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BURNUP VERIFICATION TESTS WITH THE FORK MEASUREMENT SYSTEM-IMPLEMENTATION FOR BURNUP CREDIT[1]

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ABSTRACT

Verification measurements may be used to help ensure nuclear criticality safety when burnup credit is applied to spent fuel transport and storage systems. The FORK system measures the passive neutron and gamma-ray emission from spent fuel assemblies while in the storage pool. It was designed at Los Alamos National Laboratory for the International Atomic Energy Agency safeguards program and is well suited to verify burnup and cooling time records at commercial Pressurized Water Reactor (PWR) sites. This report deals with the application of the FORK system to burnup credit operations.

BURNUP CREDIT

The "burnup" of reactor fuel is a crucial parameter in fuel management and in calculations of nuclear criticality and residual fissile content. Burnup of the reactor fuel is determined by monitoring the thermal output of the reactor and is usually specified as the integrated thermal output per ton of uranium (gigawatt days/metric ton of uranium). The average burnup for each fuel assembly is determined by distributing the measured thermal output among the fuel assemblies based on measurements taken during reactor operation by an array of in-core instruments. In this report, assembly burnup will be taken to mean the average burnup assigned to a discharged spent fuel assembly. Once an assembly has been removed from the reactor, a direct burnup measurement is no longer possible. However, activation and fission reactions in the assembly produce residual radioactivity that can be correlated with the reactor history for burnup. Studies have concluded that the reactor records for assembly burnup are of higher precision (about 2%) than could be determined by post-discharge radiation measurements [Ref. 1]. The role of a radiation measurement on an assembly after its discharge from the reactor is to demonstrate the consistency of the reactor records for burnup, to detect possible misidentification of assemblies, and to detect anomalous assemblies that might affect nuclear criticality safety.

Concerns of nuclear criticality safety in the storage and transport of spent fuel arise because of the residual fissile content of the fuel and the near-optimum geometry of the rods in the assembly. For regulatory purposes, criticality calculations generally assume the most reactive composition for the fuel (fresh fuel), although the reactivity of the spent fuel has been reduced by the depletion of fissile material and the production of neutron absorbers as fission and activation products. Taking credit for the reduced reactivity of a spent assembly (burnup credit) can result in more efficient and economic transport and storage arrays of spent fuel assemblies [Ref. 2]. This is accomplished by increasing the number of assemblies that can be accommodated in a container and by reducing the amount of neutron absorber needed for criticality control.

Spent fuel containers designed using burnup credit are restricted to accept only assemblies that meet certain minimum burnup restrictions that limit the maximum theoretical multiplication factor to less than 0.95. The characteristics of fuel acceptable for loading into a burnup credit cask can be specified by a loading curve, an illustrative example of which is shown in Figure 1. The numerical values on Figure 1 are not significant of any particular design. The curve delineates the minimum burnup required for a particular initial enrichment and separates the assemblies with acceptable burnup from those that are unacceptable. If unacceptable assemblies are present in the spent fuel pool, the possibility exists that some unacceptable fuel could be misloaded, due to misapplied reactor records or an error in assembly identification. For typical container designs, the unacceptable fuel is only a few percent of the inventory. However, a measurement verification of burnup prior to container loading would increase confidence in nuclear criticality safety.

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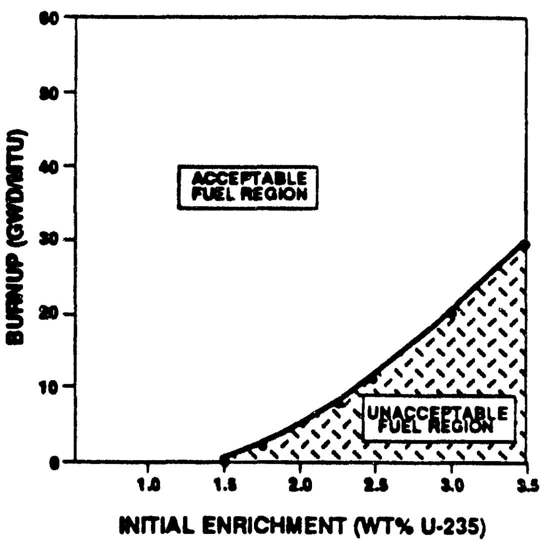

Figure 1. Example Burnup Credit Loading Curve

VERIFICATION METHOD

The radiation emitted from a discharged assembly can be correlated with the reactor power history of the assembly. The method to be described here makes use of the reactor records for burnup, initial enrichment, and time since discharge (cooling time) to establish a correlation with the measured neutron and gamma-ray emission rates for a group of assemblies of a given design. The correlation can identify inconsistencies between the reactor records and the measurements for a particular assembly by the amount of deviation from the measured correlation function. Analysis of the radiation from spent fuel assemblies to which burnup credit will be applied is simplified by the fact that the assemblies have been cooled for over five years, leaving only a few significant gamma and neutron sources. The predominant neutron emitter is curium-244, which is formed by successive neutron capture beginning with uranium-238 and decays by spontaneous fission with a half-life of 18 years. The neutron signal follows a power law relationship with burnup, in which the neutron signal increases with burnup to about the fourth power. The neutron signal is therefore very sensitive to burnup. Since this neutron emitter is an activation product, the relationship of the neutron emission to burnup depends on the initial enrichment of the assembly in a way that is well specified by an isotopic production code that has been benchmarked with radiochemical data from spent fuel. The major gamma emitter is cesium-137, a fission product that decays with a half-life of 30 years. The production of cesium-137 is essentially a linear function of burnup. The combination of gamma and neutron measurements allows both the burnup and the cooling time of each assembly to be checked, as described below.

FORK MEASUREMENT SYSTEM

The FORK measurement system has been used for more than a decade to verify reactor burnup records by measuring neutron and gamma-ray emissions from spent fuel assemblies [Ref. 3]. The FORK system has been used to verify burnup at eleven reactor facilities in five nations and is being used in Belgium for verification prior to reprocessing of spent fuel. Comparison tests of the FORK technique with more complex active and high-resolution measurement techniques have indicated essentially equal effectiveness [Ref. 4]. The FORK system is designed to be immersed in the spent fuel storage pool at a reactor site and perform the measurements without removing the assembly completely from the storage rack. The FORK detector and its associated electronics are shown in Figure 2. The battery-powered electronics unit and microprocessor shown in Figure 2 are used to supply all power to the detectors, collect and analyze the detector outputs, and perform necessary calculations and documentation. Each of the two arms of the FORK detector contains two fission chambers to measure the yield of neutrons and one ion chamber to measure gross gamma-ray emission. One fission chamber (the epithermal detector) in each arm is embedded in a polyethylene cylinder that is surrounded by a thin sheet of cadmium. The other fission chamber is outside the cadmium cover and is sensitive to thermal neutrons. The polyethylene cylinders containing the detectors are inserted into the polyethylene outer cover. The epithermal detectors provide the primary data used in the FORK technique. In the safeguards application, the thermal neutron detectors have been used to check the variation of the boron content among the spent fuel pools at different locations. In the present use, the thermal detectors serve as a back-up measurement to the epithermal data. The gamma-ray measurement serves as an additional consistency check on the reactor records. The gamma-ray data are analyzed using the assumption that the gamma-rays are produced by fission products and are used to back up the neutron data, which are more sensitive to burnup.

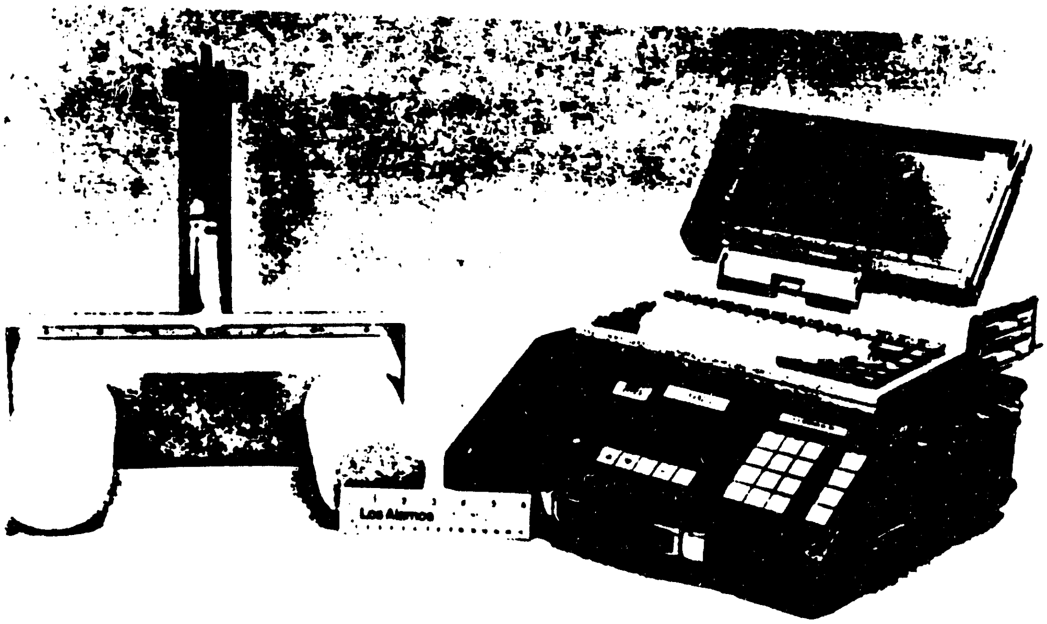

Figure 2. FORK Detector and Control Electronics

PROCEDURE FOR MEASUREMENT

The system is diagrammed in an operational arrangement in Figure 3. Stainless steel pipes are used to support and manipulate the detector. The pipes also enclose the electrical cables from the detector to the electronic controls. The entire array is close to neutral buoyancy in the storage pool. The pipe is fixed to the fuel handling bridge by an adjustable mounting that allows the detector to be raised, lowered, and moved into position. The detector is positioned above the top of the storage rack so that the radiation shielding provided by the water of the storage pool is adequate to ensure that the measurement is not influenced by radiation from nearby assemblies. About 18 inches of clearance between the top of the rack and the detector has proved to be sufficient. The assembly is raised in the storage rack so that its midpoint is located at the detector. It is not necessary to completely remove the assembly from its location in the storage rack for the measurement. The detector is moved into contact with the assembly, and the neutron and gamma-ray data are collected. A counting time of 100 seconds has proved to be adequate to accumulate over 10,000 counts in the neutron channels to ensure one-percent statistics. The ion chamber reaches its equilibrium reading in about one second. The detector is moved away from the assembly, which is then lowered to its normal position in the rack.

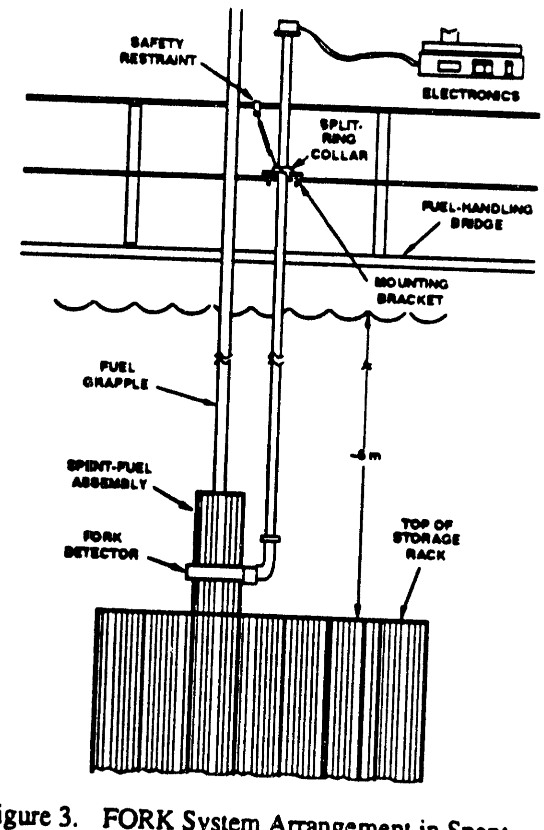

Figure 3. FORK System Arrangement in Spent Fuel Pool

ANALYSIS OF DATA

The neutron data are correlated with the reactor records under the assumption that the neutrons are produced by curium-244. The neutron count rates are corrected for the decay of curium-244 since discharge from the reactor by extrapolating the observed count rate back to the date of discharge of the assembly using the 18-year half-life of curium-244. This extrapolation produces a neutron count rate at discharge, which is multiplied by a factor that corrects for the variation in initial enrichment among the assemblies. This correction factor, calculated using well-proven isotope production codes that have been benchmarked with destructive analyses of spent fuel, is described more fully in Appendix B of Reference 5. The resulting corrected neutron signal is then correlated with the reactor record for burnup by least-squares fitting to a power law function. The initial calibration of the power law function is based on measurements of four assemblies, chosen to cover the burnup range of interest. As each measurement is completed, the deviation in burnup from the calibration is determined. If the deviation is not greater than about 10%, the measurement is accepted and a new calibration (best-fit power law) is generated using the additional data point. By accumulating measurements from a number of assemblies, an internal self-calibration is obtained that can sensitively identify measurements that are inconsistent with the burnup from the reactor records. The data and its deviation from the calibration curve are displayed on the screen of the laptop data processor at the time of the measurement, and a decision on the adequacy of the data can be made before the assembly is returned to its rest position. The signals from both the epithermal and thermal neutron detectors are automatically reduced and analyzed by software in the laptop processor. The epithermal signal is the primary measurement on which a decision will be made on whether or not the data verify the burnup. The gamma-ray data are analyzed assuming that the signal from the ion chambers is proportional to burnup, i.e., the gamma-rays are due to fission products. The gamma-ray current reading is divided by the burnup for the assembly and is displayed on a plot of current/burnup vs. cooling time.

EXAMPLE: MEASUREMENTS AT OCONEE NUCLEAR STATION

The FORK measurement system was used to examine spent fuel assemblies at the Oconee Nuclear Station of Duke Power Company in a cooperative test program involving Sandia National Laboratories, Los Alamos National Laboratory, Duke Power Company, and the Electric Power Research Institute [Refs. 5, 6]. The tests were designed to demonstrate the ability of the FORK system to verify reactor records for burnup and cooling time, to detect deviations from those records, and to develop procedures for the use of the system that are compatible with utility operations. Ninety-three assemblies were examined in three and one-half days of operation. The initial enrichment of the assemblies ranged from 2.91 to 3.92 weight percent uranium-235. The range in assembly average burnup was from 20.3 to 58.3 GWd/MTU. The cooling times varied from 4.2 to 14.8 years. The epithermal neutron data are shown in Figure 4, a log-log plot of neutron signal versus burnup

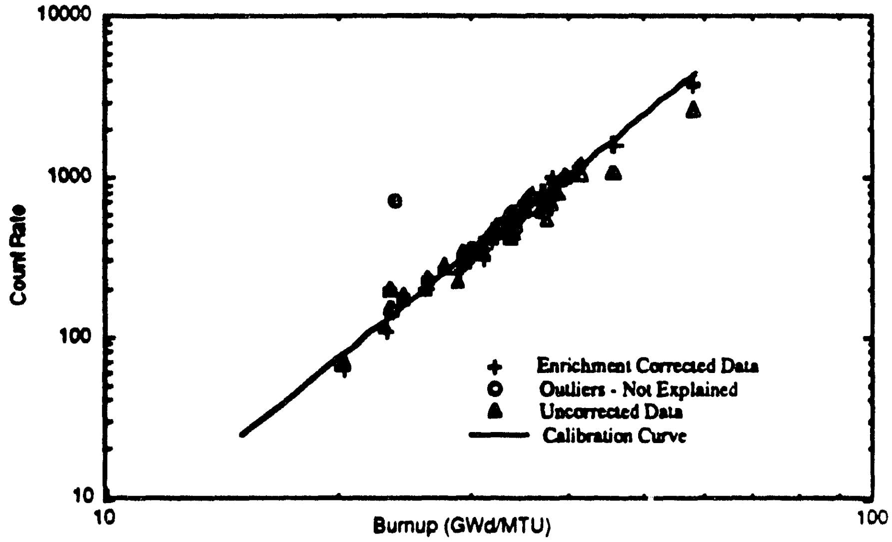

Figure 4. Neutron Data and Calibration

(reactor record) for each assembly. The data are shown with and without a correction for the initial enrichment of the assemblies. The "uncorrected data" (uncorrected for initial enrichment, but extrapolated to the date of discharge using an 18-year half-life) for 91 assembly measurements can be fit by a power law curve determined by a least-squares fit such that the average absolute deviation in burnup is about 10%. This would be the best fit to the data if the initial enrichments were unknown. A factor to adjust the observed count rates for the variation in initial enrichment among the assemblies was calculated as described above. For the Oconee data, the enrichment correction factors (applied to the neutron count rate) varied from 0.93 to 1.53.

The "Enrichment Corrected Data" are fit by the calibration curve shown in Figure 4, for which the analytical expression derived from a least squares fit to the data is

$$N = C \cdot B^{3.81} \quad \text{(Eq. 1)}$$

where N is the corrected neutron count rate in counts per second, B is the burnup in GWd/MTU, and C is a fitted constant whose value is 0.000788. The neutron signal is proportional to the 3.81 power of the burnup. This value is consistent with the values observed in earlier operations with the FORK system [Ref. 3]. With the enrichment correction applied, the data have an average absolute deviation in burnup from the calibration curve of about 2.2%. Among the 91 assemblies, only one assembly deviated by more than 6%. This indicates remarkable consistency of the reactor records, since the standard statistical deviation of the measurement is about 1% and the reactor calculations of assembly burnup have an expected accuracy of about 2%.

The two data points marked "Outliers - Not Explained" in Figure 4 indicate two assemblies that exhibited much higher neutron signals than expected from the burnup records. These two data were not included in fitting the calibration curve. Both sets of neutron detectors indicated anomalous data for these two assemblies, but the corresponding gamma signals were not anomalous. The anomalies were noted at the time of measurement and the assemblies were remeasured with unchanged results. Subsequent examination of the reactor records and histories for these assemblies revealed that the two anomalous assemblies contained primary neutron sources for a substantial part of their early history in the reactor. Two assemblies with the same reactor history that were located symmetrically in the reactor to the two anomalous assemblies were also measured and did not indicate an anomalous neutron output. The symmetrically located assemblies did not contain neutron sources at any time. A complete explanation is still being investigated, but at this time, one plausible explanation is that the neutron sources produced interactions that resulted in an additional neutron source, perhaps curium, in the portion of the assembly sampled by the detector, without causing fissions throughout the assembly that would have increased the gamma-ray signal.

The gamma-ray data for the Oconee measurements are plotted in Figure 5, in which the gamma-ray current reading divided by the assembly burnup is plotted versus the cooling

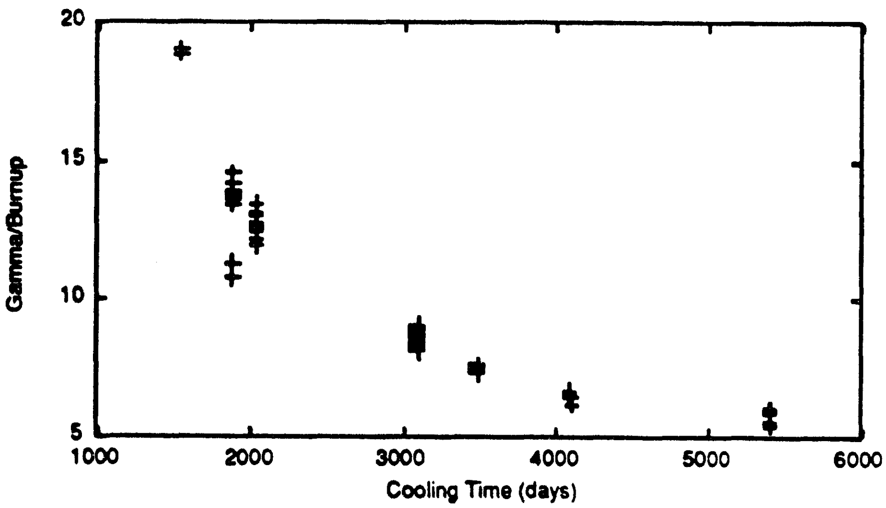

Figure 5. Gamma-Ray Data

time. If the assumption is valid that the gamma-ray signal is proportional to burnup, then for each value of cooling time there will be a singlevalue of current/burnup. The average deviation from the mean value at each cooling time is about 15%. The batch discharge of spent fuel assemblies is evident in this plot from the clustering of data at certain cooling times.

PROPOSED BURNUP VERIFICATION OPERATION

Experience with burnup verification using the FORK detector indicates that the most effective procedure would be to measure a large number of assemblies in a single campaign in advance of loading operations. The utilities have suggested that perhaps all the assemblies to be loaded in one year (perhaps 50 to 100) would be an efficient number of assemblies to measure in a verification campaign. This number of assemblies would ensure a statistically adequate calibration to provide a sensitive analysis of the reactor records. Anomalous results, if any, could be analyzed and possibly resolved at the conclusion of the measurement campaign, prior to loading operations. Access to qualified assemblies would be administratively controlled until the loading operation begins. An example of one possibility of administrative control would be the physical segregation of qualified assemblies (or perhaps the unqualified, anomalous assemblies) in a special section of the spent fuel pool. Special tagging of qualified assemblies is another option. The loading operation could then proceed efficiently without interruption for measurements and decisions. If measurements were performed on individual assemblies during the loading of a container, the measurement could potentially interfere with loading operations and increase risks of accident or radiation exposure. The verification campaign could be performed by a certified team or vendor, rather than commit utility resources and personnel to an additional training, certification, and maintenance program specifically to perform the measurements.

RESOLUTION OF ANOMALIES

If an anomalous measurement, that is, one that indicates a 10% or greater discrepancy between the reactor record burnup and the calibration function, is detected in the epithermal neutron data, the measurement will be repeated. If the discrepancy still exists, the thermal neutron data will be analyzed and compared to the epithermal data. If both sets of neutron data show an anomalous result, the gamma-ray measurements will be analyzed. If the reason for the anomaly is not apparent, a partial axial scan of the anomalous assembly will be obtained by taking data at four or more axial locations along the upper half of the assembly to determine if the axial profile is also anomalous (that is, not within the norms for that assembly design). If an anomalous profile is detected, additional axial measurements will be performed on the lower half of the assembly. Visual identification of serial numbers may also be employed to resolve anomalous results by checking for a misidentification of an assembly. Anomalous assemblies will be analyzed at the conclusion of the measurement campaign and will be considered unqualified for loading unless a satisfactory explanation for the anomaly can be determined from the data.

QUALIFICATION OF ASSEMBLIES FOR LOADING

Assemblies for which the measurement indicates a deviation from the calibration of less than 10% will be considered qualified for loading if the reactor record for burnup is greater than the burnup credit required for that assembly (determined by the initial enrichment and the burnup loading curve for the container). With proper administrative control, these assemblies can be loaded into qualified containers in a loading operation without further measurement.

CONCLUSION

The FORK measurement system can increase confidence in nuclear criticality safety in the loading of burnup credit containers by verifying consistency of reactor records and by detecting discrepancies between reactor records and the radiation emitted from spent fuel assemblies. It can be employed most effectively in a verification campaign involving 50 to 100 assemblies prior to loading operations.

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collaborated in the Oconee measurements. Duke Power Company made its facilities and personnel available in support of the measurements.

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