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BURNUP VERIFICATION MEASUREMENTS ON SPENT FUEL ASSEMBLIES AT ARKANSAS NUCLEAR ONE

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ABSTRACT

Burnup verification measurements have been performed using the Fork system at Arkansas Nuclear One, Units 1 and 2, operated by Entergy Operations, Inc. Passive neutron and gamma-ray measurements on individual spent fuel assemblies were correlated with the reactor records for burnup, cooling time, and initial enrichment. The correlation generates an internal calibration for the system in the form of a power law determined by a least squares fit to the neutron data. The values of the exponent in the power laws were 3.83 and 4.35 for Units 1 and 2, respectively. The average deviation of the reactor burnup records from the calibration determined from the measurements is a measure of the random error in the burnup records. The observed average deviations were 2.7% and 3.5% for assemblies at Units 1 and 2, respectively, indicating a high degree of consistency in the reactor records. Two non-standard assemblies containing neutron sources were studied at Unit 2. No anomalous measurements were observed among the standard assemblies at either Unit. The effectiveness of the Fork system for verification of reactor records is due to the sensitivity of the neutron yield to burnup, the self-calibration generated by a series of measurements, the redundancy provided by three independent detection systems, and the operational simplicity and flexibility of the design.

INTRODUCTION

The need for burnup verification arises from the incorporation of burnup credit concepts in the design of storage and transport systems for spent nuclear fuel. By taking into account the reduced reactivity of spent fuel in calculations of nuclear criticality, burnup credit results in more efficient and economic transport and storage. To ensure criticality safety, burnup credit cask designs restrict assemblies acceptable for loading according to burnup and initial enrichment. Verification measurements may be used to qualify assemblies for loading into casks designed using burnup credit. The Fork measurement system has been used for many years to examine spent reactor fuel as part of the International Atomic Energy Agency's Safeguards program. The objective of the test program described here is to demonstrate the utility of the Fork system in verifying the burnup records at U.S. nuclear utilities.

BURNUP

The thermal output of a reactor is determined from temperature and flow measurements of the cooling water circulating in the reactor. The time integral of the thermal power (Gigawatt days, GWd) produced by the reactor is the basis of the burnup assignment to individual assemblies. In-core radiation measurements located throughout the reactor core are used to distribute the GWd to each assembly through a distribution function provided by the manufacturer of the reactor. The distribution function assigns a fraction of the total GWd to each assembly based on the in-core measurements and the history of the assembly. A common unit for assembly burnup is GWd/MTU, gigawatt days per metric ton of uranium metal in the assembly. Since the sum of the GWd of all assemblies must equal the total GWd of the

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reactor over any time span, if the burnup for one assembly is "high", another must be "low". The distribution function could possibly generate errors that can be characterized as random, because of the "zero-sum" aspect of the errors. The most likely source of a possible systematic error, one that applies to all assemblies, is the integral of the power output of the reactor, which is measured very accurately (uncertainty about 2%). A relative burnup measurement performed on a group of assemblies can determine the extent of the variations generated by the burnup distribution function among the assemblies, and indicate any assembly whose radiation output is inconsistent with its record for burnup.

Radiation measurements on spent fuel can be used to verify the burnup assigned to the assembly by correlating the emitted radiation with the burnup experienced by the assembly while it was in the operating reactor. In the application of nuclear criticality safety to the transport and storage of spent fuel from commercial nuclear reactors, the fuel assemblies of interest have been cooled for over five years, which simplifies the analysis of the emitted radiation, due to the decay of short half-life isotopes. After several years of cooling time the predominant neutron emitter is curium-244, which is formed by successive neutron capture beginning with uranium-238. The production of curium-244 is found to increase with about the fourth power of the burnup. The neutron emission is therefore very sensitive to variations in burnup. Cesium-137, the major gamma emitter after five years of cooling, is produced as a fission product. Its production is essentially a linear function of burnup.

FORK SYSTEM

The Fork system is designed to determine the extent of the variation among assembly burnups, and to identify any anomalous values. Measurements of the neutron and gamma-ray emissions from individual spent-fuel assemblies are taken while the assembly is in the storage pool. The Fork system was designed at Los Alamos National Laboratory for the International Atomic Energy Agency (IAEA) to verify reactor records for safeguard applications. The results of those measurements are summarized, and publications cited, in Reference 1.

The approach used in the analysis of the data is to accumulate measurements from a number of assemblies and generate an internal calibration by comparing each assembly to the best derived fit to all the data. This self-calibration eliminates the uncertainties and complications that are introduced by external calibration techniques, while retaining the sensitivity to detect measurements that are inconsistent with the reactor records. The analysis of the Fork data makes use of the reactor records for cooling time, burnup, and initial enrichment in such a way that errors in any of these parameters for a given assembly is likely to increase the deviation from the calibration. The observed deviations incorporate the uncertainties in the measurements (about 2% with corrections) as well as any errors in the reactor records. The average deviations are therefore likely to be upper bounds on the random errors in the reactor records for assembly burnup.

The Fork detector head is designed with two detector-containing arms that contact opposite sides of the fuel assembly. Each of the arms 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 which serves to absorb thermal energy neutrons. The other fission chamber, outside the cadmium cover, is sensitive to thermal neutrons. The polyethylene cylinders containing the epithermal detectors are inserted into a polyethylene outer cover. The epithermal detectors provide the primary data used in the Fork technique. The thermal detectors serve as a backup measurement. The gamma-ray measurements are used as additional backup and for the analysis of anomalous neutron data. Because the gamma-ray data are less sensitive to variations in burnup, they confirm burnup with an uncertainty of about 15%.

The system is diagrammed in an operational arrangement in Figure 1. The detector is moved in the storage pool to the location of the spent-fuel assembly that is to be examined. The assembly is raised in the rack until the measuring point (usually the center plane of the assembly) is located at the detector head. The assembly is not raised completely out of the rack. The detector head is moved into contact with the assembly, and the neutron and gamma-ray data are collected for approximately 100 seconds. A battery-powered electronics unit and microprocessor are used to supply all power to the detectors, collect and analyze the detector outputs, and perform necessary calculations and documentation. To correct the observed data for the variation in cooling times among the assemblies, the neutron data (after background subtraction) are extrapolated back to the date of discharge of each assembly using an exponential factor with a half-life of 18 years, the half-life of the principal neutron emitter, curium-244. A factor to adjust the observed count rates for the variation in initial enrichment among the assemblies is calculated using the reactor records for the initial enrichment and burnup for each assembly as described in detail in the Appendix B of Reference 2. This correction is required because curium-244, which produces the neutrons, is produced by activation of uranium-238, and is determined by the reactor flux rather than the fission rate.

ARKANSAS NUCLEAR ONE-UNIT 1

Arkansas Nuclear One is a two-unit generating site located at Russellville, Arkansas. Unit 1 utilizes a Babcock and Wilcox 2568 MW (thermal) pressurized water reactor currently fueled with 177 Mark B8 fuel assemblies. The assembly design is a 15 x 15 array that contains 208 fuel rods and 16 guide tubes. The cross section of the assembly is 8.54 X 8.54 inches, and overall length is 165.6 inches. The nominal uranium weight is 464 kilograms per assembly.

Thirty-four assemblies were measured with the Fork system in one and one half working days of operation. The initial enrichment of the assemblies ranged from 2.016 to 3.209 weight percent uranium-235. The range in assembly average burnup was from 19.9 to 57.3 GWd/MTU. The cooling times varied from 6.1 to 17.6 years. Background counts were generally less than 1% of the signal from the assembly.

The neutron count rates in the epithermal neutron detector (corrected by the cooling time and enrichment corrections described above) are shown in Figure 2, a log-log plot of neutron signal versus burnup (reactor record) for each assembly. The calibration curve shown in Figure 2 is the power law best fit (least squares) to the data, and is given by:

$$N = C \bullet B^{3.83}$$

where N is the neutron count rate in counts per second, B is the burnup in GWd/MTU, and C is a fitted constant whose value is 0.00100. The neutron signal is proportional to the 3.83 power of the burnup. This value agrees closely with the value, 3.81, for this parameter observed in earlier measurements in the essentially identical assemblies at Oconee Nuclear Station [Ref. 2]. The observed average absolute deviation in burnup from the calibration curve is 2.7%. The maximum deviation observed for a single assembly was 9.1%. At Oconee Nuclear Station, the average deviation was 2.2% for ninety-one assemblies, and the maximum deviation was 8.9%.

ARKANSAS NUCLEAR ONE-UNIT 2

Unit 2 of Arkansas Nuclear One utilizes a Combustion Engineering pressurized water reactor rated at 2815 MW (thermal) that is currently fueled with 177 fuel assemblies. The assembly design is a 16 x 16 array that contains 5 guide tubes. The assembly cross section is slightly less than 8 X 8 inches, and overall length is approximately 177 inches. The active portion of each fuel rod is 150 inches overall, and contains 2114 grams of uranium metal. An additional feature of the assemblies of Unit 2 is the use of rods of two different initial enrichments in assemblies received after 1983. Eight rods of slightly lower enrichment surrounded each of the five guide tubes, and three such rods were located at each corner of the assembly. For the analysis of this data the average enrichment for each assembly was used.

Measurements were performed on thirty-nine standard assemblies that had cooled longer than 3.8 years, and two non-standard assemblies of about two years cooling time that contained small neutron sources (plutonium-berylliuum). Measurements were performed at several locations along the vertical axis of the assembly on one standard assembly and on both of the non-standard assemblies to determine the location and effect of the neutron sources. The non-standard assemblies were not included in the burnup curve fitting analysis. The average initial enrichment of the assemblies ranged from 1.9 to 3.9 weight percent uranium-235. The range in assembly average burnup was 12.3 to 50.7 GWd/MTU. The cooling times varied from 3.8 to 13.7 years. The analysis of the data followed the approach described in Ewing above. The calibration curve is given by:

$$N = C \bullet B^{4.35}$$

where N is the neutron count rate in counts per second, B is the burnup in GWd/MTU, and C is a fitted constant whose value is 0.000145. The neutron signal is proportional to the 4.35 power of the burnup. The observed average absolute deviation in burnup from the calibration curve is 3.5%. The maximum deviation observed for a single assembly was 8.6%. The neutron sources in the non-standard assemblies were detected by a rise in signal in the neutron detectors of 25 to 40% near the midpoint of the assemblies, at the location of the sources.

CONCLUSIONS

The Fork system proved to be compatible with utility operations and equipment at both reactors, and the measurements correlated well with the reactor records. The correlation of the burnup records with the emitted neutrons indicated average deviations of 2.7% and 3.5% in burnup. The maximum deviation for a single assembly was less than 10%. The effect of the different assembly designs in the reactors is shown by the functional dependence of the neutron emission on burnup. For the Babcock and Wilcox assemblies at Oconee Nuclear Station and at Arkansas Nuclear One-Unit 1 the neutron signal increased as the 3.8 power of the burnup. For the Combustion Engineering assemblies at Arkansas Nuclear One-Unit 2 the neutron signal increased as the 4.35 power of the burnup. These results suggest that the burnup dependence of the neutron signal may be specific to each assembly design. A variation in the burnup exponent has been noted in IAEA measurements with the Fork system [Ref. 1]. This variation is probably due to details in the assembly design and reactor operating parameters among the different reactor designs. The neutron sources in the two non-standard assemblies at Arkansas Nuclear One-Unit 2, were detected by a rise in the neutron count rate of 25 to 40 %. This effect may account for the anomalous results observed in two assemblies at Oconee Nuclear Station [Ref. 2]. The two anomalous assemblies had been cooling for about 15 years, which would emphasize the relative effect of small neutron sources due to the decay of curium-244. The effectiveness of the Fork system for verification of reactor records is due to the sensitivity of the neutron yield to burnup, the self-calibration generated by a series of measurements, the redundancy provided by three independent detection systems, and the operational simplicity and flexibility of the design.

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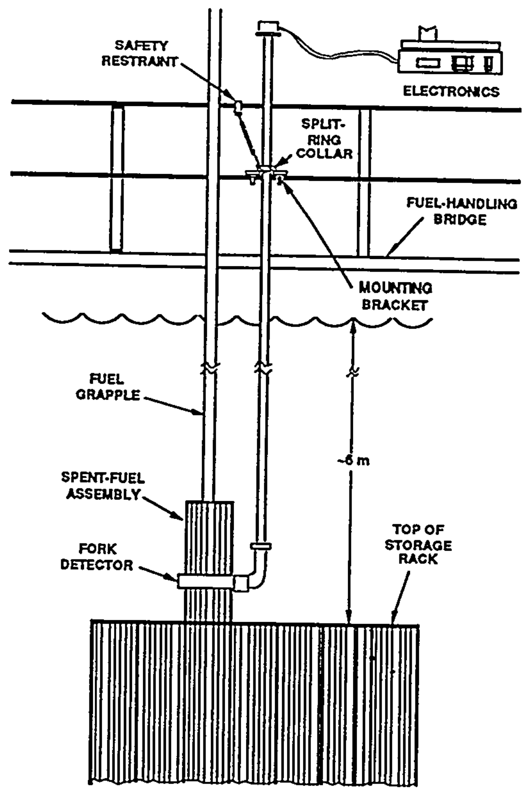

Figure 1.FORK System Arrangement in Spent Fuel Pool

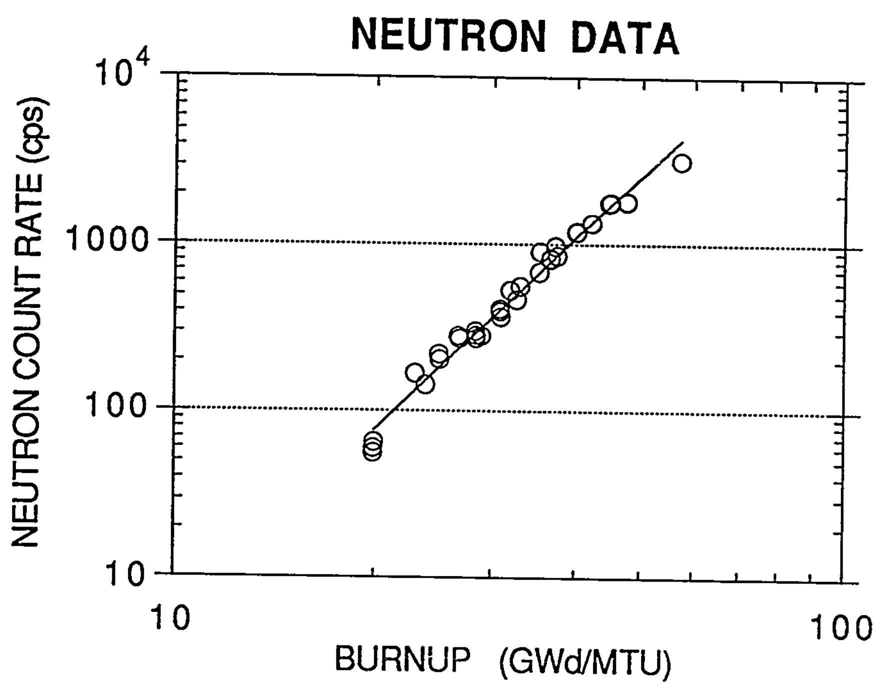

Figure 2 Neutron Data and Calibration, ANO-1