Application of a Specific High-Burnup Spent Nuclear Fuel Analysis Methodology to the ENSA ENUN Transportation Packages

IAEA
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1. Overview of Spent Nuclear Fuel Transportation in Spain

- > 20% electricity generated from nuclear.
- 10 reactors at 7 NPPs:
  - 7 operating:
    - 1 permanently shutdown;
    - 2 under dismantling & decommissioning;
- Open cycle strategy for the back-end:
  - a) Interim dry storage in ISF at nuclear sites;
    - 2 technologies: bare fuel casks & canister systems
  - b) Interim dry storage in a Centralized Storage Facility;
  - c) Deep Geological Repository;
- > 6.700 MtU (20.000 FA), after 40 years of NPPs operation.
1. Overview of Spent Nuclear Fuel Transportation in Spain

![Diagram of nuclear fuel transportation in Spain](image)
1. Overview of Spent Nuclear Fuel Transportation in Spain

- 70’s to mid 80’s:

The majority of the Spent Nuclear Fuel (SNF) produced by the first generation of Spanish NPPs was transported **abroad**:

- *Sta. María de Garoña (BWR)*;
- *José Cabrera (PWR)*;
- *Vandellós I (GCR)*;

✓ Transported to U.K. and France, for **reprocessing**.

✓ Advantageous economical agreements, and severe control of nuclear materials;
1. Overview of Spent Nuclear Fuel Transportation in Spain

➢ 70’s to mid 80’s:

SNF from Sta. María de Garoña NPP was transported to Windscale/Sellafield (UK)

Fuel parameters (SNF):

• Design: GE-7 (BWR);
• Burnup: 8.6 - 22.7 GWd/MTU;
• U-235 enrichment: 2.1% - 2.5%;
• Cooling time: < 5 years;

Transportation packages:

• Design: NTL9 and NTL11 flask, Type B(M)F;
• Validated by Spanish Ministry of Industry in 1980;
• Capacity: 7 and 17 FA;
• Maximum allowed burnup: 36.5 and 38.5 GWd/MTU;
• Maximum allowed thermal power: 24.5 and 35 GWd/MTU;

Transportation data:

• 52 transportations performed (36 with NTL9 package and 16 with NTL11 package);
• 500 FA were transported
• Road and maritime transport routes;
1. Overview of Spent Nuclear Fuel Transportation in Spain

- **From mid 80’s onwards:**
  - Agreement conditions changed. It implied *Spain shall be responsible of the final radioactive waste, after reprocessing*;
  - SNF transport from *Sta. María de Garoña* and *José Cabrera NPPs* ceased.
  - Only the remaining spent fuel from Vandellós I was transported in late 80’s, because early shutdown of the NPP:
    - Transported by road to *Marcoule* (France), for reprocessing;
    - Spain pays a daily fee to France for storing the vitrified HLW;
    - 4 units of TN-81 casks have already been specially fabricated (ENSA), to return to Spain the vitrified HLW (*date not already decided*);

- **1984:**
  - A public company, *ENRESA*, was created to manage all radioactive waste produced in Spain, including SNF from power reactors;
  - All remaining of SNF is *wet* and *dry* stored at 7 different NPP sites;
  - Spain has decided an *open cycle strategy* for the management of the spent fuel;
2. Scope & Goals of ENSA’s Approach to HBU SNF Transportation

- **ENSA** is the designer and Certificate Holder of **ENUN 32P** and **ENUN 52B** SNF, dual purpose casks.

- **ENRESA** has contracted ENSA to modify the design, and supply new casks to load SNF from Almaraz, Trillo and Santa María de Garoña NPPs.

- Scope of new projects include **dry storage** and **transportation** of **high burnup (HBU)** SNF.
2. Scope & Goals of ENSA’s Approach to HBU SNF Transportation

➤ Characteristics of HBU:
  • Increase of cladding corrosion layer thickness.
  • Hydrogen absorption.
  • Increase in the release of fission gases.

➤ Consequences:
  ▪ Drop of cladding temperature during dry storage.
  ▪ Increase of the **susceptibility to brittle fracture**.
  ▪ Gap variation between cladding and fuel pellets.
  ▪ Pressure increase inside fuel rods.

➤ Increase of the risk of fuel rod damage

➤ Guidance and regulation:
  • National standards (Storage) + IAEA SSR-6, Rev. 1 (Transportation).
  • U.S. NRC, Interim Staff Guidance 11, Rev. 3 -> Average burnup ≥ **45,000 MWd/MTU**.
  • Other countries consider additional parameters, without specific threshold.
  • U.S. NRC, NUREG-2224: engineering assessment + license approaches.
2. Scope & Goals of ENSA’s Approach to HBU SNF Transportation

✓ 2016 – 2018: Develop a specific **analysis methodology** to evaluate the structural integrity of HBU SNF assemblies and the impact on the safety functions of ENUN 32P and ENUN 52B casks.

✓ 2021: Obtain the **technical approval** of the methodology by the Spanish Nuclear Safety Council (CSN).

➢ 2018-2022: **Apply the methodology** to the safety evaluations of ENUN 32P and ENUN 52B casks, to evaluate an increase of the authorized content for PWR and BWR HBU.

➢ 2022 - ?: Obtain **revised Certificates of Compliance (COCs)** of ENUN 32P and ENUN 52B casks for dry storage, and transportation as Type B packages.
2. Scope & Goals of ENSA’s Approach to HBU SNF Transportation

- **Steps of the licensing approach:**
  
  - **Design basis evaluations**, to demonstrate compliance of the cask safety requirements:
    - Assure *structural integrity* of SNF rods, during all postulated events;
    - Quantify the *decay heat* and demonstrate passive removal;
    - Assure compliance of *dose* regulatory limits;
    - Assure the *subcriticality* of the radioactive content;
    - Perform *containment* evaluation of the radioactive products;
    - Assure *retrievability* of SNF during dry storage.

  - **Additional defence in depth analysis**, assuming hypothetical failure of the fuel rods and reconfiguration of the radioactive material inside the cavity, to:
    - Consider the uncertainties in the *ageing* effects of the HBU SNF;
    - Evaluate the performance of the HBU SNF, after **20 years of dry storage**.
3. Safety Analyses: Design Basis Evaluations

- Analyses that justify the structural integrity of the SNF rods:
  - Dry storage up to a maximum of 20 years.
  - Off-site transportation immediately after loading the SNF inside the cask from the spent fuel pool.
  - Off-site transportation of SNF that has been dry stored less than 20 years.

1) Structural evaluation of the fuel rods (dynamic calculations of cask drop events), considering specific HBU SNF parameters:
   - Establishment of a bounding End Of Cycle (EOC) inner rod pressure.
   - Best estimate mechanical properties for the cladding material, considering embrittlement.
   - Bounding value for the thickness of the cladding corrosion layer.
   - Fatigue evaluation during normal conditions of transport, using cumulative damage approach.

2) Thermal evaluation.

3) Shielding evaluation.

4) Criticality evaluation.

5) Containment evaluation.
4. Defence in Depth Analyses

- **Mitigate** uncertainties in the ageing of irradiated materials, after dry storage of the HBU SNF $\geq$ 20 years.
- Complementary analyses for the safety functions of the cask, assuming **hypothetical but credible scenarios of fuel reconfiguration of SNF**, after a loss of structural integrity of any of the fuel rods.
- Shall demonstrate **compliance with the applicable regulation** for storage (national standards) and transportation (IAEA No. SSR-6).
- Most of the hypothetical scenarios selected for the reconfiguration analyses have, extracted from NUREG 2224 and NUREG/CR-7203.
4. Defence in Depth Analyses → **Thermal**

- **Phenomena identified due to SNF reconfiguration:**
  
  a) **Change on the physical and thermal properties of the environment of the inner cavity:**
     - *Fission and filling gases released* due to the failure of the fuel rods;
     - Increase of the pressure;
     - Impact on the **thermal conductivity** of the environment.
  
  b) **Change in the distribution of the heat source.**

- **Additional considerations:**

  - Percentage of *failed fuel rods*: 1% (Normal), 10% (off-Normal) and 100% (Accident);
  - Sensitivity analysis of *packing fraction* of material mixture (rod cladding + fuel pellets);

- **Two different scenarios analyzed,** to maximize cask temperatures:

  ✓ Scenario 1(a) (*breached fuel rods*): material of the fuel pellets kept inside the fuel rod cladding;

  ✓ Scenario 1(b) (*damaged fuel rods*): material of the fuel pellets, in the form of 'debris', distributed inside the inner cavity, depending on cask orientation:

    - horizontal;
    - vertical;
4. Defence in Depth Analyses → **Thermal**

- ENUN 32P cask, with fuel reconfiguration -> **FEM model:**

**Vertical orientation**
- Mixture of gases

**Horizontal orientation**
- Heat source: mixture of UO₂ + rod cladding + gases
4. Defence in Depth Analyses → Thermal

- ENUN 32P cask, with fuel reconfiguration -> $T^a$ distribution for different packing fractions:
4. Defence in Depth Analyses ➔ Structural

- Specific evaluations of the structural integrity of the **fuel rods are not required**, because reconfiguration scenarios conservatively assume that 100% HBU fuel rods fail under accident conditions.

- **Analysis process for cask materials:**
  
  i. **Additional pressure** contribution inside the cask cavity (internal load), to account for release of fission and filling gases from failed fuel rods.
  
  ii. Comparison of the maximum temperatures achieved in the cask materials, as a consequence of fuel reconfiguration.
  
  iii. Assessment of the **materials properties** at new maximum temperatures:
    - New mechanical stress limits.
  
  iv. **Verification of the acceptance criteria:**
    - Maximum mechanical stresses vs. new stress limits.
4. Defence in Depth Analyses → Shielding

- Shielding models characteristics:
  - Debris is modelled as UO₂ with a packing fraction of 0.58.

- Scenarios analyzed, to obtain maximum doses:
  1. **Normal Conditions**, scenario 1(a) (**breached fuel rods**): material of fuel pellets kept inside fuel rod cladding.
     - 100% source term is considered as in design basis evaluations.
     - 3% extra source term added inside each cask cell location, according to cask orientation.
       - Extra 3% is considered to come from the most radiative part of the fuel and calculated without cladding, to avoid self-shielding:
         - horizontal (0°);
         - horizontal (45°);
         - vertical;
4. Defence in Depth Analyses ➔ Shielding

- **Shielding models characteristics:**

  - Debris is modelled as UO₂ with a **packing fraction** of 0.58.

- **Scenarios analyzed, to obtain maximum doses:**

  2. **Accident conditions**, scenario 1(b) (**damaged fuel rods**): material of the fuel pellets, in the form of 'debris', distributed inside the inner cavity:

    - 100% of the fuel is relocated according to cask orientation. Rod cladding material not considered, but associated activation source is located among the relocated fuel.
      - horizontal (0º);
      - horizontal (45º);
      - vertical;

![Diagram showing different scenarios](image)
4. Defence in Depth Analyses → Shielding

- ENUN 32P cask with fuel reconfiguration -> dose analysis model:

Reconfigured radioactive material
4. Defence in Depth Analyses \(\rightarrow\) Criticality

- Criticality models characteristics:
  - The different types of fuel distortion and reconfiguration, merged up in a single conservative model.
  - The 2-region model is composed by two concentric regions:
    - outer region consists of a single rod width shell, where rods are disposed as close as they can and in touch with the wall of the basket cell, acting as reflector;
    - inner region is disposed as a rectangular array of rods, separated searching for the optimal pitch.

Fuel Assembly Model

- \(P_1\) = rod-to-rod pitch of the outer region;
- \(L\) = inner width of the basket cell;
- \(P_2\) = rod-to-rod pitch of the inner region;
- \(L_2\) = width of the inner region = \(L - 2P_1\);
4. Defence in Depth Analyses → Criticality

- The 2-region model has been validated comparing the results, with equivalent single region model results (Design Basis).

- The 2-region model results in an increase in the $k_{\text{eff}}$ of $\approx 9\%$. 
4. Defence in Depth Analyses → Containment

Same approach and criteria in the reconfiguration scenarios respect to the design basis conditions:

- Verify the fulfilment of the tightness of the containment barrier:

  ✓ **Leak-tight** criteria, for the containment barrier. It precludes any significant release of radioactive material;

  ✓ **Water-tight** criteria, for exclusion barrier (redundant to the containment barrier): it precludes any access of water, necessary for BWR type packages;
5. Conclusions

- Ensa has developed a specific **analysis methodology** to evaluate the safety functions of **ENUN dual purpose casks**, for storage and transportation of **HBU SNF**.

- The methodology has been technically accepted by Spanish Nuclear Safety Council.

- The assumptions are currently being implemented in the design modifications of ENUN 32P and ENUN 52B SNF casks, to evaluate an **increase in the authorized content**.

- Final goal is to obtain **revised CoCs** of **ENUN 32P** and **ENUN 52B** casks, to load the majority of HBU SNF inventory from Almaraz, Trillo and Santa María de Garoña NPPs.

- The methodology establishes two groups of **safety analyses**:
  
  i. **Design basis** analyses, that evaluate and assure **structural integrity of HBU SNF rods**, during all postulated events for storage and transportation;
  
  ii. **Defence in depth** analyses, **assuming reconfiguration of HBU SNF rods inside the cavity**, after 20 years of dry storage, demonstrating compliance of storage and transportation regulations.
Thanks for your attention!

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