The Irradiation Testing of Thorium-Plutonium Fuel

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WHY?:
- Context for testing (Th,Pu)O$_2$ fuel
  - Th angle

WHAT?:
- Fuel behaviour
  - Representative fuel ceramic

HOW?:
- Instrumented fuel test-rig
  - Halden test reactor
Why Test this Fuel?

An irradiation test program is expensive:

• Commercialization Goal
  – Creating value in terms of future fuel sales (IP component)
  – No value in ’resource saving’ arguments
  – Leveraging: Operation benefits (safety margin), Waste management benefits (fissile recycle)

• NOT a thorium test program
  – Th-MOX fuel must be attractive to nuclear utilities
  – Not testing Th for the sake of it
  – ThO$_2$ is a merit-worthy fuel component, eg, as a tough fertile matrix
Experiment Objective

.... to yield data that can be used to demonstrate the safe, long term performance of ceramic thorium-plutonium oxide fuels, and that this information can directly support the planning and approval of a commercial irradiation for such a fuel.....

Regulator & Operator Audience: & not purely academic
Thorium Diversion

Main Motivators for Th fuel Development

1. A New Energy Resource
   ✅ Diversification from Uranium
   ✅ Hypothetical low cost & potential ’sustainability’ merits

2. Fissile Recycle / Waste Actinide Consumption
   ✅ Plutonium / MA destruction & wasteform attributes
   ✅ Energy extraction from accumulated Pu

3. Higher Reactor & Fuel Safety Margins
   ✅ Higher power / burnup operation

4. Liberation of Rare Earth Resources

5. Niche Benefits
   ✅ eg, burnable absorber replacement

Classifies, but does not edify
Thorium Diversion

Numerous Specific Merits... But Complex:

“Huge resources”

“Multi-recycling of fissile material”

“Highly stable waste-form”

“No long-lived waste”

“Thermal spectrum breeding”

“Excellent Pu destruction”

“Diversify from uranium”

“Proliferation resistant”

“Integratable”

“Toughness for in-core operation”
Fissile (Pu) Consumption $\rightarrow$ Highly stable waste-form $\rightarrow$ Hi-power / Hi-burnup operation $\rightarrow$ “No long-lived waste”

Thermal $^{233}$U Conversion $\rightarrow$ Multi-recycle of fissile material

$^{232}$Th + n $\rightarrow^{233}$Th $\rightarrow^{233}$Pa + β $\rightarrow^{233}$U + β

Complex. You can’t get everything...

Question becomes What the Thorium Fuel must do?
\[ ^{232}\text{Th} + \text{n} \rightarrow ^{233}\text{Th} \rightarrow ^{233}\text{Pa} + \beta \rightarrow ^{233}\text{U} + \beta \]

- **Th**
- **Th**
- **Th**

**Homogeneous - Th+fissile**
Best for fissile consumption

**Seed-Blanket** arrangement

**Heterogeneous - Th+fissile**
Best for conversion

**k-eff** vs. Burnup, EFPD

**FIR** vs. Burnup, EFPD

- **Reference Case**
- **ThU conf, first guess**
- **ThU conf, larger blanket**
- **ThU conf, smaller seed**
- **ThU conf, much larger blanket**
- **optimized axial power**

**Thor Energy**

Scandinavian Advanced Technology
Establish what you want the Thorium Fuel to achieve:

- large extent of plutonium consumption?
- large extent of $^{233}U$ production - from Pu?
- will it be recycled – and for what components?
- gain large amounts of energy from a Th resource?

Does this accord with national nuclear energy policies:

- Fits with current / planned nuclear energy infrastructure?
- Fits with national fuel cycle vision / priorities (waste, sustainability, PR, etc)?
- Licensing and R&D infrastructure available?
- Starting out with nuclear?

Guides technology choice
<table>
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<tr>
<th>Situation &amp; Policy Drivers</th>
<th>Platform Options</th>
<th>Considerations for the Thorium Proponent</th>
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<tbody>
<tr>
<td>Long Established N-Power</td>
<td>LWRs</td>
<td>Prioritize plutonium consumption?</td>
</tr>
<tr>
<td>— <strong>SNF a key issue</strong> (eg, USA, Finland, Slovakia)</td>
<td>PHWRs</td>
<td>Include MA components for W/M?</td>
</tr>
<tr>
<td><strong>Long Established N-Power</strong></td>
<td>LWRs</td>
<td>Keep option for $^{233}$U recycle</td>
</tr>
<tr>
<td>— <strong>Resource expansion</strong> (eg, Korea, India, Argentina, Brasil)</td>
<td>PHWRs Gen IV</td>
<td>Integrate with any future fast reactor plans?</td>
</tr>
<tr>
<td><strong>Establishing N-Power</strong></td>
<td>LWRs</td>
<td>Initial fissile driver?</td>
</tr>
<tr>
<td>— <strong>Long-term fuel supply</strong> (UAE, Turkey, Poland, Chile…)</td>
<td></td>
<td>Ways to optimize for $^{233}$U conversion.</td>
</tr>
<tr>
<td><strong>“Not Yet” N-Power</strong></td>
<td>Gen IV</td>
<td>Reprocessing strategy?</td>
</tr>
<tr>
<td>— <strong>Optimal sustainability</strong> (eg, Singapore, Saudi Arabia)</td>
<td></td>
<td>Option to use ‘Th-MOX’ in LWRs?</td>
</tr>
<tr>
<td><strong>Other/Special Cases</strong></td>
<td></td>
<td>Prioritize energy share from thorium?</td>
</tr>
<tr>
<td>(eg, Italy, UK, Japan)</td>
<td></td>
<td>Public acceptance</td>
</tr>
<tr>
<td><strong>Repeat:</strong> Know what you want the Th fuel to do, &amp; where it will go**</td>
<td></td>
<td>Ensure proliferation resistance credentials</td>
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</tbody>
</table>

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Thorium-capable Thermal Reactor Platforms

- Heavy Water Reactor (CANDU, PHWR)
  - Flexible bundle design for 'breed' or 'burn', high neutron-economy
- Boiling Water Reactor
  - Design flexibility & reduced-moderated designs for high conversion
- Pressurized Water Reactor
  - Industry workhorse, but feasible – economic case tough
- High Temperature Gas-Cooled Reactor (HTR, PBMR...)
  - High burn-up capability… tending to once-thru
- Molten Salt Reactor (MSR, LFTR...)
  - Flexible. Sustainable cycles envisioned – materials still an issue

Technological Readiness varies.
“What” is being done in this Experiment?

- Characterise Irradiation Behaviours – safety significant
- Representative Fuel Ceramic
Behaviours to Characterize

Pellet properties evolve as fuel burns – the most important safety-significant changes to know about are:

• Temperature & Thermal Property Changes
  — temperature, conductivity decrease, expansion, heat capacity

• Fission Gas Release
  — amount, onset and composition

• Mechanical Interactions
  — densification, swelling

• Chemical Interactions
  — corrosion, oxygen movement

- expect later onset for ThO₂, more I?
- expect less creep, more swelling for ThO₂
- O behaviour very different in ThO₂
  I yield higher (released?)
Paucity of performance data on Th-MOX fuel ceramics

Thermal Conductivity (W/mK) vs Temperature (K) for various thorium oxide (ThO$_2$) and uranium oxide (UO$_2$) compositions with different levels of plutonium oxide (PuO$_2$) addition.
Pellet Properties

Test-fuel ceramic must represent that which can be deployed commercially. Pu content effects things wrt UOX:

- **Microstructure**
  - density / porosity & pore size distribution
  - grain size & grain distribution
  - Pu homogeneity

- **Composition**
  - *impurities*: metals, non-metals
  - stoichiometry

- **Shaping**
  - dishing, L/D

Need to characterize fresh pellets in terms of density, grain structure, Pu distribution, chemical purity, thermal properties
Pellet Manufacture

High density ceramic paramount:

- Powder – Pellet Processing
  - blending: co-mill parameters
  - pressing & sintering
  - O\M ratio
  - industrial (MOX) relevance
  - time pressure
  - Ce surrogate for Pu
  - additives?
Complex Issues

A few technical points needed specific/careful resolution:

• Assurance re non-metal impurity levels
  – sample size requirement
  – QA processes

• Stoichiometry Control
  – different for thoria: risk is hypostoichiometry

• Procurement
  – Pu headache
  – transport
ThO$_2$ powder morphology (not ideal)

(Th,Ce)O$_2$ ceramic microstructure:
Some (Th,U)O$_2$ fuel being tested too:
(i) carrier enrichment
(ii) burnable absorber minimization
“How” to collect the data we need?

- Sophisticated on-line instrumentation & PIE analyses
- Halden test reactor
to be Measured

Experiment design involves compromises & risk assessment. Online measurables defined early.

• On-Line Measurable
  — temperature: centerline & rod wall
  — pellet stack elongation
  — clad elongation
  — rod internal pressure

PCMI
FGR
swelling
densification

• Post-Irradiation Examination
  — FG analysis
  — microscopy: optical, SEM, TEM, EPMA
  — conductivity
  — radiography

microstructure
nuclide composition
FP distribution
structural dimension
IFA-730
Test Matrix – Phase 1a

PF – Pressure transducer
TF – Fuel thermocouple
EC – Cladding elongation detector
IFA-730
Test Matrix – Phase 1b

PF – Pressure transducer
TF – Fuel thermocouple
EC – Cladding elongation detector

U/Th
Pu/Th
U/Th
Pu/Th
U/Th
Pu/Th
U/Th

(NNL)

Thor Energy
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Max thermal power</td>
<td>20 MW</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>235°C</td>
</tr>
<tr>
<td>Operating pressure</td>
<td>30 bar</td>
</tr>
<tr>
<td>Moderator</td>
<td>Heavy water</td>
</tr>
<tr>
<td>Heavy water volume</td>
<td>14 m³ total</td>
</tr>
<tr>
<td>Type of fuel</td>
<td>Uranium dioxide</td>
</tr>
<tr>
<td>Thermal neutron flux</td>
<td></td>
</tr>
<tr>
<td>Ramp configuration</td>
<td></td>
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<td>Fast neutron flux</td>
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<td>Booster rigs</td>
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![Diagram of reactor core with annotations]
In-core contact
• ambient conditions: 325°C and 165 bar

Fuel thermocouple
• Max. Temp: 2300°C

Pressure sensor:
• range: 1–150 bar
LVDT:
Fuel stack & cladding extension

Thermocouple installation
First Measurements

Promising early indications about thermal conductivity.
Final Remarks

- Nuclear fuel R&D...... problematic

- Thorium Fuels – waste management only credible incentive
Economic & Financing Considerations:

Hard Realities.

• The low marginal cost for fuelling an NPP means any new fuel suggestion is unfavorable in raw-terms.
• Thorium-uranium fuel is not cost-effective w.r.t. U & SWU cost
• Development & demonstration times for nuclear energy systems are long
• The nuclear industry is not set up for attracting ‘innovation’ financing
• No current consensus on platform for a moon-landing-type project support
• Splitting financing across platforms may risk completion of all
• Large investment needed
• R&D effort must be focussed & collaborative or effort will fail
• Uranium IS cheap, and could stay that way
• The less new hardware involved, the easier / shorter the roadmap will be…