DECAY HEAT AND CHARACTERIZATION OF SPENT NUCLEAR FUEL FOR REPOSITORIES AND TRANSPORT

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Abstract

For the disposal, intermediate storage and transport of spent nuclear fuel a number of properties of each fuel assembly must be determined, both for operational and safeguards needs. Important examples of these parameters are decay power, multiplicity, burn-up (BU), initial enrichment (IE), cooling time (CT), completeness of fuel assemblies, weight, amount of fissile material and nuclide inventory. This is done through a combination of known fuel history, measurements and codes. In addition, the status of the fuel assemblies is necessary to characterize. Failed or damaged fuels must be identified prior to final disposal in order to treat them appropriately, as are other mechanical and chemical issues that may affect the handling in the system. The uncertainties of these determinations are crucial in the use of the parameters, and are judged to be fairly large at present. Particularly the uncertainly of the decay power has a direct relationship to the cost of any repository due to temperature requirements in the systems. These cost savings are potentially very high, in the order of billions of Euros. A thorough understanding of these issues also opens ways to optimize the facilities, for example economically and environmentally. Due to the large amount of fuel assemblies to be measured, high through-put and robustness of the methods and instruments are paramount, as is the capacity to make fast decisions made on the measurement results and codes. The status and future needs of development of instruments, basic fuel data and cross sections, and codes is discussed in the paper, and how this is done in various collaborations world-wide. Potential problems, such as errors in fuel data, uncertainties in basic nuclear data, uncertainty propagation, conflicting methods and results etc., is illustrated and discussed. An international effort to blindly test the capacity to calculate decay power on fuel history, led by SKB and in collaboration with NEA/OECD – with more than 25 participating organizations and groups, using most of the internationally available codes, is described.

1. INTRODUCTION

For the disposal, intermediate storage and transport of spent nuclear fuel a number of properties of each fuel assembly must be known, both for operational and safeguards needs. Important examples of these parameters are decay power, multiplicity, burn-up (BU), initial enrichment (IE), cooling time (CT), completeness of fuel assemblies, weight, amount of fissile material and nuclide inventory. These can be determined through a combination of known fuel history, measurements and codes.

In addition, the status of the fuel assemblies is necessary to characterize. Failed or damaged fuels must be identified prior to final disposal in order to treat them appropriately, as are other mechanical, chemical and other integrity issues that may affect the handling in the system. Some of these properties are less direct than the parameters mentioned in the previous paragraph and will be more challenging to clearly describe and to put into requirements.

It is importance to realize that there are several scientific communities that characterize the fuel, in different ways, but often the same fuel property. These are for example fuel ’physics’, fuel ‘chemistry’ and the safeguards verification methods community. These have historically not collaborated to a large extent, although this has somewhat changed the last years. Not least because this type of nuclear research is expensive, substantial improvement in efficiency, accuracy, and optimisation of resources is possible with more collaboration between the communities.

It is also important to establish methods with sufficient statistics, so they be general, which is a challenge due to cost and rarity of measurements on real nuclear material. This highlights the need for international collaboration. IAEA has initiated activities on spent fuel characterisation [1].

2. FUEL CHARACTERIZATION

The implementer and operator has to determine to the best possible extent the key characteristic parameters of each individual spent fuel assembly in order to be able to design and operate a safe and economically optimized disposal system of the spent fuel. This is planned to be done through a combination of known fuel history, measurements and codes. These parameters include the following:

— Decay heat
— Burn-up (BU), Initial enrichment (IE), Cooling time (CT).
— Criticality – multiplicity
— Radiation: primarily gammas and neutrons
— Nuclide inventory

For international safeguards verification by IAEA and in Europe Euratom, a number of fuel parameters are verified. These are partly the same as for operational use, a potential issue which is further discussed below.

— Safeguards verification:
  - Identify correct fuel
  - Missing pins - completeness of fuel assemblies
  - Contents of fuel – amount of fissile material
  - Weight

The parameters are planned to be determined by a gamma and neutron measurement system in conjunction with the encapsulation process together with modelling codes and known history and properties of the fuel assemblies. Due to the large amount of fuel assemblies to be measured, high through-put and robustness of the methods and instruments are paramount, as is the capacity to make fast decisions made based on the measurement results and codes.

2.1 Decay heat

The decay heat is a fundamental property of any spent fuel activity. It is often the limiting factor, which means it has implications for safety as well as economy. It changes as the content of the fuel decays, and in the very long term it will almost disappear. Often the so-called thermal pulse is considered gone after 1000 years.

It is important in all parts of the back-end system, such as transportation, drying, intermediate storage (wet and dry), and final disposal. There are typically temperature requirements, typically highest allowed temperature. There are potential issues where a certain temperature interval could be of concern, such as Delayed Hydride Cracking (DHC). There can be situations where the total deposited amount of energy (heat times time) in a certain material or volume is of interest. There can also be requirements on the maximum decay power itself.

There are two basic modes of intermediate storage, dry and wet. In dry, the fuel is stored in casks, and there is a maximum allowed amount of decay power in each cask. Uncertainties are fairly prominent as the few fuel elements in each cask gives statistical uncertainty.

For wet storage the decay power has to be known in order to cool the pools sufficiently, and the total amount of power in the pool will determine the timing of severe events such as loss of cooling of the pool. As there are so many assemblies in a pool, the total uncertainty is small, but the bias is very important.

A final geological repository is passively cooled by non-flowing processes in the rock, which is an inefficient way to perform cooling. As an example, the Swedish final repository will in total have about 10 MW of decay power (about the same as a research reactor) but over a large volume of almost a cubic kilometer. Typically, there are temperature requirements on the canister, the bentonite and sometimes the rock (and perhaps in some circumstances the fuel itself) to be fulfilled. Of particular high economic importance is the potential for optimization of the design of the repository. Examples include amount of fuel in each canister and the distance between deposition holes and deposition tunnels. These cost savings are potentially very high, in

the order of billions of Euros. Although different types of repositories are different, they will all have some temperature requirements. A typical example in the Swedish concept KBS-3 is 100 degrees C. in the bentonite.

Other important uses of decay power are as a fundamental verification parameter in codes such as Scale/Origin, where nuclide content (e.g. U, Pt), radiation, multiplicity etc. are determined.

It can also be noted that it is an important parameter to evaluate in reprocessing as a large part of the spent fuel's decay power is included in the 'waste' portion of the result of reprocessing, and the footprint of a geological repository may be almost as large as if the fuel had not been reprocessed.

Finally it can be employed in safeguards, as it is a parameter considered difficult to falsify.

2.1.1. Calorimetry

The basic method to measure decay power is calorimetry. The fuel is measured in a device like a 'thermos'. One of the few full-scale ones, where entire fuel assemblies can be measured, have been operated at the Swedish Intermediate storage facility, Clab, since several decades. The results have been used, among other things, to verify several codes. A lot of measurements have been openly published.

Calorimetry has the potential to be accurate; in the order of 2 % uncertainty. The problem is that it requires long measurement times for each assembly several days for highest accuracy (and around 10 h for normal use at Clab). In the case of SKB, around 12 assemblies have to be determined per day in the encapsulation plant. This would then require many calorimeters, in different pools, as if they are in the same pool they interfere. This would be very impractical and uneconomic. Thus, indirect determination methods must be developed to a reasonable accuracy. [2]

2.1.2. Indirect methods

An indirect method that has been developed over many years, and particularly the last ones, is to use gamma to determine the decay power. Particularly the cesium and europium peaks are suitable. [3,4,5,6,7]

2.1.3. Blind test on decay power

An international effort to blindly test the capacity to calculate decay power on fuel history, led by SKB and in collaboration with NEA/OECD – with more than 25 participating organizations and groups, using most of the internationally available codes, - is presently underway. 5 spent fuel assemblies from Clab has been chosen in secret and typical data about these given to the participating groups. The groups then independently determine the decay power. The results will be compared to new calorimetric measurements of the fuels.

The overall aim with the blind test exercise is to:

- Learn more about characterization and decay heat determination of nuclear fuel
- To evaluate:
  - How accurately available simulation codes can predict the decay heat compared to the measured decay heat;
  - How the different codes predict the decay heat compared to each other;
  - How different levels of detail in the operating history data impact the decay heat prediction.

At the time of writing all groups have not been able to deliver their results, and the results are not yet public. Consequently, nothing about the results can be presented in this paper.

2.2. Radiation

Radiation is another result that comes from these determinations more or less automatically. Radiation is seldom a limiting factor, but obviously a very important factor due to safety. It is very important for several reasons to be able to determine radiation dose (all types) with sufficient accuracy, and with *known* uncertainties.

It is used for radiation protection, design of equipment and shields etc. in all parts of the back-end system: transport, intermediate storage (wet and dry), encapsulation and final disposal.

It is often assumed that there are considerable conservatisms in the predictions of radiation. This is generally true, but there have been a few recent examples in more than one country where this is not necessarily true.

2.3. Criticality

All nuclear material outside a reactor must not go critical. Normally the criticality is determined with codes for a certain set-up. However, there are some situations where there may be large benefits from checking a single assembly in order to treat it more accurately in the system. It is, just as with radiation, something that comes more or less with the rest of the characterization, as multiplicity.

It must be remembered that in the back-end the important parameter, k_{eff}, is not so far from 1 (=critical), as the fuel elements are designed to get critical. Thus, criticality always an issue, however usually not a limiting one. It is relevant for all parts of back-end system: transport, intermediate storage (wet and dry), encapsulation and final disposal. As the half-life of uranium-235 is around 700 million years, the criticality issue does not decay as quickly as radiation and decay heat.

2.4. Nuclide inventory

The nuclide inventory is important for the safety analysis of the geological repository. However, the required accuracy of the determination this parameter is low, as a factor of two often is sufficient. The nuclide inventory is an output of the codes, and is an integral part of the characterisation in terms of the other parameters, such as decay power.

Part of the nuclide inventory is the safeguardable fissile material such as uranium and plutonium.

2.5. Safeguards

From a safeguard point-of-view, geological repositories are an exception in the sense that the nuclear material is not readily inspectable anymore. This means that there will be strict requirement on verification before disposal.

Several of the parameters that have to be determined are also safeguards related in the sense that these parameters are declared by the owner and operator of the nuclear material. These can then be verified. An important issue for the operation of final disposal system is that these parameters have to be determined in the best possible way. One reason is the direct operational optimisation of the system (see above). Another is the long term risk, for example that it must not be reassessed in the future so that the safety and dependability of the disposal is put into question. A very substantial problem with two or more determinations of the same parameters is the adjudication between these. What should be used for operational use? The operator must use the best one. If any are considered sub-par, a fundamental problem has occurred.

Therefore, a joint measurement system is proposed by SKB and the Swedish regulator SSM, used by both operator and authorities and inspecting bodies. All relevant data for the fuel, such as its operating history, initial enrichment, burn-up etc. will be used for the best possible determination of the parameters together with the measurements of gammas and neutrons. Calorimetric measurement of the heat will be done on part of the fuel inventory as a way to anchor and verify the determinations. As a result of this investigation most likely results to some extent different from the safeguards accountancy data will be reported. The measurement system and electronic would be put under safeguard seals, and the signals split with data authentication techniques.

In addition, it is also foreseen that Cherenkov radiation devises will be used to inspect the assemblies.
Another issue with verification of declared data is that several of the parameters have been calculated by a certain code version at a certain time. For example, a fuel assembly declared in 1980 could have a different value than the same fuel assembly, with exactly the same operational history, declared in 2019 just because a new code version would be used.

A further issue that has to be considered is the mistakes in the records and data bases – 'true errors'. We find these in the Swedish records, and it is highly likely that they exist in all countries. These are completely non-systematic. In the proposed system they would be found due to the multiparameter approach with would raise flags for abnormalities. The multi-approach determination still gives reliable value for these, although possibly with a slightly larger uncertainty.

But the assemblies with faulty records must be dealt with, and they must be possible to dispose; it cannot be reasonable to suggest that they forever would not be disposed due to non-verification- it may never be possible to resolve these mistakes in some (likely few) cases. It must be better to have them safely disposed underground than not.

In summary it is proposed that at the time of disposal the best possible characterization of the fuel assemblies is done, using the history and properties of the fuels, codes and state-of-art measurements. This determination then represents the future record.

It should be continued to be investigated if it is possible to develop one joint measurement system, which also confirms that no rods have been removed, for both operator and IAEA/Euratom. The continuity-of-knowledge for each fuel assembly will be relied on. [8]

2.6. Uncertainties

The concept of uncertainty plays an important role in the strategy. For the safe and cost efficient disposal of the spent fuel the demands of accuracy and uncertainty for the final verification of the different parameter are typically:

- Decay heat: very high accuracy, order of few percent uncertainty;
- Criticality: very high accuracy, order of few percent uncertainty;
- Radiation doses: high accuracy – maybe 10 %;
- Nuclide inventory: for most nuclides fairly low accuracy need; <100 % (for some nuclides higher accuracy needed);
- Safeguard verification: amount of fissile material, burn-up, initial enrichment, cooling time, missing pins: intermediate accuracy.

3. FUEL CHARACTERISATION ACTIVITIES AND INTERNATIONAL COLLABORATIONS

For SKB, various activities aiming at making sure that by the time of start of operation of the encapsulation plant, sufficient measurement methods, codes, fuel data and knowledge and understanding of the nuclear fuel for operational and safeguards issues, and in the end for long-term safety are known and developed; and also, that sufficient competent human resources are available.

The planning horizon is around 10 years (approximate start of operation of the encapsulation plant). Important activities are Project Fuel characterisation, Project Fuel information, and code development.

These projects develop measurement detectors and systems and methods, and related codes, to be placed in the encapsulation plant and potentially used for all disposed fuel elements.

Several large and important international collaborations exist. There has been since several years collaboration between Sweden and USA – Department of Energy and Los Alamos NL, Oak Ridge NL, Lawrence Livermore NL and Pacific Northwest NL for example. A number of other countries, such as Belgium, Japan, South Korea, Germany, Euratom and the European Commission JRC are also involved. The new European Commission project EURAD ('Joint programming') is just about to be initiated; in EURAD one large work package is devoted to spent fuel characterization. IAEA has activities with consultancy and technical meetings underway, with a policy report as its goal.

The measurements of the so called SKB-50 - 25 BWR and 25 PWR fuel assemblies in Clab (the Swedish intermediate storage facility in Oskarshamn) - with calorimetry, gammas and neutrons, and other techniques, constitute an important basis for the activities. [3,4,5,6,7]

Another fundamentally important issue is the basic nuclear data and cross sections. The management and assessment of these may be of great importance to the effort. In various collaborations this is also covered, where laboratories, for example, as SCK Mol, in Belgium and Oak Ridge NL play prominent roles.

3.1. Fuel data management

SKB has a special long term project on fuel data management. It aims to preserve sufficient fuel data for all fuel elements to be finally disposed and restore records where applicable. Apart from the records and databases of SKB itself, records at the nuclear power plants, fuel suppliers and laboratories are utilized. It also defines what data that have to be preserved and available for the final repository (and partly for other parts of the back-end system).

One conclusion so far is that there is missing and erroneous data present in the records. The extent of this has not been completely determined yet. The implications of this are discussed elsewhere in this paper [9].

4. CHARACTERIZATION OF FUEL INTEGRITY

Damaged or failed fuel must be found and treated before final disposal. It is beyond the scope of this paper to describe the methods to do this; there are a number of commercially available methods. Sweden is carrying out a complete programme to find and treat all its damaged fuel in a way acceptable also for final geological disposal.

The spent fuel from the nuclear reactors will in many cases have a very long history before final disposal, from a few years up to perhaps more than a hundred years. It is known that in singular cases, for example fuel assembly handles have been broken during handling. For the handling of the spent fuel it is essential that the vast majority of assemblies can be handled without issues at least up to encapsulation for final disposal. Therefore, fuels with some known property that enhances the probability of failure should be characterized as potentially problematic. Examples include fuel materials, high burn-up and chemistry in storage pools. The potential long storage times mentioned above for spent fuel together with these other potential issues have not been fully investigated yet, but investigations and inspections are continually performed in many countries.

In nuclear chemistry and physics there has for a long time been research on the fuel behaviour in different time frames. Large project to be mentioned include the SCIP I-III (the OECD/NEA project Studsvik Cladding Integrity Project; phase four is now under initiation) [10]. The issue will be also included in the European Commission project EURAD mentioned above (part of the joint programming effort by the European Commission, now under contract signing) in the work package on spent fuel characterization [11]. Another European Project, DISCO, investigates dissolution rates and behaviour of for example doped fuels and MOX fuel [12].

TABLE 1. TENTATIVE TABLE OF VARIOUS IMPORTANT CHARACTERIZATION PARAMETERS TO DETERMINE IN THE BACK-END SYSTEM

Characterization parameter
Decay power
Radiation dose Radiation gamma Radiation neutrons
Criticality/multiplicity
Nuclide inventory
Burn-up
Initial enrichment
Cooling time
Safeguards parameters Burn-up Initial enrichment Cooling time Amount fissile material Weight Cherenkov radiation

Damaged
Risk to integrity
Dissolution rate in water

5. CONCLUSIONS

Fuel characterization is a necessary step in all parts of the back-end of the nuclear fuel cycle. The international development of this field is strong, and it is planning to be mature at the appropriate times for the various spent fuel programmes in the world.

In the paper it has been shown how the various parameters necessary to characterize are connected, and how a combination of fuel data, codes and measurements can give determination with sufficient accuracy and uncertainty (Table 1).

In terms of economy the decay power parameter is considered the most important, and in most need of development, as it is beneficial for safety and economy if the decay power can be determined with a very high accuracy and very low uncertainty.

Fuel integrity has been discussed, and the conclusion is that also properties such as if a fuel assembly is damaged, or if its integrity is at risk in the handling process, should be part of the list of characteristics of the fuel assembly. Also, the fuel chemistry properties should be characterized, such as dissolution rates in water.

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