Thorium – an alternative nuclear fuel cycle

5th Smart Grids & Clean Power Conference,
Cambridge, 5 June 2013
www.cir-strategy.com/events/cleanpower

Kevin Hesketh, Senior Research Fellow

Outline

NATIONAL NUCLEAR LABORATORY

- General Principles of the thorium fuel cycle
- Sustainability
- Economics
- Radiotoxicity
- Proliferation resistance
- Advantages and disadvantages
- An industrial view

Fertile thorium

NATIONAL NUCLEAR LABORATORY

- Th-232 is the only naturally occurring thorium nuclide
- It is a *fertile* nuclide that generates *fissile* U-233 on capturing a neutron
  - Th-232 is *fissionable* in that it fissions on interacting with fast neutrons > 1 MeV kinetic energy
  - Fertile conversion occurs with thermal neutron captures:

    Th-232 (n,γ) Th-233 (β^-) Pa-233 (β^-) U-233
- U-233 has a high thermal fission cross-section and a low thermal neutron capture cross-section
  - The fission/capture ratio for U-233 is higher than the other major fissile nuclides U-235, Pu-239 and Pu-241
  - This is very favourable for the neutron multiplication factor and minimises the probability of neutron captures leading to transuranics

Thorium fuel cycles

- Once-through fuel cycle with Th-232 as alternative fertile material to U-238 with U-235 or Pu-239 driver
  - U-233 fissioned in-situ without reprocessing/recycle
  - Modest reduction in uranium demand and sustainability
- Recycle strategy with reprocessing/recycle of U-233
  - Much improved sustainability analogous to U/Pu breeding cycle
  - But some technical difficulties to overcome
- Th-232 breeder requires long residence time

U fuel cycle for comparison

NATIONAL NUCLEAR LABORATORY

Neutron balance in a thermal reactor

- For U-235 fissions average number of fission neutrons $\nu \sim 2.4$
- Only about 0.6 to 0.7 neutrons available for fertile captures of U-238 to Pu-239
- Conversion ratio of ~0.6-0.7 means U-235 thermal reactors cannot operate as breeder reactors

General Principles

<u>Thermal breeder</u>

- The neutron balance for U-233 is more favourable and a conversion ratio just above 1.0 is possible in a thermal reactor
  - This is a breeding system
  - Not ideal, but much better than other fuels
  - Not possible with U/Pu fuel cycle

<u>Fast breeder</u>

- Fast breeder technology is less mature

Sustainability

NATIONAL NUCLEAR LABORATORY

- Thorium abundance higher than uranium
- Thorium demand lower - no isotopic enrichment
- Thorium economically extractable reserves not so well defined
- India plans to implement U-233 breeding in fast reactors and to burn it in Advanced Heavy Water Reactors (AHWR)
- Rate of expansion of thorium fuel cycle will be limited by the slow conversion rate

Economics

NATIONAL NUCLEAR LABORATORY

- U-233 recycle has lower demand on thorium than uranium - no isotopic enrichment
- U-233 recycle potentially reduces the ore procurement cost and eliminates the enrichment cost
- Future uranium and thorium market prices unknown
- Reprocessing costs will offset the reduction in front-end costs
- U-233 recycle will have an impact on the design and cost of fuel fabrication
- Short term economic barrier presented by need for R&D to demonstrate satisfactory fuel performance
- No utility will want to be the first to introduce a new fuel type

It is too soon to say whether the thorium fuel cycle will be economically advantageous

Radiotoxicity

NATIONAL NUCLEAR LABORATORY

- Spent fuel activity/radiotoxicity is dominated by fission products for 500 years after discharge
  - U/Pu fuel activity from 500 years to 10^5 years determined by activity of Np, Pu, Am and Cm
  - Th/U-233 fuel activity has only trace quantities of transuranics and lower radiotoxicity during this period
- However, this only applies to the long term equilibrium condition with self-sustained U-233 recycle
  - Need to account for the U-235 or Pu-239 fissions used to generate the initial U-233
- Also, radiotoxicity depends on the cooling time – long tail due to U-233 and U-234 decay chains

Radiotoxicity benefit varies with time after discharge and point in the reactor cycle

Inherent proliferation resistance

- U-233 is a viable weapons usable material
- U-233 classified by IAEA in same category as High Enriched Uranium (HEU) - Significant Quantity defined as 8 kg compared with 32 kg for HEU
  - High U-232 inventory gives high doses in casting/machining operations unless shielded
- Low inherent neutron source suggests that U-233 weapon design may be simplified and potentially more accessible
- U-233 fissile quality hardly changes with irradiation

Thorium history

NATIONAL NUCLEAR LABORATORY

- In the 1950s through to the 1980s, there were thorium research programmes for:
  - Pressurised water reactors (PWR)
    - Shippingport breeder core
    - Germany-Brazil collaboration
  - High temperature gas reactors (HTR)
    - DRAGON (UK), Fort St Vrain (USA), Peach Bottom (USA), AVR (Germany)
  - Molten salt reactors (MSR)
    - Molten Salt Reactor Experiment (Oak Ridge, USA)

Why did thorium research stall?

NATIONAL NUCLEAR LABORATORY

- Thorium cycle requires neutrons from uranium or plutonium fissions to get started
- U/Pu fuel cycle already established
- Barrier to entry for a new system
- Technological issues
  - THOREX reprocessing and fabrication of U-233 fuels

Advantages of Th fuel cycle

NATIONAL NUCLEAR LABORATORY

- Thorium is more abundant than uranium
- Combined with a breeding cycle thorium is potentially a major energy resource
- Low inventories of transuranics and low radiotoxicity after 500 years’ cooling
- Almost zero inventory of weapons usable plutonium
- Theoretical low cost compared with uranium fuel cycle
- ThO_2 properties generally more favourable than UO_2 (thermal conductivity; single oxidation state)
- ThO_2 is potentially a more stable matrix for geological disposal than UO_2

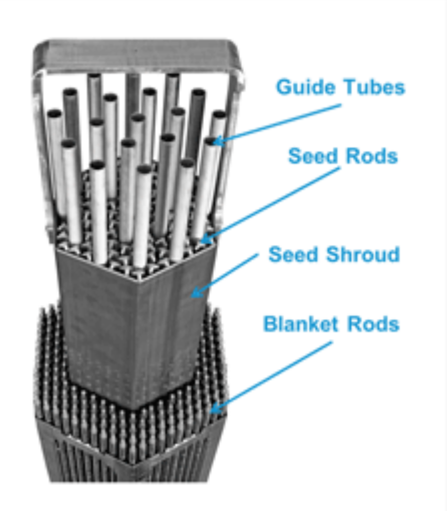
Disadvantages of Th fuel cycle

NATIONAL NUCLEAR LABORATORY

- Th-232 needs to be converted to U-233 using neutrons from another source
- The conversion rate is very low, so the time taken to build up usable amounts of U-233 are very long
- Reprocessing thorium fuel is less straightforward than with the uranium-plutonium fuel cycle
- The THOREX process has been demonstrated at small scale, but will require R&D to develop it to commercial readiness
- U-233 recycle is complicated by presence of ppm quantities of U-232 - radiologically significant for fuel fabrication at ppb
- U-233 is weapons useable material with a low fissile mass and low spontaneous neutron source

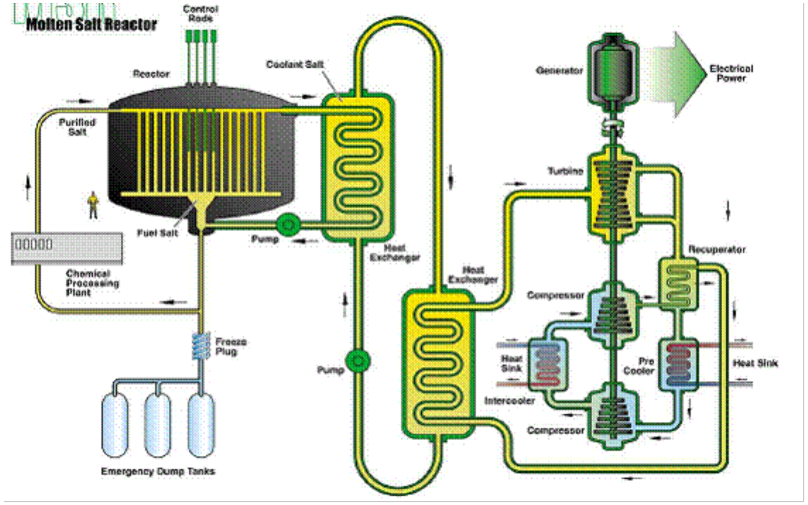
Current research

- India
  - Synergistic fuel cycle involving fast reactor and Advanced Heavy Water Reactors (AHWR)
  - Fast reactor will breed U-233 in a thorium blanket
  - U-233 will be recycled into AHWR fuel
- Lightbridge
  - Seed/blanket assembly design for PWRs
  - Low enriched uranium (LEU) seed region provides spare neutrons
  - ThO_2 blanket breeds U-233
  - Seed and blanket regions have different in-core dwell times



Molten salt reactor

- Molten Salt Reactor (MSR)
  - Generation IV International Forum project is researching MSR
  - Gen IV MSR will be a fast spectrum system
  - Molten salt fuel circulates through core and heat exchangers
  - On-line reprocessing to remove fission products
  - Ideally suited to thorium fuel as fuel fabrication is avoided
  - Equilibrium fuel cycle will have low radiotoxicity (fission products only)

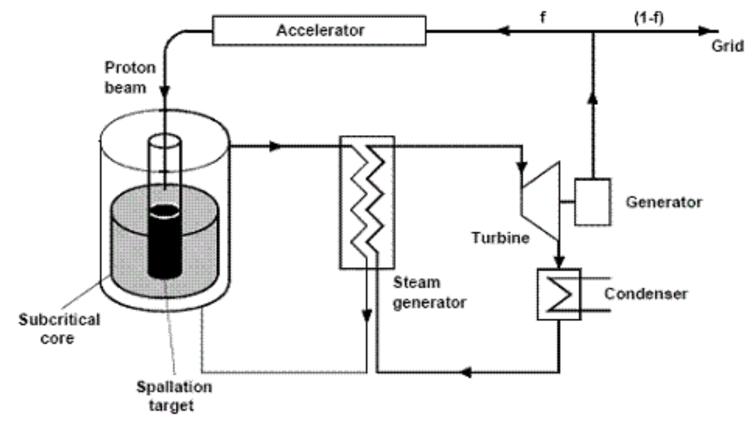


There are a number of technical issues to resolve

Accelerator driven system

NATIONAL NUCLEAR LABORATORY

- Accelerator driven system (ADS)
  - Sub-critical reactor core (multiplication factor k < 1)
  - Proton beam provides neutron source in spallation target
  - Neutron source multiplied by sub-critical core by factor 1/(1-k)
  - Energy Amplifier and Accelerator Driven Sub-critical System (ADSR) both use thorium fuel for low equilibrium radiotoxicity (fission products only)



Pu/Th MOX

- AREVA are investigating PuO_2/ThO_2 MOX fuel for the eventual disposition of PWR MOX fuel assemblies
- PWR MOX fuel currently not reprocessed in France
  - Held in long term storage pending eventual recycle in SFR fleet
  - Requirement to cover all contingency that SFR fleet is not built
    - Recycle of Pu from MOX fuel preferred over disposal
    - PuO_2/ThO_2 MOX is another option with potential advantage of low development cost and high stability as a final waste form

R&D requirements

NATIONAL NUCLEAR LABORATORY

- Fuel materials properties (unirradiated and irradiated)
- Fuel irradiation behaviour
- THOREX reprocessing
- Waste management/disposal
- U-233 fuel fabrication
- Systems development
  - Engineering design
  - Materials
  - Liquid salt chemistry and properties
  - MSR fuel and fuel cycle
  - Systems integration and assessment
  - Safety
- Scenario modelling

Summary

- Thorium is a valuable strategic alternative to uranium
- Sustainability is a main driver
- Radiotoxicity benefit is real, but modest
- Long term equilibrium radiotoxicity a simplistic measure
- Inherent proliferation resistance not proven for thorium
- Economics of thorium not known at present
- Minimum 15-20 year timescale for commercial deployment

An industrial view

- Thorium fuels offer theoretical advantages and disadvantages
- Balance between advantages and disadvantages not yet established
  - This balance will be context dependent
- Significant development required before industrial implementation with long timescales
- A clear case will need to be presented which identifies the problem that a thorium fuelled reactor will solve and evidence presented to demonstrate that thorium is the best solution
- More research is needed – and should be commissioned