RADIOMETRIC CHARACTERISATION SUPPORTS, BURNUP CREDIT, SAFEGUARDS AND RADIONUCLIDE INVENTORY DETERMINATION FOR SPENT FUEL TRANSPORT, STORAGE AND DISPOSAL

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Abstract

Spent nuclear fuel characterisation measurements play an essential role in a range of fuel handling activities. In particular, they are necessary to support the application of burnup credit to the transport of spent fuel, to detect diversion of safeguarded nuclear material and to determine the radionuclide inventory of materials destined for final disposal. To apply measurements to these activities the measurement procedures need to be approved by the relevant regulatory bodies. Often key to the measurement procedures is the method of instrument system calibration and what a priori data is acceptable to aid the measurement process. Discussion of these, pertinent to the three areas of application mentioned above, is presented with suggestions of alternative approaches where considered appropriate.

1. INTRODUCTION

To encourage the renewed interest in nuclear power as an energy provider which produces very little greenhouse gas emissions, it is important to head off criticisms frequently aimed at the nuclear fuel cycle. These are often concerned with (i) the enhanced risk of nuclear weapons proliferation resulting from the increased amounts of plutonium generated from burning low enriched uranium (LEU) fuels and (ii) the lack of a closed cycle in terms of a satisfactory disposal route for the radioactive waste products. As in other areas of the nuclear fuel cycle, the use of better radiometric instrumentation may offer some help by improving the integrity of safeguards operations and reducing the costs of waste disposal whilst providing a traceable path for materials through the cycle.

Specifically, fuel characterisation measurements can provide a vital supporting role in a range of fuel handling activities including: (i) the use of burnup credit in storage, transport and disposal operations, (ii) the in situ verification of burnup and fissile content particularly for mixed oxide (MOX) fuels for safeguards and, (iii) the determination of radionuclide inventories for direct disposal of spent fuel or wastes resulting from reprocessing.

Better instrumentation may result from improvements in the way technology is applied to practical measurements, through to achieving greater measurement sensitivity and accuracy by using improved detectors and data processing technology. Presented in this paper are illustrations of the practical application of measurements associated with burnup credit for the transport of spent PWR commercial fuel in the U.S., along with a discussion of how far measurement sophistication should be taken to support safeguards.

2. FUEL CHARACTERIZATION MEASUREMENT APPLICATIONS

2.1. Burnup credit

Taking account of the reduction in the neutron reactivity (multiplication) of spent fuel, which results from irradiation, is known as burnup credit. The reduced reactivity is caused by the net loss of fissile and fissionable nuclides together with the generation of fission product poisons. The nuclides of major criticality importance were identified in an international study on burnup credit [1]. These are the fissile and fissionable nuclides: $^{235}\text{U}$, $^{236}\text{U}$, and $^{238}\text{U}$, and $^{239}\text{Pu}$, $^{240}\text{Pu}$ and $^{241}\text{Pu}$. The major fission products were also listed, these are: $^{90}\text{Mo}$, $^{99}\text{Tc}$, $^{101}\text{Ru}$, $^{103}\text{Rh}$, $^{109}\text{Ag}$, $^{133}\text{Cs}$, $^{147}\text{Sm}$, $^{149}\text{Sm}$, $^{150}\text{Sm}$, $^{151}\text{Sm}$ and $^{152}\text{Sm}$.
 Burnup credit offers the nuclear industry a means of increasing the packing density of spent nuclear fuel in storage racks as well as in transport and disposal casks. Alternatively, it can allow a reduction in the amount of expensive neutron absorbers required in the containers. The present, very conservative, method of using the unirradiated or fresh fuel reactivity for spent fuel in criticality cask design calculations, known as the “fresh fuel assumption”, leads to unnecessarily over-engineered and expensive cask designs of limited packing density. In anticipation of licensing approval of a burnup credit methodology, cask vendors are considering designs based on the reduced reactivity offered by burnup credit.

In the United States the Nuclear Regulatory Commission (NRC) controls the issue of licenses for spent fuel casks in accordance with the requirements of Title 10 to the Code of Federal Regulations (CFR), Part 72 (Storage), Part 71 (Transportation), and Part 60 (Disposal). A programme to change the licensing policy to one in which burnup credit can be used is being pursued by the United States Department of Energy (USDOE) through their series of topical reports on PWR actinide only1 burnup credit [2,3]. The reports propose a methodology for the application of burnup credit. This is encompassed in five major steps:

1. Validate a computer code system to calculate isotopic concentrations in the spent nuclear fuel created during burnup in the reactor core and subsequent decay.
2. Validate a computer code system to predict the subcritical multiplication factor, \(k_{eff}\), of a spent nuclear fuel package.
3. Establish bounding conditions for the isotopic concentration from criticality calculations.
4. Use the validated codes and bounding conditions to generate storage, transportation, and disposal package loading criteria (burnup credit loading curves).
5. Verify that spent nuclear fuel assemblies meet the package loading criteria and confirm proper fuel assembly selection prior to loading.

The last of the steps introduces the need to confirm the reactivity of spent fuel; this will, almost certainly, be achieved via the measurement of burnup. Such verification measurements are aimed at enhancing the administrative control to ensure beyond any doubt that fuel loaded into a cask is fully compliant with the prescribed burnup credit loading curves. In addition, the measurements will assist in the confirmation of the identity of each assembly by verifying other fuel history parameters.

The burnup credit loading curves, described in the topical reports, provide a means of segregating fuel assemblies into “specified” assemblies, that meet the acceptance criteria for loading into a particular fuel storage rack or transport cask designed to take account of burnup credit; and “non-specified” assemblies that do not meet the criteria. The criteria are based on a combination of fuel burnup and wt.% \(^{235}U\) initial enrichment. Figure 1 shows an example of a loading curve.

The burnup credit loading curves are biases to account for any uncertainties in the data that relate burnup to the reactivity of the spent fuel. However, before using the cask loading curve to determine the loading status, it is necessary to determine the assembly’s minimum assured burnup. The minimum assured burnup being the “actual” burnup minus the uncertainty on this value.

Based on the increases in cask capacities, significant commercial and operational advantages are anticipated giving in the region of 25% to 40% reduction in handling costs [4]. The USDOE estimate spent fuel transport cost savings of 35% using a 4 PWR assembly truck cask with actinide only burnup credit rising to 40% for full (principal isotope) burnup credit [5]. For rail transport, in which the anticipated unit costs are considered to be lower than those for truck due to the possibility of using larger casks of 21, 24 or 32 PWR assembly capacity, cost savings of up to 26% are anticipated. Depending on the mix of transport modes, the overall cost savings for transport of fuel from utility to repository is estimated to be between $200M to $1b if full burnup credit is used. These

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1 Consideration of fission products is not included. Only the following actinides, and their effect on neutron reactivity are considered: \(^{234}U, \(^{235}U, \(^{236}U, \(^{238}Pu, \(^{239}Pu, \(^{240}Pu, \(^{241}Pu, \(^{242}Pu\) and \(^{241}Am.\)
figures are based on transporting 126,000 PWR assemblies in a mixture of General Atomics GA-4 truck casks and 24 to 32 assembly capacity rail casks.

Although cost savings are expected by the use of burnup credit, various cost factors have to be considered to determine the total net savings. These factors include: (i) the reduced storage costs associated with the use of cheaper casks designs or the use of fewer casks as alluded to above, (ii) the potential added value of radiometric measurement data acquired prior to shipment. This could eliminate the need to re-open casks at the final repository for measurements that may be required to satisfy waste acceptance criteria, (iii) implementation costs of burnup credit in terms of license approval and administration, (iv) the cost of radiometric measurements and (v) the amount of burnup credit taken, i.e. actinide only or full burnup credit with fission product poisons included. The poisons reduce the multiplication, $k_{eff}$, by approximately a further 10%.

2.2. Application of burnup credit measurements

Verification of the "candidate" fuel assemblies, i.e. those expected to fall beneath the loading curves based on the reactor operator records, is anticipated to be made by physical measurement. The procedure detailed in the latest topical report [3] describes the use of a rejection criterion to judge whether the measured burnup of an individual fuel assembly is consistent with that declared in the reactor records. Rejection would result in the assembly being disqualified for loading into a burnup credit cask.

The specification of the rejection criterion can be used, however, as a good illustration of the difficulties involved with handling the uncertainties in two data sets when one is intended to verify the other. In this case, the two sets are the burnup values declared by the reactor operator and those derived from measurement.

In the topical, the proposed criterion is that "the measured burnup must be within 10% of the reactor record burnup". The measurement being intended to be used to confirm the reactor record value of burnup and the uncertainty in the reactor record to be accounted for by a related reduction in the burnup before comparison to the loading curve, i.e. to give the minimum assured burnup. Any disagreement between the measurement and the reactor record is not intended to be used to reduce the burnup credit but rather as an indication that something is wrong. The question then arises as to whether an unnoticed error of 10% would lead to an unsafe condition. The answer in the topical report is that approximately half of this difference is accounted for in the reduction of the assembly burnup due to uncertainty in the reactor records, i.e. 5%. However, if the assembly was at the low end of the reactor record uncertainty, the maximum error in burnup could be 10%, comprising 5% record and 5% measurement uncertainty. The DOE view this as acceptable (although not accepted by the NRC) because there is a significant change in the reactivity of the assemblies from fission products.
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that are not accounted for in the derivation of the loading curves in the actinide only burnup credit proposal.

A calibration derived from the correlation between a measurable parameter, e.g. the activity of the fission product Cs-137 or the neutron emission rate principally from Cm-244, and the declared burnup for a representative set of assemblies is known as a "dependent" calibration. The use of such a calibration is viewed as appropriate for the application of burnup credit on commercial fuels because of the general acceptance that for a group of assemblies representing a reactor core there is very little, if any, systematic bias in the declared burnup. The proposed acceptance criterion to be used to qualify the dependent calibration and determine each assembly status is as follows:

(i) A calibration curve of the following form is to be derived and used to correlate the measured parameter (or count rate) to the reactor record burnup:

\[
y_{\text{counts}} = a + bx_{\text{rec}}
\]

where \(a\) and \(b\) are constants, \(y_{\text{counts}}\) is the count rate of the measurable parameter, and \(x_{\text{rec}}\) is the reactor record burnup value (when using neutron emission as a burnup indicator a non-linear expression may need to be substituted);

(ii) The validity of the calibration is then tested over the entire range of \(x\) by applying a 10% limit to the count rate Prediction Band Width [6], i.e.:

\[
\text{Prediction Band Width (converted to units of burnup) / Assembly Burnup} < 0.1, \text{ where the}
\]

\[
\text{Prediction Band Width (count rate)} = \left\{ \frac{(n+1)/n + \frac{(x - \bar{x})^2}{S_{xx}}}{\sqrt{n-2}} \cdot \frac{SS_R}{\sqrt{n} \cdot t_{n-2}^2} \right\}
\]

\[
S_{xx} = \sum_{i=1}^{n} (x_i - \bar{x})^2
\]

\[
SS_R = \sum_{i=1}^{n} (y_i - ax_i - b)^2
\]

\(n\) is the number of assemblies in the calibration set; and

\(t_{n-2,0.05}\) is the t-statistic at the 100(1-\(\alpha\))% confidence level for \(n-2\) degrees of freedom (\(\alpha = 0.05\) for 95% confidence);

The test therefore defines a range of \(x\) for which the inequality holds and the calibration is valid (procedures for dealing with the ranges of \(x\) that do not satisfy the inequality are suggested in the Topical; splitting the calibration range into smaller groups each with their own calibration is suggested);

(iii) For an assembly to be accepted for loading, the difference between the measured burnup derived via the measurement with the validated calibration and the declared burnup must be less than 10% of the declared burnup.

The procedure for taking a measurement and verifying the reactor records therefore appears to be well conceived and workable with the assumption that the reactor records data has for each assembly approximately a 5% uncertainty in burnup and that the measurement also contributes a 5% uncertainty. The difficulty, however, occurs when the uncertainty values, taken to be at a 95% confidence, do not meet the arbitrary value of 5%. In particular the reactor records, though accepted to be of a good accuracy with an average uncertainty at 1 sigma of 2% across a reactor core, for individual assemblies may be somewhat greater than 5%. The net result of this is that either the calibration may not meet the test criterion or some of the individual assemblies may fail the 10% test. If either of these occur, the identified assemblies may be disqualified from being loaded into a burnup credit cask, even though, as may be the case, the burnup is well below that prescribed by the applicable loading curve.
An alternative procedure, proposed by BNFL Instruments (BI) for discussion, recommends that measurements should play a greater role in the process of determining, with high confidence, the minimum assured burnup for each assembly. This procedure is as follows:

1. Calibrate the measured burnup indicator against the declared burnup records. In this, the linear expression is inverted to give:

   \[ y_{\text{rec}} = a + bx_{\text{count}} \]

   in which \( y_{\text{rec}} \) is the declared burnup and \( x_{\text{count}} \) is the count rate of the measured burnup indicator;

2. The calibration set is recommended to be consistent, in number of assemblies, with a reactor core load of fuel comprising approximately 200 or more assemblies. This calibration should be carried out before commencing fuel loading;

3. Check the calibration data set for outlier assemblies. In this case an outlier assembly is defined as one for which the difference between the declared and the measured burnup is greater than a pre-defined percentage. This is to eliminate assemblies that are clearly badly measured or incorrectly declared;

4. If any assemblies are identified as outliers these should be removed from the calibration data set. The assembly reference numbers of the rejected assemblies should be recorded pending an investigation that may include further measurement and other checking procedures. Failure to evaluate and rectify the cause of their outlier positions will make those assemblies ineligible for burnup credit;

5. If any assemblies are rejected during step 3 then a new reduced calibration data set will be used to recalibrate the burnup indicator;

6. Steps 2, 3 and 4 are repeated until there are no rejections identified at step 2;

7. Determine the assembly burnup, \( y \), using the measured burnup indicator in conjunction with the established calibration curve for each of the assemblies that remain in the calibration data set and where appropriate other assemblies in the larger measurement campaign;

8. Determine the uncertainty on each of the measured burnup values by propagating the uncertainty in the calibration and the uncertainty in the individual measurement of the burnup indicator;

The uncertainty in \( y \) based on the scatter in the calibration data set, is:

\[
y = a.x + b \pm \left\{ \frac{1}{n} \cdot \frac{(x - \bar{x})^2}{S_{xx}} \cdot \frac{SS_N}{(n-2) \cdot I_{a,n-2}} \right\} \tag{1}
\]

where

\[ S_{xx} = \sum_{i=1}^{n} (x_i - \bar{x})^2 \]

\[ SS_N = \sum_{i=1}^{n} (y_i - ax_i - b)^2 \]

and \( I_{a,n-2} \) is the t-statistic at the 100(1-\( a \))% confidence level for \( n-2 \) degrees of freedom.

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Identification of outliers can be based either on data points that fall outside a specified confidence interval, or, as in this case outside a specified percentage range. The choice of a fixed percentage is suggested to ensure that the probability of assembly rejection is lower for calibration data sets in which the amount of scatter is small. In this case it is possible that there are no rejected assemblies. If on the other hand a confidence limit, derived from the scatter in the calibration set, is chosen, there will always be a fixed proportion of the set rejected regardless of the quality of the data.
The overall uncertainty \( \sigma_y \) (shown at 95% confidence level) is calculated at a stated confidence level based on the uncertainty in the measured count rate, \( \sigma_x \) and the scatter in the calibration data:

\[
\sigma_y = \sqrt{(a.1.65\sigma_x)^2 + \left[ \frac{1}{n} + \frac{(x - \overline{x})^2}{S_{xx}} - \frac{SS_R}{(n-2)I_{a,n-2}} \right]^2}
\]

(2)

9. Calculate the minimum assured burnup for each fuel assembly by decreasing the measured burnup by its total uncertainty to a specified confidence level. The confidence level, to be defined by the regulators, will ensure that the reduced burnup value gives a minimum assured burnup at the required level of confidence. (For example, to be 95% confident that the true value of burnup is greater than or equal to the minimum assured value one would have to use a t statistic with \( \alpha = 0.05 \) and a multiple of 1.65 for the uncertainty on the individual measurement. This uncertainty would be determined from a critical review of the measurement procedure with appropriate error propagation. The value of 1.65 assumes, however, that the uncertainties are well described by a Gaussian distribution). From equations (1) and (2) the minimum assured burnup, \( M_{BU} \) at the specified confidence level is:

\[
M_{BU} = y - \sigma_y
\]

10. Compare the minimum assured burnup, as defined by the measured burnup and its associated uncertainty, with the cask loading curve for each assembly to establish its loading qualification.

BI considers that this methodology has several beneficial features, compared to methods that use the measurement purely as a verification of the declared burnup. Firstly, it is a very simple method that does not rely on any arbitrary assumptions about the scatter of the declared data set used during the production of the calibration. Secondly, it is capable of providing a determination of the uncertainty in burnup for each individual fuel assembly.

As with any dependent calibration this approach relies on the accepted position that the operator declared values for burnup have, when taken en-masse, negligible systematic error. This is commonly viewed as a key strength of the declared data, which enables an unbiased dependent calibration to be defined. The weakness in the reactor records is that the uncertainty in the burnup associated with individual assemblies is often undetermined. This weakness is overcome by the use of the declared data with the measured data as outlined by this alternative proposed methodology. The improvement stems from the use of a verifiable measure of the burnup and its associated uncertainty for each individual fuel assembly.

It should also be noted that this approach takes credit for both the quality of the declared burnup records and for the precision of the measurements. The better these are the greater will be the minimum assured burnup for each assembly. This, in turn, means that the number of assemblies that qualify for burnup credit loading may be increased.

In summary, it is suggested that the alternative measurement based approach offers a more realistic determination of minimum assured burnup for each assembly. Their values are likely to be higher, and hence of greater economic value, than those derived from a method that utilises an assumed operator declared uncertainty for each assembly. BI anticipate that this latter value would have to be fairly pessimistic to ensure that the worst uncertainties in the records are assumed for each assembly. This would result in lower minimum assured burnup values at the required level of confidence.

The BI methodology has been tested on a campaign of commercial PWR spent fuel. The campaign comprised 203 assemblies measured in the U.S. in 1997. In these the burnup was measured using the burnup indicator Cs-137 corrected for cooling time and axial burnup profile to give the
assembly average burnup. Figure 2 shows the measurement data used to determine a calibration for
the burnup indicator. Table I shows the derived minimum assured burnup along with the operator
declared burnup for a set of 31 assemblies chosen randomly from the 203 assemblies in the campaign.
The effectiveness of the approach is demonstrated by the relatively small amount that the minimum
assured burnup is below the declared burnup. For the 31 assemblies in the table this is 4% ± 3%.

![Calibration of Cs-137 662 keV gamma ray emission burnup indicator for a campaign of 203 assemblies](image)

**FIG. 2. Calibration of Cs-137 662 keV gamma ray emission burnup indicator for a campaign of 203 assemblies**

2.3. Safeguarding of spent fuel

As the global quantity of spent nuclear fuel steadily grows the need for rigorous control of the
large quantities of fissile nuclides, predominantly \(^{235}\text{U}\), \(^{239}\text{Pu}\), and \(^{241}\text{Pu}\), within the fuel is becoming
increasingly important from a safeguards standpoint. Plutonium content represents about 1% of spent
fuel assembly mass. Globally the current stocks of more than 150,000 t HM in spent fuel assemblies
contain more than 1,000 tonnes of plutonium. The amount accumulated through the lifetime of the
currently operating reactors may rise by a factor of 2 or 3 depending on the quantities reprocessed and
recycled in the form of mixed oxide (MOX) fuels.

Measurement and verification of such large quantities of plutonium and fissile uranium within
spent fuel assemblies, beyond the level of simply item counting, are potential requirements. If so,
rigorous measurement methodologies, similar to those proposed for burnup credit, will be equally
relevant to safeguards for fissile material quantification or verification. Improved safeguards
measurements may not only be of benefit to aid non-proliferation but could enhance the public
acceptability of handling and transportation of fissile materials. For example, in the U.S. this may
improve the prospects for conversion of DOE owned fissile material into commercial fuel for burning
as MOX. Alternatively, improved faith in safeguards could encourage the earlier transfer of material
from DOE sites and power utilities to a long term repository.

2.4. Measurements in support of safeguards

The application of measurements to safeguards, in contrast to burnup credit, is likely to require
direct measurement of fissile content. For burnup credit, though fissile content is the real issue for the
purpose of criticality calculations, the measurement of burnup in combination with a given initial \(^{235}\text{U}\)
enrichment is an approach that is generally accepted (though not yet approved in the U.S.) for
commercial power generation spent fuel. Such an arrangement for safeguards would not guarantee diversion detection.

**TABLE I. A RANDOM SELECTION OF 31 ASSEMBLIES SHOWING THE DERIVED MINIMUM ASSURED BURNUP COMPARED TO THE OPERATOR DECLARED BURNUP**

<table>
<thead>
<tr>
<th>Assembly Reference</th>
<th>Assembly Value</th>
<th>Burnup Indicator Value</th>
<th>Burnup Indicator Uncertainty</th>
<th>Burnup (MW-d/(U)) Declared</th>
<th>Burnup (MW-d/(U)) Measured</th>
<th>Burnup (MW-d/(U)) Minimum Assured</th>
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</tbody>
</table>

The above table contains a subset of data from a campaign of 203 assembly measurements. The minimum assured burnup is calculated in each case from the measured burnup indicator and its associated uncertainty and the uncertainty derived from the dependent calibration. The following are the calculated terms used in the uncertainty analysis:

- The number on assemblies measured during this campaign, \(n=203\)
- The average burnup indicator, \(\bar{I}=3073\)
- The calibration parameters, \(a=8.53, b=0\)
- Summations of the residuals, \(S_S=134026293, S_C=138643969\)
- The one tailed \(t\) statistic for \(n-2\) degrees of freedom at the 95% confidence interval, \(t_{0.05, n-2}=1.65\)

Safeguards monitoring therefore requires direct measurement of fissile content with an ability to discriminate between fissile uranium and plutonium. The candidate measurement approaches are therefore likely to comprise a combination of active and passive neutron techniques with gamma spectrometry. Elements of such systems are currently being developed in the nuclear countries.
As for burnup credit, the question arises, as to the most appropriate method of calibration of these instruments. Clearly a calibration independent of any operator declared information would be preferred. Though at first this appears quite straightforward, it is difficult to fully achieve because of the strong dependence of a fissile measurement on the fuel geometry as well as the fissile content. The standard approach would be to calibrate the measurements systems by modelling or simulating the given fuel and measurement geometry. During safeguards measurement it is therefore important that the geometry is as expected, otherwise the measurement could be invalidated or at least inaccurate. This is an important aspect of safeguard monitoring, as good knowledge of measurement uncertainty is key to gaining high confidence that a fraction of the declared amount of fissile material has not been diverted (partial defect).

The solution may be, therefore, to combine the radiometric techniques (active and passive neutron counting and gamma spectrometry) with a means of confirming the geometrical arrangement, using for example real time radiography (RTR). This approach could also offer the ability to correct a measurement for the effects of damaged fuel or research fuels for which detailed geometrical information may be lacking. Currently an instrument offering this combination of techniques is not yet available but could be developed in response to the demands of the safeguards regulators.

2.5. Spent fuel waste disposal

Under present policies a significant proportion of the world’s commercial spent fuel is viewed as waste. Although the waste in the UK is not in general spent fuel, but industrial radionuclides and residues from reprocessing, there is a requirement to measure (or infer from measurement) some 78 radionuclides. Similar requirements for radionuclide content assessment therefore seem likely for spent fuel disposal. The measurement of burnup and associated irradiation history parameters such as cooling time could be used, as it is for waste under the U.K definition, to provide the required radionuclide inventory data for spent fuel.

2.6. Measurement techniques and methodologies

Available techniques include high resolution gamma spectrometry, passive neutron counting and active neutron counting. When used in conjunction with nuclide inventory computer codes, such as ORIGEN or FISPIN, the radiation measurements allow burnup, cooling time, initial wt.% $^{235}$U enrichment, residual wt.% $^{235}$U equivalent enrichment and radionuclide inventories to be determined for intact fuel assemblies and for dismantled assemblies or fuel debris.

The successful use of the characterization measurements depend, in a similar way to the other applications outlined above, on development of appropriate techniques together with the availability and acceptance of methodologies that cover the measurement process and the related calibration procedures. These are necessary to correlate the measurable radiation emissions with the required spent fuel parameters, such as burnup, and will be essential to the regulatory control of spent fuel contaminated waste destined for interim or final disposal.

A range of modular spent fuel monitoring systems for fuel characterization has been developed by BNFL Instruments. Historically, these were based on instrument systems produced for reprocessing facilities at Sellafield; their primarily role being related to process control, radionuclide inventory assay and safeguards applications. The systems use a variety of radiometric techniques along with different approaches to calibration and validation procedures necessary to ensure reliable and accurate operation that is appropriate to the customer requirements. In the case of the direct disposal of spent fuel, as is currently favored in the U.S., the calibration of measurement systems is likely to be more akin to the application of burnup credit where it may be appropriate to rely on some operator declared parameters. This is in contrast to safeguards measurement in which, little if any, operator declared data should be relied upon.
3. CONCLUSIONS

It is clear that radiometric measurements play a key role in a range of fuel handling activities and can provide benefits that may be financial or safety related. In relation to this there are essentially two questions posed in this paper. The first is, what is the best approach to confirm reactor operator declared burnup for the application of burnup credit, and the second is how far should safeguards measurements go in terms of the degrees of blindness under which they are made.

In answer to the first; a burnup credit measurement methodology that is an alternative to the USDOE approach is suggested. This alternative approach puts a greater emphasis on the measurement. It is the measured term minus its uncertainty that is used to derive the “minimum assured burnup”. The minimum assured burnup for each spent fuel assembly is then compared to the appropriate loading curve for the selected transport cask. This approach differs from that proposed by the USDOE in which the measurement is intended only to route out badly declared assemblies. The minimum assured burnup being determined by deducting an assumed uncertainty from the declared burnup before application to the loading curves. This is criticised on the grounds that because of the variability of the reactor records burnup uncertainty for individual assemblies, it will be necessary to assume a pessimistic uncertainty value and thereby produce a smaller and less valuable minimum assured burnup.

With regard to the second question, should safeguards measurements for the purpose of identifying diversion operate totally blindly from operator (or state) input. In particular, for fuel assemblies should this blindness include the geometrical structure of the fuel? If this is the correct way forward, the measurement challenge will have to be met with more sophisticated measurement techniques and systems that will be able to measure the fissile content of fuel assemblies in absence of geometrical and other supporting information.

REFERENCES