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Application of a Burnup Verification Meter to Actinide-Only Burnup Credit for Spent PWR Fuel

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INTRODUCTION

A measurement system to verify reactor records for burnup of spent fuel at pressurized water reactors (PWR) has been developed by Sandia National Laboratories and tested at U.S. nuclear utility sites. The system makes use of the Fork detector designed at Los Alamos National Laboratory for the safeguards program of the International Atomic Energy Agency. A single-point measurement of the neutrons and gamma-rays emitted from a PWR assembly is made at the center plane of the assembly while it is partially raised from its rack in the spent fuel pool. The objective of the measurements is to determine the variation in burnup assignments among a group of assemblies, and to identify anomalous assemblies that might adversely affect nuclear criticality safety. The measurements also provide an internal consistency check for reactor records of cooling time and initial enrichment. The burnup verification system has been proposed for qualifying spent fuel assemblies for loading into containers designed using burnup credit techniques. The system is incorporated in the U.S. Department of Energy's "Topical Report on Actinide-Only Burnup Credit for PWR Spent Nuclear Fuel Packages" [DOE/RW 1995].

BURNUP CREDIT

The need for burnup verification arises from the incorporation of burnup credit principles in the design of storage and transport systems for spent nuclear fuel. For regulatory purposes, calculations of nuclear criticality safety traditionally have assumed that the fuel is unburned (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 (Sanders, et al. 1987). 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.

Actinide-only burnup credit is a form of partial burnup credit that accounts for the changes in actinide isotopes due to exposure in the reactor, but ignores the reduction in reactivity caused by fission products that are efficient neutron absorbers. The isotopes that are considered in actinide-only burnup credit (DOE/RW 1995) are: uranium (234,235,236,238); plutonium (238,239,240,241,242); and americium (241). As the uranium-235 is depleted during reactor operation the reactivity of the assembly is reduced. The fissile plutonium isotopes (239 and 241) are produced during reactor operation and increase reactivity. The remaining isotopes are neutron absorbers and reduce reactivity.

The application of burnup credit calculations to the nuclear criticality safety of a package for spent reactor fuel results in a loading curve that relates minimum acceptable burnup to the initial enrichment of the assembly. The loading curve is specific to a particular packaging design. For the purpose of illustration, a hypothetical loading curve is shown in Figure 1. The margin of safety is increased by raising the curve, i.e., increasing the minimum burnup required for each initial enrichment. Standard practice requires that the minimum burnup would limit the neutron multiplication (k_{eff}) of the loaded container to less than 0.95 of critical, even if the package (which is sealed dry, vastly reducing reactivity) were to be flooded with pure water. In the proposed application of actinide-only burnup credit (DOE/RW 1995) the curve is raised by an additional 5% in burnup to account for possible inaccuracies in the reactor records. The margin of safety is further increased by the omission of fission product neutron absorbers, which are known to be present , and which reduce reactivity for each burnup calculation. The reactor records for burnup can be used to qualify assemblies for loading into the package for which the loading curve was developed. Actinide-only burnup credit results in significant efficiencies and economies, while reducing the dependence of nuclear criticality safety on the accuracy of the burnup value for each assembly.

ROLE OF MEASUREMENTS

A verification measurement prior to loading assemblies into a burnup credit container can be used to ensure that the reactor records are accurate and that each assembly has been properly identified. The measurement can ensure that only those assemblies that meet the minimum burnup criteria are qualified for loading. The accuracy of the verification becomes significant only for those assemblies whose burnup values are slightly above the loading curve, essentially within the uncertainty of the verification. The requirements of the measurement technique are determined by the method for assigning the assembly burnup used to generate the reactor record. The absolute value of the burnup is determined by measuring and integrating the thermal output of the reactor, which is measured with an uncertainty of less than 2%. In-core radiation measurements located throughout the reactor core are used to distribute the burnup to each assembly. The distribution function is expected to generate variations from assembly to assembly that can be characterized as random, because of the "zero-sum" aspect of the variations. If the burnup for one assembly is "high", another must be "low", since the total must equal the burnup experienced in the reactor during the cycle. 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.

In the case of actinide-only burnup credit, the dependence of the criticality safety margin on the uncertainty of the assembly burnup is reduced. As a result, a relative neutron measurement that is extremely sensitive to variations in burnup can provide adequate support for nuclear criticality safety calculations .

FORK SYSTEM

The Fork system is designed to sensitively determine the extent of the variation among assembly burnups, and to identify any anomalous values. 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 (Bosler and Rinard 1991).

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.

The system is diagrammed in an operational arrangement in Figure 2. 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 (at or near 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 of (Ewing, et al. 1994). 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.

The approach used in the analysis of the data is to accumulate relative measurements from a number of assemblies and generate an internal calibration by comparing each assembly to the best derived fit to all the data. The deviations in burnup from the derived calibration are calculated for each assembly and compared to the average deviation for the group of assemblies, to determine if any significant discrepancies exist. 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 is likely to increase the deviation from the calibration. The observed deviations incorporate the uncertainties in the measurements and correction factors as well as any errors in the reactor records. The observed average deviations are therefore upper bounds on the random variations in the reactor records for assembly burnup.

APPLICATION TO BURNUP CREDIT

The objective of the burnup verification measurement is to qualify individual assemblies for loading into a burnup credit container by verifying that each assembly meets the minimum burnup criteria for the container. Prior to the loading operation, candidate assemblies that meet the criteria specified by the loading curve are selected using the reactor records. A group of candidate assemblies (generally thirty or more) are then measured to determine the calibration function, the average deviation for the group, and the deviation for each assembly. Assemblies for which the deviation is considered exceptional (such as three standard deviations) would be set aside as unacceptable, pending further investigations (such as the relation to the loading curve). Assemblies that meet the acceptable criteria are then segregated in the spent fuel pool and administratively controlled until the loading procedure is carried out.

TEST RESULTS AT U.S. NUCLEAR UTILITIES

To demonstrate the application of the Fork system to burnup credit, the system was tested at two U.S. nuclear utilities: Duke Power's Oconee Nuclear Station (Ewing, et al. 1994), and the two reactors at Arkansas Nuclear One (ANO) (Ewing 1995), operated by Entergy, Inc. The tests were accomplished by a cooperative partnership directed by Sandia National

Laboratories involving Los Alamos National Laboratory, the Electric Power Research Institute, and the nuclear utilities. The Fork system proved to be compatible with utility operations and equipment, and the measurements correlated well with the utility records at all three reactors. The measured average deviation was 3.5% for 39 assemblies from the Combustion Engineering reactor at ANO. For the two Babcock & Wilcox reactors located at Oconee and at ANO, respectively, the average deviations were 2.2% (91 assemblies) and 3.0% (34 assemblies). Four anomalous assemblies were detected. In each case, small neutron sources contained in the assemblies could account for the anomaly.

CONCLUSIONS

A measurement system employing the Fork detector has been shown to be well suited to verify assembly burnup for spent fuel containers making use of actinide-only burnup credit. The Fork system proved to be compatible with utility operations and equipment at three U.S. reactor sites, and the measurements correlated well with the reactor records. The sensitivity of the neutron measurements permits an accurate determination of the average deviation among a group of assemblies, and the detection of anomalous assemblies.

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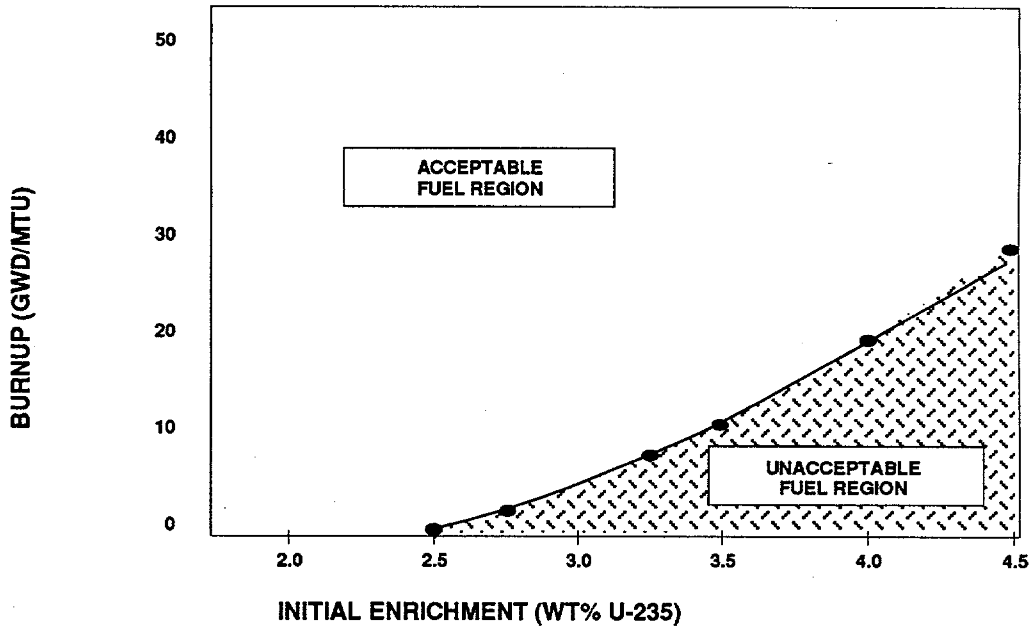

Figure 1. Hypothetical Loading Curve

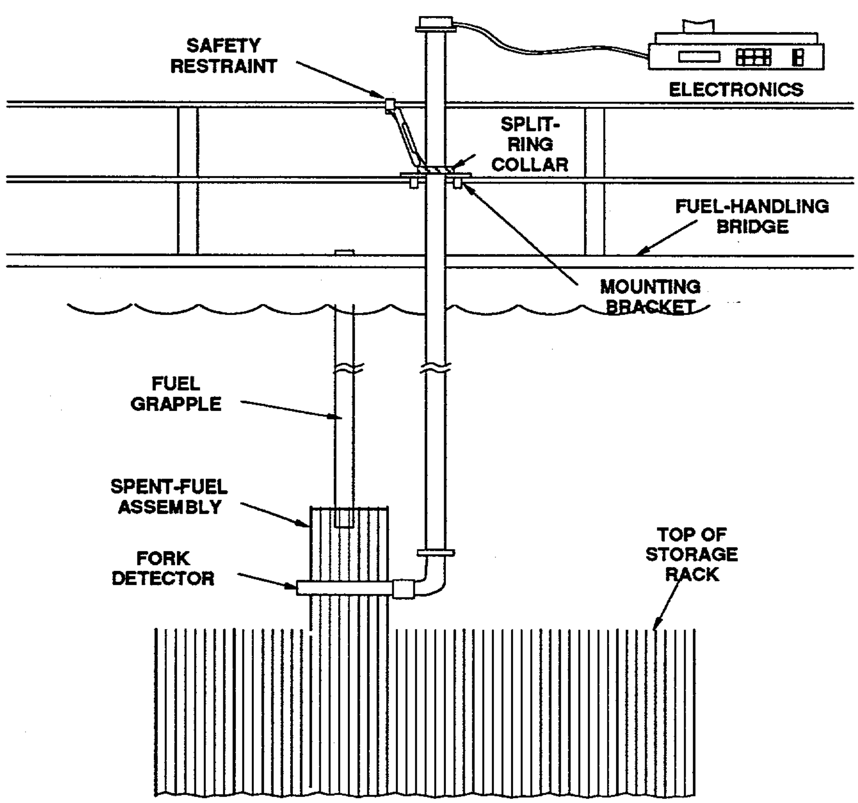

Figure 2. Fork Arrangement