Thorium fuelled reactors: do they need an accelerator?

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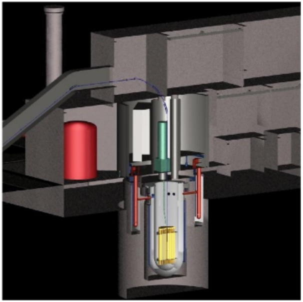
Accelerators for Thorium

ADSR systems can be fuelled by uranium or thorium
Thorium reactors can be critical or subcritical
But the accelerator + thorium combination is often found together.

Why?

The accelerator consumes 10-20% of the reactor output and of the capital cost.
"These costs are outweighed by the benefits."
What are the benefits?

Do these benefits just apply to thorium? Or breeding? And/or to MA incinerators?



The Aker/Jacobs ADTR™

Reason #0: Because we can

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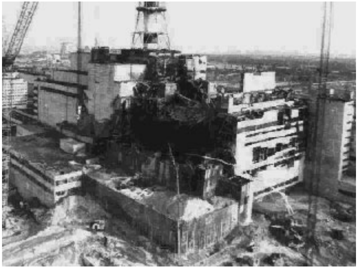
Reason #1: Safety

The Big Red Switch

"Switching off the accelerator switches off the reactor. No more Chernobyls."



But

Chernobyl design obsolete

Today's designs safe - negative void coefficient

6 reactors at Fukushima Daiichi:

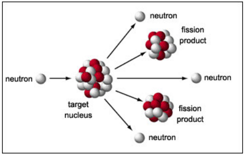
- 3 were switched off instantly.
- 3 were already switched off.
- Decay heat is another story

No extra safety from Big Red Switch – any 'benefit' purely cosmetic/political.

Reason #2: We need extra neutrons for breeding

thorium reactors must be breeder reactors

Fission produces ~ 2.5 neutrons. Depends slightly on target and energy (Rubbia [1] quotes 2.3 for $^{233}\mathrm{U}$ but standard refs. quote 2.48-2.55)



$$n_f + n_b + n_c = \nu$$

Standard Criticality: 1 neutron for fission, 1.5 captured/lost
Breeder: 1 neutron for fission, 1 for breeding, 0.5 captured/lost

Losses to absorption by moderator, cladding, by fission products, by intermediate $^{233}\mathrm{Pa}$ or $^{239}\mathrm{Np}$, by non-fission fuel reactions, and externally. So you need the extra spallation neutrons

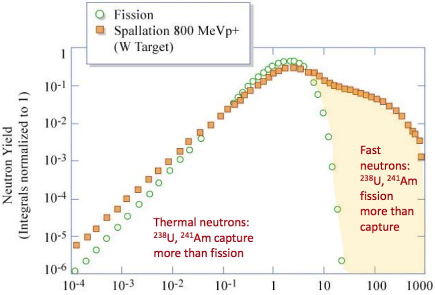
But ADSRs typically run with $k_{eff} = 0.95 - 0.98$. Spallation neutrons only 1 in 20 to 1 in 50. Not a big contribution.

It can't be impossibly hard to increase $k_{eff} = 0.95$ to $k_{eff} = 1.0$

If you are seriously short of neutrons you need a very big accelerator .

[1] F Carminati et al, 'An Energy Amplifier for cleaner and inexhaustible nuclear energy production driven by a particle accelerator, CERN/AT/93-47

Reason#3: High energy spallation neutrons give MA Incineration



Spallation spectrum is harder than fission spectrum
(thanks to Bob Cywinski for the plot)
Fission/absorption ratio increases with neutron energy
Destroy long-lived minor actinides (MA) by transmutation

But (1) Studies show little difference. Spallation neutrons quickly lose energy through moderation. [2]
(2) The spallation spectrum is only 2%-5% of the total neutron spectrum. There is very little difference in the overall neutron spectra: not enough to make a big difference to the possibility of incineration.

[2] Maurcio Gilberti *et al.*, 'Transuranics Transmutation Using Neutrons Spectrum from Spallation Reactions,' Science and Tech. of Nucl. Installations, 104739, (2015)

Reason# 4: To get a really strong neutron flux

Bowman's proposal[3] used a flux of $10^{16} n/cm^2/s$ (usually $\sim 10^{14}$)
Reasons
(1) Several MA chains become positive contributors to reactivity due to neutron reactions on intermediate states

Low flux $^{237}Np \underset{n}{\rightarrow} {}^{238}Np \rightarrow {}^{238}Pu \underset{n}{\rightarrow} {}^{239}Pu \underset{n}{\rightarrow} \mathrm{Fission...}$

High flux $^{237}Np \underset{n}{\rightarrow} {}^{238}Np \underset{n}{\rightarrow} \mathrm{Fission}$

(2) The MAs have already survived months of normal neutron flux. Need something much stronger.

But (1) high flux reactors are, though difficult, possible
(2) Most ADSR proposals are not high flux, as the $^{233}\mathrm{Pa}$ is destroyed.

[3] C D Bowman *et al.*'Nuclear energy Generation and Waste Transmutation using an accelerator-driven intense neutron source' Nucl. Instr & Meth. **A320**, 336-367 (1992)

Reason # 5: Overcome nasty properties of Minor Actinides

'Critical reactors loaded with fuel containing large amounts of minor actinides pose safety problems caused by unfavorable reactivity coefficients and small delayed neutron fractions. '[4]

Delayed neutron number for $^{233}\mathrm{U}$ is 2.7×10^{-3} compared to 6.5×10^{-3} for $^{235}\mathrm{U}$ and 2.1×10^{-3} for $^{239}\mathrm{Pu}$

Seriously lower for MA isotopes: $(0.4 - 2.4 \times 10^{-3}$. 1.3×10^{-3} for $^{241}\mathrm{Am}$).

Incinerator design 'unsafe' for critical operation. [5]

But: All important MAs are net contributors of neutrons in a fast spectrum

If MA component is not too large, there still ample delayed neutrons.

$\sim 10 - 20\%$ would give scope for home-grown MAs plus imports.

(Westlen incinerator has 35% Am.)

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[4] J.-L. Biarrotte *et al.*, 'A reference accelerator scheme for ADS applications', Proc AccApp05, 656, (2006),

[5] D Westlen and J Wallenius, 'Neutronic and Safety Aspects of a Gas-Cooled Subcritical Core for Minor Actinide Transmutation', Nuclear Technology **154** 41 (2006)

Go ahead and try!

Your ideal reactor

- Thorium Fuelled
- Fast neutrons
- Breeds its own fuel: long-lived fuel rods
- Burns its own MA waste, some spare capacity
- Load-following (vital in 21st century)

Design reactor with $n_f = n_b = 1$, subject to $n_f + n_b + n_c = \nu$
Conditions will change with time.

- Fuel evolution (slow)
- Fuel change (rare)
- Power. Coupled to neutronics. To adjust: move control rods, wait, then move back. But $^{233}\mathrm{Pa}$ conversion feeds through at the old rate.

Want to adjust to keep $n_f = n_b = 1$. But only one knob: control n_c.
Must keep $n_f = 1$, so n_b will vary. Breeding will not match fission rate.

Evolution

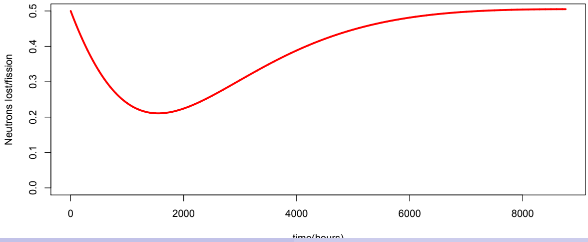
There is negative feedback, but it's slow

Assume fixed power: N fissions/vol/time. Variations in ρ_f, ρ_{Pa}, n_b, n_c
Decay, breeding and fission (ignoring change in ρ_b): $\lambda = ln(2)/27d$

$$\dot{\rho}_{Pa} = Nn_b - \lambda\rho_{Pa} \qquad \dot{\rho}_f = -N + \lambda\rho_{Pa}$$

Balance imposed by varying control rods: force $n_f = 1$

$$\frac{dn_c}{d\rho_f} = -\frac{dn_b}{d\rho_f} = \frac{\nu - 1}{\rho_f}$$



Neutron capture fraction (inc. control rods) over 1 year, to maintain steady $n_f = 1$ from start-up
Thought you had 0.5 spare neutrons: only have 0.2!
Exact shape depends on power, volume, fuel

The Punchline

Why your ideal reactor fails

1. Need to vary n_c, using control rods, to keep $n_f = 1$ (reactor criticality)
2. Leaves the breeding fraction n_b free to oscillate.
3. Leads to changes in fuel density ρ_f
4. Pushes changes to n_f requiring changes to n_c
5. These changes are large, and you run out of neutrons

Two obvious questions

But there are breeder reactors!

True. (Programme has problems, but related to coolant)

These control fuel composition on a short term system. Fuel-rich rods frequently moved out for reprocessing. Time of months not years. Or on-stream chemical reprocessing of liquid fuel.

But opens up whole new ball game of complication, and risk of proliferation.

How does an accelerator help?

You don't need to allow for 0.3 neutrons (or whatever) in your control rod neutron budget.

Vary beam current to load follow and compensate for variations in n_f

Use control rods to keep $n_b = 1$.

Or omit the control rods and ride out the variations in n_f

Do thorium reactors need an accelerator?

Yes they do, if they are to operate as self-contained breeder reactors.
Though not for the usual reasons# 1-5.