Department of Energy
Washington, DC 20585

SEP 13 1993

Mr. Carl J. Paperiello, Director
Division of Industrial and Medical
Nuclear Safety
Office of Nuclear Material Safety
and Safeguards
U.S. Nuclear Regulatory Commission
Washington, DC 20555

Dear Mr. Paperiello:

Enclosed is a collection of reports and papers on the Fork detector and burnup credit that have been assembled for your information. As indicated in the U.S. Nuclear Regulatory Commission/U.S. Department of Energy meeting on August 27, 1993, the Fork detector will be used to verify the utilities records on the burnup of spent fuel. The Fork detector principle is based on the trend of the relationship between measured gross neutron count rate and the burnup provided by the utility. Any discrepancies in the utility records with respect to spent fuel burnup would appear as an anomaly in the neutron count rate/burnup relationship.

If you have any questions, please call William Lake at (202) 586-2840 or Priscilla Bunton at (202) 586-8365.

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Enclosures: On the Shelf; Filed in [illegible] 9309220319 930913 & 9309220321 930913

(1) Ron I. Ewing, G.E. Bosler, and Gary Walden, "Burnup Verification Measurements at a U.S. Nuclear Utility Using the Fork Measurement System," Institute of Nuclear Materials Management Annual Meeting, Scottsdale, Arizona, July 1993
(2) G.E. Bosler and P.M. Rinard, "Burnup Measurements with the Los Alamos Fork Detector," Institute of Nuclear Materials Management Annual Meeting, New Orleans, Louisiana, July 1991
(3) Phillip M. Rinard and Gerald E. Bosler, "BWR Spent-Fuel Measurements with the Ion-1/Fork Detector and a Calorimeter," LA-10758-MS, Los Alamos National Laboratory, 1986

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(4) P.M. Rinard and G.E. Bosler, "Safeguarding LWR Spent Fuel with the Fork Detector," LA-11096-MS, Los Alamos National Laboratory, 1988

(5) T.L. Sanders, K.D. Seager, and R.I. Ewing, "Overview of Burnup Credit Issues," Institute of Nuclear Materials Management Annual Meeting, Washington, D.C., January 1992

(6) Ronald I. Ewing, "Measurement Techniques for Verifying Burnup," Institute of Nuclear Materials Management Annual Meeting, Washington, D.C., January 1992

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(8) William H. Lake, "Strategies for Certifying a Burnup Credit Cask," Institute of Nuclear Materials Management Annual Meeting, Washington, D.C. January 1992

(9) Charles R. Marotta, M.C. Brady, D.G. Napolitano, "Effects of Axial Exposure Distributions in Burnup Credit Criticality Analyses," Institute of Nuclear Materials Management Annual Meeting, Washington, D.C., January 1992

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BURNUP VERIFICATION MEASUREMENTS AT A U.S. NUCLEAR UTILITY USING THE FORK MEASUREMENT SYSTEM

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INTRODUCTION

The FORK measurement system, designed at Los Alamos National Laboratory (LANL) for the International Atomic Energy Agency (IAEA) safeguards program, has been used to examine spent reactor fuel assemblies at Duke Power Company's Oconee Nuclear Station. The FORK system measures the passive neutron and gamma-ray emission from spent fuel assemblies while in the storage pool. These measurements can be correlated with burnup and cooling time, and can be used to verify the reactor site records. Verification measurements may be used to help ensure nuclear criticality safety when burnup credit is applied to spent fuel transport and storage systems. By taking into account the reduced reactivity of spent fuel due to its burnup in the reactor, burnup credit results in more efficient and economic transport and storage. The objectives of these tests are to demonstrate the applicability of the FORK system to verify reactor records and to develop optimal procedures compatible with utility operations. The test program is a cooperative effort supported by Sandia National Laboratories, the Electric Power Research Institute (EPRI), Los Alamos National Laboratory, and the Duke Power Company.

BURNUP

Burnup is a crucial parameter in fuel management and in calculations of nuclear criticality and residual fissile content. Burnup of the fuel is determined by monitoring the thermal output of the reactor, and is usually specified as the integrated thermal output per tonne of uranium (gigawatt days/metric ton of uranium). The average burnup for each assembly is determined with an accuracy of about 2% from in-core neutron measurements taken during reactor operations. The reactor site records of interest for each spent fuel assembly are the initial enrichment, the burnup, and the date of discharge from the core.

Studies have concluded that the reactor records are of higher precision and reliability than could be provided by post-discharge radiation measurements [Ref. 1]. The role of a burnup measurement after discharge is to demonstrate the consistency of the reactor records, to detect possible mis-identification of assemblies, and to detect anomalous assemblies that might affect safety or safeguards concerns.

FORK

The FORK measurement system, designed at Los Alamos National Laboratory, has been used for more than a decade by the International Atomic Energy Agency to verify reactor records by measuring neutron and gamma-ray emissions from spent fuel assemblies [Ref. 2]. This technique has proved to be adequate, and eliminates the need for more complex active or high-resolution measurement techniques [Ref. 3]. The system appears to be particularly well suited for application to spent fuel verification measurements at U.S. storage sites.

The system is diagrammed in its operational arrangement in Figure 1. The detector head is moved in the storage pool to the spent fuel assembly to be examined. The assembly is raised in the storage rack so that its midpoint is several feet above the top of the rack. The detector head is positioned at the midpoint of the assembly for the verification measurement. A burnup profile can be obtained by performing measurements at various locations along the length of the assembly.

Each arm of the FORK contains two fission chambers to measure the yield of neutrons and one ion chamber to measure gross gamma-ray emission. A battery-powered electronics unit is used to supply all power to the detectors, collect and analyze the detector outputs, and perform necessary calculations and documentation.

Analysis of the measurements is simplified by the fact that the fuel assemblies of immediate interest have been cooled for over five years, leaving only a few gamma and neutron sources.

ENCLOSURE I

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* A U.S. Department of Energy Facility, operated under contract DE-AC04-76DP00789.

The predominant neutron emitter is curium-244, which is formed by successive neutron capture beginning with uranium-238, and decays following discharge with a half-life of 18y. 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 The major gamma emitter is cesium-137, a fission product that decays with a half-life of 30y. The production of cesium-137 is essentially a linear function of burnup. The combination of the gamma and neutron measurements allows both the burnup and the cooling time of each assembly to be checked.

OCONEE SPENT FUEL

Oconee Nuclear Station is a three unit generating site utilizing Babcock and Wilcox 2568 MWt Pressurized Water Reactors. Duke Power Company began commercial operation on the site in 1973. The FORK measurements were performed in the spent fuel storage pool that is shared by Units 1 and 2. The demineralized water in the pool contained approximately 2000 ppm boron. There is about 25 feet of water above the top of the storage racks. During testing the fuel assemblies were lifted in the storage racks by means of an auxiliary hoist mounted on the Stearns-Roger fuel handling bridge. No assembly was completely removed from the rack. The spent fuel assemblies are a Babcock and Wilcox 15 X 15 design that accepts separate control components such as control rods, burnable poison rods, and neutron source rods. Each assembly contains 208 fuel rods and 16 guide tubes. The maximum cross section is 8.54 inches, and overall length is 165.6 inches. The nominal uranium weight is 464 kilograms.

PROCEDURES

The FORK detector was suspended from a moveable carriage on the fuel handling bridge over the spent fuel pool. The detector head was fixed at a location about six feet above the top of the storage rack in the spent fuel pool. Each selected assembly was raised in its rack until the detector was at the center point of the asssembly. The detector was placed in contact with the assembly, and data were accumulated for 100 seconds to ensure that more than 10,000 neutron counts were obtained. The ion chamber (gamma) current reaches its maximum value in about one second.

RESULTS

Ninety-three assemblies were measured in about 3.5 working days of operation. The initial enrichment of the assemblies ranged from 2.91 to 3.92 weight per cent uranium-235. The range in burnup was from 20.3 to 58.3 GWd/tU. The cooling times varied from 4.2 to 14.8y. Background data (no raised assembly) were taken each time the location of the detector was changed appreciably, and were found to be less than one percent of the signal with the assembly in place.

The observed data were extrapolated back to the date of discharge for each assembly. The gamma data fit an inverse time curve, and could also fit a 30y exponential decay (cesium-137). The gamma-ray data correlated with the reactor records for burnup ± 25%, with no significant anomalies.

The neutron data were extrapolated using an exponential decay of half-life 18y, the half-life of the principal neutron emitter, curium-244. The extrapolated neutron data are shown in Figure 2., a log-log plot of neutron signal vs. burnup (reactor record) for each assembly. The data are shown with and without a correction for the initial enrichment of the assemblies. The neutron signal depends on the initial enrichment since curium-244 is produced by activation rather than fission. The "uncorrected data" can be fit by a power law curve 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. An enrichment correction factor was derived for the IAEA application using the CINDER isotope production code benchmarked against destructive analysis of spent fuel from several reactors. The correction factor (applied to the neutron signal) varied from -7% to +40% for these data. The "Enrichment Corrected Data" are fit by the calibration curve shown, in which the neutron signal is proportional to the 3.81 power of the burnup. This value matches closely the values observed in earlier operations with the FORK system. With the enrichment correction applied, the data have an average absolute deviation in burnup from the calibration curve of about 2.5%.

The two data points marked "Outliers-not explained" indicate two assemblies that exhibited much higher neutron signals than expected from the burnup records. Both sets of neutron detectors indicated this anomalous result, but the gamma signals fell within the expected range. The anomalies were noted at the time of measurement and re-measured, but since the objective of this operation was to examine as many assemblies as possible, the two assemblies were not investigated further. For the purposes of this test it is adequate to determine that anomalous assemblies can be detected. The exact source of the anomalous signals has not yet been identified.

UTILITY COMMENTS

In general, the FORK detector performed quite well and proved relatively easy to set up and operate. It would provide an acceptable means for verifying burnup of fuel assemblies prior to loading into a burnup credit cask or canister. The preferred mode of operation would be to verify burnup of all the assemblies to be loaded in a specified time period in a single sustained campaign, and segregate the acceptable assemblies in a seperate section of the spent fuel pool until they are actually loaded. It would be preferable to have this campaign performed by a certified vendor, rather than to commit utility resources and personnel to a training, certification, and maintenance program. A number of specific recommendations concerning operations, interfaces, shielding, radiation protection, decontamination, etc., have been noted, and will be integrated with further tests of the FORK at utilities.

CONCLUSIONS

The FORK measurements correlated with the Oconee reactor records to a high degree of accuracy (2.5%). Two anomalous assemblies were detected that would require further study in a verification campaign. The system proved to be compatible with utility operations, and appears to be adequate to verify reactor records for assemblies to be loaded into burnup credit casks.

ACKNOWLEDGEMENTS

Richard Siebelist of LANL prepared the FORK equipment and participated in all the measurements. The authors appreciate the help of the staff at Oconee Nuclear Station and Duke Power Company in the training, planning, and execution of this operation. The essential support of EPRI is very much appreciated.

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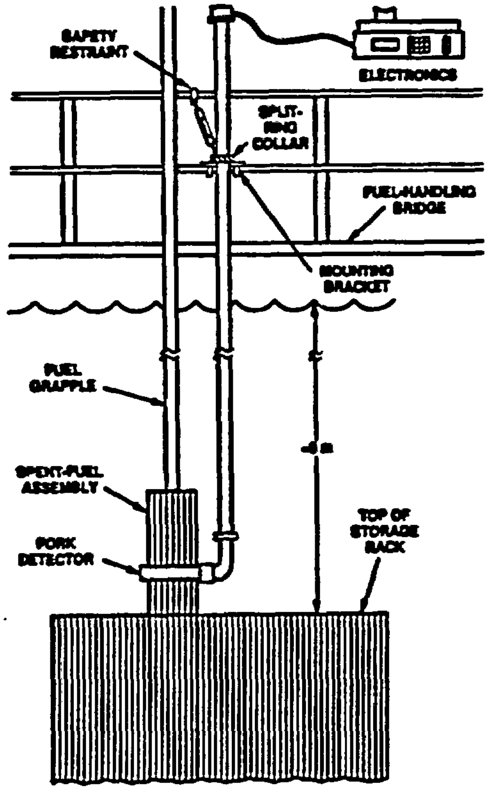

FIG. 1 FORK ARRANGEMENT

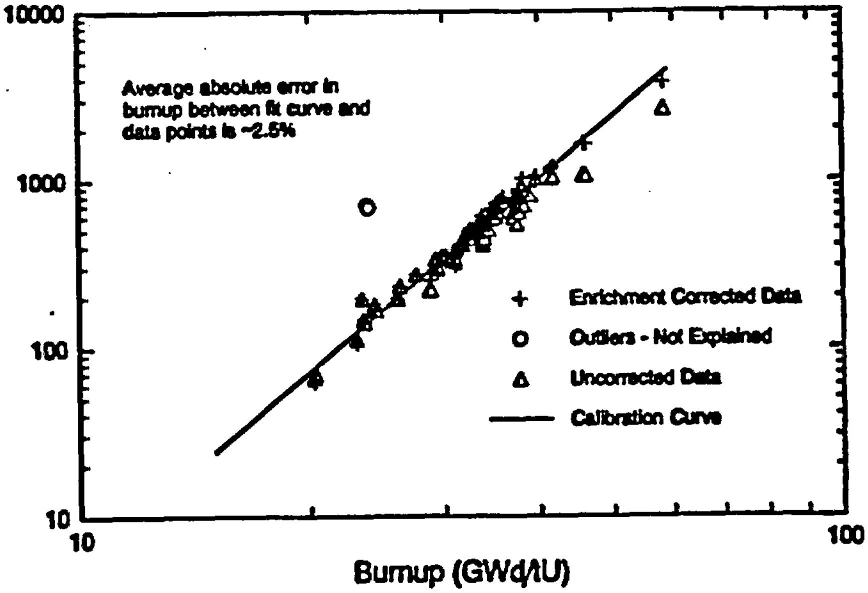

FIG. 2 NEUTRON SIGNAL VS. BURNUP

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BURNUP MEASUREMENTS WITH THE LOS ALAMOS FORK DETECTOR

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ENCLOSURE 2

BURNUP MEASUREMENTS WITH THE LOS ALAMOS FORK DETECTOR

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ABSTRACT

The fork detector system can determine the burnup of spent-fuel assemblies. It is a transportable instrument that can be mounted permanently in a spent-fuel pond near a loading area for shipping casks, or be attached to the storage pond bridge for measurements on partially raised spent-fuel assemblies.

The accuracy of the predicted burnup has been demonstrated to be as good as 2% from measurements on assemblies in the United States and other countries. Instruments have also been developed at other facilities throughout the world using the same or different techniques, but with similar accuracies.

INTRODUCTION

Ability to determine burnup of spent-fuel assemblies is important for storage, transportation, and safeguards purposes. The fork detector was developed at the Los Alamos National Laboratory for international safeguards applications to verify the burnup of assemblies stored underwater. The detector system was designed to minimize the impact on facility operators by requiring only minimal fuel movement to isolate the assembly being measured from other assemblies in the storage grid.

Instruments for measuring spent-fuel assemblies using passive neutron, passive gamma-ray, and active neutron methods have been developed at several laboratories throughout the world. Measurement systems using combinations of these various signals are designed for specific applications. The fork detector was designed to be transportable for use by international safeguards inspection agencies to obtain data from a large number of assemblies as quickly as possible. The fork uses passive neutron measurements for determining burnup and passive gamma-ray measurements for verifying cooling time.

The fork detector can be assembled and suspended from the bridge across a fuel pond in about 30 minutes. On the bridge, the fork is moved to the vicinity of an assembly to be measured. Measurements are made by placing the fork tines around an assembly, which has been lifted about two-thirds of the way out of the storage rack. Neutron and gamma-ray measurements are made for 30 to 60 s and the data can be immediately analyzed on a portable computer. An immediate remeasurement can be recommended if an anomaly is indicated.

In another application, the detector has also been mounted permanently on the wall of a storage pond between the main storage pool and the shipping-cask loading area. In this application, assemblies were brought to the detector for measurement as they were moved to shipping casks. The small detour and pause at the fork detector only slightly increased the total fuel handling time.

Accuracies of about 2% in the predicted burnups have been obtained with the fork detector from developmental measurements in spent-fuel ponds in the United States and Europe over the last several years.

THE FORK DETECTOR

Hardware

This spent-fuel instrument (Fig. 1) consists of a detector head in the shape of a two-tined fork, pipes, a portable, battery-powered electronics module, and an optional portable computer.[1]

Each tine of the fork contains two fissions chambers, one surrounded by a thin sheet of cadmium, plus an ion chamber. The ion chambers measure the gross gamma signal. Fission chambers are used for measuring neutron signals. The ratio of signals from the cadmium-wrapped and bare fission chambers can be used to estimate boron concentration in the pond water, should a verification of the concentration be desired. The cadmium-wrapped fission chambers in the two tines are used to gather the data for determining the burnup of the assembly. If boron concentration verification is not needed, measurements with the bare fission chambers can be omitted.

A battery-operated electronics module, called the GRAND-I, is used for the measurements. The GRAND-I is a commercial version of the ION-1 prototype which was designed and built at Los Alamos. The microprocessor-based GRAND-I provides high voltages to the detectors, simultaneously receives neutron and gamma signals from the detectors, collects data for a predetermined time, and stores the raw data and other pertinent information in internal memory for later retrieval.

A portable computer can be linked to the GRAND-I through an RS-232 serial port. The computer can control the GRAND-I and receive and analyze the data immediately after a count is completed and before the assembly is lowered into the storage rack. If the data analysis done by the computer reveals a possible anomaly, the user is advised to repeat the measurement at the same location or another location along the assembly's length.

Data Analysis

Burnup is determined from the measured neutron count rate through correlations between burnup and the buildup of ^{244}Cm, the principal neutron producing isotope in spent-fuel assemblies with burnups greater than 15 GWd/tU and cooling times longer than three years. For short cooling times and low burnups, other isotopes such as ^{242}Cm can also be an important neutron contributor. For these assemblies, the fractional contribution for isotopes other than ^{244}Cm can be calculated and used for determining the portion of the measured neutron count rate coming from ^{244}Cm. A computer code for calculating the contribution of various actinide isotopes to the total neutron source rate in a spent-fuel assembly

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*This work is supported by the US Department of Energy, Office of Safeguards and Security.

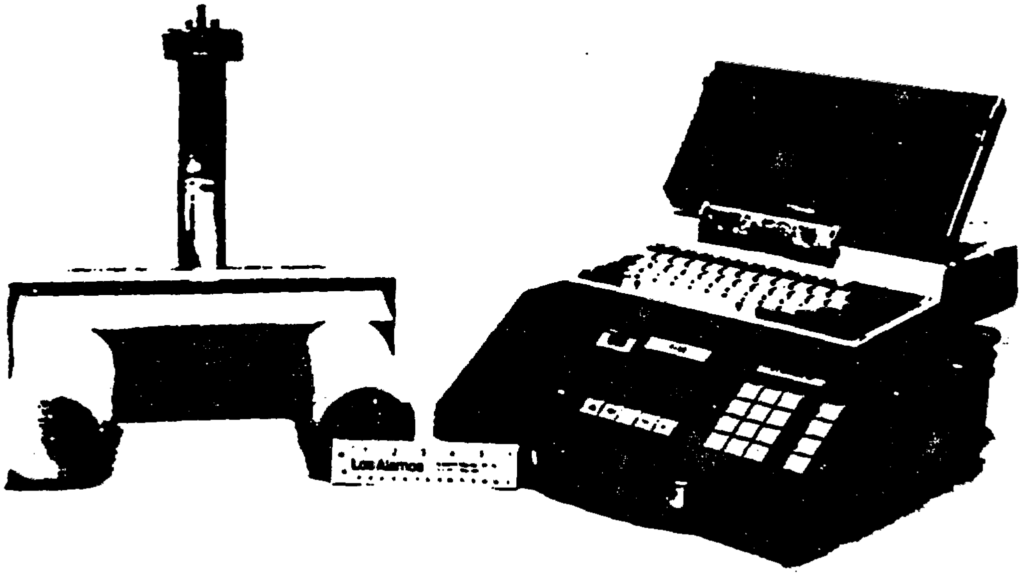

Fig. 1. The fork detector head on the left is suspended from a pipe when in use. The electrical cables between the head and the GRAND-I (bottom right) run through piping (not shown). The optional computer (on top of the GRAND-I) provides immediate feedback on the measurement being performed.

has been written for IBM-PC computers. Initial ^{235}U enrichment and power history information are provided as input to this code.

After the ^{244}Cm count rate is adjusted to the date of discharge, the adjusted count rate (*cr*) is proportional to the burnup (*BU*) raised to a power: $cr = \alpha BU^{\beta}$. The value of β depends on the assembly's geometry, the irradiation history, and other such factors present at a particular storage pond.[1,2]

The ion chambers in the fork measure all gamma rays from an assembly. For long-cooled assemblies, gamma signals are primarily from ^{137}Cs. During the first year of cooling, other significant gamma-ray emitters are present with ^{134}Cs being an important gamma contributor.

The ion chamber data (*IC*) allow verification of cooling time (*CT*) through another power law function, namely, $(IC/BU) = a\,CT^{-b}$, where the power b is a little less than one.[3] The slope of this curve approaches zero with time and thus is a useful estimator of cooling time only for about the first 10 years.

Software

If a portable computer is not attached to the GRAND-I during the measurements, the user controls the data-taking process through a keypad on the GRAND-I. The data are displayed on an LCD screen; printed on a small, built-in printer; and stored in the GRAND-I memory. These data can then be transferred to a computer at a later time through the RS-232 link.

With the computer present during the measurements, the user selects menu items from the computer's keyboard. Data from the GRAND-I are immediately processed by the computer and stored on disk. If a predicted burnup differs from the declared burnup by more than a factor set by the user, a message is given to that effect. A graph of all data and a calibration curve can be displayed on the computer.[1]

BURNUP MEASUREMENT EXPERIENCES

The fork detector has been used by Los Alamos personnel at five facilities in the United States, plus additional facilities in Germany, Belgium, Finland, Czechoslovakia, and Brazil in conjunction with the International Atomic Energy Agency (IAEA) and European Atomic Energy Community (EURATOM) Inspectorate. Most of the fuel studied has been for pressurized-water reactors (PWR), although two of the measurements in the United States were done on boiling-water reactor (BWR) fuel.

Almost all of the measurements were made with the fork mounted on a bridge and moved to partially raised assemblies. However, in one facility the fork was mounted on the wall of a pond for a year to measure assemblies being moved to long-term storage casks.[4]

Assessing the accuracy of the fork measurements is done by comparing the predicted burnups with the best operator values. The best available estimates of burnups are those calculated by operators, even though there are uncertainties in these calculated values. One of the biggest problems in determining burnup through such correlations is the lack of destructive data for establishing a data base and independent calibration.

Two sets of data are especially comprehensive and will be described in more detail than the other data sets.

Three Mile Island

A physical inventory verification exercise for IAEA inspectors was held at Three Mile Island Unit 1.[5] Two teams of inspectors worked independently. One team measured 60 PWR assemblies, the other team measured 38; 14 assemblies were common to both sets.

Burnups ranged from 13 to 32 GWd/tU. Cooling times ranged from 6 to 9 years. Assemblies with lower burnups generally had the longer cooling times. There were four initial enrichments from 2.06% to 3.05%.

The ^{242}Cm had decayed to insignificant amounts; therefore it was only necessary to adjust the data for the decay of ^{244}Cm to the date of discharge. No adjustments were made for assemblies with different enrichments; sets of assemblies with the same enrichment were analyzed separately. Average absolute percent differences between the operator's declared burnup data and the curves fitted to the measurement data are given in Table I along with standard deviations of the differences. (These are deduced from Tables X-XIII of Ref. 5.) It can be concluded that an overall accuracy of about 2% was obtained.

TABLE I. Three Mile Island Absolute Differences Between Declared and Measured Burnups

Initial Percent Enrichment	Average Percent Difference	Std Deviation of Percent Differences
2.06	2.74	1.28
2.64	0.74	0.46
2.75	2.00	1.53
3.05	1.79	1.20

The two teams of inspectors obtained the same count rates from the set of assemblies they measured in common to within a few percent (Table VIII of Ref. 5). The average absolute percent difference between the two sets of count rates was 2.38% with a standard deviation of 1.43%.

Tihange

Measurements at this Belgium PWR facility were made jointly by IAEA and EURATOM personnel, each using one of their own fork systems.[6] This was also the first application of calculated correction factors to obtain ^{244}Cm neutron count rates from the measured count rates.

Twenty assemblies with burnups from 9.661 to 41.167 GWd/tU were measured with each fork. Cooling times varied from 36 days to 8.6 years; the ^{244}Cm correction factors were especially important for the data from assemblies with shorter cooling times. These data and a fitted power-law curve are shown in Fig. 2.

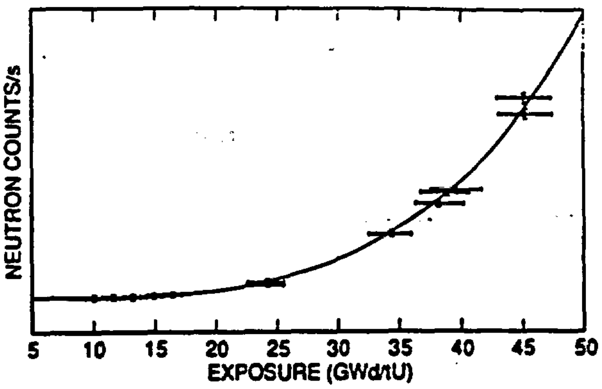

Fig. 2. The neutron count rates from assemblies at Tihange are plotted against the declared burnups. The fitted curve is $cr = 0.1121\, BU^{6.130}$.

Table II shows the average absolute differences between the measured burnups and the declared values for the IAEA and EURATOM forks individually. (These values were calculated from Table 11b in Ref. 6.) The two sets of data both show about a 2% accuracy.

TABLE II. Tihange Absolute Differences Between Declared and Measured Burnups

Fork	Average Percent Difference	Std Deviation of Percent Differences
IAEA	2.17	2.22
EURATOM	2.10	1.84

Other Fork Measurements

A EURATOM exercise[7] with a fork in Germany was made on many assemblies with short cooling times. Data from this exercise were not adjusted for a contribution from ^{242}Cm. For these data, the average absolute percent difference between measured and declared burnups was about 4.5% with a standard deviation of 3.5%.

Measurements in Finland[8] with a fork on assemblies with the same initial ^{235}U enrichment also were not corrected for ^{242}Cm. For these measurements, assemblies were grouped by cooling times and analyzed separately. Measurements on assemblies with 731 days of cooling had an average absolute percent difference from declared values of 1.3%; measurements on assemblies with 195 days of cooling had only a 0.9% difference.

COMPARISON WITH OTHER INSTRUMENTS

A burnup instrument called Python has been developed in France[9,10] with many features in common with the fork. Python has the same type of neutron detector tubes but is designed to rest on a storage rack into which assemblies are moved for measurement. The purpose of the instrument is to determine burnup of assemblies before they are loaded into shipping casks. With the Python, differences between predicted and declared burnups had a standard deviation of 4% in one exercise.

Python can also be used in an active-neutron interrogation mode by driving a ^{252}Cf source to one side of the assembly and counting neutrons with the detectors on the opposite side. This has the potential of measuring the remaining fuel directly, rather than correlating fuel characteristics with ^{244}Cm neutron emissions.

An active and passive instrument from Germany[11] also uses a ^{252}Cf source for the active portion. This instrument sits on the storage rack or is mounted on the pond's wall. The uncertainty of burnup measurement is given as 1.2 GWd/tU. This is an accuracy of 4% for an assembly with a burnup of 30 GWd/tU.

Burnup instruments applying high-resolution gamma spectral techniques have been produced. Results from Hungary[12] have an average absolute percent difference of 10.4% with a standard deviation of 1.9%. A Finnish[13] instrument built into a pond uses the ^{137}Cs gamma-ray activity as a burnup indicator; the average absolute percent difference for the Finnish data is about 3.2% with a standard deviation of 2.0%.

A French instrument[14] has been developed for a reprocessing plant to verify PWR and BWR fuel assemblies before dissolution. This instrument uses a combination of high-resolution gamma and neutron measurements to determine burnup, cooling time, and plutonium content. Burnup determined from gamma isotopic ratios agreed with operator declarations to within 7% or better. Plutonium mass determined from passive neutron measurements had differences of less than 1% compared to operator declarations and destructive analysis values.

SUMMARY

The accuracy of burnup determined from fork measurements during instrument development exercises has generally been about 2%. Other instruments using the same or different techniques have about the same accuracy or worse.

The fork has the following advantages: it is compact and transportable, it immediately gives feedback to the user, and it can be either mounted permanently on a pond's wall or attached to a bridge and moved to a stored assembly.

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