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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

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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

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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’

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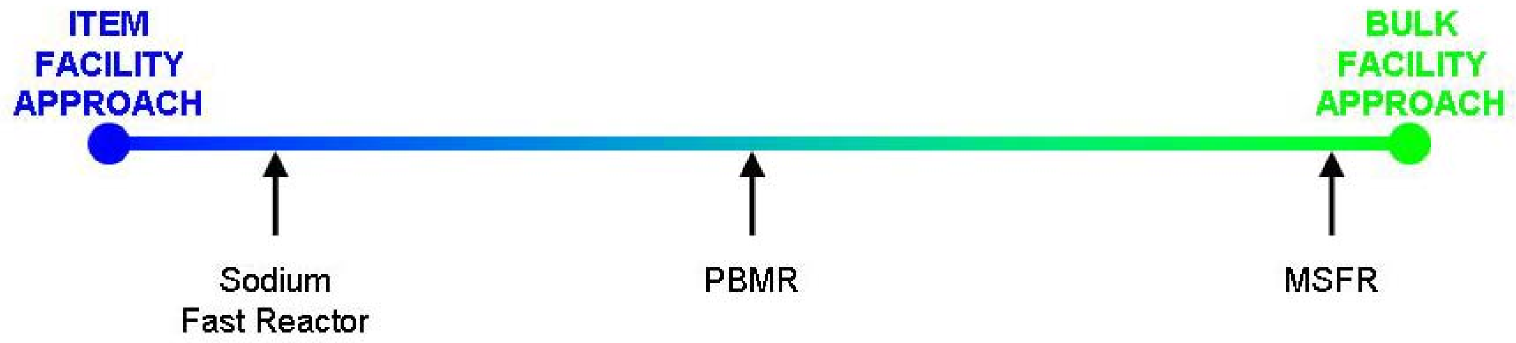
Safeguards Approach Gap

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 <u>Continuity of Knowledge</u>



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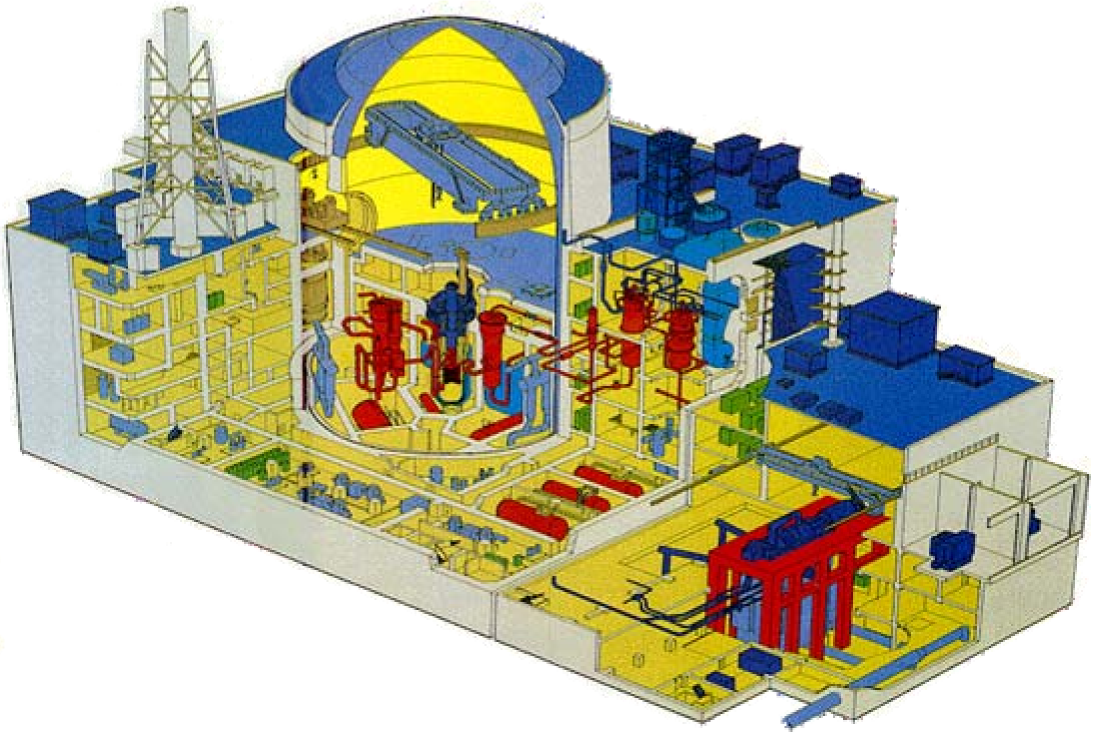
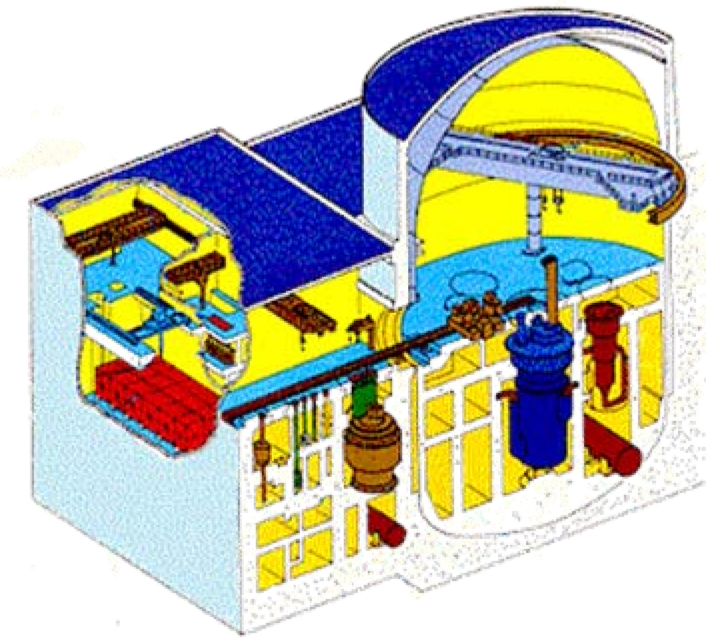
LMBR



Issues:
- Opaque Coolant
- Reactive Coolant
- Remote Handling
- Canned Spent Fuel

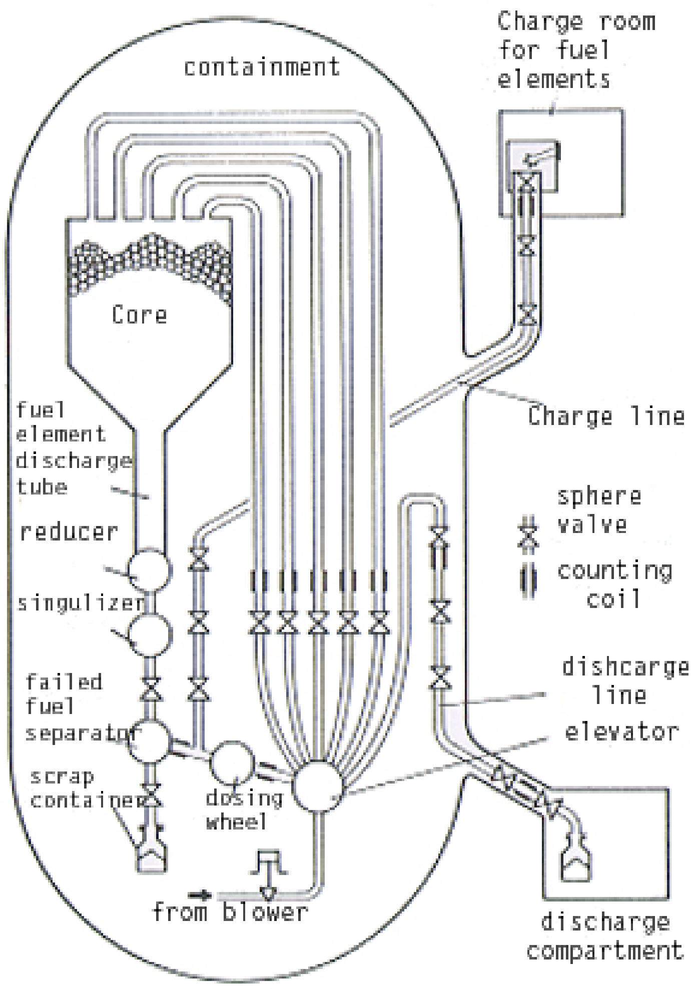


Current Approach:
- C/S
- Heavy reliance on Continuity of Knowledge

PBMR

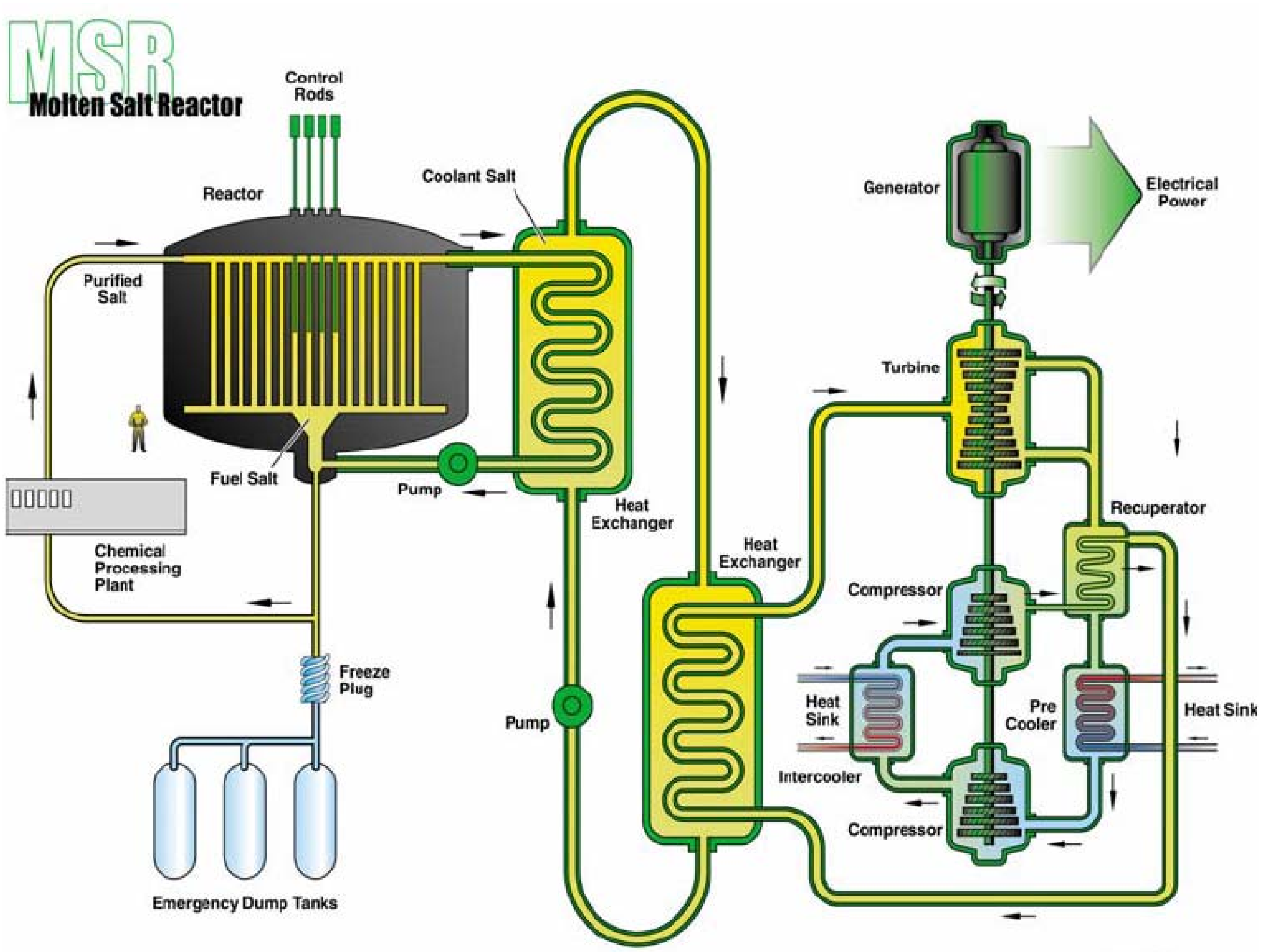
Issues:
- Items not serialized
- Large number of items
- On-Line refueling and fuel handling

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

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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, σ_{MUF}
  - PIVs during scheduled outages

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LMFR

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

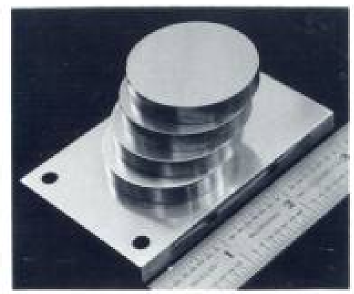
LMFR Item Counting: Under-Sodium Viewing

- Developed in the late 1960s for the Hanford FFTF.
- Further development in Japan for 3-d imaging, Karasawa, et al, 2000.
- Ongoing development In Europe for Pb-Bi, Kazys et al, 2005

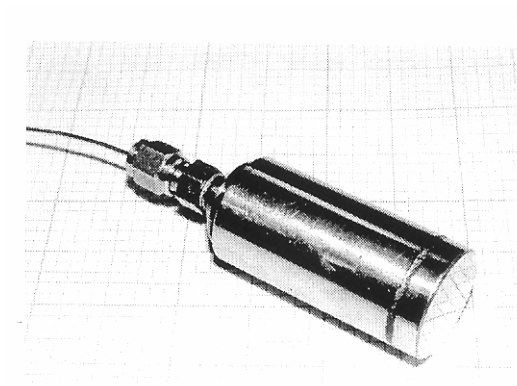
UNDER-SODIUM VIEWING SYSTEM

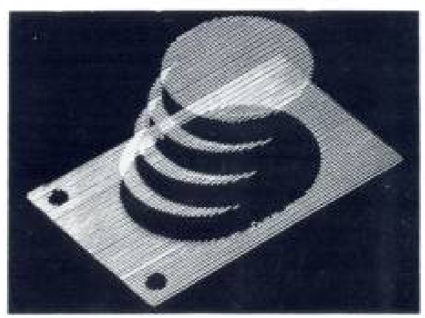
TEST RESULTS

COMPARISON OF WATER & SODIUM DATA

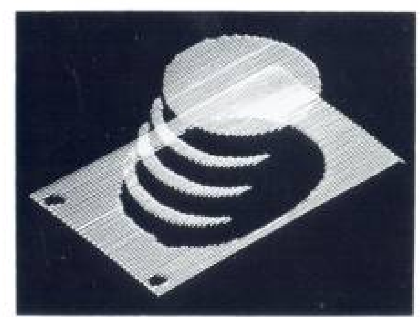


TARGET PHOTOGRAPH





ULTRASONIC IMAGE FROM OPERATION IN WATER



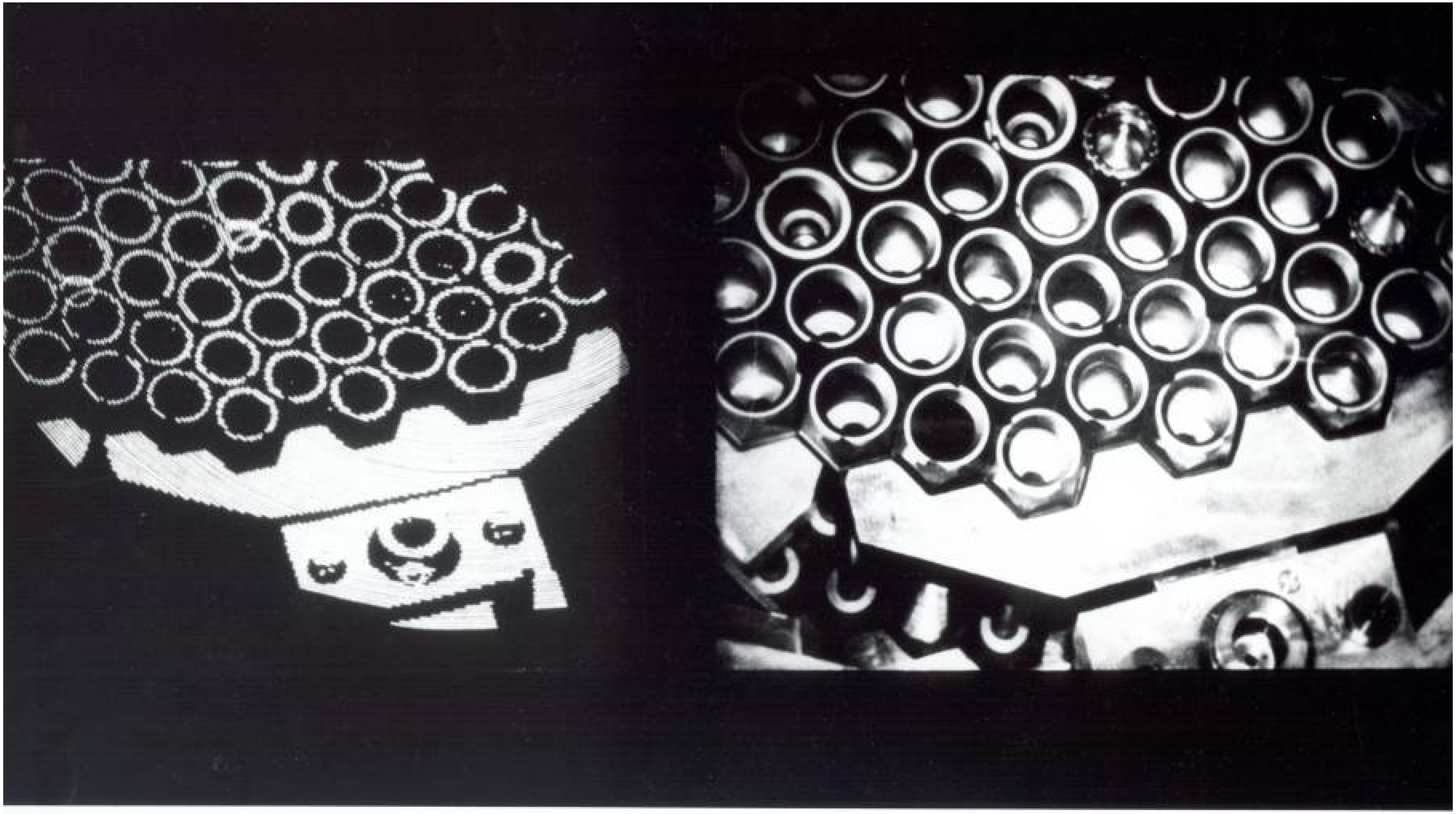
ULTRASONIC IMAGE FROM OPERATION IN 500°F SODIUM

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

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LMFR Item Counting: Under-Sodium Viewing

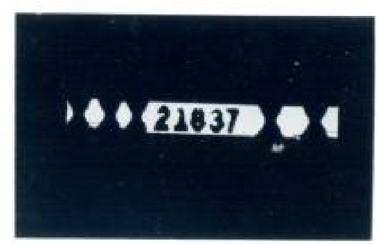
TEST RESULTS ILLUSTRATING
FFTF CORE COMPONENT IDENTIFICATION CAPABILITIES
OF THE UNDER SODIUM VIEWING SYSTEM

PHOTOGRAPH OF TARGET

ACOUSTIC IMAGE

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

PHOTOGRAPH OF TARGET

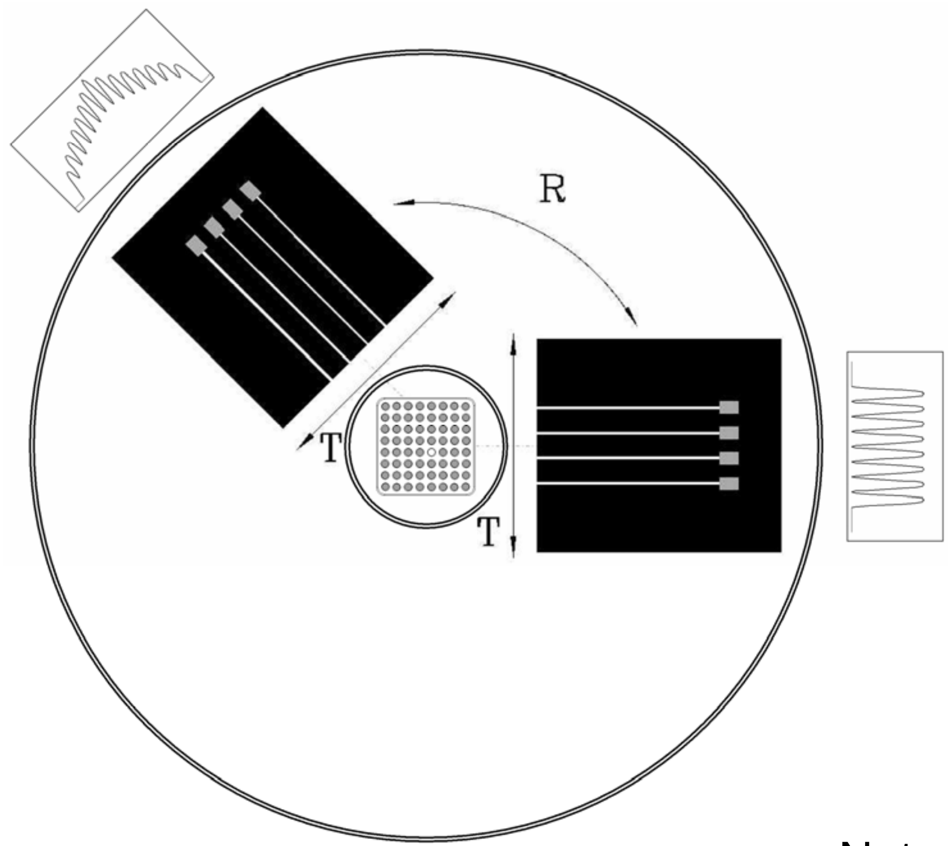


ACOUSTIC IMAGE

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



From: Svärd Dissertation, 2004

Uppsala University

Impressive imaging resolution

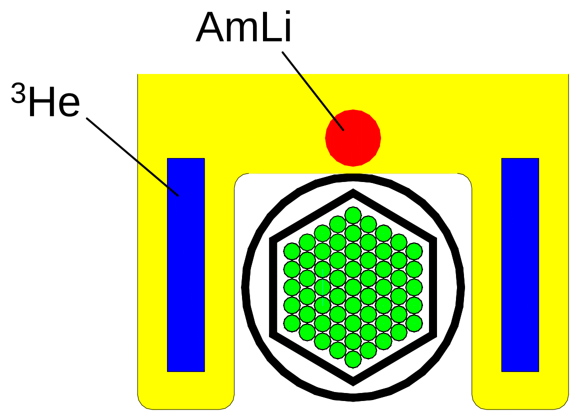
Pin diversion in canned fuel is easily detected

Requires a dedicated pit in the spent fuel

Expensive & complex

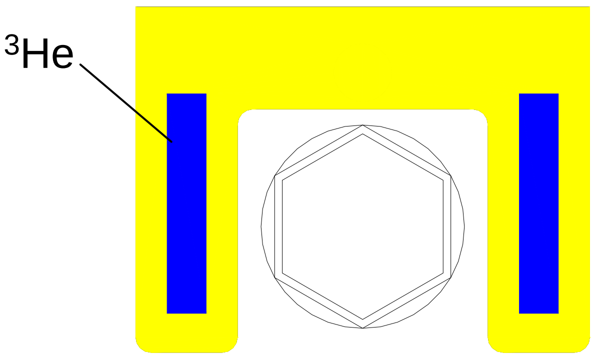
Not practical for only reverification use

LMFR Reverification: Fork Detectors



Active Fork

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



Coincidence Fork

Coincidence Fork using Cd-Albedo
Fissile/fertile ratios

Both Techniques would require investigation to determine pin removal sensitivity

PBMR

- 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:

Reactor	Rated Thermal Power (MW)	Core Inventory (Pebbles)	Fresh Fuel Uranium Mass (gU/Pebble)	Initial ^{235}U Enrichment (%)	Pu Mass in Equilibrium Discharge Pebble (gPu/Pebble)
HTR-10	10	27,500	5.0	17.0	~0.08
PBMR-400	250	360,000	7.0	8.0	0.154
ESKOM	400	440,000	9.0	9.0	0.114

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

PBMR

Hybrid Approach:

Item Number Balance + Bulk Accounting (+ C/S)

- Fresh fuel:

  Enrichment verification and item counting

- In-Core:

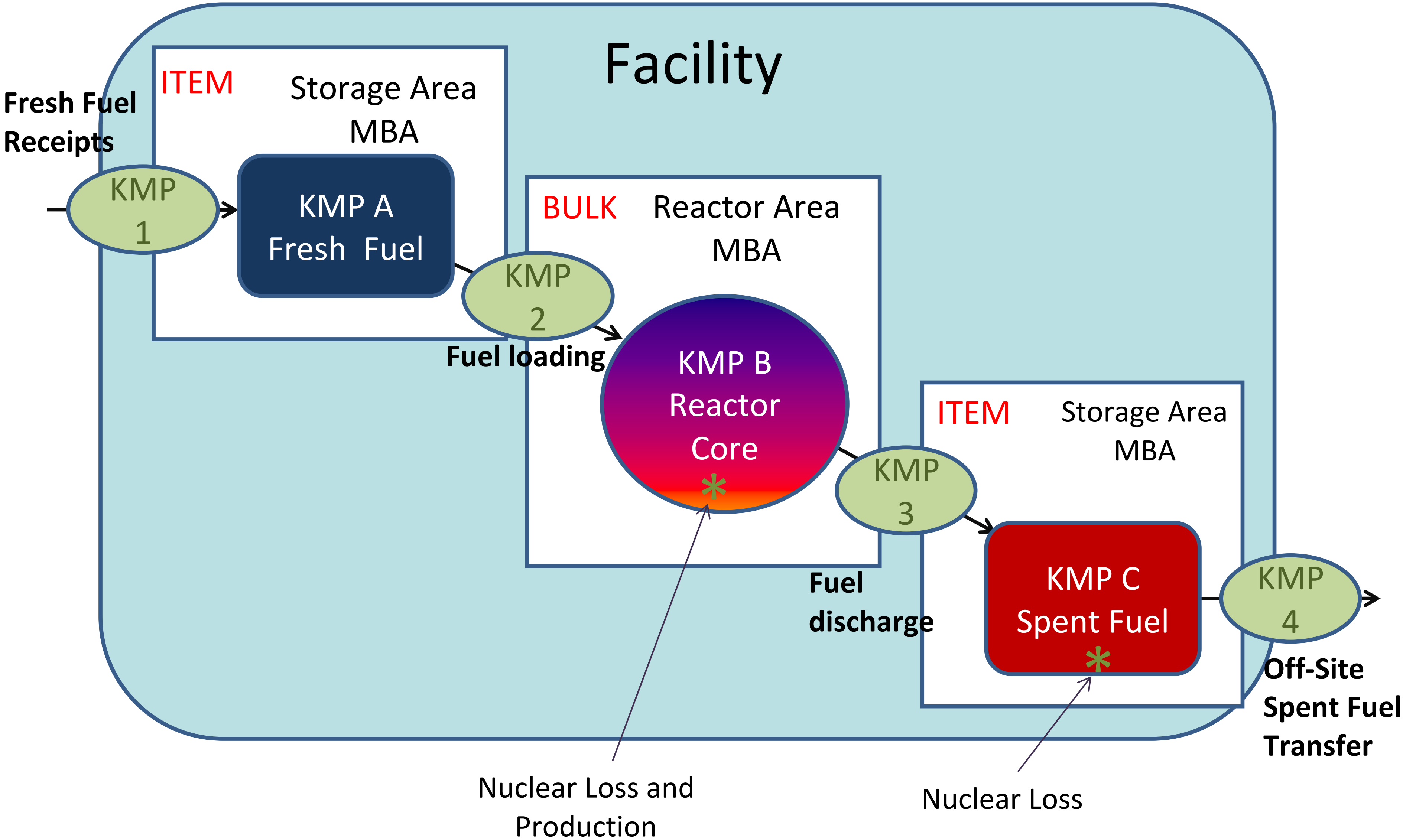
  Treat as a bulk Accountancy Area

  - Engineered temporary fresh/spent fuel holding to limit to excess material accrual as MUF
  - Accommodate counter errors/uncertainty as MUF/σ_{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



MSR

Current Approach:

- None Known

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)

$\Rightarrow$ A difficult balance to close.

A Bulk Facility Approach would be required.

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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.