Thorium-Plutonium LWR Fuel

October 2010
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Presentation Aim

Describe Status of Thorium Fuel Development Activities of *Thor Energy*

First — a FAQ:

Why a Private Norwegian Company?

- Explain that “thorium fuel” =
  Thorium-plutonium LWR fuel (Th-MOX)

Thorium-MOX for LWRs — the **Nearest-term Deployment Route** to accessing energy from thorium
Scatec Solar Czech
Scatec Solar Asia-Pacific
Scatec Solar Nth America
Scatec Solar Germany
NorSun
Scatec Solar Power
Thor Energy
NorWind
OceanWind
Norsk Titanium
Scatec Adventure
Scatec Sunrise
Carbon Cones
Norway’s Thorium
Norwegian Energy Debate

Norwegian Government Commissioned ‘Thorium Report’ released 02/08

Thorium Initiative Established

Thor Energy

Detailed Feasibility Study + VATTENFALL

Fuel Development Program:
• Modelling
• Test Irradiation
• Advocacy
Thorium-MOX Fuel in Context

Key nuclear fuel cycle realities:

• Uranium resources are secure for a long time, but prices are likely to be substantially higher at some point – after 2020. An alternative nuclear fuel will be more attractive at this time, but it takes this time to bring into service.

• The light water reactor is here to stay as the nuclear power generating workhorse for the rest of the century.

• Fast reactors are meritorious, but have proven slow to license and deploy. It will be at least three decades before there is a sizeable fast reactor fleet.

• The absence of credible waste management strategies and solutions will be a bottleneck in the development of nuclear energy in numerous countries.

• Proliferation concerns will remain, and these center on inventories of accumulated plutonium in SNF and with the ubiquity of centrifuge enrichment technology.
Fuel Development Activities

**Thorium-Plutonium Fuel Irradiation**
- Test irradiation of Th-Pu fuel in Halden – collecting data to demonstrate safety & performance

**Building Computational Tools**
- Los Alamos National Labs – fuel ceramic fabrication & model development
- In-House – adapting irradiation performance code for Th-Pu fuels
- University of Tokyo / CRIEPI – atomistic simulations of (Th,Pu)O$_2$
- EU Benchmarking Project – compute depletion for an irrad Th-Pu pin

**Thorium Fuel Assembly Design**
- Specific Th-Pu fuel bundle design for a BWR

**Future closed cycles**
- MIT & Chalmers University – high $^{233}$U conversion in "RBWR"
$k_{\text{eff}}$ dependence on burn-up for a number of fuels arranged in a GE14 10-by-10 BWR assembly.

(non-optimized)

Greater net consumption of added Pu. Need more Pu to start, but less residual & energy share from Th
Thorium-$^{233}$U Hi-Conversion Fuels
Reduced-Moderated BWR

- **Heterogeneity Design**: balance seed & blanket dimensions according to reaction rates
- ’Familiar’ fuel material
- **Multi-recycled uranium**: vector deteriorates due to significant $^{234}$U & $^{236}$U buildup. ~1700ppm $^{232}$U.
- **Power Peaking**: high – needs attention
Thorium-Plutonium LWR Fuel

An Irradiation Experiment

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Presentation Overview

1. **Describe a Thorium-Plutonium Fuel Irradiation Experiment**
   that is a

2. **Ready-to-Roll Activity**
   that serves

3. **The Nearest-term Deployment Route** to accessing energy from thorium

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**First Comment:**

How does thorium-plutonium LWR fuel integrate with evolving fuel-cycles?
Existing Situation

- A large amount of plutonium exists in SNF inventories.
- This is both energy-rich & a management liability.
- Increasing calls for credible, non-proliferative strategies to deal with this Pu.

Current policy looks to Fast Reactor cycles to meet actinide management goals. Fast reactors are meritworthy, however:

- No industry ‘standard’ design
- Limited operator experience
- Licensing uncertainty
- Breeder / Burner configuration? (DU or Pu)
- More plutonium in circulation
- Significant risk of slow / no commercial deployment

Thermal thorium fuel solutions meet FR cycle goals & are achievable

Thorium-Plutonium LWR Oxide Fuel
- Power from stockpile Pu
- Thorium energy share
- ‘Familiar’ fuel material
- Reactor-operable
- Optimizable (BU, CR)
- Achievable in foreseeable future

ACTINIDE TRANSMUTATION Thorium Fuels
using matrix properties of ThO₂
eg, 2nd-gen MOX Pu, WG-Pu, MAs

HI-CONVERSION Thorium Fuels
using breeding potential of Th
(eg, RBWRs, PHWRs)
- Significant Th utilization
- Zero/low Pu requirements
- Reduced waste-per-MWh
- No enrichment requirements
Planning an Irradiation Experiment

The planning process had five elements:

• Defining Experiment Objective/s
• Identifying Fuel Behaviours to Characterize
• Selecting Measurables
• Defining Test Pellet (& rodlet) Properties
• Setting an Experiment Execution Plan
Experiment Objective

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

Regulator & Operator Audience, eg & not purely academic
Behaviours to Characterize

Pellet properties evolve as fuel burns – the most important 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
  — SCC, oxygen movement

expect later onset for ThO$_2$, more I?

may be less creep but more swelling for ThO$_2$

O-FP behaviour different in ThO$_2$
I yield higher (released?)
Behaviours to Characterize

Some property evolution expected to be different for ThO$_2$:

• Thermal Properties
  – higher conductivity – is difference maintained (Pu, FPs & T)?

• Fission Gas Release
  – more Kr & Xe generated, but less released from ceramic (T)
  – more iodine after long burnup

• Mechanical Interactions
  – less thermal expansion, less elastic and lower creep rates
  – swelling – may be more (gas/solid FP distribution)

• Chemical
  – oxygen behaviour different, iodine yield & behaviour
  – funct of FP suite & affinity for I & O, migration, etc
  – ultimately, will cladding integrity be challenged?
to be Measured

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

- **On-Line Measurables**
  - *temperature*: centerline & coolant
  - pellet stack elongation
  - clad elongation
  - rod internal pressure

- **Post-Irradiation Examination**
  - fission gas analysis
  - *microscopy*: optical, SEM, TEM, EPMA
  - conductivity
  - radiography
  - microhardness
  - $\gamma$ scanning
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
  – Pu and americium
  – 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.
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
  - thermo-gravimetric test = re-oxidation condition

- Specification of Microstructural Parameters
  - grainsize distribution........ bad
Lessons Learned

General wisdom was gained re ordering a two-phase, plutonium-bearing fuel:

• Importance of QA Procedures
  - QA can provide confidence on impurity limits where measurement not possible / feasible
  - ‘surrogate’ strategies can be considered, but have limitations

• The need for Compromise
  - when ordering a batch of Pu-containing pellets
Experiment Execution

- Rig Layout
  - number and length of rods

- Instrumentation
  - combination of pressure, temperature & extension

- Rod Design
  - pellet-clad gap, fill gas

- Power ’Roadmap’
  - starting LHGR

- Discharge Schedule
  - intermediate B/U steps

Not all parameters need be locked-in now.
But early consideration beneficial for reactor operator.
Rig Loading Schematic

Lower cluster

1. U
2. T
3. M
4. T
5. T
6. T

(Th, Pu)O₂
(Th, Pu)O₂ - alt. fill gas

Upper cluster

7. U
8. T
9. T
10. T
11. T
12. T

(U, Pu)O₂
UO₂
After ~2 years, a (Th,Pu)O$_2$ rod and a (U,Pu)O$_2$ reference rod are discharged from the lower cluster at around 20 MWd/kgHM.
These rods are replaced by fresh UO$_2$ fuel rods (to maintain rig power)
Accumulated burnups after ~6 years at moderate LHGR

- Lower cluster: 52 MWd/kgHM
- Upper cluster: 60 MWd/kgHM

U (Upper cluster) - 60 MWd/kgHM
T (Upper cluster) - 60 MWd/kgHM
M (Upper cluster) - 60 MWd/kgHM
Conclusion: Thorium Fuel Testing .... Ready to Go
Planning for the irradiation experiment is at an advanced stage

• *Thor Energy* has put in considerable effort and $$ into key planning aspects:
  
  ≡ Objective peer reviewed - & accords with predicted licensing roadmaps
  ≡ Produced well-reviewed (Th,Pu)O$_2$ pellet fabrication specifications, material sourcing
  ≡ Established with IFE a detailed irradiation plan – engineering drawings, waste management, data logging, rig variants
  ≡ Different Pu vectors considered - and americium
  ≡ Transport logistics
  ≡ Government approvals in place (*incl* IFE NRPA operating licence)
Calibration valve for power calibration of test assembly

Inlet turbine assembly for power calibration of test assembly

Fuel rod thermocouple

Neutron detectors vanadium

Fuel stack elongation detector for measuring densification / swelling of fuel

Extension tube

Outlet steam holes for coolant

Fuel rod pressure transducer

Outlet turbine for power calibration of test assembly

Stainless steel shield plug

Top seal assembly, sealing against the reactor top lid
Indicative Schedule for the Test Irradiation

Loading fuel in Halden Reactor:  Nov/Dec 2011

Pre-project by IFE, prelim rig design, guaranteed space

9 months  Pellet Specs

6 months  Contract Fabricator

2 months  Pellet Production

9 months  Pellet Transport

2 months  Rod & Rig Assembly

5 months  HBWR Irradiation

Today
Economics:

A favorable cost-benefit analysis for Th-MOX relies on factoring-in semi-intangible fuel cycle benefits.

• The Low Marginal cost for fuelling an NPP means any new fuel suggestion is unfavorable in raw-terms.

• Waste Management dimension significant
  — bottleneck for new-nuclear capacity in the West
  — doing nothing with accumulated SNF is less of an option
  — states will invest in credible strategies that recover energy value

• Thorium-enriched uranium fuel is not cost-effective wrt U & SWU.

• Projected uranium price
Fuel Technology Synergies

Some suggested LWR fuel technology developments go hand-in-hand with thoria fuels, *eg*:

- High B/U ceramic claddings
- Recycled irradiated zirconium
- Thorium hydride fuels (though this is a long shot)

Envisionable processing technologies would facilitate closed-cycle thoria-based fuels, *eg*:

- $^{233}$U extraction (non-complete ThO$_2$ dissolution)
- Thermochemical (*eg*, sulfide) routes may prove cost effective