Thorium fueled molten salt micro modular subcritical reactor using an electron accelerator

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The Reactor - an Overview

- MMR. A Micro Modular Reactor
- Electron ADSR. (Accelerator Driven Subcritical Reactor)
- Molten salt fuel and coolant
- Neutron production through high energy photons
- Criticality close to 1
- Thorium fuel to minimise actinides and to extend fuel life through breeding

Small Modular Reactors (SMR)

A lot of interest: several advantages

- Flexible power generation, up to 300 MW/module.
- Enhanced safety performance through advanced design but simple.
- Cost reduction through modularization, and used as single modules or in multiples.
- In-factory fabrication that improves construction and scheduling cost
- Deployment at remote locations if needed.

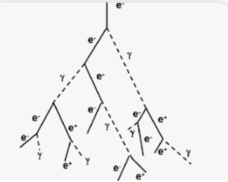
We consider the design of a Micro Modular Reactor (MMR) which is a subcategory of SMR capable of generating up to 10 MWe.

Thorium, electron accelerator, neutron production

Problem: Radioactive waste
Solution: Thorium fuel, reducing minor actinide production by approximately 100-fold compared to uranium-based fuels

Problem: Large and expensive proton machines
Solution: Electron accelerator, smaller and cheaper, though not nearly so effective at producing neutrons.

Neutron production through a two stage process:
1) The electrons produce an electromagnetic (EM) shower through Bremsstrahlung ($e^- \to e^-\gamma$) and pair production $\gamma \to e^+e^-$
2) The gamma component produces neutrons off target nuclei, chiefly through the giant dipole resonance, around 10 MeV and favouring large Z



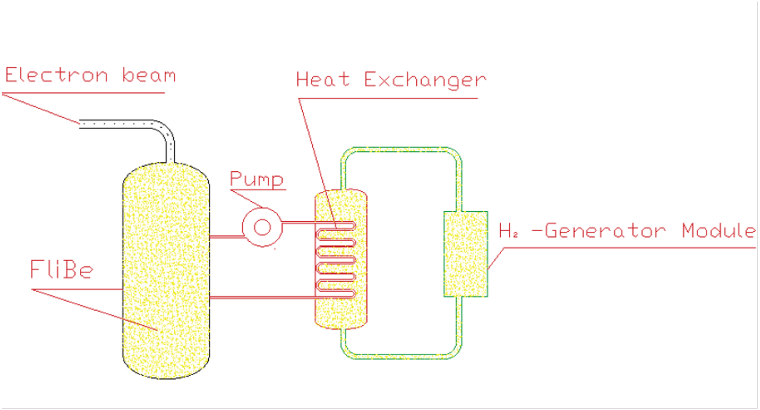


Figure 1: Design model

Temperature difference 500 C (cold) to 700 C (hot)
Flow rate 10 litres/sec for 10 MW
Cylinder radius and length in the tens of cm

Fuel

Molten salt as the fuel, simplifying construction and unifying fuel, coolant, moderator and target.

FLIBE - $\mathrm{Li_2BeF_4}$, containing dissolved fissile $^{233}\mathrm{U}$ and fertile $^{232}\mathrm{Th}$

Fuel composition: To observe the effect from different elements, the following compositions are considered, each for one mole of FLiBe:

- U - 0.1 mole, Th - 1 mole
- U - 0.15 mole, Th - 1.5 mole
- U - 0.2 mole, Th - 2 mole

These are illustrative. Actual mix will probably be different

Simulation programs

1. EGS
2. Geant4
3. MCNPX

Studies of EM showers in molten salt with various additives - EGS program and Geant4.

Neutron production - Geant4.

The criticality of the reactor - MCNPX.

Using different programs gives a check on the validity of our conclusions.

Photon production
EGS

The number of high energy photons in the shower increases with the electron energy, but so does the input power required. We quantify this by dividing the photon performance by the electron energy.

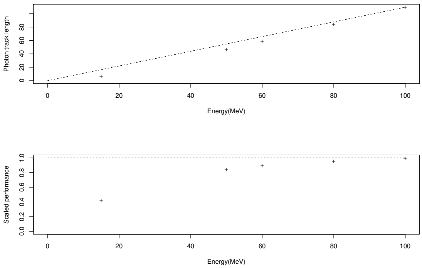


Figure 2: Photon track length and performance as a function of energy (EGS)

Photon production

Geant4 (with different fuel compositions)

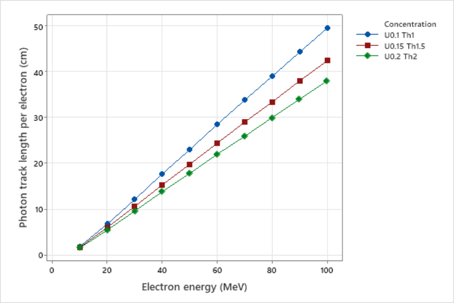


Figure 3: Photon track length as a function of electron energy (Geant4)

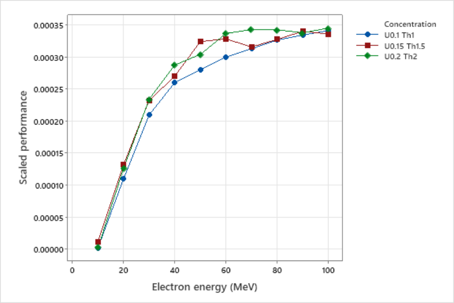


Figure 4: Photon performance as a function of electron energy (Geant4)

Increasing the concentration doesn't significantly effect the track length.
60 MeV is taken as the ideal electron energy for photoneutron production.

Photon production

Other elements - tantalum and lead

Since the photonuclear cross section for tantalum and lead are similar to that of thorium, these elements are then added with the same concentration as that of thorium.

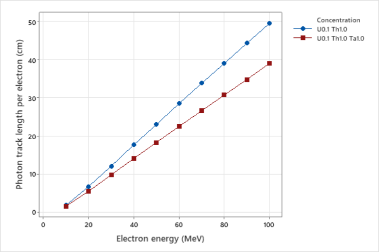


Figure 5: Effect of adding tantalum on photon track length

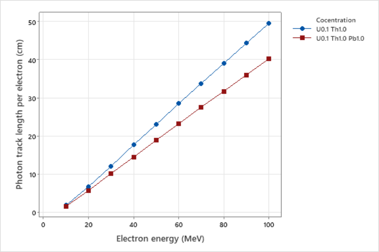


Figure 6: Effect of adding lead on photon track length

No benefit (in track length) of adding lead or tantalum in the mixture

Neutron production

Geant4

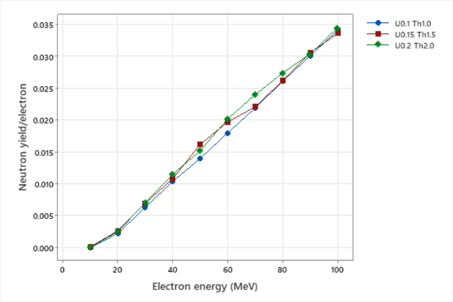


Figure 7: Number of neutrons/electron as a function of electron energy for different concentrations of uranium and thorium

Significant increase in neutron yield by increasing the beam energy. At 60 MeV about 0.02 neutrons are produced for each incident electron.

Neutron production

Other elements - tantalum and lead

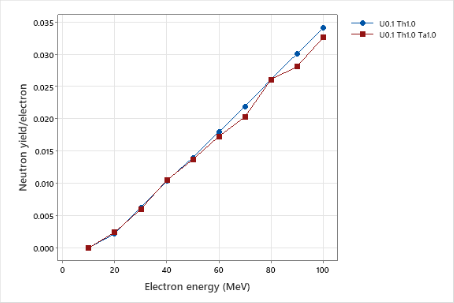


Figure 8: Effect of adding tantalum on neutron production

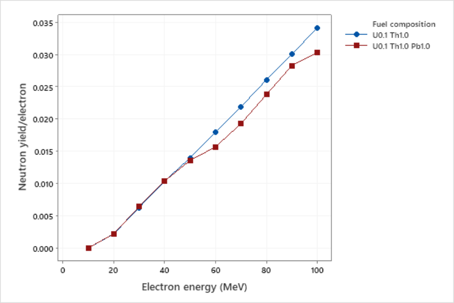


Figure 9: Effect of adding lead on neutron production

No benefit of adding tantalum and lead and after 50 MeV the production rather decreases.

Neutron energy distribution

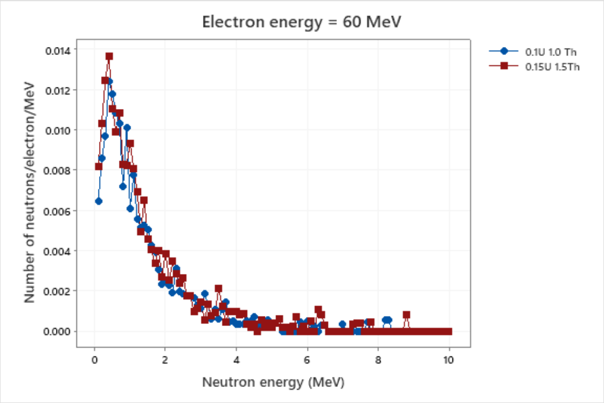


Figure 10: Neutron energy spectra at 60 MeV electron energy

A peak corresponding to 0.014 neutrons/MeV at around 1 MeV, which will be taken as the typical photoneutron energy.

Criticality (no thorium)

Geometry

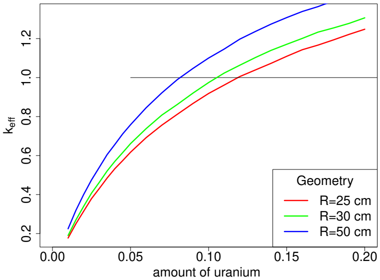


Figure 11: Criticality k as a function of $^{233}\mathrm{U}$ concentration for various geometries. (Units are moles of uranium per mole of FLiBe.)

The desired criticality is slightly below 1.0, achieved with concentrations of around 0.1 $^{233}\mathrm{U}$ atoms per FLiBe molecule, for a radius of 30 cm.

Increasing or decreasing the radius (or length) has a small effect on the criticality (or: on the concentration needed to achieve a criticality)

Criticality
Lithium purity

Natural lithium is 92.5% $^{7}\mathrm{Li}$ with 7.5% $^{6}\mathrm{Li}$. This absorbs a lot of neutrons. Increasing the isotopic purity has a big effect on the criticality and will probably be needed.

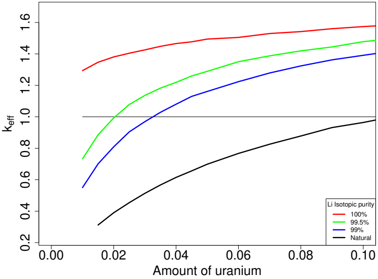


Figure 12: Criticality *k* as a function of $^{233}\mathrm{U}$ concentration for various lithium purities

Criticality when other elements are added

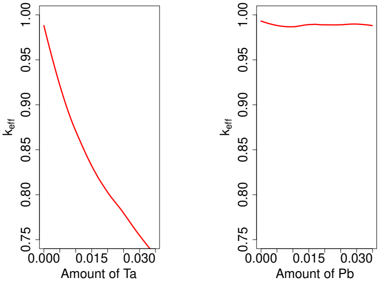


Figure 13: Criticality *k* as a function of tantalum and lead concentrations. (Statistical fluctuations have been smoothed by the R loess algorithm)

Adding tantalum reduces the criticality, if lead (taken as pure $^{208}\mathrm{Pb}$) is used instead, this has very little effect on the criticality.

Criticality: Thorium concentration

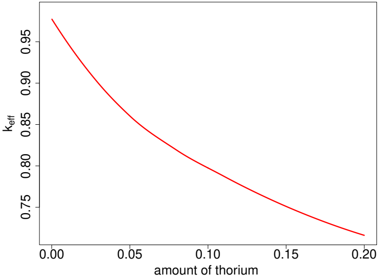
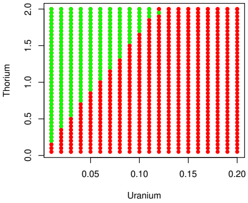


Figure 14: Criticality k as a function of thorium concentration. (Statistical fluctuations have been smoothed by the R loess algorithm)

Addition of thorium for breeding lowers the criticality - inevitably, as neutrons used for breeding are not used for fission.
Compatibility of criticality and breeding is a challenging problem

Breeding - is complete replacement possible?



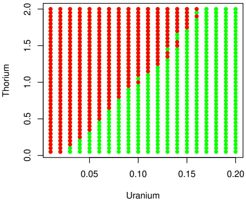


Figure 15: Criticality and replenishment rates for different concentrations of uranium and thorium.

The left shows the region of uranium and thorium concentration where the replacement exceeds 1, the right the region where the number of fissions per neutron exceeds twenty
Oh dear, no overlap

Yes it is

If the dimensions are doubled, solutions can be found.

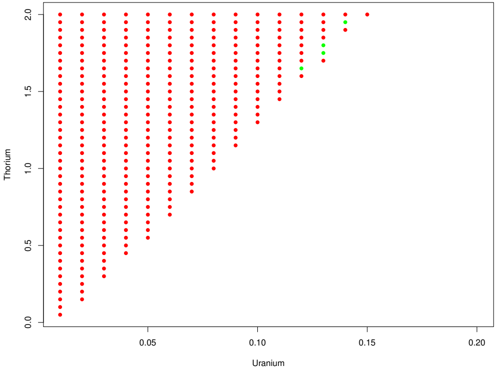


Figure 16: Combination of the replenishment and criticality requirements for a larger reactor. Outcomes with a criticality greater than 1 are not shown.

Conclusions

- Design of a micro modular sub-critical molten salt breeder reactor, driven by an electron accelerator. The seed fissile material is $^{233}\mathrm{U}$, and this is continually replaced during operation by breeding from the thorium present.
- No purpose is served by adding tantalum (or lead) beads.
- Criticalities between 0.9 and 1.0 can be achieved despite the addition of thorium to the uranium-loaded FLiBe salt. However the lithium in the mixture will have to be isotopically purified, to remove the ^{6}Li which has a high neutron absorption cross section.
- To obtain near-criticality, $k \approx 0.98$, and complete fuel replacement requires concentrations in the region of 1 $^{232}\mathrm{Th}$ atom per FLiBe, and 0.1 $^{233}\mathrm{U}$ atoms.

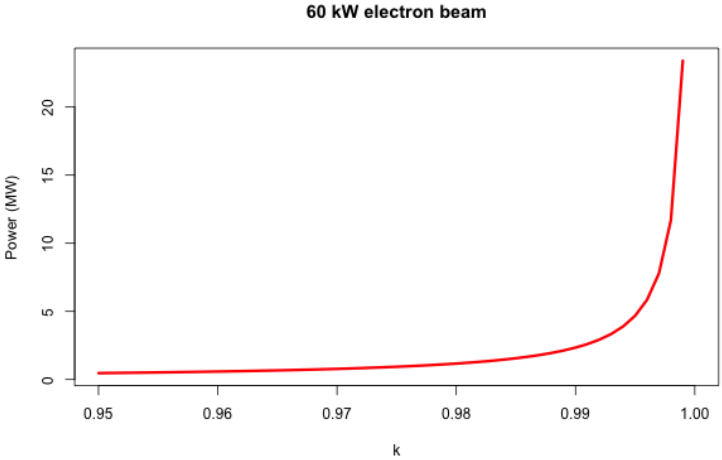
Viability

- For a viable power source the energy produced has to exceed the energy put in:

$$\eta_1 \frac{E_f}{1-k} r\nu > \frac{E_e}{\eta_2} \tag{1}$$

  where η_1 is the efficiency for thermal to electrical power conversion, E_e is the electron energy, η_2 is the efficiency of the accelerator, E_f is the energy from fission, k is the criticality, ν is the number of photoneutrons produced by an electron and r is the fraction of these which cause fission.
- At 60 MeV, 0.02 photo neutrons per electron are obtained which is slightly below the 0.03 needed for viability, given by Equation 1 with $k = 0.98$. The current design is thus on the edge of viability. This could be relaxed by increasing the criticality: this has implications for safety but molten-salt systems are guarded by negative feedback.

Output power



Conclusions

1. The design is viable (just)
2. We need to do a more detailed and exact optimised design of the accelerator and neutronics to fix dimensions and fuel composition, including the intermediate protactinium.
3. For that we need better measurements of neutron production by electrons on relevant targets. Data used by simulations is old and sparse.
4. We also need to know more about the chemistry of U and Th in molten salt, and subsequent changes to density, viscosity, etc.
5. We need a detailed design of the salt flow and heat transfer, and materials for the vessel, pipes, and pumps.