Supplement of Safety of Nuclear Waste Disposal

Antineutrino detection concepts for safeguarding spent nuclear fuel

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ANTINEUTRINO DETECTOR CONCEPTS FOR SAFEGUARDS MONITORING OF SPENT NUCLEAR FUEL

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Introduction: Spent Nuclear Fuel

• Spent Nuclear Fuel (SNF) produced by reactors
  – Total global SNF: ~300,000 t HM* + ~7,000 t HM annually

• Discharged SNF after refuelling goes to:
  – Spent fuel ponds (several years)
  – Interim storage facilities (several decades)
    or reprocessing
  – Ultimately: geological repository
    (none yet – Onkalo starting ’25, ~100 years operation)

• Even without operating reactors:
  – Decades to centuries of actively managing SNF

* Nuclear Technology Review 2021, GC(65)/INF/2, IAEA Report,

Fuel assembly containing SNF being loaded into a cask
https://www.gns.de/language=de/21562/behaelterbeladung
Safeguarding Spent Nuclear Fuel

• SNF requires safeguards:
  – Mostly $^{238}$U (93-96%), but also: <1% $^{235}$U, ~1% Pu
  → interim storage & final disposal subject to safeguards

• Current safeguards often rely on Continuity of Knowledge (CoK)
  – Nuclear material accountancy
  – Containment/Surveillance (C/S)
  – Design information verification (DIV)

• Declarations verified by regular inspections

<table>
<thead>
<tr>
<th>Material</th>
<th>In SNF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}$U</td>
<td>93-96%</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Fission fragments (e.g. $^{90}$Sr)</td>
<td>3-5%</td>
</tr>
<tr>
<td>Pu</td>
<td>~1%</td>
</tr>
<tr>
<td>Minor actinides</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>
Safeguards R&D for SNF Storage

• Safeguards impact on facility operation
  – Inspections require **access** and **radiation exposure**
  – Re-establishing CoK ("re-verification") in case of discrepancies or incident requires **huge effort & time**

• Safeguards R&D aims
  – **Lessening** operational burden (automated/remote systems)
  – **Complement** existing methods

• Under development for interim storage facilities
  – **Improved C/S** techniques (e.g. "laser curtains")
  – **Muon tomography** of casks (measuring content density)

• Under development for geological repositories
  – **Muon tomography** for design information verification

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Antineutrinos as Reactor Safeguards Tool

• Concept originally proposed for reactor safeguards
  – Several active experiments, prototypes and groups
  – Physics community interested in practical applications
    → NuTools report, annual Applied Antineutrino Physics workshops

• During beta-decay: emission of electron antineutrinos $\bar{\nu}_e$
  – Spectra and flux depend on isotope
  – Fission fragments rich in beta-decaying isotopes

• Unique to antineutrinos: cannot be shielded
  – Signal even penetrates heavy shielding
  – Unique signal: nuclear decays main source of antineutrinos
  – Emission spectrum correlated with decaying isotope
  – But also: very low interaction rates

• Most approaches: detection via Inverse Beta-Decay (IBD)
Antineutrino Detection: Inverse Beta Decay

- **Inverse Beta-Decay (IBD)**
  - Main channel of interest
  - Process: $\bar{\nu}_e + p \rightarrow e^+ + n$

- **Double coincidence time structure:**
  $\rightarrow$ powerful **background rejection**

- **Kinematics impose energy threshold**
  - **1.806 MeV** for (semi-)free protons
  - Require **hydrogen-rich** detection medium: scintillators, organic media

**Prompt Signal**

- $e^+$ energy $\propto \bar{\nu}_e$ energy

**Delayed Signal**

- $n$ direction $\propto \bar{\nu}_e$ direction
Antineutrino Detection as SNF Safeguards Tool

• From reactor measurements to SNF safeguards
  – Fission fragments in SNF continue to beta-decay for decades/centuries
  – Lower energy, lower flux than reactors
  – Main detectable isotope: $^{90}\text{Sr}$

• Advantages apply to SNF as well
  – Signal penetrates containment
  – Direct measure of content complementary to muon (density) or n/γ measurements

• Complementary characterisation of SNF
  – Ongoing decays → continuous monitoring
  – No need for direct physical access → no radiation exposure for staff

• NU-SAFEGUADS project investigates several candidate technologies
  – LAB, PVT scintillators + TMS time-projection chambers
  – Investigate several storage scenarios
Antineutrino Flux Modelling: Understanding the SNF Signal

**Fuel Simulation**
- **ONIX**: simulate fuel assemblies
  - Example: GKN II fuel assembly at 54 MWd/kg burn-up
- Tally isotopic contents after burn-up

**Antineutrino Spectrum**
- Select main contributing isotopes (high $\bar{\nu}_e$ energy + long half-lives)
- NDS ENDSF database/BetaShape for beta & $\bar{\nu}_e$ energy spectra

**Detectable Signal**
- Convolve with IBD cross-section
- Determine interaction rate per ton of SNF
- Repeat for different SNF ages
Example Geological Repository: Layout & Interaction Rates

- Modelling sensitivity of idealised 80m$^3$ detectors (no background)
  - **Eight locations**: 50m above casks

- Simplified geological repository
  - 1,120 **canisters** x 10 fuel assemblies
  - Uniform age for all canisters (50, 100 or 200 years)

- Modelled diversion of 1.25% of content
  (14 canisters: ~78.4t HM)

- Three detection media compared – all similar overall performance
  - Use TMS as example medium
Example Geological Repository: Expected Sensitivity

- Criterion for detection: 90+% CL that diversion occurred
- Time $t_{CL90}$ to reach 90% CL for all scenarios for removed group
  - Scenario 1 (50 years): $t_{CL90}$ (median) = 8.6 months (5.0-12.5 months), 90% quantile = 11.5 months
  - Scenario 2 (100 years): $t_{CL90}$ (median) = 14.2 months (10.6-17.3 months), 90% quantile = 16.7 months
  - Scenario 3 (200 years): $t_{CL90}$ (median) = 20.6 months (19.4-21.8 months), 90% quantile = 21.6 months
Example Interim Storage Facility: Layout & Interaction Rates

- Modelling sensitivity of idealised 80m³ detectors (no background)
  - **Four locations:**
    - 10m distance from casks
    - One side (left) service building/access
    - Iterative optimisation of locations

- Simplified interim storage
  - 130 fuel casks x 19 fuel assemblies
  - SNF stored 20-60 years ago

- Modelled following scenarios:
  - Diversion of 1 cask (~10.6 t HM)
  - Diversion of ½ cask (~5.3 t HM)
  - Re-verification of 1 cask w/ directional capability
• Criterion for detection: 90+% CL that diversion occurred

• Time $t_{CL90}$ to reach 90% CL for both scenarios for each cask location
  – Scenario 1 (1 cask): $\tilde{t}_{CL90}$ (median) = **6.4 months** (0.4-15.2 months), 90% quantile = 10.9 months
  – Scenario 2 (½ cask): $\tilde{t}_{CL90}$ (median) = **10.3 months** (0.6-28.4 months), 90% quantile = 18.1 months
Example Interim Storage Facility: Re-verification with 30º Directional Capability

- Re-verification of **single cask of interest**: verify full or declare empty cask
  - Use Sequential Probability Ratio Test (SPRT) - allow 10% false negatives, 20% false positives (can be tuned)
  - Assume 30º directional selection for incoming antineutrinos (angular resolution is technology dependent)

- Time $t_{SPRT}$ to verify/reject a cask (30º selection cone)
  - Full Cask: $\tilde{t}_{SPRT}$ (median) = 2.6 months (0.1-14.6 months), 90% quantile = 5.6 months
  - Empty Cask: $\tilde{t}_{SPRT}$ (median) = 2.2 months (0.1-10.6 months), 90% quantile = 4.7 months
Conclusions

- **Antineutrino detection for safeguards**
  - *Attractive* features: reduce need for direct (staff) access & unique signal for SNF
  - Information complementary to density or n/γ measurements
  - But: *challenging* signal rates in any scenario

- **Geological repositories**
  - Long-term monitoring (100+ years) difficult: 
    - **limited by** $^{90}$Sr *half-life* of ~30 years
  - Monitoring during filling: better signal rate but hard to cover whole repository

- **Interim storage**
  - Newer SNF & lower stand-off distances: **high signal rates**!
  - **General monitoring**: < 1 year to detect removal
  - **Re-verification** with directional detector: < 5 months required

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Interim Storage: Monitoring Scenario

Interim Storage: Re-verification Scenario

Empty Cask

90% quartile

90% quartile

Time to decision [months]
**Summary & Outlook**

- **NU-SAFEGUARDS**: studying feasibility of antineutrino detection as safeguards for SNF

- Sensitivity analysis of two model SNF storage sites
  - Ideal conditions: signal within few months
  - Statistical tests can be tuned to specific use cases
  - Directionality can speed up re-verification

- Ongoing project to investigate:
  - Embedding application for antineutrino monitoring in overall safeguards concepts & use cases
  - Understand properties & background rates for each detector technology

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