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THE VERIFICATION OF REACTOR OPERATING HISTORY USING THE FORK DETECTOR*

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ABSTRACT

A technique has been developed for verification of light-water reactor operating history from measurements of irradiated fuel assemblies. The Fork detector is used to measure neutron and gross gamma-ray emissions from fuel assemblies. The measurements can be performed a few days after discharge or up to several years later. The neutron and gamma-ray ratios are used to check the consistency of the declared number of irradiated cycles for the assembly in the core. Reactor burnup calculation codes are used to correct the measured neutron rates for different initial enrichments and discontinuous irradiation histories. We have modified the Fork detector so that it can operate in the intense gamma-ray field emitted from freshly discharged fuel. This modification makes it possible to perform fuel verification during the annual fuel-reload and maintenance period.

I. INTRODUCTION

The Fork detector\(^1\) was originally developed to measure gross gamma-ray and neutron emissions from irradiated fuel assemblies to verify the consistency of reactor-fuel burnup declarations. The relative measurements do not give the absolute burnup or the corresponding plutonium content in the spent fuel. We have modified the use of the Fork detector by using the neutron/gamma ratios to verify the irradiation cycle history of the fuel assemblies.

ORIGEN-2 calculations are used to predict the relative neutron and gamma-ray emissions from pressurized-water reactor (PWR) fuel with one, two, and three cycles of reactor irradiation.

In the case of loss of containment and surveillance of a reactor, it might be necessary to reestablish continuity of knowledge by the measurement of the irradiated fuel in the reactor core. During the reload operation, a short measurement (~1 min) can establish the gross gamma and neutron activity. Distinct data patterns emerge from the relative measurements that are very different for fuel assemblies that have differing numbers of irradiation cycles.

Because these measurements relate to the in-core (rather than storage) fuel assemblies, the measurements normally would be performed during the reactor refueling operation. Thus, the fuel cooling time would be a few days rather than a few years (for the storage pool fuel assemblies). This results in gamma activity that is one to two orders of magnitude higher than normally encountered in the Fork measurement of irradiated fuel in the storage pool. To accommodate this higher gamma rate, we have modified the Fork detector to be less sensitive to the gamma dose.

We will describe the basic concept of reactor-history evaluation using the Fork detector, and also modifications made to the Fork detector to accommodate high gamma levels, below.

II. CONCEPT OF THE IRRADIATION HISTORY VERIFICATION

The gross gamma activity and the gross neutron emission rate from irradiated fuel behave very differently as a function of burnup. For short cooling times of less than approximately two months, gross gamma activity is dominated by fission products with short half-lives; these isotopes have reached a saturation condition in the core so that their number is approximately the same for one, two, or three cycles. The activity depends primarily on the reactor power level during the few months of operation prior to shutdown.

Figure 1 shows the relative gamma contribution from the isotopes as a function of cooling time. Some of the dominant isotopes at short cooling times are \(^{103}\)Ru, \(^{140}\)Ba, \(^{97}\)Zr, and \(^{95}\)Nb that have half-lives of 39.4 d, 12.8 d, 64 d, and 35 d, respectively. After several years of cooling, the \(^{137}\)Cs (30.17-yr half-life) becomes the dominant gamma source and then the gross gamma rate is directly proportional to the burnup.

Figure 2 shows the calculated neutron rates from \(^{242}\)Cm and \(^{244}\)Cm, as both isotopes have a strong dependence on burnup. After

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Fig. 1. Measured total gamma-ray activity divided by burnup as a function of cooling time for PWR fuel assemblies.

Fig. 2. The neutron yield from $^{244}$Cm as a function of burnup for PWR and PWR mixed-oxide fuel.

only one cycle (~15 GWd/tU) of irradiation, the $^{242}$Cm contribution is larger than the $^{244}$Cm contribution. However, after three cycles, the $^{244}$Cm is dominant. For spent fuel in the storage area with several years of cooling time, the $^{242}$Cm ($T_{\text{1/2}} = 163$ d) will have decayed away and the $^{244}$Cm ($T_{\text{1/2}} = 18.1$ yr) will be dominant for one, two, or three cycles.

If we plot the neutron/gamma ratio, we get a strong dependence of the irradiation cycle. Figure 3 shows the ratios for both 30 days of cooling and 3 years of cooling. We see that the cycle differences in the neutron/gamma ratios remain even after several years of cooling because the $^{244}$Cm has a stronger burnup dependence than $^{242}$Cm. For the three-year cooling time case, the long-lived fission-product isotopes such as $^{137}$Cs have become dominant and they are dependent on the burnup. However, this gamma dependence is approximately canceled by the strong $^{244}$Cm dependence on burnup in the neutron/gamma ratios shown in Fig. 3.

Figure 4 shows a plot of neutron rate vs the gross gamma rate for Fork measurements in 1986 of the spent fuel assemblies from the Angra-1 reactor. The fuel had burnup of ~15 GWd/tU and a cooling time of about one year. Each fuel assembly was measured at its midpoint, and we see some variation in the gamma and neutron rates depending on the position of the fuel assembly in the reactor core.

We have normalized the measured data from Fig. 4 (~15 GWd/tU) with the ORIGEN-2 calculations for one-, two-, and three-cycle irradiations; the results are shown in Fig. 5. We see that the neutron rates increase by about an order of magnitude with each full irradiation cycle. For fuel with very short cooling times, corrections to the gross gamma activity can be made to account for decay and time differences between assembly measurements. A simple inverse time relationship can be used for this correction. Figure 6 shows this decrease in activity as a function of time where the dose at the Fork position was assumed to be $5 \times 10^9$ R/h at 30 days of cooling time.

For fuel assemblies that have an irregular irradiation history, the curium activity will have some variation. For the case in which the fuel is held out of the core for one or more cycles and then returned to the core, the $^{244}$Cm
will increase. This is caused by the increase in the precursor $^{241}$Am that is fed by the 14.7-yr decay of $^{241}$Pu. Burnup calculations must be performed for these irregular cases to predict their deviation from normal patterns. Prior calculations of this type have shown that deviations in neutron rates are typically less than a factor of two from the normal case.

### III. DETECTOR MODIFICATIONS

The Fork detector is shown in Fig. 7 and the inside detector assembly is shown in Fig. 8. The standard Fork was modified to increase efficiency by removing the cadmium liner. The fission chambers (FCs) have been wired so that they are symmetric to the fuel assembly. The cadmium removal increased the counting rate by a factor of 3.4 in air; this factor would be larger in water.

The pulse-height spectrum from the FC is shown in Fig. 9. The low energy counts come from alpha decay in the $^{234}$U and the higher energy counts come from neutron fission counts in the chamber. Normally the neutron discrimination level (DL) is set at the upper edge of the alpha spectrum. We have defined the neutron counts above the DL as $R_a$. For normal gamma dose levels (<$5 \times 10^4$ R/h), the gamma pileup is below the DL. However, for higher gamma dose levels, the pileup can be expected to move above the DL and give gamma interference in the neutron channel. To avoid this problem, we have set two new DL levels at DL(A) and DL(B) as shown in Fig. 9. The new DLs are set at 0.4 $R_a$ for DL(A) and 0.2 $R_a$ for DL(B). Two levels were selected so that the ratio of A/B can be used to show that the gamma pileup has not interfered with the neutron counts. For a pure neutron spectrum, $A/B = 2.04$; however, if the pileup is a problem it will interfere with the counting rate in A much before B.

### IV. EXPERIMENTAL TESTS

To test the modified Fork, experiments were performed using the Los Alamos mockup fuel assembly containing 204 PWR rods with 3.19% enrichment. A $^{252}$Cf source (CR-11) with a yield of $8.02 \times 10^5$ n/s ($95-10-10$) was placed inside the fuel assembly in the underwater test facility. Figure 10 shows the axial profile from moving the point source along the central axis of the fuel assembly. The counting rate in neutron channel A is about two times larger than channel B.
Fig. 7. The fork detector is on the left of this photograph. It is constructed from polyethylene and contains fission chambers and ionization chambers in each tine. Preamplifiers for the fission chamber pulses are inside the stainless-steel pipe attached to the rear. The Davidson GRAND-3 electronics unit is on the right beneath a representative portable computer.

Fig. 9. Fission chamber spectrum, showing the high discrimination levels for the A (0.4 R₀) and the B (0.2 R₀) detector pairs.

Fig. 8. The modified Fork detector with fission counter pairs A and B with all cadmium removed.

Fig. 10. Fork detector neutron axial profile for a 252Cf point source on the axis of a PWR fuel assembly under water.
To test the neutron emission rate as a function of fuel rod removal, underwater experiments were performed by removing uniformly spaced groups of rods and measuring the reduction in the neutron rate. The observed rate from the $^{252}$Cf was reduced by the fraction of the removed rods to simulate the curium neutron source term in each rod of spent fuel. Figure 11 shows the percent change in the counting rate vs the percent change in the fuel rod loading. When depleted uranium (DU) rods were substituted for the low-enriched uranium (LEU) rods, the emission rate drops more rapidly than the empty rod case primarily because of the neutron absorption in the $^{238}$U. When the LEU rods are removed, with water filling the fuel-rod position, there is a small increase in the neutron multiplication of the remaining rods and this increase partially offsets the neutron source term reduction from the rod removal.

![Figure 11. Neutron reduction vs rod removal for a 204-rod (3.19%) PWR fuel assembly under water.](image)

VI. CONCLUSIONS

The Fork detector can be used to verify the number of reactor-irradiation cycles. The constant A/B ratio can demonstrate that the gamma pileup did not significantly interfere with neutron counting in the FC. However, the high-ionization current from the intense gamma dose can cause a small gain reduction in the FC neutron spectrum.

For fuel assemblies with long cooling times, the gamma dose represents $^{137}$Cs that is proportional to the burnup, whereas for short cooling-time fuel, the gamma dose represents the recent power profile in the reactor core. Fuel assemblies with higher fissile content will have a higher fission rate in the core and thus a higher gamma rate.

The neutron profile from the older fuel is dominated by $^{244}$Cm that is proportional to a power function of the burnup. The short-cooling-time fuel has a neutron yield that is a mixture of $^{242}$Cm and $^{244}$Cm. The $^{244}$Cm fraction increases with the burnup.

The core fuel management tends to move the fuel assemblies from lower flux zones to higher flux zones as the irradiation cycle progresses from one to two to three cycles. This has the effect of decreasing the spread in the burnup for a particular cycle group.

For fuel assemblies with irregular irradiation cycles, the declared cycle history can be used together with burnup codes to make corrections for the perturbation in the curium populations.

REFERENCES


