Characterization of spent nuclear fuel for repositories and transport

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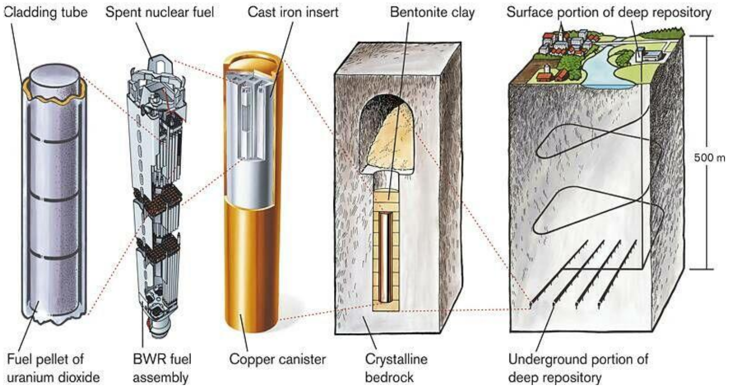
Parameters to characterize

- *Decay heat* – to fulfil temperature requirement on canister, bentonite, rock and fuel
- *Criticality* – multiplicity: to assure that criticality does not occur
- *Radiation doses* – both gamma and neutrons: For safety
- *Nuclide inventory: For safety analysis*
- *Safeguards verification*

Identify correct fuel, missing pins

Contents of fuel – amount of fissile material- Burn-up (BU), Initial enrichment (IE), Cooling time (CT), weight



Decay heat

Important in all parts of back-end system:

- Transportation,
- Intermediate storage (wet and dry),
- Final disposal: temperature requirements, typically highest allowed temperature

Intermediate storage:

Dry casks: uncertainties gets prominent due to few fuel elements in each cask

Wet pools: – decay power has to be known in order to cool the pools sufficiently; time after loss-of-cooling

Decay heat cont'd

Final geological repository

- Passively cooled by non-flowing processes in the rock:
- Important for the design of canisters and repository
- Strict temperature requirements on canister and bentonite (KBS-3 100 deg C) (and on rock)
- Important for the optimisation of canisters and repository (what fuels are encapsulated, distance between cansiters in the rock)

Decay heat cont'd

- Fundamental parameter in codes such as Scale, where content (e.g. U, Pt) is determined
- Important parameter to evaluate in reprocessing: main argument for reprocessing economical, but then also cost of storage must be included
- Safeguards: a parameter monitored as it is considered difficult to falsify

Closely linked with thermal modeling and verification

Calorimetry

- SKB has had for decades one of the few (if not the only) calorimeter that can measure whole fuel assemblies, and have published lots of measurements
- Calorimetry has the potential to be accurate; in the order of 2-3 %
- Problem: requires long measurement times for each assembly several days for highest accuracy
- SKB has to determine around 12 assemblies per day
- This would then require hundreds of calorimeters, which would be very inpractical

International Blind test of decay power predictions

- SKB blind test in prediction of decay power together with NEA/OECD
- Around 25 groups and organizations in many countries participate
- Virtually all relevant codes represented
- 5 Swedish fuel elements predicted and compared to calorimetric measurements

Objective

- Overall Aim with Blind Test Exercise:
  - ✓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.

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Objects for investigation

- 5 PWR fuel assemblies
  - ✓4 without burnable absorber
  - ✓1 containing burnable absorber

Fuel assembly ID	Cooling Time [y]
BT01	3.8
BT02	7.9
BT03	9.1
BT04	12.8
BT05	20.8

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Prerequisites

- Input-data to phase 1

BT01	Cycle 1	Cycle 2
Power operation (days):		
Subcritical (days):		
Average assembly power (MW):		
Average specific assembly power (W/g):		
Average core coolant temperature (Celsius):		
Boron concentration cycle start (BLX):		
Boron concentration cycle stop (EOC):		

BT01	
Manufacturer:	Areva
Model:	HTPM5
Initial weight of heavy metal (kg):	
Initial enrichment w/o U-235 (%):	
Pellet density UO2 (g/cm^3):	
Cladding - Material:	
Spacer - Material:	
Spacer - Mass per unit length (g/cm)	
Spacer - Density (g/cm^3)	
Fuel temperature (K):	
Pellet radius (cm):	
Cladding inner radius (cm):	
Cladding outer radius (cm):	
Instrument tube inner radius (cm):	
Instrument tube outer radius (cm):	
Guide tube inner radius (cm):	
Guide tube outer radius (cm):	
Pin pitch in fuel assembly (cm):	

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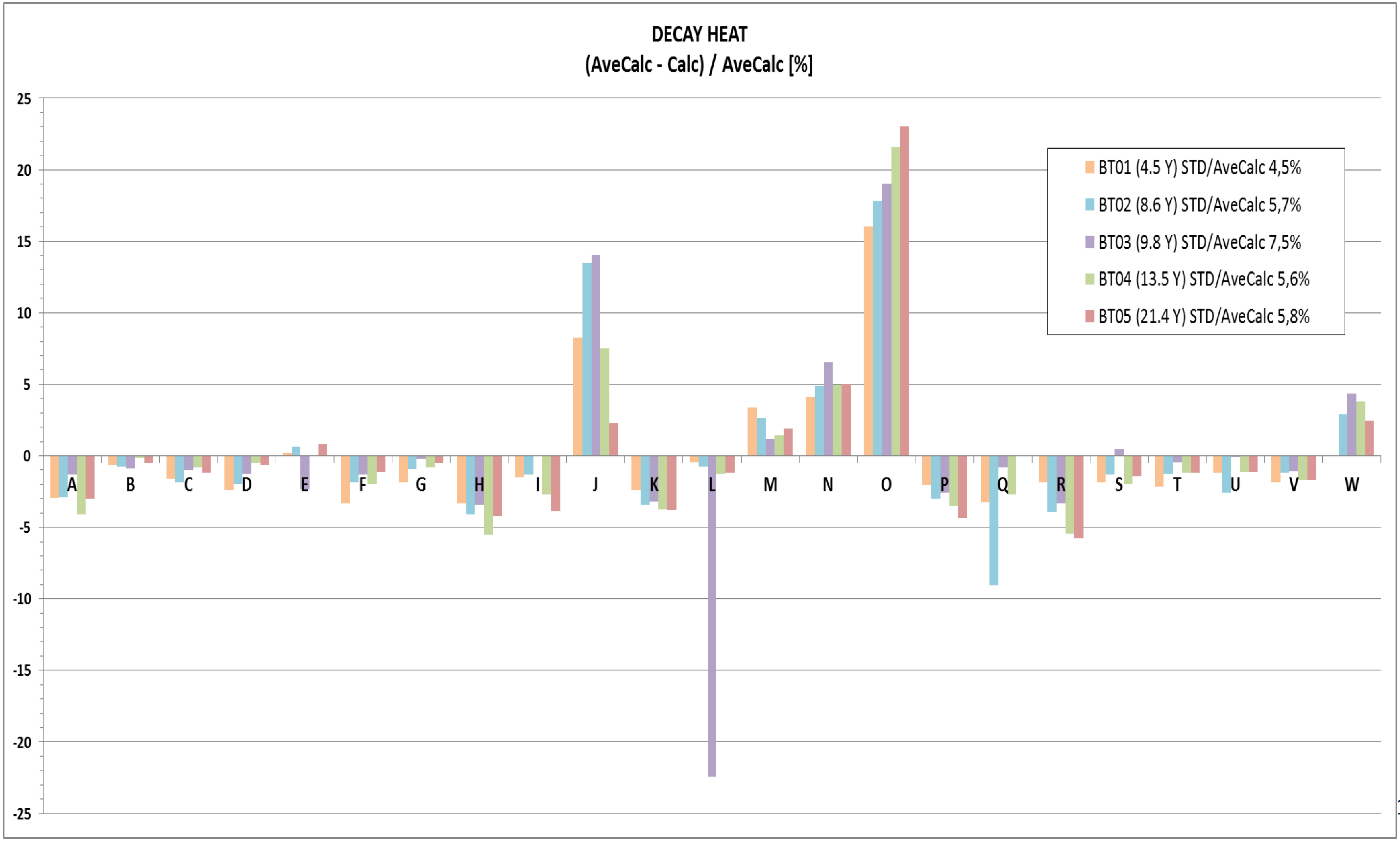
DECAY HEAT (CALC)



Radiation dose determinations

- Often assumed that there is considerable conservatisms in the results. Recent determinations show examples in more than one country where this is not necessarily true
- Very important for several reasons to be able to determine radiation dose (all types) with sufficient accuracy, and with *known* uncertaianties
- Radiation *protection*, *design* of equipment and shields etc.
- All parts of back-end system: transport, intermediate storage (wet and dry), encapsulation, final disposal

IAEA Safeguards of nuclear material

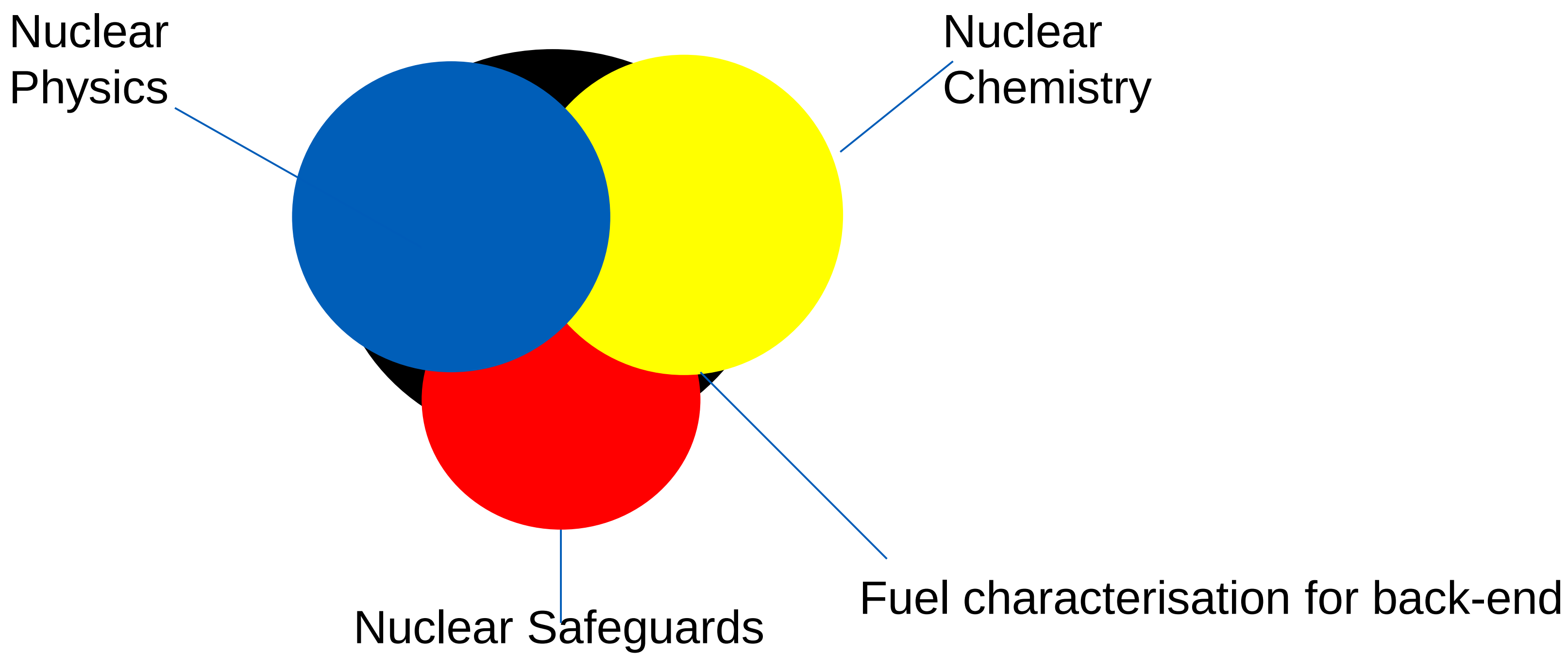
- Normally an owner of nuclear material declares it, and then IAEA and other authorities can inspect that it is
- A final geological repository is different from other storages of nuclear material in that it cannot be inspected once it is deposited
- This means that the safeguards procedure before deposition will be strict: measurements will be necessary of each fuel assembly

Safeguards of nuclear material, contd.

Important questions:

- SKB does not want double measurements – how to arbitrate? Below-par measurement methods
- How to deal with results that indicate ’non-complience’ – there may never be any resolution to this
- Codes used at time of declaration different from now and other times – can gives different results
- Mistakes in the records and data bases – ’true errors’.
- How to deal with those that never can be set straight? The spent fuel must be possible to dispose

Nuclear Physics, Nuclear Chemistry, Safeguards



- Safeguards, nuclear physics and nuclear chemistry different aspects of same things in these respects – more collaboration, break down division!

Uncertainties - required

- *Decay heat*: very high accuracy, order of few percent uncertainty
- *Criticality*: very high accuracy, order of few percent uncertainty
- *Radiation doses*: high accuracy, order of 10 %
- *Nuclide inventory*: for most nuclides fairly low accuracy need; <100 % (for some nuclides higher accuracy needed)
- *Contents of fuel* – amount of fissile material - Burn-up (BU), Initial enrichment (IE), Cooling time (CT): intermediate accuracy

Fuel measurements

- All parameters can ideally be determined with one joint measurement system together with modelling code and known history of the fuel
- Nuclear (gammas, neutrons) and chalorimetric (’thermos’) measured
- Important establish methods with sufficient statistics so they be general
- Present safeguards measurement devices: mobile, sampling (non-complete), for use in the field (´rough, unsophisticated’), low through-put etc.
- System at encapsulation plant: permanent, complete (all assemblies), robust, must give unambigeous results, complexity in principle acceptable, high through-put, low uncertainty

As there is sufficient information in the radiation field from the fuel, this is possible to achieve,

but with significant method development

SKB

Project Fuel Characterisation

– Develops measurement systems and methods, and codes to be placed in the encapsulation plant for all disposed fuel elements

– Based on measurments of the so called SKB-50: 25 BWR and 25 PWR in Clab with chalorimetri, gammas och neutrons

– Code development

– Method will mostly likely be based on a combination of fuel data, codes and measurements

Project Fuel information

- Aims to preserve sufficient fuel data for all fuel elements to be finally disposed
- At the nuclear power plants
- At Clab/SKB
- Other actors such as fuel vendors and laboratories

- Define what data have to be presevered and available for the final repository (and partly for other parts of the back-end system)

Need of nuclear data 'management'

- All relevant cross section, Q-values, branching ratios etc. must be known
- Codes – harmonization of data libraries – or are there good reasons to employ different libraries
- Are nuclear data used in the same way in all codes – and should they
- Arbitration between different measurements of nuclear data – new and historic – which are best
- How many measurements for each data point is necessary or to be wished – some central ones have just one or a few measurements now
- Uncertainties, combined uncertainties and biases fundamental to many issues concerning the back-end of the nuclear fuel cycle

Wide collaborations to attack these issues

- Sweden (SKB), USA (DoE, LANL, ORNL, LLNL and more) , Euratom, Belgium, Japan, Korea

SKB-50: 50 fuel assemblies (25 PWR, 25 BWR) measured with a variety of techniques: gammas, calorimetry, neutron measurements, novel instruments etc.

- Europe: ’Eurad’ WP Spent fuel characterization collaboration

- *Few experts in each country*
- *Competence development and broadening vital*

CHARACTERIZATION OF FUEL INTEGRITY

- Damaged or failed fuel must be found and treated before final disposal.
- Fuels with some known property that enhances the probability of failure should be characterized as potentially problematic. fuel materials, high burn-up and chemistry in storage pools.

International projects:

SCIP I-III, IV (the OECD/NEA project Studsvik Cladding Integrity Project.

European Commission 'joint programming' project EURAD n the work package on spent fuel characterization [11].

European Project, DISCO, investigates dissolution rates and behaviour of for example doped fuels and MOX fuel.[12]

SKB

Sweden’s back-end

- After leaving the reactor the fuel goes through the following steps in the Swedish back-end system:

- Transport to fuel pools at NPP.
- In pools at the NPP, cooled for a few years
- Dried for transportation in transport casks in vacuum. Normally 12 h, maximum about 24 h. Max temperature 400 deg. C.
- Transport in dry transport casks, max temperature 400 deg. C. He gas. Normally around two weeks. Max 240 days.
- Transport cask off-loaded at Clab interim storage – from dry to wet
- Moved to service pools, then to storage pools – all wet.
- Storage pools, decades (typically 10 – 40 years), around 36 deg. C.
- Moved to dry hot cell in Clink.
- Dried at max X deg. C. X not finally decided, but probably will be between 125 and 250 deg. C.
- Put into copper canister - dry. Gas changed to argon in canister – now >90 % Ar concentration, (may be higher purity eventually).
- Canister moved in transport cask to ship, and then to geological repository.
- Disposed of in the KBS-3 multibarrier system – eternity.

Joint SKB- SSM paper - ESARDA 2019

Aspects on declared accountancy data for the Final Spent Fuel Disposal in Sweden

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Abstract:

Sweden is in the final stages of planning and licensing an encapsulation plant and a geological repository that together will handle and dispose of all spent fuel from the nuclear programme. This process will include approximately 50,000 spent fuel assemblies which are planned to be stored in about 6000 copper canisters 500 m below ground. This paper outlines some important principal questions in relation to the declared accountancy data.

The Operator will recalculate and by measurement verify the isotopic composition for all spent fuel assemblies. The purpose is to have the best possible knowledge of important parameters of each individual assembly. This data is a key information for a safe and optimal use of the copper canisters and repository capacity. As a consequence of the re-evaluation, updated and most likely different safeguards accountancy data will need to be reported. 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 desired 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.

The nuclear State Authority is responsible for supervising the safety, security and safeguards in the country. These three areas are partly interconnected. National control measures for these areas consist of traditional authority supervision by legislation, documentation and paper trail of Operator's data. From the national perspective, it is of the highest importance to ensure that all deposited spent fuel is correctly declared and safely disposed. In case of anomaly and potential future dispute over past nuclear activities the completeness of the documentation of relevant operational data is essential.

Keywords: safeguards, final repository, encapsulation plant, spent fuel characterization

1. Introduction

As the planning for the final geological repository proceeds the issue of how to characterize the spent fuel before encapsulation is getting more attention. For safety reasons, it is essential to have the best estimates of important parameters such as the decay heat and criticality. Furthermore, it is important to define the different roles of the Operator, State Authority and the international organizations, respectively, and how the Operator´s data is related to safeguards declarations.

- **DETERMINING INITIAL ENRICHMENT, BURNUP, AND COOLING TIME OF PRESSURIZED-WATER-REACTOR SPENT FUEL ASSEMBLIES BY ANALYZING PASSIVE GAMMA SPECTRA MEASURED AT THE CLAB INTERIM-FUEL STORAGE FACILITY IN SWEDEN**

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- **ABSTRACT**

- The purpose of the Next Generation Safeguards Initiative (NGSI)–Spent Fuel (SF) project is to strengthen the technical toolkit of safeguards inspectors and/or other interested parties. The NGSI–SF team is working to achieve the following technical goals more easily and efficiently than in the past using nondestructive assay measurements of spent fuel assemblies: (1) verify the initial enrichment, burnup, and cooling time of facility declaration; (2) detect the diversion or replacement of pins; (3) estimate the plutonium mass [which is also a function of the variables in (1)]; (4) estimate the decay heat; and (5) determine the reactivity of spent fuel assemblies. Since August 2013, a set of measurement campaigns has been conducted at the Central Interim Storage Facility for Spent Nuclear Fuel (Clab), in collaboration with Swedish Nuclear Fuel and Waste Management Company (SKB). One purpose of the measurement campaigns was to acquire passive gamma spectra with high-purity germanium and lanthanum bromide scintillation detectors from Pressurized Water Reactor and Boiling Water Reactor spent fuel assemblies. The absolute ^{137}Cs count rate and the ^{154}Eu/^{137}Cs, ^{134}Cs/^{137}Cs, ^{106}Ru/^{137}Cs, and ^{144}Ce/^{137}Cs isotopic ratios were extracted; these values were used to construct corresponding model functions (which describe each measured quantity's behavior over various combinations of burnup, cooling time, and initial enrichment) and then were used to determine those same quantities in each measured spent fuel assembly. The results obtained in comparison with the operator declared values, as well as the methodology developed, are discussed in detail in the paper.

- **KEYWORDS**: *passive gamma, initial enrichment, burnup, cooling time nondestructive assay of spent fuel, germanium detector, $LaBr_3$ detector.*

accepted for publication in NIM A.

Additional information

- EURAD – Joint European Programming approved

One Work Package on Spent fuel characterization with SKB as coordinator. Supported by IAEA

- IAEA – Technical meeting November 2019

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 ratiation
Damaged
Risk to integrity
Dissolution rate in water

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.
- 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.