LA-UR -91-2508

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

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DE91 016316

SUBMITTED TO Institute of Nuclear Materials Management (INMM)
32nd Annual Meeting
New Orleans, Louisiana
July 28-31, 1991
(INVITED PAPER)

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FORM NO. 836 R4

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

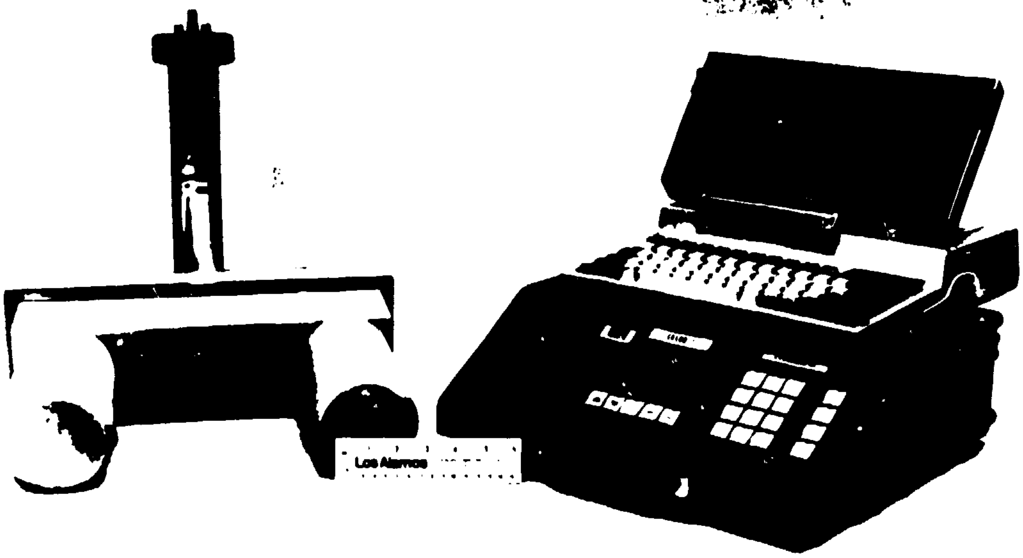

Fig. 1. The fork detector head on the left is suspended from a pipe when in use. The electrical cables between the head and the GRAND-I (bottom right) run through piping (not shown). The optional computer (on top of the GRAND-I) provides immediate feedback on the measurement being performed.

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.

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 IIb in Ref. 6.) The two sets of data both show about a 2% accuracy.

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%.

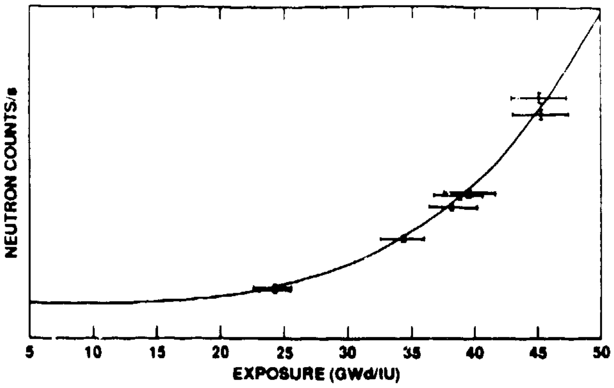

Fig. 2. The neutron count rates from assemblies at Tihange are plotted against the declared burnups. The fitted curve is cr = 0.1121 BU$^{6.130}$.

TABLE II. 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

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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