The back-end fuel: focus on spent nuclear fuel characterization

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Back-end in Sweden

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

At NPP

- Transport to fuel pools at NPP.
- In pools at the NPP, cooled for a few years

Transportation

- Dried for transportation in transport casks, maximum 24 h, normally around 12 h. Max temperature 400 deg C.
- Transport in dry transport casks, max temperature 400 deg C. Normally around 2 weeks, max Y months.

Back-end in Sweden cont.

Interim storage, Clab

- Transport cask off-loaded at Clab interim storage – from dry to wet
- Moved to service pools, then to storage pools – all wet; around 20-30 deg C.
- Storage pools, decades, 20-30 deg C.

Encapsulation, Clink

- Moved to dry hot cell in Clink.
- Dried at max X deg C. X not finally decided yet; will probably be between 125 and 250 deg C. depending on drying method
- Put into copper canister - dry.

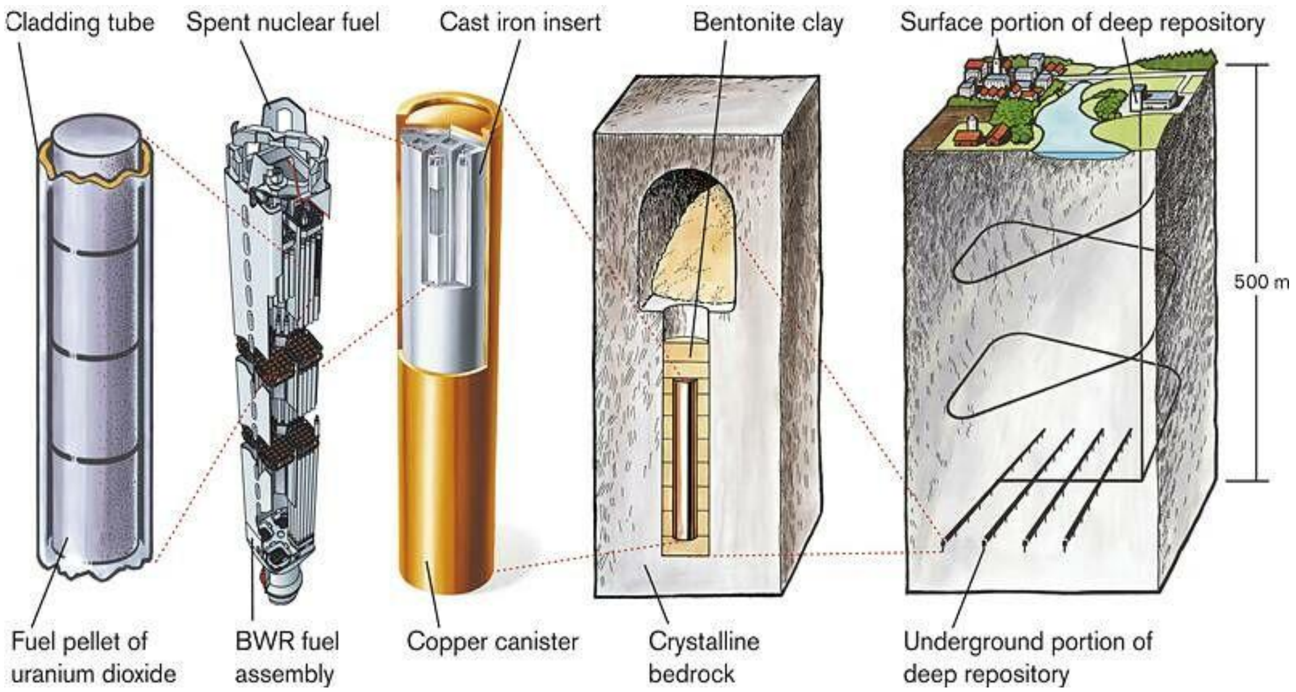
Back-end in Sweden cont.

Transportation to geological final repository

- Canister moved in transport cask to ship and then to geological repository.

Geological final repository

- Disposed of in the KBS-3 multibarrier system – ***eternity***.



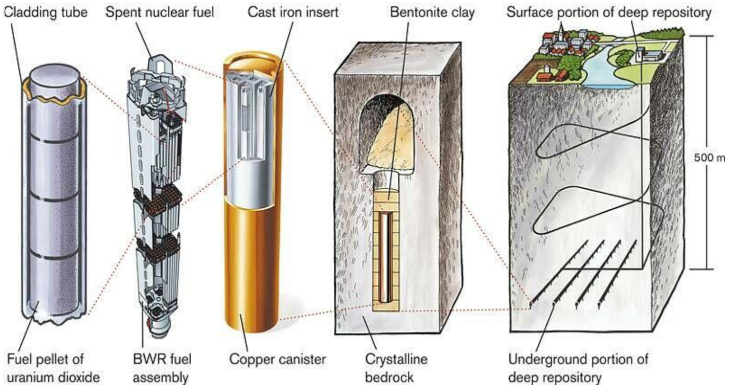
Parameters to characterize

- *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

- Fuel integrity and mechanical properties



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
- The regulations on Safeguards says that ’If the operator intends to permanently store a nuclear material in a place difficult to access for identification and verification... All such nuclear material shall be characterized by the operator to such an extent that sufficient information and knowledge exist about the nuclear material *prior* to such storage.
- This means that the safeguards procedure before deposition will be strict: measurements will be necessary of each fuel assembly

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

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What are the realistic uncertainties, biases and required margins for decay power and thermal issues in the back-end?

- The international community must come to some type of decision and agreement on this eventually
- Not completely clear today what these numbers should be, but within a few years the picture should be much better
- Low statistics validation
- How should conservatisms be judged?
- Example: number of sigmas to be employed – some of the statistics is a bit exotic
- Swedish (in-direct) example: none of the 6000 final disposal canisters must penetrated in 1000000 years for the safety analysis to work

Importance of ‘mistakes’ and human errors

- Incorrect values in the records of the fuel elements exist - investigated systematically in Sweden now, but difficult to completely abolish
- Codes and scripts in various parts of the determination chain can contain errors
- Running of codes by different modelers often gives different result with the same code and the same input data
- Can be many decades between the different parts of the calculations in the back-end – facts may be forgotten, and understanding develops
- Etc.
- These are completely unsystematic and very difficult to analyze

Need for redundancies in the determination system that can flag anomalies – systematic measurements

Optimization and economy

- >25 % of production cost of electricity is for the back-end in Sweden
- According to both the nuclear act and the environmental act, economy must be considered when designing nuclear systems
- Therefore, optimization is now a very important thing in the back-end in Sweden
- One, perhaps the most important, way is thermal optimization for the back-end, and particularly the final repository system
- Decay power determination, accuracy, materials, thermal modeling etc. are paramount in this process

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Optimisation

- Back-end getting increasingly costly – owners a bit worried
- One important avenue to optimize is through thermal methods
- Requires very deep understanding in order to move regulatory limits and need for margins
- Also linked to thermal modeling
- Relevant for all parts of the back-end

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

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

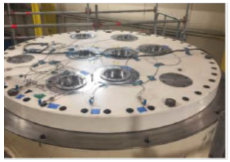
International Blind test of decay power predictions

- 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

Temperature

- Often the requirement linked to decay power is temperatures
- Temperature modleing essential - often been considered ’easy’, but may not always be
- Often requirements and determinations contain large conservatisms

Thermal Phase II Round Robin Summary

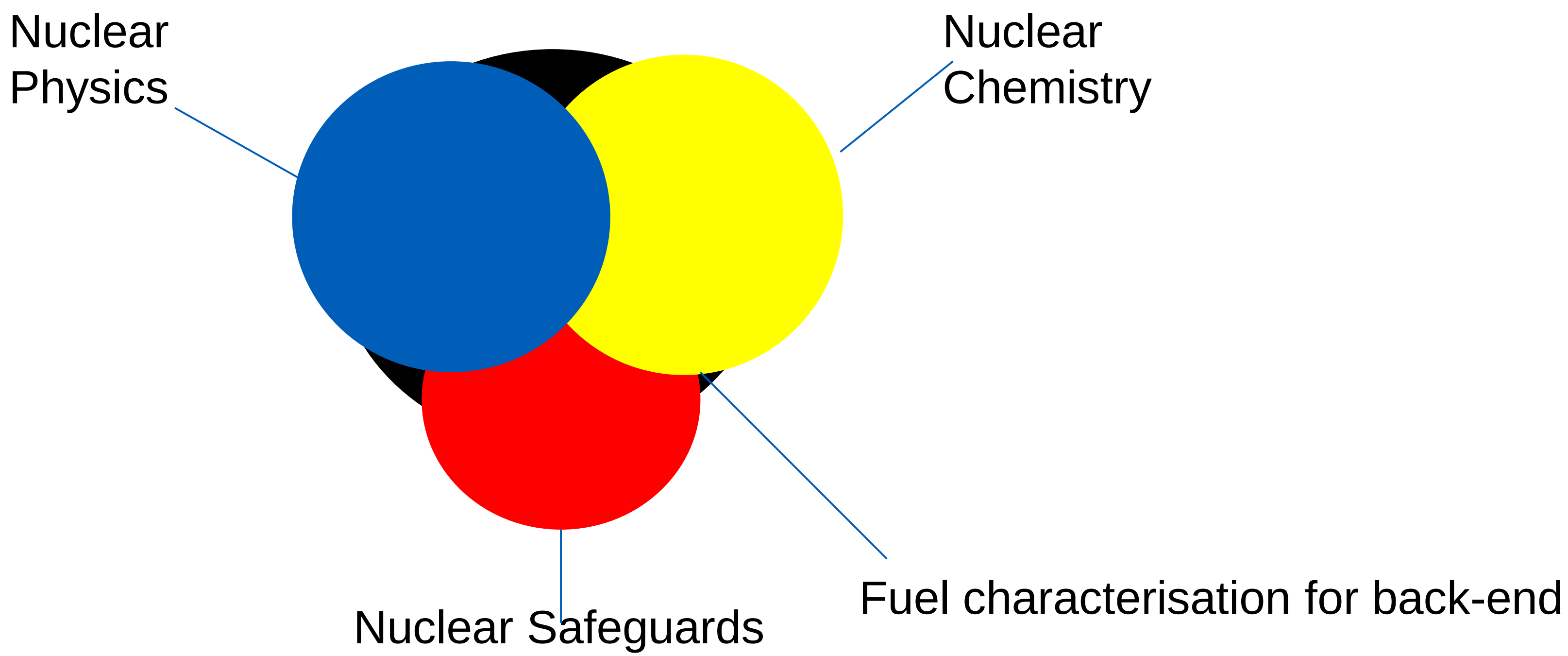


- Steady state PCTs from all models and measurements significantly lower than the design licensing basis:

Parameter	FSAR	LAR	Best-Estimate	HBU Cask Measurements
PCT (model vs data)	348°C	318°C	254-288°C	229°C
Heat Loadouts	36.96kW	32.934kW	30.456kW	30.456kW
Ambient Temperature	100°F	93.5°F	75°F	75°F
Design Specifics	Gaps	Gaps	Gaps	No Gaps?

Slide courtesy of Al Csontos, Co-chair of EPRI ESCP Thermal Subcommittee

Nuclear Physics, Nuclear Chemistry, Safeguards



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

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.

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

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
- Requirement – example: 1 Gy/h on the surfcae of copper canister – in reality around 0.5 Gy/h.
- Usually not limiting

Effects of radiation

- Direct radiation damage
- Activation – the radiation reacts with nuclides and creates new nuclides
- Radiolyses – chemical decomposition of molecules through ionizing radiation
- Contamination – radioactive nuclids contaminates

Criticality

– 'Mother' of all nucelar technology requirements: criticality must not occur outside a reactor

– Keff= 1 – critical = reactor – self-sustaining chain reaction

– Most often not limiting, but small margins to Keff=1.

– Requirement usually Keff<0.95, in some cases Keff<0.98.

– Relevant for ~ 1 billion years due to the half-life of U235 – 700.000.000 yr.

Nuclide inventory

– Composition of the nuclear material on the nuclide level
– Used primarily for safety assessments
– For the safety assessment of the final repository, the total amount of the various nuclides are used for alla canisters
– Usually not close to critical limits, therefore low requirements of accuracy
– Some of the nuclides, the fissile material such as U and Pu, are under international safeguards.

Fuel integrity

The strength of the fuel and ability to keep its properties

Affected by a large number of parameters, such as:

–Temperatures

–Temperature cyclings

–Chemistry of the water

–Hydration of the cladding

–Type of Zircalloy in the cladding

–How it is run in the reactor

–Mechanical impact

–Time – properteis in long time spans often not known

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

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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