OPERATIONAL EXPERIENCE IN RADIOMETRIC INSTRUMENTATION FOR SPENT FUEL MONITORING

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ABSTRACT
As the global quantity of spent nuclear fuel steadily grows and the regulatory basis for the U.S spent fuel disposal program is developing, radiometric monitoring requirements are becoming increasingly important. Spent fuel measurements can be used for burn-up credit (for storage and transport), safeguards verification and radionuclide inventory quantification to meet disposal criteria. Verification measurements reduce reliance on operator data and ensure that the fuel is fully compliant with the prescribed envelope. Measurement assists in the confirmation of the identity of each assembly by verifying fuel history parameters. BNFL Instruments has developed a series of modular spent fuel monitoring systems. This series is based on systems that have been used to monitor more than one million fuel items at the UK's Sellafield reprocessing plant. The radiometric measurement techniques employed include high resolution gamma spectrometry, passive neutron measurements and active neutron measurements. This paper presents BNFL Instruments' global operational experience in spent fuel monitoring under wet and dry conditions. Systems have been deployed to verify the cooling time, burn-up and enrichment of fuel assemblies in dry fuel handling facilities and storage ponds. In the United States, at Arkansas Nuclear One (ANO), in-pool measurements were performed to provide burn-up credit prior to cask loading. Calibration, validation and operational experience with these systems is presented. Recommendations are given on the use of measurement systems to provide an acceptable level of confidence in the measurement result to allow these activities to take place safely and with the support of the regulators and the public.

INTRODUCTION
In the new regulatory environment surrounding disposal of spent nuclear fuel at Yucca Mountain, the requirements for radiometric measurements to support the safety of transport and storage are evolving. A number of non-destructive assay methods are available to measure spent fuel [1]. Based on a combination of gamma and neutron based assay techniques, a series of modular spent fuel monitoring systems have been developed by BNFL Instruments. These system have been deployed in the UK and USA in fuel storage and reprocessing facilities. Calibration, validation and operational experience with the systems is presented. The economic and safety benefits that are offered by fuel characterization are discussed in the context of regulatory requirements.

SPENT FUEL CHARACTERISATION REQUIREMENTS
(i) BURNUP CREDIT MEASUREMENTS
Taking account of the reduction in the reactivity of spent fuel which occurs during irradiation is known as burnup credit. Irradiation results in a net loss of fissile and fissionable nuclides together with the generation

of neutron poisons. Burnup credit offers a means of either increasing the packing density of fuel in storage racks and transport casks, or reducing the amount of costly neutron absorbers required in such containers. The conservative method of using the fresh (unirradiated) fuel reactivity in cask design, leads to unnecessarily over-engineered and expensive casks with limited packing density.

Burnup credit loading curves (based on fuel burnup and initial enrichment) provide a means of segregating fuel assemblies that do or do not meet the appropriate acceptance criteria for loading. Verification measurements will enhance the administrative control to ensure that fuel loaded into a cask is compliant. In addition, the measurement will assist in the confirmation of the identity of each assembly by verifying operator declared fuel history parameters.

It has been estimated that the potential cost savings in spent fuel transport that may be realized by burnup credit is between $200M to $1000M. Achieving fewer shipments will also reduce transportation risks. In addition more potential cost benefit may be yielded by pre-shipment assay eliminating the need for assay at the final repository to satisfy the evolving waste acceptance criteria. By analogy, assay at the point of shipment is in line with the current requirements for shipment of transuranic waste to WIPP.

(ii) SAFEGUARDS REQUIREMENTS

The need for rigorous control of the large quantities of fissile nuclides within the fuel is extremely important. In the United States, it is estimated that spent fuel assemblies will account for ~ 1000 metric tonnes of plutonium over the lifetime of the existing reactor fleet. Measurement and verification of fissile materials within spent fuel assemblies may be required. Verification measurements include methods such as the "partial defect" approach [2] developed for international safeguards inspection. This utilizes reactor core gate monitors (a package comprising an ion chamber, a fission chambers and ^{3}He tubes) to compare neutron emission rates of fuel assemblies as they are transferred between the core and the cooling pond.

Safeguards measurements would not only be of benefit to aid nonproliferation but could enhance the public acceptability of handling and transportation of fissile materials.

(iii) WASTE MONITORING REQUIREMENTS

Under present policies, a significant proportion of the world's commercial spent fuel is viewed as waste. In the United States, current policy is for the permanent disposal of spent fuel at a geological repository. Past experience with waste disposal regulations overseen by the DOE indicates that rigorous characterization of individual waste packages is a key requirement. For example, in order to dispose of relatively lightly contaminated transuranic waste at the WIPP facility in New Mexico, multiple characterization activities are required to be performed at the shipper's site [3]. Assay of each container of waste is required in order to quantify the specific alpha activity, determine the inventory of key radionuclides and confirm that the fissile content and thermal power of shipments are below regulatory limits. The regulations do not allow the sites to take full credit for regulatory compliance of previous characterization of their waste. Furthermore, for sites with well documented acceptable knowledge, such data may only be used provided that it is backed up with confirmatory measurements on each package.

In making the above analogy between spent fuel characterization and transuranic waste characterization it is important to realize two key differences that will drive the evolution of assay requirements for the former. Firstly due to the highly radioactive nature of spent fuel, the ALARA principle will restrict fuel handling activities to the minimum necessary to ensure safe transportation and storage. Secondly, operator records are generally far more reliable for spent fuel than for transuranic waste. For these reasons, only confirmatory measurements are more likely to be required on a sample of the shipment population.

For the more highly radioactive spent fuel waste, the waste acceptance criteria for the geological repository are still in early stages of their evolution [4,5 and 6]. It is possible that some form of assay may be required to confirm operator declared data, measure individual radionuclides and verify the fissile content of the assemblies prior to disposal. Measurements may also assist in the classification of fuel received at the repository surface facilities. Instrumentation could be required to operate in wet or dry conditions to verify fuel identity, confirm cooling time (for example in the UK Thorp reprocessing plant fuel cooling of > 5 years is required before reprocessing), and segregate fuel from non-fuel components (e.g burnable poison rod assemblies, control rod elements or assemblies containing neutron sources). Fuel that is categorized as “non-standard” or “failed” may require special handling, storage and disposal procedures or facilities.

SELECTION OF MEASUREMENT TECHNIQUES

One or more techniques may be selected for spent fuel monitoring in order to characterize the parameters of interest. The selected method must provide the required level of diversity in the characterization techniques employed and be capable of meeting and regulatory accuracy and precision criteria whilst achieving the operator required throughput rate. Other important factors to consider are the extent to which utility operator declared data may be used to assist in the processing of the measurement data, the level of access to the fuel and physical constraints on fuel movement.

BURNUP CHARACTERIZATION

Burnup is characterized by the measurement of key fuel parameters by non-destructive assay techniques such as gamma spectroscopy or passive neutron counting. Some of the major techniques used are described in Table 1.

TECHNIQUE	ADVANTAGES	DISADVANTAGES
Absolute count rate of the 662 keV gamma ray from ^{137}Cs..	👍 Simple linear relationship between ^{137}Cs and burnup. 👍 Half life of 30 years. 👍 Insensitive to variations in reactor power rating and dwell time.	👎 Absolute measurement requires a well defined and reproducible geometry between the detectors and the fuel assembly.
The nuclide activity ratio: ^{134}Cs/^{137}Cs.	👍 The ratio method makes it insensitive to geometry.	👎 2.2 year half life requires significant decay correction and can only be applied to fuel with cooling time < 20 years. 👎 Burnup correlation is dependent on initial enrichment and power rating.
The nuclide activity ratio: ^{106}Ru x ^{137}Cs/(^{134}Cs)^2 .	👍 Insensitive to geometry. 👍 Independent of enrichment and rating.	👎 Only useful for fuel < 9 years cooling time (^{106}Ru has a 372 day half life).
Passive neutron measurement (predominantly from ^{244}Cm).	👍 The neutron signals are received uniformly from all pins in the assembly (gamma measurements are only sensitive to the outer pins). 👍 Good for safeguards applications, as it is sensitive to missing or removed fuel pins.	👎 ^{244}Cm is a strong function of initial enrichment. 👎 Neutron assay is very geometry sensitive and can also be affected by multiplication and neutron poisons in the pool or within the assembly.

Table 1 Pros and cons of various burnup characterization techniques

CALIBRATION OF BURNUP MEASUREMENT SYSTEMS

Traditionally, systems that determine burnup are calibrated by measuring burnup indicators from a representative sample of fuel assemblies with well defined irradiation histories. This method has the benefit that the calibration assemblies have the same geometry as the fuel to be measured. Moreover, other fuel parameters such as cooling time can be determined independently to provide validation of the operator declared parameters for the reference assemblies.

There is interest, however, in using methods of calibration that are independent of operator declared data. One independent approach is to determine the correlation between the burnup indicators and burnup by the use of fuel inventory codes such as ORIGEN and FISPIN [7]. These codes, established for many years and validated by comparison with destructive analysis data [8], provide inventories of a wide range of fission products and actinides.

The key to the success of an independent approach is to select burnup indicators that can be calibrated by the use of the inventory codes and which can be measured reliably. There are several geometry insensitive gamma activity ratios that are good candidates for this approach, however these ratios have limited applicability for long cooled fuels and often have dependency on initial enrichment.

The most useful burnup indicator for fuel with a broad range of enrichment, burnup and cooling times is the absolute measurement of ^{137}Cs. The activity of this nuclide in spent fuel has been shown to be consistently predicted by the different inventory codes and validated by destructive analysis. If the measurement geometry and detection efficiency are well known and are reproducible, ^{137}Cs can be used to provide a calibration fully independent of operator irradiation history. The key is to ensure that no changes occur between the calibration conditions and the measurement conditions. A measurement procedure that uses this approach should, therefore, include suitable checks to eliminate the possibility of these systematic errors. Initial tests of this approach at a US utility gave a good correlation between measured and calculated ^{137}Cs count rate [10].

To provide diversity and increased confidence in a burnup instrument, a combination of the empirical/operator declared and independent computer code approaches to calibration may be used in a system. Consistency between the two calibrations provides mutual validation.

OPERATIONAL EXPERIENCE

A series of modular spent fuel monitoring systems have been developed by BNFL Instruments to meet the fuel characterization measurements requirements in a diverse range of applications. These instruments, can be installed in a pool as a wall fitted configuration, or as a mobile configuration to be operated over a fuel rack. The common system features are:

- Re-entrant tubes for insertion of detectors at variable monitoring positions.
- Gamma collimator between the fuel and the detector in a shielded housing.
- Optional neutron monitoring collar and neutron interrogation source.
- Built in self-checking to ensure high integrity measurements.

DRY FUEL MEASUREMENTS

(i) THE FUEL HANDLING PLANT COOLING TIME MONITOR

The Sellafield Fuel Handling Plant (FHP) receives spent metallic uranium fuel elements for reprocessing. An HRGS system [9] was installed in the plant to monitor the input fuel. The role of this system is to confirm that each fuel element fed to the plant is more than 150 days cooled. This ensures that the short lived ^{131}I has decayed to insignificant levels.

The HPGe detector is roof mounted, viewing the fuel elements through a collimator plug. Cooling time and burnup are determined using various fission product activity ratios. The fully automated system has been in operation at the facility for over 15 years.

(ii) SWARF INVENTORY MONITOR

The Swarf Inventory Monitor (SIM) uses HRGS to measure spent uranium fuel mass and the radionuclide inventory in spent fuel debris at the Sellafield FHP. In addition to providing inventory data to meet regulatory requirements, this system's software includes alarms that enable operators to identify large pieces of fuel within the waste. Retrieved pieces are re-routed to join the fuel stream for reprocessing. After measurement, the waste is exported to an adjacent encapsulation plant. The system performs the task of integrating the total inventory assigned to each exported waste bin. The amount of uranium carried with the waste is used as an entry in the site's special nuclear material account.

Burnup is determined from the $^{106}Ru \times {}^{137}Cs/({}^{134}Cs)^2$ ratio. Cooling time comes from $^{134}Cs/^{137}Cs$ ratio. Where detected, the activities of individual radionuclides are quantified from the HRGS measurement. In addition, the activities of non measurable radionuclides are determined by their FISPIN (ORIGEN) derived correlation to ^{137}Cs via the measured burnup and cooling time. Other features incorporated in the system algorithms include: background correction, an energy dependent relative gamma detection efficiency correction and a self-attenuation correction to account for the effect of different sizes of fuel debris.

The results of a performance assessment [9] have shown that for over a million fuel elements measured to date the accuracy of fuel mass determination as assigned to the exported swarf bins is in the range of ± 8% at one sigma.

WET FUEL MEASUREMENTS

(i) THORP FEED POND FUEL MONITORS

The Sellafield Thermal Oxide Reprocessing Plant (THORP), has two identical spent fuel instruments called the Feed Pond Fuel Monitors (FPFM) shown in Figure 1. These operate in parallel in order to meet the throughput requirements and measure a number of fuel parameters to ensure that only those fuel assemblies within prescribed limits are reprocessed. Thus the instrument provides a go/no-go signal indicating if the fuel is within the plant's acceptance envelope. The limiting parameters relate to the minimum cooling time and maximum burnup and final enrichment U-235 equivalent (originally initial enrichment) for both light water reactor (LWR) and advanced gas cooled reactor (AGR) fuel. The change from an initial enrichment parameter to final enrichment took place this year in conjunction with a reduction in neutron gadolinium poisoning of the dissolver vessel. The reduction was made possible by the adoption of a burnup credit fuel management regime. The vessel was originally poisoned on the assumption that the dissolved fuel was enriched to its initial enrichment rather than its final enrichment as recognized under the burnup credit revision. As a result the Gd usage has been reduced by approximately 50% giving considerable cost savings and benefits to the vitrified waste stream product quality.

The FPFMs each use a 15% efficiency HPGe detector, and five fission chamber neutron detectors that are split into two modules arranged at 90^o to each other. A neutron source transfer system, controlled by the FPFM, moves a ^{252}Cf source between exposed and shielded positions to allow active and passive neutron measurements. Prior to each assay, measurement control is implemented by an automated standardization routine. Once the fuel assembly has been transferred to the measurement position, assays are performed at four measurement heights as the fuel rotates.

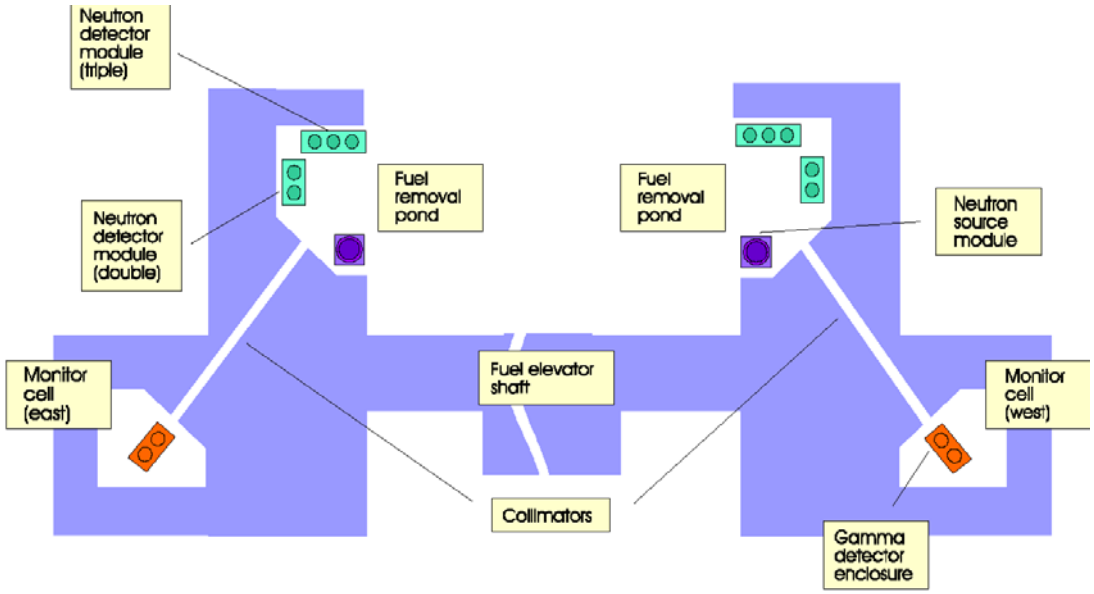

Figure 1 THORP Feed Pond Fuel Monitors

A combination of three techniques are used to characterize the fuel. Cooling time is determined by HRGS using fission product gamma activity ratios. Burnup is determined using a diverse combination of HRGS and passive neutron data. Initial enrichment is calculated from a combination of the final enrichment and measured burnup. Final enrichment is determined by a combination of the measured burnup and a neutron multiplication parameter determined from the active neutron measurements using the external ^{252}Cf neutron interrogation source. The only operator declared input that is required is the fuel type e.g PWR, BWR or Advanced Gas Cooled Reactor (AGR).

Over the past decade, thousands of assemblies have been successfully measured. Figure 2 indicates the results of a cross-comparison between operator declared and measured burn-up. Good agreement was achieved, providing validation of the methods used.

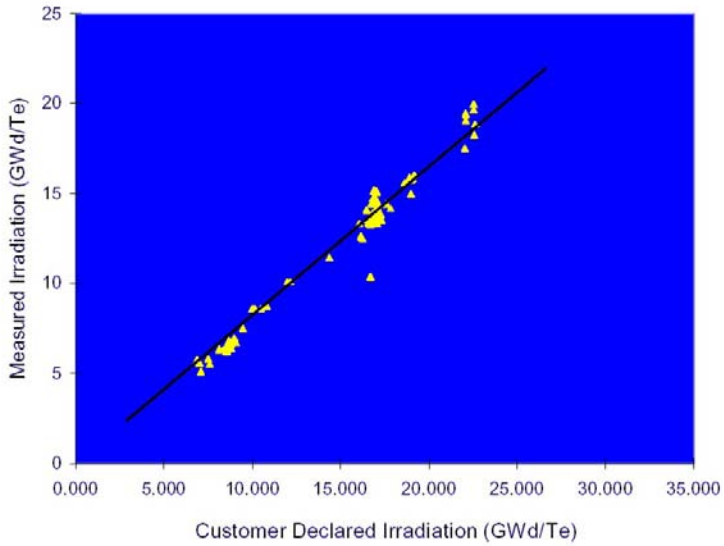

Figure 2 Comparison of Measured and Declared Burnup (Irradiation) for THORP Feed Pond Fuel Monitors

(ii) ARKANSAS UTILITY MEASUREMENTS.
Measurements of several hundred PWR assemblies were made in a US utility pool during 1996-97 using an HRGS based pool wall configuration system [10]. The irradiation history ranges were; 12.5 - 37.8 GWd/Te(U), cooling 7 - 20 years, initial enrichment 1.9 to 3.9 wt.% ^{235}U. The objectives of the measurements were; (i) to demonstrate the use of HRGS to measure burnup with minimal use of operator data, (ii) to produce records for burnup credit use, (iii) to promote the feasibility of performing assay within a fuel transfer procedure in which fuel is moved from a storage pool to dry storage casks, and (iv) to demonstrate proof of principle to aid the burnup credit methodology review by the NRC.

Measurements were performed prior to fuel loading into VSC-24 type dry storage casks. The arrangement of the gamma collimator and fuel handling machine is shown in figure 3. A vertical re-entrant tube was fixed to the pool wall for the insertion of a gamma detector, which was lowered into a shielded enclosure to minimize the magnitude of background radiation reaching the detector. The system included a horizontal gamma collimator with the field of view defined by lead apertures and a v-shaped fuel location fixture. This permitted simultaneous views of two faces of the fuel assemblies.

For each assembly, axial burnup profile and fixed point gamma spectroscopy measurements were made at several positions along the length of the assembly. From this data, assembly average values of cooling time and burnup were determined. The total assay time was less than 30 minutes per assembly.

The majority of the fuel assemblies were cooled to greater than 9 years, thus the principal burnup indicator was ^{137}Cs. The one sigma uncertainty derived from the correlation between measured and declared burnup was 3-5% (with no uncertainty component attributed to the declared values). The measured cooling time obtained from isotopic ratios had an uncertainty of +/-100 days.

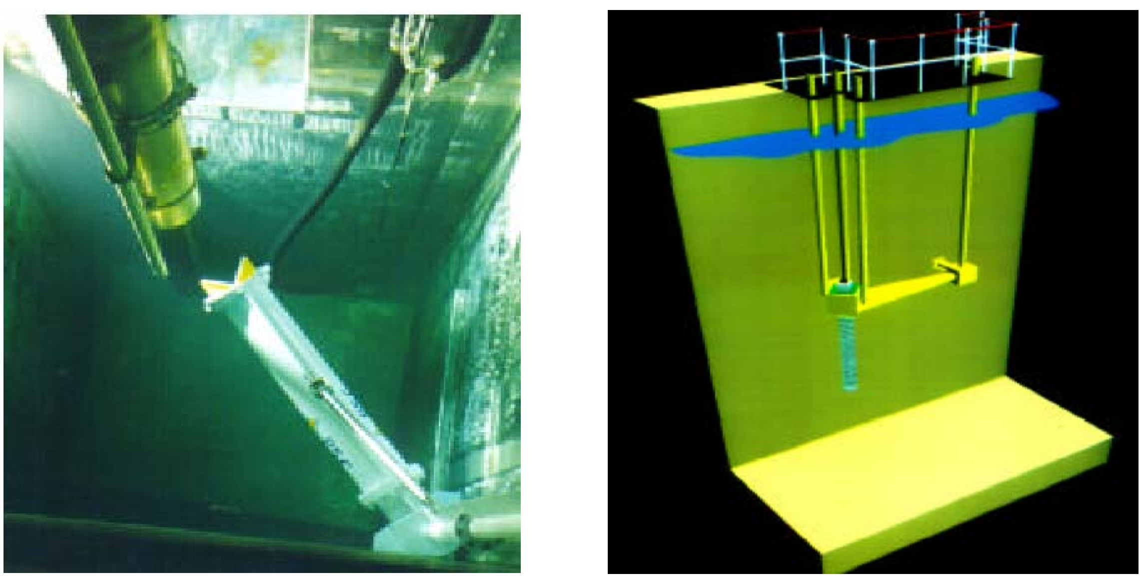

Figure 3 Gamma collimator and fuel handling machine deployed at US reactor site.

CONCLUSIONS AND RECOMMENDATIONS

The measurement of spent fuel is likely to play a crucial role in the support of three key fuel handling activities; burnup credit, safeguards verification and waste characterization for transportation and disposal of spent fuel in a repository.

For each of these spent fuel measurement applications, the measurement procedures would need to satisfy the regulators. Particular attention to methods of calibration and error analysis are expected with an emphasis as much as possible, on the use of calibrations independent of operator declared fuel history data.

The experience gained by the development and use of spent fuel monitors at the UK Sellafield reprocessing facility and in a campaign of demonstration measurements at a US utility have provided invaluable experience in meeting the evolving spent fuel measurement requirements.

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