Regulatory nuclear material control of STUK – NDA methods of Spent Nuclear Fuel in Finland prior Geological Disposal

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TECHNICAL MEETING ON SPENT FUEL CHARACTERIZATION FOR MANAGEMENT OF SPENT FUEL IN THE BACK END OF THE FUEL CYCLE
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• What data is needed for verification and analysis?
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Goal of NM verification
Safeguards challenge of geological disposal

• Goal of geological disposal is to store the spent fuel environmentally safely and non-accessibly, forever.
• 1 canister ~ 1-2 IAEA Significant Quantity (3000-5000 canisters in case of Finland)
• >50 SQ stored every year, 50 % partial defect of that =…!
• All parties involved must have clear and unambiguous common understanding about what has been disposed of.
• It is imperative not to encapsulate and dispose any items which may in later stages generate open questions.

Image, Posiva Oy
Security challenge

• Similar to safeguards challenge, but even smaller defects matter
  – A single missing pin is highly relevant
• NM Security and Safeguards have many common goals and means
  – The difference is mainly a question of methods used and against what you protect
• STUK has set the goal that pin level defect should be possible to detect
Characterization vs Verification

- **Verification** in this presentation means *Safeguards verification* conducted by an inspectorate (IAEA, EC, STUK)
  - Typically NDA measurement
- Goal of *verification* is to verify the correctness and completeness of *declaration*.
- Declaration is provided to the inspectorate by the nuclear facility.
- Nuclear facility can obtain the data for declaration in multiple ways, which sometimes may be called *characterization*
  - Own measurement (primarily NDA, DA)
  - Modeling (most typical)
Verification vs characterization

• Usually:

\[ \text{precision of characterization (~5\%) >> precision of verification (~50\%)} \]

• It would be very cost effective to use the same method for both verification and characterization BUT:
  – Roles must be kept clear
  – Independency of the inspectorate verification shall be taken care of

Typically the methods used for verification have not provided much value in characteristics due to their poor precision.
Finnish national safeguards concept
Project GOSSER

• STUK has internal project called GOSSER (=Geological Disposal Safeguards and Security R&D)
• GOSSER develops methods needed for spent fuel disposal project
• GOSSER has two subprojects
  – Development of NDA
  – Development of surveillance, environmental monitoring and geological tools needed

Any resemblance of project name to any brand is purely coincidental.
Proposed NDA tool by GOSSER: PNAR+PGET integrated verifier

- PGET = Passive Gamma Emission Tomography
- PNAR = Passive Neutron Albedo Reactivity

- Proposed tool for national verification concept

- Verification time 5 min/assembly

- Fuel assembly is lowered to the verifier from the top
- Stands at the bottom of the pool, underwater instrument.
PGET – hardware and operating principle will be presented by IAEA SG
PGET development

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>Idea proposed</td>
</tr>
<tr>
<td>1999</td>
<td>1999: Proof of concept</td>
</tr>
<tr>
<td>2003</td>
<td>The first tests</td>
</tr>
<tr>
<td>2004</td>
<td>The first full test prototype development</td>
</tr>
<tr>
<td>2009</td>
<td>IAEA decision to support construction</td>
</tr>
<tr>
<td>2012</td>
<td>Tests in ISPRA</td>
</tr>
<tr>
<td>2014</td>
<td>Tests in Lovisa</td>
</tr>
<tr>
<td>2017</td>
<td>Tests in BWR, PWR, VVER</td>
</tr>
<tr>
<td>2018</td>
<td>IAEA approval</td>
</tr>
<tr>
<td>2019</td>
<td>Commercialization</td>
</tr>
<tr>
<td>2020-</td>
<td>The first commercial PGETs delivered</td>
</tr>
</tbody>
</table>

TRL = Technology Readiness Level
PGET performance

• The performance of PGET method is not yet fully unleashed.
  – Analysis is still developing
  – New hardware is coming
• An idea has been proposed, if the method is capable of quantitative burn up estimation at the pin level
  – This is not needed in safeguards.
• The latest campaign data suggests that the current system is capable of detecting sub pin level burn up profile.
PNAR – hardware and operating principle
PNAR = Passive Neutron Albedo Reactivity

- Neutron albedo = reflection of slowed neutrons from moderator (pool water)
- PNAR studies reactivity by modifying neutron albedo
- 2 measurements
  - Maximal neutron albedo
  - Suppressed neutron albedo (Cd)
- Ratio of these measurements = PNAR Ratio
  - Proportional to neutron multiplication of albedo neutrons
  - PNAR Ratio is correlated with $M$, $k_{\text{eff}}, \inf$
- Neutron multiplication is only an attribute of fissile material

**Diagram:**
- Spent nuclear fuel
- Neutron albedo
- Fast neutron detector
- Neutrons from fission induced by reflected neutrons
- Water/Polyethylene
- SF neutrons and 1st order multiplication
**PNAR device**

- Underwater measurement
- 4 identical measurement pods with polyethen cover
  - 1 $\gamma$ and 1 He-3 neutron-detector per pod
    - He-3 lined with Cd and shielded with Pb
- Preamp shielded
- Cadmium sheet moves as close the fuel as possible
Modular design of the PNAR instrument around the cadmium liner
Operating principle

- Cadmium sheet is pulled between neutron detectors (He-3) and the fuel
- Cadmium absorbs thermalized neutrons.
MCNP simulations

• Design was designed by simulations before manufacturing
• Homogenic isotropic distribution assumed in the fuel
• Response:
  – PNAR Ratio is proportional to the fissile material content. (Initial enrichment, burn-up)
  – Dynamic range is important, it tells how reliably the fissile material content can be verified.
  • Minimization of errors is crucial
PNAR performance (based on July 2019 campaign)

- A typical assembly has a PNAR Ratio of 1.044 while MCNP model predicted ~1.12 (??)
- STD of PNAR Ratio determination is ±0.0013 (!!!)
- Non-multiplying assembly is expected to have PNAR ratio ~0.98 (MCNP estimation using “nonu-card”; this can not be measured directly)
- Thus; detection sensitivity of the instrument is ~40 sigma!!!
Combined PNAR and PGET results

- Areas of lower burnup can be identified from PGET reconstructions
- In theory
  low BU rod = more U-235 and Pu-239
  = higher PNAR Ratio
- In reality enrichment profiling, reactor history etc. has an effect
# IAEA’s ASTOR expert group recommendations

<table>
<thead>
<tr>
<th>ASTOR NDA Focus Group Recommended</th>
<th>PGET</th>
<th>PNAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capable of pin level detection</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Capable of verifying that the declared assembly is consistent with measured signatures</td>
<td>?</td>
<td>Yes</td>
</tr>
<tr>
<td>Capable of measuring assembly neutron multiplication</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Capable of measuring all fuel assemblies at the measurement location and in the medium of interest (fresh water, borated water, air)</td>
<td>Yes</td>
<td>Yes (specific design is required for every FA type)</td>
</tr>
<tr>
<td>Robust, low maintenance and have a low false alarm rate</td>
<td>?</td>
<td>Yes</td>
</tr>
<tr>
<td>Difficult to trick with pin substitution</td>
<td></td>
<td>System Attribute</td>
</tr>
<tr>
<td>Measure the weight of the assembly</td>
<td></td>
<td>Load Cell Attribute</td>
</tr>
</tbody>
</table>

The table above lists the recommendations made by the ASTOR NDA Focus Group regarding various attributes of nuclear detection systems, along with their ratings by two different systems, PGET and PNAR. The ratings are indicated as 'Yes' or 'No' for PGET, and additional notes are provided for PNAR where relevant.
Pictures from PGET+PNAR campaign from Olkiluoto, July 2019

Pictures: TVO
PNAR+PGET campaign setup, Olkiluoto 22-26 Jul 2019
Olkiluoto KPA store, July 2019
PNAR Detector controller units poolside
Reviewing the PGET results
What data is needed for verification and analysis?

Pictures: TVO
# Data useful for safeguards purposes

<table>
<thead>
<tr>
<th>Batch number</th>
<th>Design: Description of the handle and other supporting structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of NM</td>
<td>Rod cassettes geometry information</td>
</tr>
<tr>
<td>Design: Fuel geometry, Number of rods</td>
<td>Burn up history: Cooling time</td>
</tr>
<tr>
<td>Design: partial length rod positions</td>
<td>Burn-up history (BU/cycle, off reactor cycles )</td>
</tr>
<tr>
<td>Design: water rods and their positions</td>
<td>High fidelity burn-up history (weekly BU history)</td>
</tr>
<tr>
<td>Averaged burn-up of an assembly.</td>
<td>Operator calculated isotopics and Isotopics distribution</td>
</tr>
</tbody>
</table>

**Initial Enrichment**

<table>
<thead>
<tr>
<th>Batch number</th>
<th>Design: Pin-by pin info about burnable poisons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burn up profiles, axial and pin by pin</td>
<td>Total weight in air/water</td>
</tr>
<tr>
<td>Detailed info about enrichment of different pins and enrichment profiles</td>
<td>Design: Number and location of spacers</td>
</tr>
<tr>
<td>Design: Pin-by pin info about burnable poisons</td>
<td>Total weight in air/water</td>
</tr>
<tr>
<td>Heat generation</td>
<td>Design: Number and location of spacers</td>
</tr>
<tr>
<td>Positions in the reactor, location history</td>
<td>Design: Number and location of spacers</td>
</tr>
<tr>
<td>Fuel maintenance: Pin replacements and removals, rebatching</td>
<td>Design: Number and location of spacers</td>
</tr>
<tr>
<td>Fuel maintenance operations not affecting NM: openings, dechanneling, etc.</td>
<td>Design: Number and location of spacers</td>
</tr>
</tbody>
</table>
Reasonings why data is needed for safeguards

• Some are stipulated by the agreements, they are mandatory
  – Amount of NM, batch number, Initial enrichment and burn-up at the assembly level
• Some data is needed for analysis.
  – Fuel history, detailed enrichment profiles
• Some data may be useful for result interpretation helping to resolve any inconsistencies
  – High fidelity burn-up history
Data management issues
Storing the data – how and for how long?

State of the art data storage
~100 years ago
At least as long as the repository is active > 100 y

For every fuel element, at least
• Fuel number
• NM Mass
• Fuel history
Safeguards verification data (NDA) shall also be kept but but at which level?
   This is subject to investigation.
   Future generations should be able to perform (if not all, at least the most important)
   analyses, if they want

• The long timelines and requirements for trustworthiness of data place high demands on
  the upkeep of the system.
• After the repository is closed and backfilled, the responsibility is transferred to the state