

Counting times are 30 to 60 seconds and 6 to 12 assemblies can be measured in an hour, depending on the speed at which the assemblies are handled by facility operators. Two NDA techniques are available with FORK:

- total gamma counting, which leads to the cooling time of the irradiated assembly and
- passive neutron counting, which leads to the burnup of the irradiated assembly.

The detector head has a polyethylene body in the shape of a fork with two tines.

Each tine holds two neutron detectors: one fission chamber (15 cm active length) surrounded by cadmium-wrapped polyethylene and another one (same size) without a cadmium wrap. Each tine also has one gamma detector (ionization chamber).

Note: For the comparison of neutron signals between the two devices, only the results with the detector surrounded by cadmium are used.

THE COBRA TANK AND THE ASSEMBLIES

Measurements were made with the FORK and PYTHON devices at Cadarache in a water-filled tank called COBRA (Fig. 4) constructed for instrument development purposes.

One side of the tank can hold a mock-up (80 cm height) of a fresh fuel assembly and the detection heads. The other side has a shielded ^{252}Cf source for active neutron measurements, which was not used during these measurements.

It was impractical to measure irradiated fuel assembly so we measured fresh fuel assemblies. A ^{252}Cf source (emitting about 10^6 n/s) and a ^{137}Cs source (emitting 10^9 γ/s) were placed in the middle of a pin, which was moved throughout the array of pins in the assembly. (The ^{252}Cf simulated the curium emission of spent fuel, while ^{137}Cs is the actual dominant gamma-ray emitting isotope, after a few months cooling).

The signal generated by a spent fuel assembly could be simulated in this manner, with the advantage of learning the relative importance of radiations emitted from individual pins.

Data were collected for different assembly configurations to represent the detectors' responses from the neutron and gamma rays originating from different pin locations.

The different configurations studied were as follows:

- 17 x 17 array of pins with 3.5% ^{235}U enrichment in water,
- 17 x 17 array with 3.5% ^{235}U enrichment and additional pins with gadolinium inserted in water channels,
- 17 x 17 array with 3.5% ^{235}U enrichment with four boron concentrations in the water, and
- 9 x 9 array of pins with 0.25% ^{235}U enrichment (depleted uranium).

NEUTRON MEASUREMENTS

Reference Assembly

The reference assembly (17 x 17 array of pins with 3.5% ^{235}U enrichment in water) is presented with the FORK detector in Fig. 5. The numbers and letters along the edge of the array are used to identify columns and rows of pin locations.

The neutron source pin was placed in the 37 locations throughout columns 1 to 9 marked by dots inside the pins of Fig. 5. The typical measurement results are shown in Fig. 6.

The FORK neutron count rates are consistently higher than PYTHON's (average ratio of 2.74) because, although

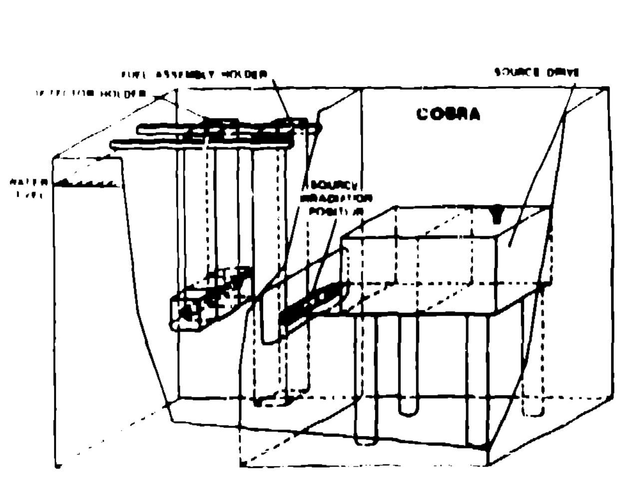

Fig. 4. The comparative measurements were made in this water filled tank called COBRA. The assemblies and detectors were placed in the left side of the tank. The right side is designed to hold a ^{252}Cf source, which can be moved to an irradiating position adjacent to an assembly for active interrogation studies; this feature of the tank was not used in these measurements. This sketch shows a prototype detector in a holder. For the present measurements, the FORK detector hung from a special bracket and PYTHON was supported from the floor of COBRA; the detector holder shown in the sketch was not used.

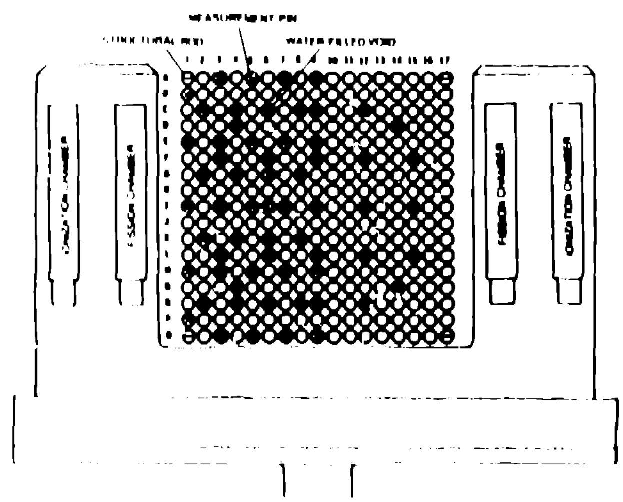

Fig. 5. The FORK instrument is placed with its back against the fuel pins and radiation is detected from opposite sides of the assembly. This view is looking downward from above the equipment. Rows and columns of pins were given the labels shown here and are used elsewhere in this paper. Solid black circles represent water channels that contained either water or poison rods. The corners of the assembly were steel support rods and are shown as circles with horizontal lines. Neutron and gamma-ray sources were placed at the pin positions marked with dots; these pins could also be pulled upward to examine the effects of different axial positions.

NEUTRONS COUNT-RATES WITH FORK DEVICE WITH 3.5% ENRICHED URANIUM PINS (NO BORON)

	1	2	3	4	5	6	7	8	9
A			76 200		73 950		72 020		[illegible]
B	[illegible]								
C		132 10		98 480				92 420	
D									
E	133 30		119 90		107 60		102 80		[illegible]
F									
G		139 00		120 10		129 50		110 10	
H									
I	136 90				126 60		113 10		
J									
K		137 70		120 90		108 60		105 90	
L									
M	128 70		111 80		103 70		98 100		96 670
N									
O		96 270		89 780				85 930	
P	59 700								
Q			71 230		64 970		64 550		67 770

NEUTRONS COUNT-RATES WITH PYYTHON DEVICES WITH 3.5% ENRICHED URANIUM PINS (NO BORON)

	1	2	3	4	5	6	7	8	9
A			21 890		20 810		19 715		18 905
B	26 440								
C		26 610		24 960				23 170	
D									
E	30 890		26 555		27 505		26 350		25 865
F									
G		31 840		29 780		28 835		28 175	
H									
I	33 745				29 865		29 775		
J									
K		32 230		29 975		29 750		29 110	
L									
M	32 065		26 170		27 850		27 480		27 605
N									
O		26 735		25 335				24 620	
P	26 100								
Q			20 810		21 255		21 165		21 370

Fig. 6. One set of FORK and PYTHON neutron count rates (counts per second) are compared in this figure for the case of COBRA water containing no boron. The rows and columns are labeled as shown in Fig. 5.

the FORK's fission chambers are less efficient, they are placed closer to the assembly.

Two observations appear:

- The radial profiles from PYTHON are flatter, which is due to the higher sensitive length of the fission chambers (with a maximum difference between I-1 and A-9 or Q-9 positions in Fig. 7 of 55% for FORK and 40% for PYTHON).
- The axial profiles from FORK are narrower than PYTHON's, which is explained by the physical sizes of the detectors and their positions relative to the assembly (cf Fig. 8).

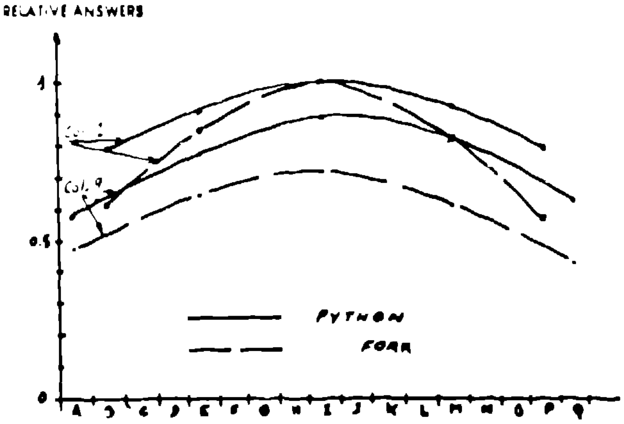

Fig. 7. Two of the many response profiles are shown here for each instrument. Each curve shows data from a single column of pins (see Fig. 5); column 1 is along an edge of the assembly while column 9 is through the center. Count rates from each instrument have been normalized to the count rate measured with the neutron source in column 1 and row 1.

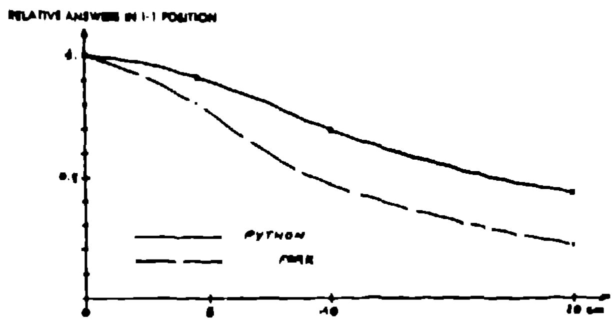

Fig. 8. One of the many axial response profiles is shown here for each instrument. The neutron source was in column 1 and row 1, the pin was raised above the plane of the neutron detectors. Count rates are normalized to the values found with the source in the plane of the detectors.

Assembly With Gadolinium

Neutron-absorbing pins containing gadolinium were inserted into the simulated assembly to measure their dampening effect on the neutron count rates. These absorbing pins consist of depleted uranium pellets with gadolinium by weight as follows:

$$Gd_2O_3 / (UO_2 + Gd_2O_3) = 8\% .$$

The ratio of the average neutron count rates with and without gadolinium are 0.72 for the PYTHON device and 0.77 for the FORK device.

These results show that the influence of gadolinium is almost the same for the two devices and that the effect has to be taken into account to understand the responses from spent fuel and fresh mixed-oxide fuel stored underwater with poison rods.

Effect of Different Boron Concentrations

Spent-fuel assemblies are often stored in water containing dissolved boron.

The table below shows the effect of concentration on the effective multiplying factor (k_{eff}):

Boron Concentration (ppm)	k_{eff}
0	0.806
500	0.7136
1000	0.6507
2000	0.5768
3000	0.525

Count rates obtained for the two devices are shown graphically in Fig. 9. As the boron concentration increases, the depression of the count rates is clearly seen. It is interesting to correlate the average count rates to the reactivity (k_{EFF}). The table below presents, for different boron concentrations, the Average Count Rates for the two devices (ACR), and the product (ACR) (1-k_{EFF}):

Boron Concentration (ppm)	ACR FORK CS-1	ACR PYTHON CS-1	ACR (1-k_{eff}) FORK CS-1	ACR (1-k_{eff}) PYTHON C2-1
0	101.6	26.6	19.7104	5.1604
500	74.24	17.34	21.2623	4.9661
1000	62.35	14.43	21.78	5.04
2000	52.27	11.85	22.12	5.015
3000	47.20	10.67	22.42	5.07

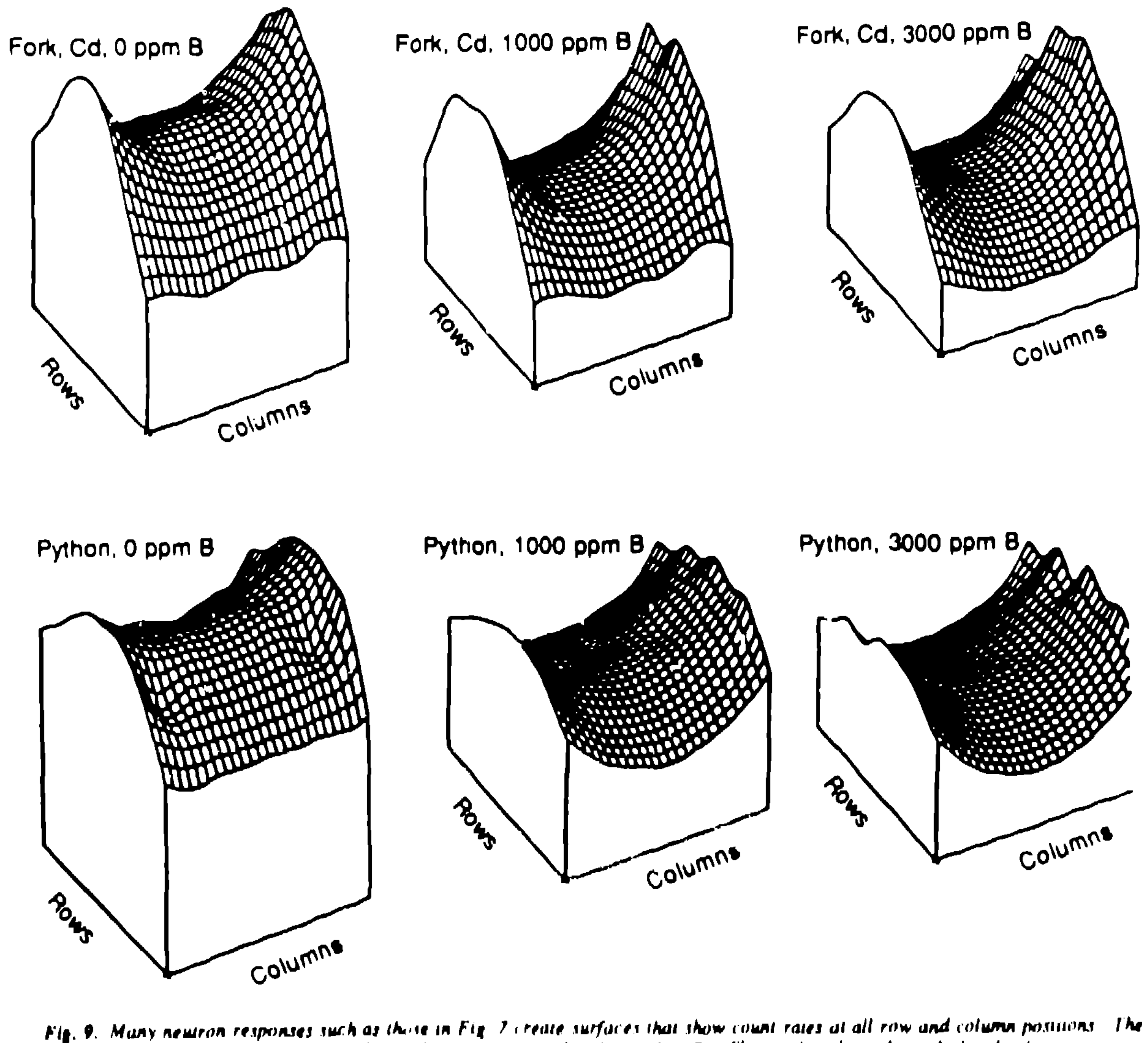

Fig. 9. Many neutron responses such as those in Fig. 7 create surfaces that show count rates at all row and column positions. The responses in columns 10 to 17 were taken to be symmetric with columns 1 to 8. (The ripples along the right-hand columns in some graphs are artifacts of the surface-generation algorithm)

The table shows that this product is constant (considering the uncertainties) and confirms that the relation between Neutronic Emission (NE) and Neutron Count Rates (NCR) is as follows:

$$NCR = C^{te} \frac{NE}{1-k_{eff}}$$

with C^{te} being the calibration constant.

Assembly With Depleted Uranium

Enough pins with depleted uranium were available to make a 9 x 9 array. The experiment consists of comparing the average count rate between 0.25% ^{235}U enrichment and 3.5% ^{235}U enrichment for a 9 x 9 array. The answers for the two devices are similar and show a reduction in count rate of about 40% because of the smaller multiplication of the assembly.

GAMMA MEASUREMENTS

As in neutron measurements, the gamma source pin was placed in different radial and axial positions (the axial information is not available with the PYTHON device because of the collimation). As the source moved toward the center of the assembly, both signals obtained with the two devices decrease with nearly an exponential law.

These measurements show that a few more columns than the first two or three should be considered for exacting work.[1]

CONCLUSION

The development of devices for spent-fuel assembly control by the United States and France have led to different designs because of different objectives and measurement conditions.

Nevertheless, the experiments described in this paper show that FORK and PYTHON devices have similar responses and that three remarks can be made.

- The FORK detectors generate higher count rates than PHYTHON's because they are placed closer to the assembly.
- The radial profiles from PYTHON are flatter, due to the higher sensitive length of the fission chambers and greater distance from the assemblies. This is an advantage, particularly for safeguards measurements, where diversion of a pin from any position is important.
- The FORK's axial neutron profiles are more narrow than PYTHON's because of the physical sizes of the fission chambers and the relative position to the assembly. This is an advantage in safeguards examinations but not necessarily in criticality-safety measurements.

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