Nuclear Safeguards Challenges at Reactors Types That Defy Traditional Item Counting

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Introduction

A Nuclear Renascence is being driven by:

- Energy Security Needs
- Global Warming Concerns
- GNEP
- Gen IV Project
- Growth in developing nuclear countries

Likely Developments:

- Increased effort to close the nuclear fuel cycle
- Improved Operating Efficiencies (New Reactor Designs)
- Small “Grid-Appropriate” Reactors (200-700 MWe)

This will result in New Safeguards Challenges for Reactors
Safeguards Approach for Nuclear Reactors

Containment & Surveillance (C/S):
- Cameras
- Seals

Item Accountancy:
- Book Reviews
- Fresh Fuel Verification
- Core Fuel Verification
- Spent Fuel Verification

Fuel Verification:
- Visual Confirmation of Serial Numbers
- Attribute Verification
Safeguards Approach Gap

Visual Confirmation and Serial Number verification are difficult in some reactor designs. This causes a breakdown in the traditional reactor safeguards approach:

Liquid-Metal-Cooled Fast Reactors:
- Opaque coolant prohibits visual confirmation
- Remote handling of fresh and spent fuel prohibits S/N confirmation
- Spent Fuel canning prohibits S/N confirmation
- Spent Fuel canning prohibits visual confirmation in cooling pond
- Temporary storage in liquid sodium after core discharge complicates timeliness issues

PBMRs:
- Items are not individually serialized.
- Large number of items

MSRs:
- There are no ‘items’
Item Counting is difficult in these reactor types.

By virtue of the facility design and operation they exist in a domain that is neither item nor bulk.

To date, suggested approaches rely on C/S and Continuity of Knowledge.
Issues:
• Opaque Coolant
• Reactive Coolant
• Remote Handling
• Canned Spent Fuel

Current Approach:
• C/S
• Heavy reliance on Continuity of Knowledge
PBMR

Issues:
- Items not serialized
- Large number of items
- On-Line refueling and fuel handling

Current Approach:
- Under Review
- CoK
- Pebble Counting for Numerical Balance

From: MIT Dept. of Nuclear Science & Engineering
MSR

Issues:
• No Fuel Items
• On-Line Fueling
• On-Line Fuel Conditioning
• Spent Fuel Accounting

Current Approach:
• None Known

From: “Gen IV Nuclear Energy Systems”, DOE Office of Nuclear Energy
Three Safeguards Approaches

- Use C/S and adjunct sensors to maintain CoK over the lifetime of the reactor.
  - CoK sensor reliability
  - Reverification technology to recover CoK

- Force the problem back to item accountancy by using new techniques.
  - New instrument types

- Treat the reactor as bulk handling facility.
  - Statistical assessment of MUF, $\sigma_{\text{MUF}}$
  - PIVs during scheduled outages
Safeguards approach is currently CoK-based.

This is a candidate reactor to introduce new technologies to enable item counting
  • Under-Sodium Viewing

Reverification technologies to enable item counting
  • New Spent Fuel Safeguards Measurements
  • Modeling and simulation for attribute variance for reverification
LMFR Item Counting: Under-Sodium Viewing

- Developed in the late 1960s for the Hanford FFTF.


- Ongoing development in Europe for Pb-Bi, Kazys et al, 2005

From: Hanford Engineering Development Laboratory Report, HEDL-TME 72-91
LMFR Item Counting: Under-Sodium Viewing

Image of Core top under 5m of sodium

Under-Sodium Ultrasound Image

Photograph in Air

From: Hanford Engineering Development Laboratory Report, HEDL-TME 72-91
LMFR Item Counting: Under-Sodium Viewing

TEST RESULTS ILLUSTRATING
FFT Core Component Identification Capabilities
OF THE UNDER SODIUM VIEWING SYSTEM

A. SIMULATED HANDLING SOCKET WITH IDENTIFICATION NOTCHES,
1/4" AND 3/8" NUMERALS IMAGED IN WATER

B. NUMERALS AND NOTCHES IMAGED IN 500°F SODIUM.

From: Hanford Engineering Development Laboratory Report, HEDL-TME 72-91
LMFR Reverification: Tomographic Spent Fuel Measurement

Uppsala University

Impressive imaging resolution

Pin diversion in canned fuel is easily detected

Requires a dedicated pit in the spent fuel

Expensive & complex

Not practical for only reverification use

From: Svärd Dissertation, 2004
LMFR Reverification: Fork Detectors

Distinguish blankets and non-fuel items
Fissile composition of low-burnup items

Both Techniques would require investigation to determine pin removal sensitivity
Because Pebbles are not serialized, item accountancy is not possible.

Item numerical balance is possible, but challenging.

Reverification of a lost numerical balance would be difficult if not impossible.

### Reactor Inventory Data:

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Rated Thermal Power (MW)</th>
<th>Core Inventory (Pebbles)</th>
<th>Fresh Fuel Uranium Mass (gU/Pebble)</th>
<th>Initial $^{235}$U Enrichment (%)</th>
<th>Pu Mass in Equilibrium Discharge Pebble (gPu/Pebble)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTR-10</td>
<td>10</td>
<td>27,500</td>
<td>5.0</td>
<td>17.0</td>
<td>~0.08</td>
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<td>360,000</td>
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<td>8.0</td>
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<tr>
<td>ESKOM</td>
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<td>9.0</td>
<td>0.114</td>
</tr>
</tbody>
</table>
PBMR

Hybrid Approach:  
Item Tracking + CoK (+ C/S)

• Fresh fuel:  
  Enrichment verification and item counting

• In-Core:  
  Use authenticated pebble counters to track movement to maintain CoK - ~Process Monitoring  
  No means of recovering CoK

• Spent Fuel:  
  Attribute verification and item counting
Hybrid Approach: Item Number Balance + Bulk Accounting (+ C/S)

• Fresh fuel:
  Enrichment verification and item counting

• In-Core:
  Treat as a bulk Accountancy Area
  – Engineered temporary fresh/spent fuel holding to limit to excess material accrual as MUF
  – Accommodate counter errors/uncertainty as $\text{MUF}/\sigma_{\text{MUF}}$
  – Close balance during maintenance shutdowns
  – Addresses material production/consumption in reactor

• Spent Fuel:
  Attribute verification and item counting to close
PBMR Bulk-Item Approach

Fresh Fuel Receipts

- KMP 1
  - KMP A Fresh Fuel
    - Fuel loading
    - KMP 2
      - KMP B Reactor Core
        - Nuclear Loss and Production
    - KMP 3
      - KMP C Spent Fuel
        - Nuclear Loss

- Storage Area MBA
  - KMP 4
    - Off-Site Spent Fuel Transfer

Spent Fuel Transfer

- KMP 5
  - KMP A Fresh Fuel
    - Fuel loading
    - KMP 2
      - KMP B Reactor Core
        - Nuclear Loss and Production
    - KMP 3
      - KMP C Spent Fuel
        - Nuclear Loss

- Storage Area MBA
  - KMP 4
    - Off-Site Spent Fuel Transfer

ITEM

BULK

Reacto Area MBA
Issues:
• No Fuel Items
• On-Line Fueling
• On-Line Fuel Conditioning
• Spent Fuel Accounting - poor spent fuel composition modeling capability

• Looks like a bulk facility that can create and destroy material.
• Fresh fuel salts receiving
• Fuel conditioning facility (details in this component have significant effect on safeguardability)
• Spent fuel conditioning (discharge)
• Fission product conditioning (discharge)

⇒ A difficult balance to close.

A Bulk Facility Approach would be required.
Conclusion

Some reactor types challenge traditional Item Accountancy -
  • Remote fuel handling
  • Opaque coolants
  • Fuel canning
  • Serialization of elements
  • Lack of elements

These reactor types will become more common.

The “CoK approach” for difficult reactors is not sufficiently robust.

The “CoK approach” has the hidden cost & effort of reverification.

New Safeguards Approaches & Technologies are needed.