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SPENT-FUEL VERIFICATION WITH THE LOS ALAMOS FORK DETECTOR

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ABSTRACT

The Los Alamos fork detector for the verification of spent-fuel assemblies has generated precise, reproducible data. The data analyses have now evolved to the point of placing tight restrictions on a diverter's actions.

I. THE FORK DETECTOR

A. Purposes

The original purpose of the fork detector was to verify operator-declared exposure, and cooling times of irradiated light water reactor assemblies stored underwater. More recently the interest has been on using the detector to locate assemblies that have undergone diversions. Most of this paper deals with the latter concern.

B. Detector Components

The detector head has a fork shape with two tines. An assembly is partially raised from its storage rack, and the fork is placed around the assembly with the tines next to opposing sides of the assembly. Neutrons and gamma rays emitted by the assembly are measured with fission chambers and ionization chambers within the tines.

The fork head is supported by a watertight pipe attached to the spent fuel pond's bridge and manipulated by an inspector. An electronics box on the bridge powers the detection chambers and records the signals. The support pipe houses the electronics cables.

C. Data Analysis

For assemblies with typical exposures, the measured neutrons are due primarily to spontaneous fissions in curium isotopes. These neutrons are used to verify that an assembly is intact and that the count rate is consistent with the declared exposure. The count rate can be correlated with the plutonium content, if so desired.

The gamma-ray data are proportional to currents in the ionization chambers. A correlation has been developed between the currents divided by exposure and cooling time. This correlation is useful after some short-lived isotopes have decayed to insignificance; this decay takes several months to a year. The primary contributors to the gamma-ray signal after the first year are the cesium isotopes. With a verified exposure from the neutron data, the cooling time can be verified with the gamma-ray correlation.

This overview of the data analysis will be enlarged upon in subsequent sections of this paper.

II. FORK CHARACTERISTICS WITH A SINGLE ASSEMBLY

A. Precision and Reproducibility

The statistical precisions of neutron and gamma-ray data after count times of 10-60 s are excellent (1-2%)[1-3] and are not important limiting factors in applying the fork.

The excellent reproducibility of fork data has been demonstrated in three ways: two independent forks and users with the same assemblies (Tihange);[4,5] one fork with two independent sets of users (Three Mile Island);[1] one fork and one user over short and long time spans (Obrigheim[2] and G.E. Morris Operations[6]).

B. Intrinsic Sensitivity

The intrinsic sensitivity of a fork detector is defined as the ratio of the fractional change in a measurement value to a fractional change in the number of pins. The opportunity to measure this sensitivity directly has not yet arisen, so the only information on intrinsic sensitivity comes from simulations.

Measurements have been made on PWR[7] and WWER[8-9] fresh-fuel assemblies in which a ^{252}Cf source inside a fuel pin could be moved throughout an assembly. These two sets of independent measurements both found that the fractional change in count rate is nearly proportional to the fractional change in the number of pins.

Gamma rays from various pins have been studied with calculations[10] and measurements.[8-9] The severe attenuation by the pins limits the fork's response to gamma rays originating from only the few rows of pins nearest the arms of the fork.

These different neutron and gamma-ray sensitivities are an advantage for safeguards because a diversion will not simply reduce the neutron and gamma-ray data by the same proportions. The pattern of the pins removed becomes another factor a diverter must consider in addition to the number of pins.

III. FORK APPLICATIONS TO A COLLECTION OF ASSEMBLIES

A. Neutron Data Analysis

The neutron data collected from assemblies[1-5] agree with calculational studies[11] that suggest this relation between exposure E and (adjusted) neutron count rate n:

$$n = a\,E^{b} \quad . \tag{1}$$

The amount of scatter about this curve is greatly reduced by adjustments made to the measured neutron count rates to obtain n. The fractions of the neutron count rates due to ^{244}Cm from assemblies with different initial enrichments and cooling times can be calculated. After these adjustments, the range of data points is about 20% on either side of Eq. (1).

The calculation of the ^{244}Cm fraction has only recently been developed[12] and has been applied to only a few sets of data.[1-5,12,13] The positive effect on the Loviisa[3] data for assemblies with quite different initial enrichments is dramatic, but the more subtle smoothing of the Tihange[4,5] data is equally important.

It is known[12,13] that improvements can be made in the codes that calculate the ^{244}Cm fraction, so it is anticipated that the scatter in the data will be further reduced in the near future. Gene Bosler of Los Alamos has adapted the CINDER[14] code to a personal computer and already has overcome some of the limitations in the early codes.

B. Gamma Ray Data Analysis

Another relationship[15] based on power laws is used to correlate the gamma ray γ with the cooling time T:

$$\gamma/E = a\,T^{b} \quad . \tag{2}$$

The scatter about Eq. (2) is generally small (5-10%) after a year's cooling. During the first year there are short-lived isotopes that introduce additional scatter for which no correction has been developed.

IV. DIVERSION STRATEGIES

A. Credible Diversion Technique

The diversions considered here involve removing whole pins.[16] If dummy replacement pins are inserted, they do not contain neutron or gamma-ray emitting materials.

Using dummy pins containing isotopes such as cesium, curium, or californium is certainly a possibility, but this use greatly complicates the diverter's actions.

B. Correct Exposures and Cooling Times

A potential diverter who wants to gain a significant quantity (8 kg of plutonium) must choose between removing (i) a large number of pins from a few assemblies or (ii) a small number of pins from many assemblies. Among the factors affecting this decision is the desire to minimize the probability of being detected. Detection probabilities can be estimated, as follows.

It is assumed that for a given exposure the (adjusted) neutron data points from many different assemblies form a normal distribution. The probability that a diversion from a single assembly will be detected depends on the position of the data point before the diversion, the size of the diversion, and the width of the normal distribution. The probabilities of detecting different-size diversions are given in Table I, for σ (relative uncertainty in the neutron count rate n) from 4% to 7%.

The first column shows the size of the diversion relative to 1σ; it is again taken that the mass diverted is proportional to the change in neutron count rate.

The second column gives four options of 4σ; they are shown as percentages of the average n (at any exposure).

The diversion fraction in column 3 is $\Delta n/n = (\Delta n/\sigma)(4\sigma/n)/4$.

The number of assemblies that must be fractionally diverted before a significant quantity of plutonium (8 kg) will be obtained is given in the fourth column. It is assumed here that typical PWR assemblies with about 30 GWd/tU exposure are being considered.

TABLE I

DETECTION PROBABILITIES OF VARIOUS SIZE DIVERSIONS

PD(N) = Probability of Detection after measuring N of the assemblies used to gain the significant quantity.
SQ = Significant Quantity of Plutonium (8 kg).

$\Delta n/s$	$4\sigma/n$ (%)	$\Delta W/n$ (%)	No. Assemblies for 1 SQ (%)	PD(1) (%)	PD(all) (%)	PD(all/5) (%)
1	16	4	41	0.14	5	1
	20	5	33	0.14	4	1
	24	6	27	0.14	4	1
	28	7	23	0.14	3	1
2	16	8	20	2.3	37	9
	20	10	16	2.3	31	7
	24	12	14	2.3	28	7
	28	14	12	2.3	24	5
3	16	12	14	16	91	40
	20	15	11	16	85	29
	24	18	9	16	79	29
	28	21	8	16	75	29
4	16	16	10	50	99.9	75
	20	20	8	50	99.6	75
	24	24	7	50	99.2	50
	28	28	6	50	98.4	50
5	16	20	8	84	100	97
	20	25	7	84	100	84
	24	30	6	84	100	84
	28	35	5	84	100	84
7	28	49	4	99.9	100	99.9

The last three columns labeled PD(N) give probabilities of detection under three conditions. PD(1) is the probability that a diversion from a single assembly will lead to a neutron data point below the lower 4σ limit. After the diversions have been performed from the necessary number of assemblies to reach a significant quantity, the probability that one or more of these assemblies will produce a neutron data point below the lower 4σ limit is PD(all). If only one fifth of the modified assemblies are selected in a measurement plan, the probability that one or more of these assemblies will produce a neutron data point below the lower 4σ limit is PD(all/5).

Small diversions ($\Delta n/\sigma$ less than 1) require a large number of assemblies to get a significant quantity, but the overall detection probability with the fork detection is less than 1%.

Large diversions ($\Delta n/\sigma$ greater than 5) are virtually (if not actually) guaranteed to be detected by the fork, as long as the measurement plan includes at least one of the assemblies.

A diverter would probably first consider making relatively large diversions from only a few assemblies [option (i) in the first paragraph of this section]. This option minimizes the diverter's effort, presents the fewest number of assemblies that could generate outliers by the fork detector, and presents fewer problems with other safeguards techniques (for example, surveillance cameras). However, even if only about 20% of the pins in an assembly were removed with $\Delta n/\sigma = 3$, the probability that the new data point would show the diversion is 16%. This action must be repeated for eight or nine assemblies to gain a significant quantity. The probability that one or more of these eight assemblies will reveal the diversion is about 75%; if only two of these assemblies are included in the measurement plan, the probability that one or more of them will indicate a diversion is still about 29%.

Diverting 50% from a few assemblies has a high probability of detection by the fork (Table I, $\Delta n/\sigma$ = 7). Even if only four assemblies are needed to gain a significant quantity (with $4\sigma/n$ = 28%), fork measurements on these four assemblies have a 98.4% chance of finding an outlier. A measurement on only one of these assemblies has a 99.9% chance of generating an outlier.

The alternative is option (ii), which reduces the risk of detection by the fork but increases the effectiveness of other safeguards techniques. Consider the smaller diversion with $\Delta n/\sigma$ = 2. After the diverter removes 10% of the pins in 16 assemblies, there may be only a 2.3% chance that data from any one of the assemblies will produce a data point outside the 4σ limits. However, if all 16 assemblies are measured, the chance of one or more of them revealing a diversion is 31%. If only four of these assemblies are included in a measurement plan, the probability of at least one of them revealing the diversion is about 7%.

Although option (ii) offers the diverter more relief from the fork detector than does option (i), it increases the diverter's level of effort and enhances the effectiveness of other safeguards techniques in force.

C. Falsely Declared Exposure

A diverter may attempt to increase the amount removed from an assembly by declaring a false exposure. Figure 1(a) shows a data point that has become an outlier after a diversion (point "b"). It could be brought back within the 4σ limits by reducing the declared exposure (leading to point "c").

However, the diversion may or may not affect the gamma ray value γ (depending on the locations of the removed pins and which sides of the assembly are placed in the fork), whereas the smaller declared exposure is used in the γ/E ratio; it is a daunting task to find a pattern that will produce a γ/E ratio nearly equal to the value before the diversion. Furthermore the diverter cannot predict how an assembly will be oriented within a fork, so the pattern needs to have 90° rotational symmetry.

The diverter must also keep in mind the effect the change in the declared exposure will have on the calculated ^{244}Cm fraction; not only will E be changed, but so will n.

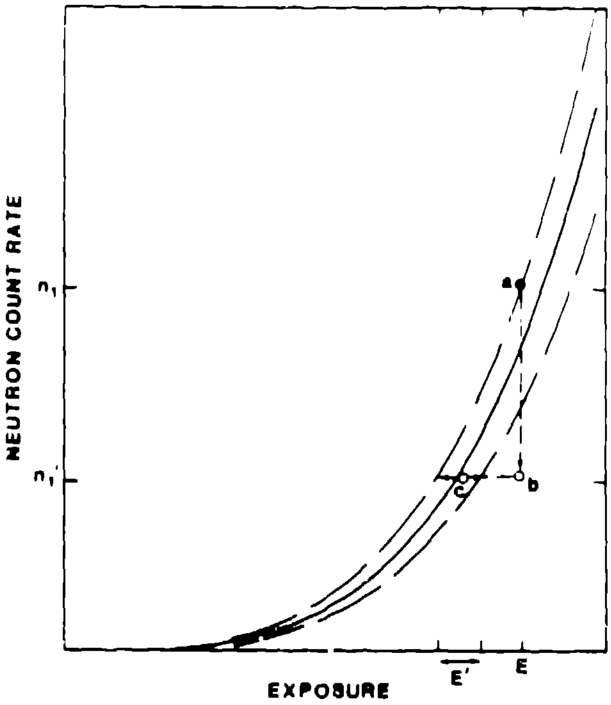

Fig. 1(a). An attempt can be made to disguise a diversion by changing the declared exposure. If an assembly would generate the data point "a" (on the 4σ outlier limit in this illustration) with neutron rate n_1 for the correctly declared exposure E, the removal of some of its pins might produce the data point "b." By reducing the declared exposure to E', point "b" could shift to "c" within the 4σ limits. Success in performing this operation depends on knowing the fork's neutron count rate before and after the diversion, calculating a plausible false exposure, and avoiding detection through the gamma ray data [as shown in Fig. 1(b)].

For a PWR assembly with a true exposure of 30 GWd/tU, 25-50% of the pins might be removed but the neutron count rate could be made plausible by reducing the declared exposure to about 27 GWd/tU. The value of 1/E in γ/E is increased by 11%; whether or not this increase produces an outlier depends on the pattern of pin removal [Fig. 1(b)]. If the diverter somehow reduces the value of γ by 11% with the diversion, the ratio γ/E will be unchanged. If the pattern does not change γ, the new value of γ/E might be an outlier. Thus, falsifying the declared exposure introduces new problems for a diverter.

D. Falsely Declared Cooling Time

Changing the declared cooling time is a difficult course to follow. Cooling times must match the well known discharge dates, which are typically about a year apart; there is not the freedom of choice of cooling times as there is for exposures. Furthermore, false cooling times are likely to lead to eventual detection.

If an assembly is assigned a certain cooling time, this assignment implies that it was part of a certain core loading. If the cooling time of one assembly is lengthened, it becomes

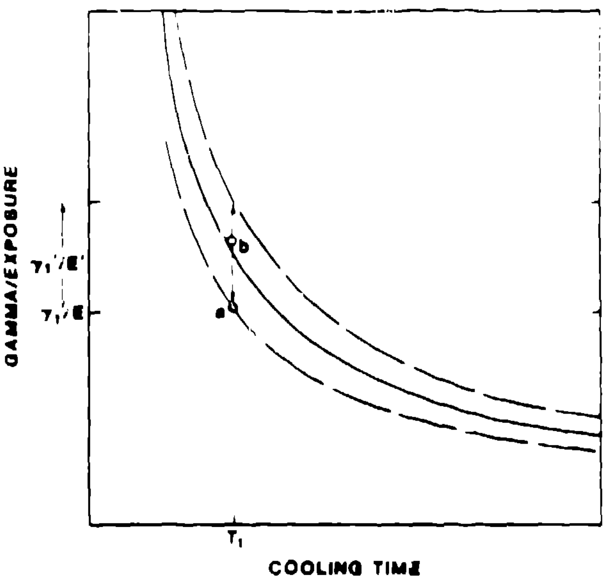

Fig. 1(b). The value of γ may or may not decrease after the diversion, depending on the geometrical pattern of the pins removed and the orientation of the assembly within the fork. Shown here is the case where γ changes less than 1/E, so the true data point "a" shifts upwards to "b." (It is also possible for γ/E to decrease.) If the new γ'/E' falls outside the 4σ limits, detection will be possible.

part of another core loading, and the cooling time of another assembly must be shortened to maintain the correct number of assemblies in all core loadings. The diverter must falsify the records for about twice as many assemblies as the number from which pins were removed.

After considering the problem of removing the proper number and pattern of pins to be consistent with highly restricted possible cooling times, a diverter may be deterred from this approach. If not, he must also ponder the results of subsequent inspections.

Because the cooling time is now incorrect, the calculated ^{244}Cm fraction will be incorrect, the neutron data point will fall into its proper place in relation to Eq. (1), and the neutron data point will not remain stationary in time as it otherwise would. Furthermore the gamma-ray data point will not slide along the cooling curve properly (Fig. 2). The time delay after the diversion at which detection becomes possible depends on many parameters; for reasonable conditions the delay can range from a month to a few years.

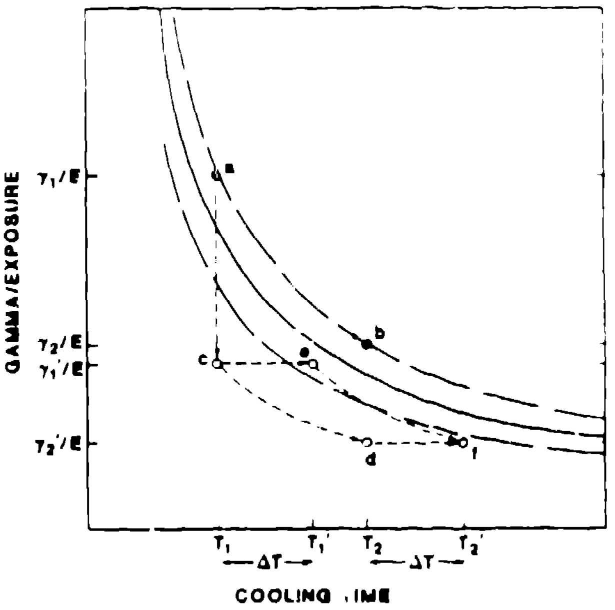

Fig. 2. An attempt could be made to disguise a diversion by falsifying cooling time. The effect on the gamma-ray data point is illustrated here. The true data point at cooling time T_1 is point "a"; it is shown on the upper 4σ limit, but it could be lower. The diversion reduces γ_1 to γ_1' so that point "c" would be found by the fork detector. To bring the data point within the 4σ limits, the cooling time is increased by ΔT to T_1' and point "e" will be found with the fork. The diverter's choice of ΔT is greatly restricted; the cooling times must be consistent with known core unloading dates, so ΔT will usually have to be about 1 year.

Although if done with the skill implied in the figure, the diversion would be disguised for the inspection at T_1, a later inspection (such as at T_2) can find that point "e" has drifted to point "f," which is outside the 4σ limits. While point "a" would drift to "b" and "c" to "d," following curves proportional to Eq. (2), the curve connecting "e" and "f" does not follow Eq. (2) because the incorrect cooling times are used.

E. Falsely Declared Exposure and Cooling Time

A diverter might think that falsifying both the declared exposure and cooling time of an assembly would increase his flexibility. Although it is true that somewhat larger diversions are possible in this case, the problems discussed in Secs. III.C and III.D with false values apply here as well. In particular, a false cooling time makes it likely that detection during a subsequent inspection is possible.

V. CONCLUSION

A knowledgeable potential diverter should feel that large diversions (20% or more of each assembly involved) are likely to be detected by the fork, whereas the number assemblies needed for small diversions (less than 20% of each assembly) is inhibiting. By removing only a small fraction (5-10%) from each of many assemblies, detection by the fork can be made unlikely. The small diversions require the diverter to handle many more assemblies in the view of other safeguards equipment (for example, optical surveillance, lasers, seals, night-vision devices, periscopes). Avoiding detection by the fork enhances the probability of detection by other means.

The interconnections among the operator's declared values and the fork's data are complex, and not all aspects of them can be predicted or controlled by the potential diverter. Attempting to disguise diversions with falsely declared exposures or cooling times has many pitfalls for the diverter.

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