Thorium

The Alternative Nuclear Fuel?

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Global Energy Requirements

In 2000, world population = $6x10^9$

Total energy consumption/year = $10x10^9$ toe
per capita consumption = 1.6 toe/year
electricity per capita = 0.5 toe/year

In 2050, world population expected to reach $9x10^9$

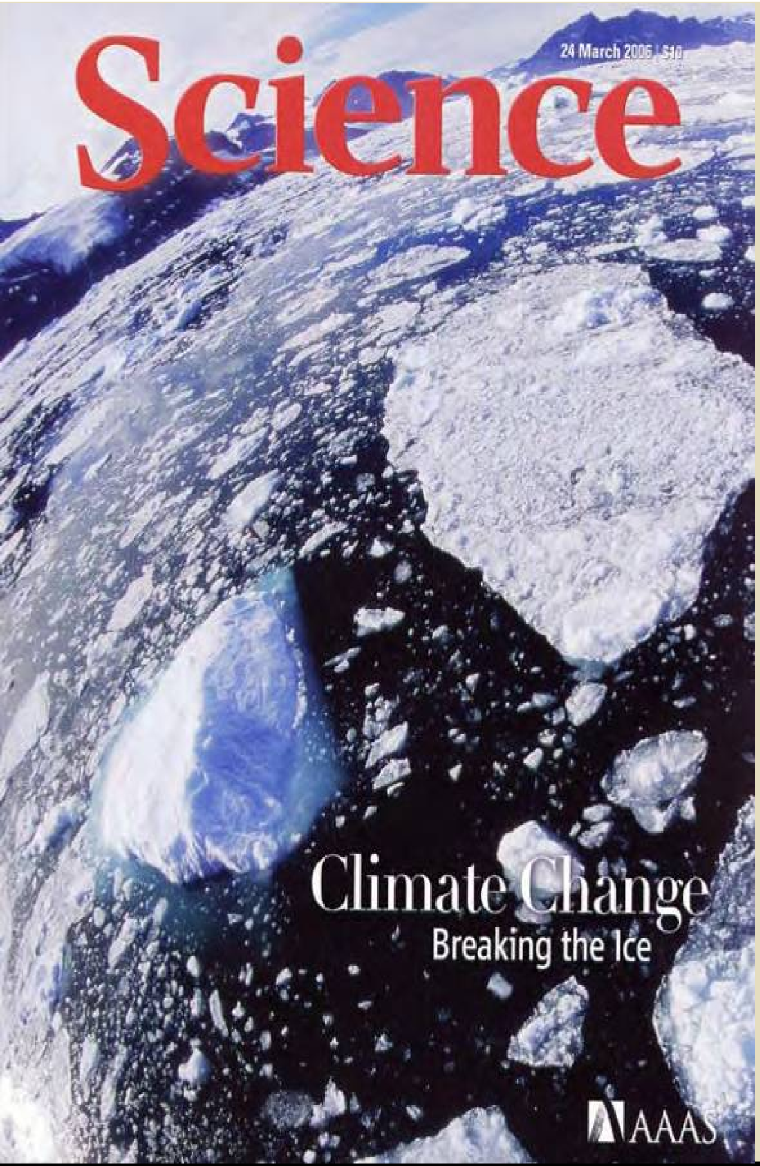
Population growth = 165000 per day

Assuming current electricity usage per capita the additional requirement is equivalent to:

a 1GW power station per day !

A new one of these every day!

...and the associated carbon emission



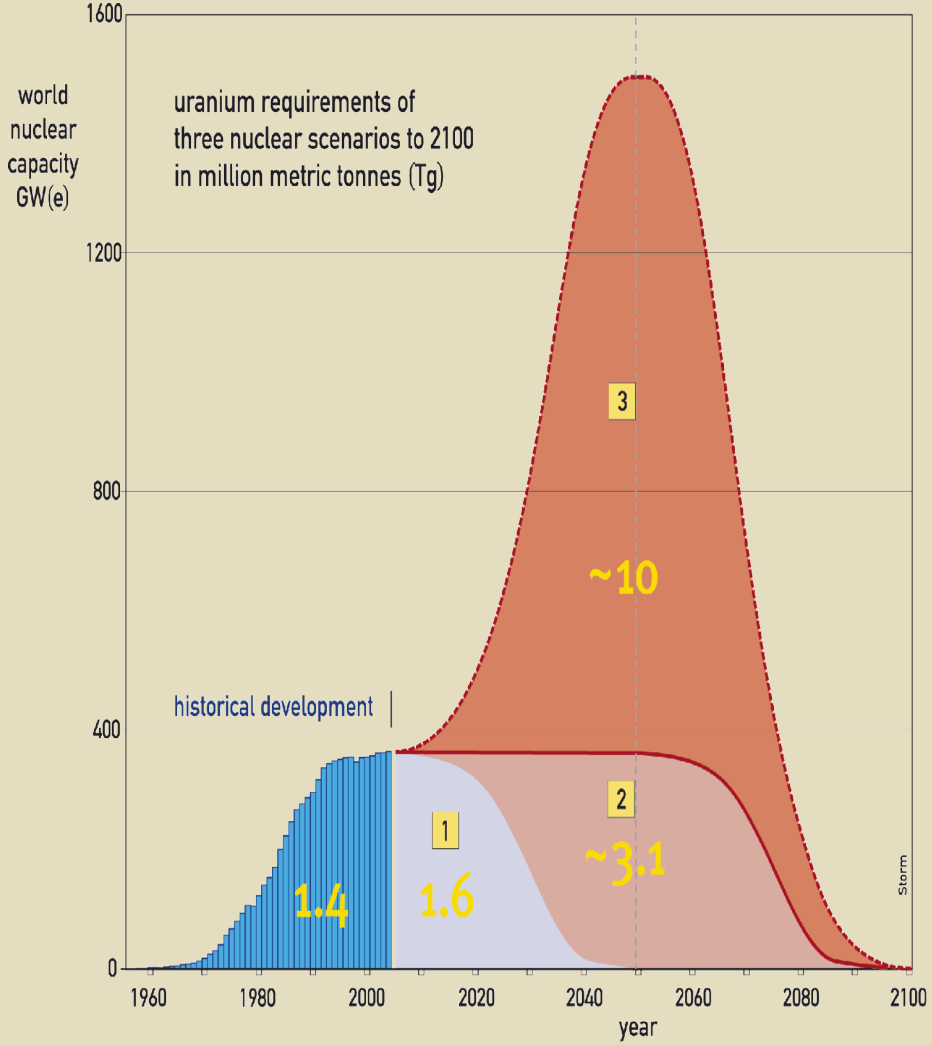
Energy source	Grammes of carbon per KWh of electricity
Nuclear	4
Wind	8
Hydro electric power	8
Energy crops	17
Geothermal	79
Solar	133
Gas	430
Diesel	772
Oil	828
Coal	955

source: Government Energy Support Unit (confirmed by OECD)

Global Nuclear Capacity

Country	No. Reactors	10^9 kWh	% Total
United States	103	754	20
France	59	395	78
Japan	53	305	34
United Kingdom	35	78	22
Germany	19	160	31
Russia	29	120	15
So. Korea	16	103	41
Canada	14	69	12
India	14	14	3
Sweden	11	55	39
21 Others			
Totals:	**437**	**2,447**	**16**

Global uranium requirements



Scenario 1

No new nuclear build

Scenario 2

Maintain current nuclear capability
(implies major increase in plant construction)

Scenario 3

Nuclear renaissance: increase in nuclear power generation to 1500 GW capacity by 2050

Available resources

Total U resources recoverable at <US$80/kg = 6Mt

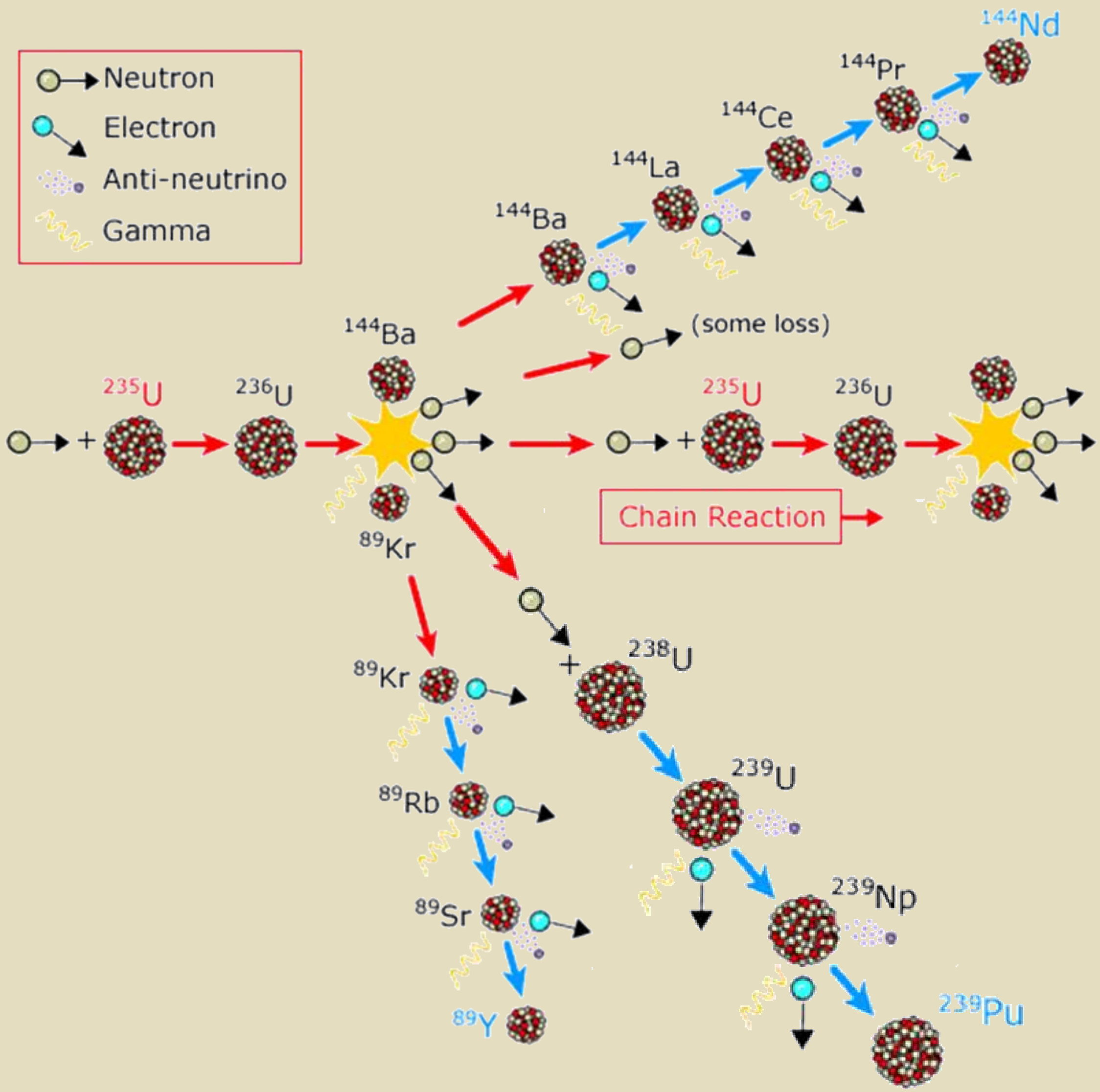
Resources recoverable at <US$130/kg may amount to ~4Mt

For scenario 3 these resources will be depleted within 70 years*

Hence the need to *breed* fuel

**assuming 170kgU/GWe*

........hence need to breed fuel



U-Pu	Th-U
^{238}U + 1 Neutron	^{232}Th + 1 Neutron
⇩	⇩
^{239}Np (2.3 Days) Beta Decay	^{233}Pa (27.4 Days) Beta Decay
⇩	⇩
^{239}Pu + 1 Neutron 65% Fission 35% Capture	^{233}U + 1 Neutron 90% Fission 10% Capture
⇩	⇩
^{240}Pu + 1 Neutron	^{234}U + 1 Neutron
⇩	⇩
^{241}Pu + 1 Neutron 75% Fission 25% Capture	^{235}U + 1 Neutron 80% Fission 20% Capture
⇩	⇩
^{242}Pu + 1 Neutron	^{236}U + 1 Neutron
⇩	⇩
^{243}Am Chemically Separable	^{237}Np Chemically Separable

IAEA, status report May 2005

I A E A

….in recent times, the need for proliferation-resistance, longer fuel cycles, higher burn up, improved waste form characteristics, reduction of plutonium inventories and in situ use of bred-in fissile material has led to renewed interest in thorium-based fuels and fuel cycles in several developed countries…….

Annual energy consumption

~5x10^9
tonnes of coal

27x10^9
barrels of oil

2.5x10^{12}
m^3 of natural gas

65x10^3
tonnes of uranium

Thorium equivalent

5x10^3 tonnes of thorium

After Sorenson

Thorium:

Abundance:

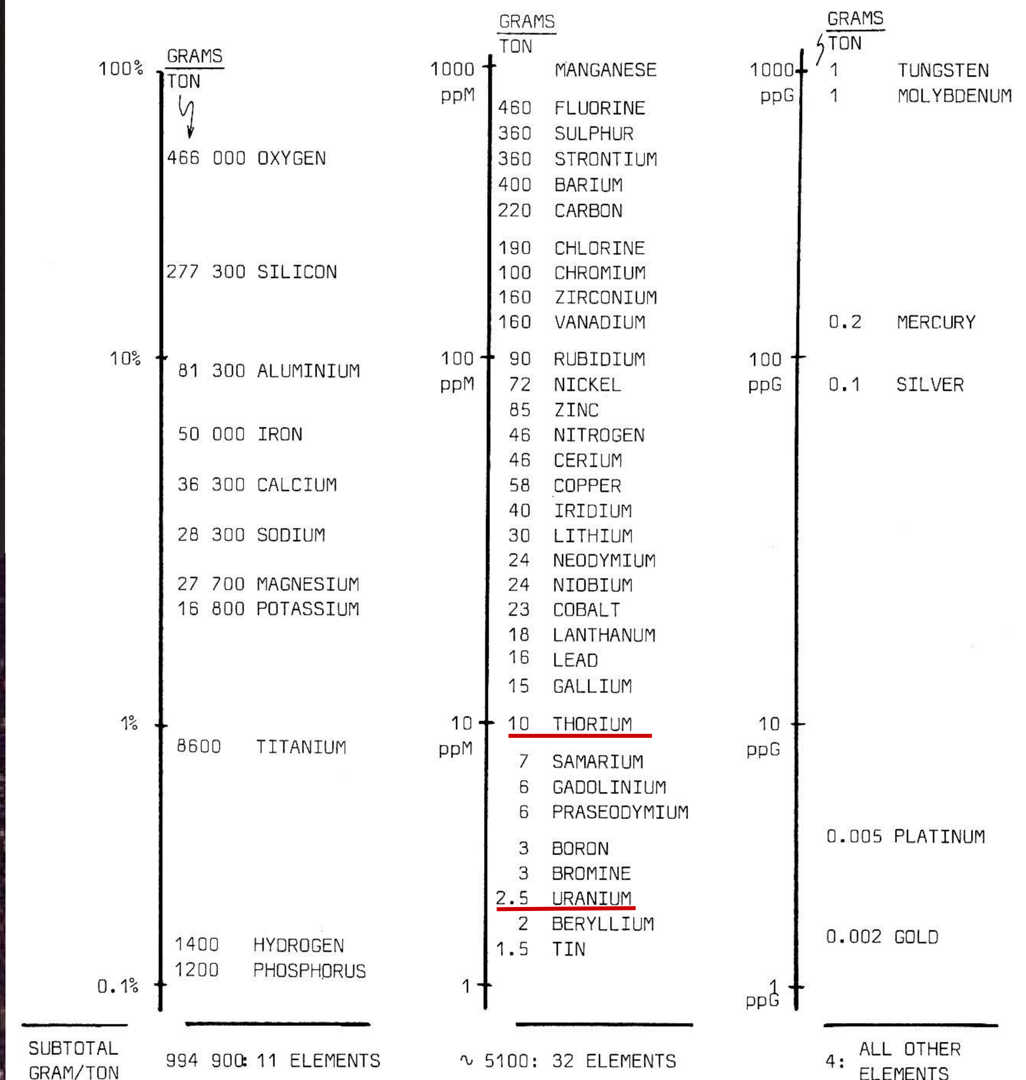


Fig. 5.13. The chemical composition of the Earth's crust.

Estimated global Th resources

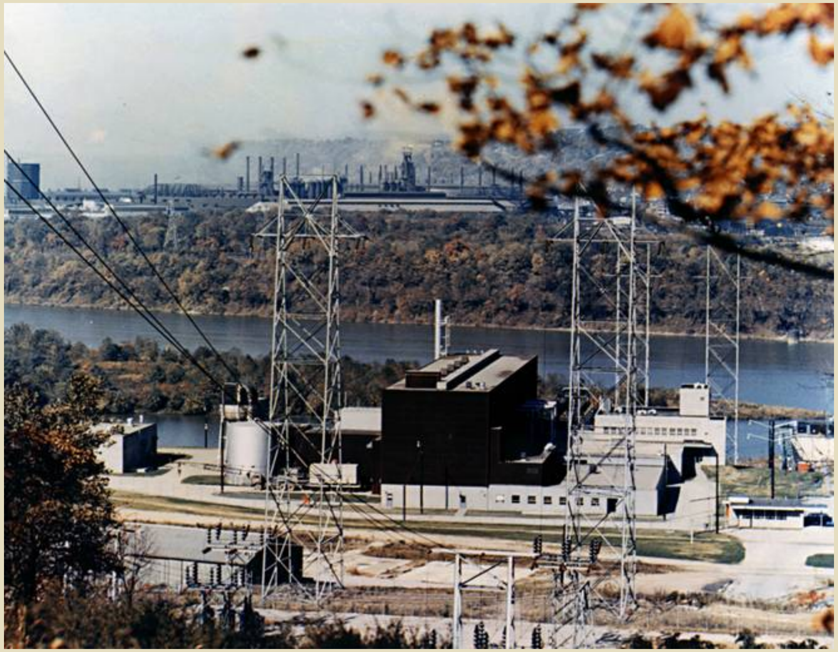
Estimated thorium resources by country

Country	Total Identified Thorium Resources ('000 t Th) <USD 80/kg Th	%
Australia	420	17
United States	400	16
Turkey	344	14
India	319	13
Venezuela	300	12
Brazil	221	9
Norway	132	5
Egypt	100	4
Russian Federation	75	3
Greenland	54	2
Canada	44	2
South Africa	18	1
Others	33	1
TOTAL	**2460**	

Sources: Data for Australia compiled by Geoscience Australia; estimates for all other countries are from: OECD, 2006: Red Book Retrospective. A review of Uranium Resources, Production and Demand from 1965 to 2003.

Thorium in power reactors

Name and Country	Type	Power	Fuel	Operation Period
AVR, Germany	HTGR Experimental (Pebble Bed Reactor)	15 MW_e	Th & U-235 Driver Fuel, Coated fuel particles, Oxide & dicarbides	1967 - 1988
THTR, Germany	HTGR Power (Pebble Type)	300 MW_e	Th & U-235 Driver Fuel, Coated fuel particles, Oxide & dicarbides	1985 - 1989
Lingen, Germany	BWR Irradiation-testing	60 MW_e	$(Th, Pu)O_2$ Test Fuel , Pellets	Terminated in 1973
Dragon, UK OECD-Euratom also Sweden, Norway & Switzerland	HTGR Experimental (Pin-in-Block Design)	20 MW_{th}	Th & U-235 Driver Fuel, Coated fuel particles, Dicarbides	1966 -1973
Peach Bottom, USA	HTGR Experimental (Prismatic Block)	40 MW_e	Th & U-235 Driver Fuel, Coated fuel particles, Oxide & dicarbides	1966 – 1972
Fort St Vrain, USA	HTGR Power (Prismatic Block)	330 MW_e	Th & U-235 Driver Fuel, Coated fuel particles, Dicarbides	1976 – 1989
MSRE ORNL, USA	MSBR	7.5 MW_{th}	U-233 Molten Fluorides	1964 – 1969
Borax IV & Elk River Reactors, USA	BWRs (Pin Assemblies)	2.4 MW_e 24 MW_e	Th & U-235 Driver Fuel, Oxide Pellets	1963 – 1968
Shippingport & Indian Point, USA	LWBR PWR (Pin Assemblies)	100 MW_e 285 MW_e	Th & U-233 Driver Fuel, Oxide Pellets	1977 – 1982 1962 – 1980
SUSPOP/KSTR KEMA, Netherlands	Aqueous Homogenous Suspension (Pin Assemblies)	1 MW_{th}	Th & HEU Oxide Pellets	1974 - 1977
NRU & NRX, Canada	MTR (Pin Assemblies)		Th & U-235 Test Fuel	Irradiation-testing of few fuel elements
KAMINI, CIRUS & DHRUVA, India	MTR Thermal	30 kW_{th} 40 MW_{th} 100 MW_{th}	Al & U-233 Drive Fuel, 'J' rod of Th & ThO_2 'J' rod of ThO_2	All three research reactors in operation
KAPS 1 & 2, KGS 1 & 2, RAPS 2, 3 & 4, India	PHWR (Pin Assemblies)	220 MW_e	ThO_2 Pellets For neutron flux flattening of initial core after start-up	Continuing in all new PHWRs
FBTR, India	LMFBR (Pin Assemblies)	40 MW_{th}	ThO_2 blanket	In operation

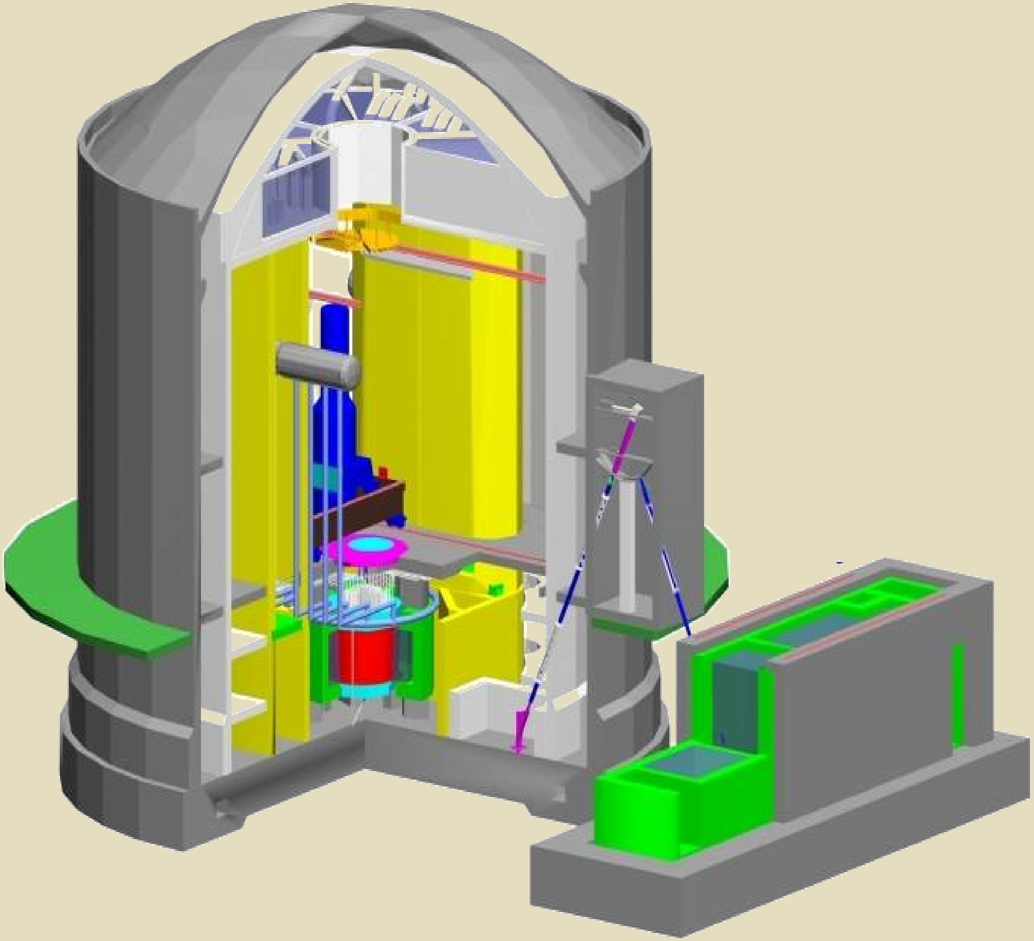


Shippingport LWBR

- Fuelled with U-233 and Th-232
- Produced 1.4% more fuel than it burned

IAEA-TECDOC 1450

Current activity



The planned AHWR (India) is a vertical pressure tube type, boiling light water cooled and heavy water moderated reactor using ^{233}U-Th MOX (Mixed Oxide) and Pu-Th MOX fuel.

IAEA TECDOC 1450

Thorium as fuel

Advantages

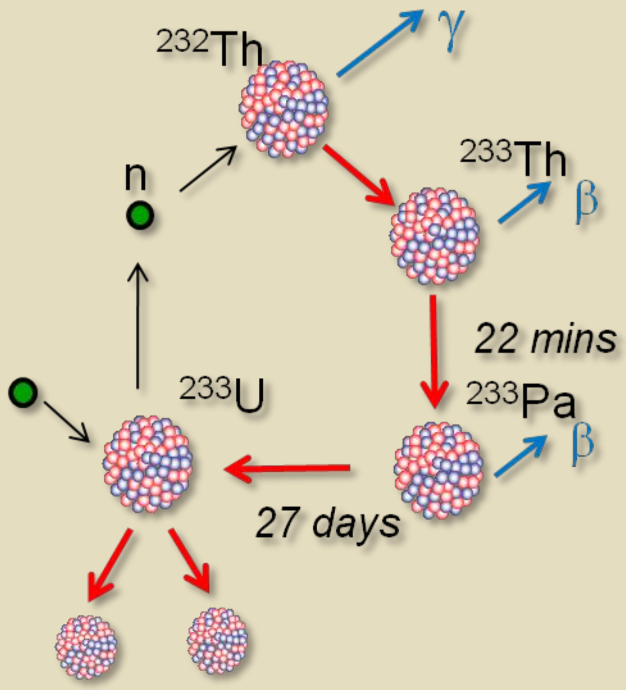
Thorium supplies plentiful

Robust fuel and waste form

Generates no Pu and fewer higher actinides

^{233}U has superior fissile properties to ^{235}U and ^{239}Pu

Proliferation *resistant*



Disadvantages

No fission until ^{233}U is produced

^{233}U is weapon grade unless denatured

Parasitic ^{232}U production results in high gamma activity

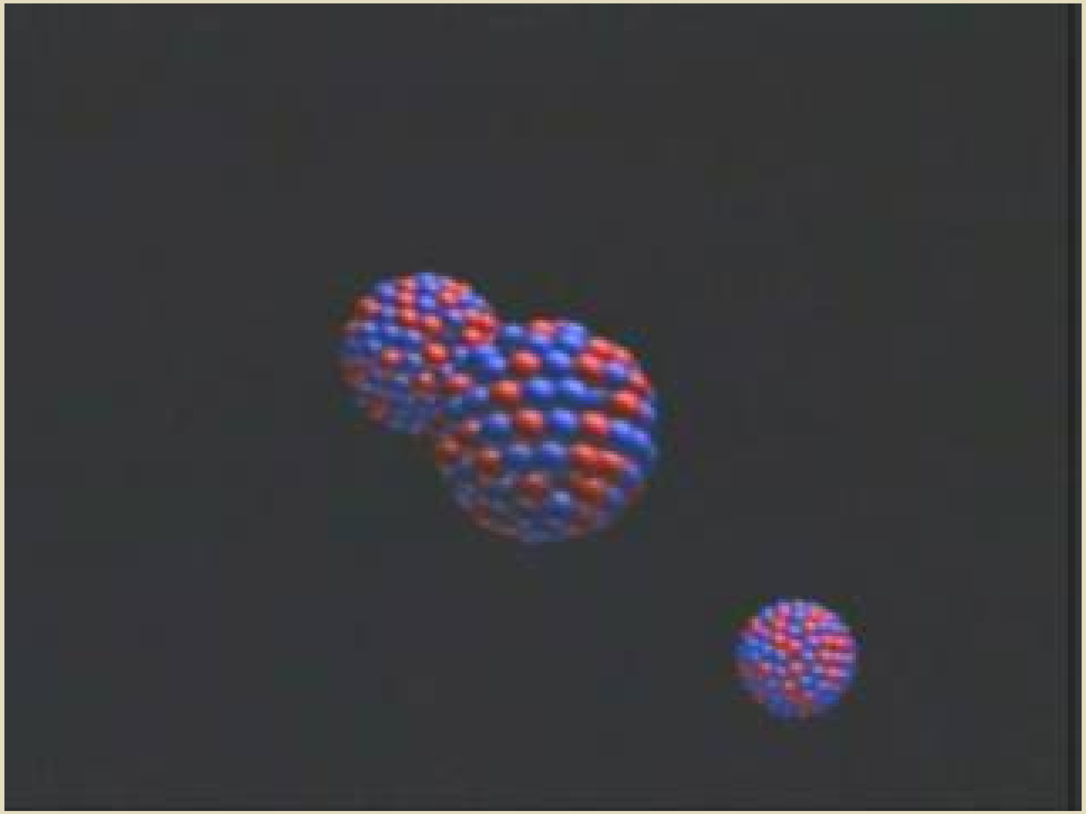
Thorex processing of waste needs substantial development

It is generally considered that the neutrons necessary to produce ^{233}U from ^{232}Th must be introduced by:seeding the Th fuel with ^{235}U or Pu for a conventional reactor, or

But ....can we dispense with U and Pu altogether ?

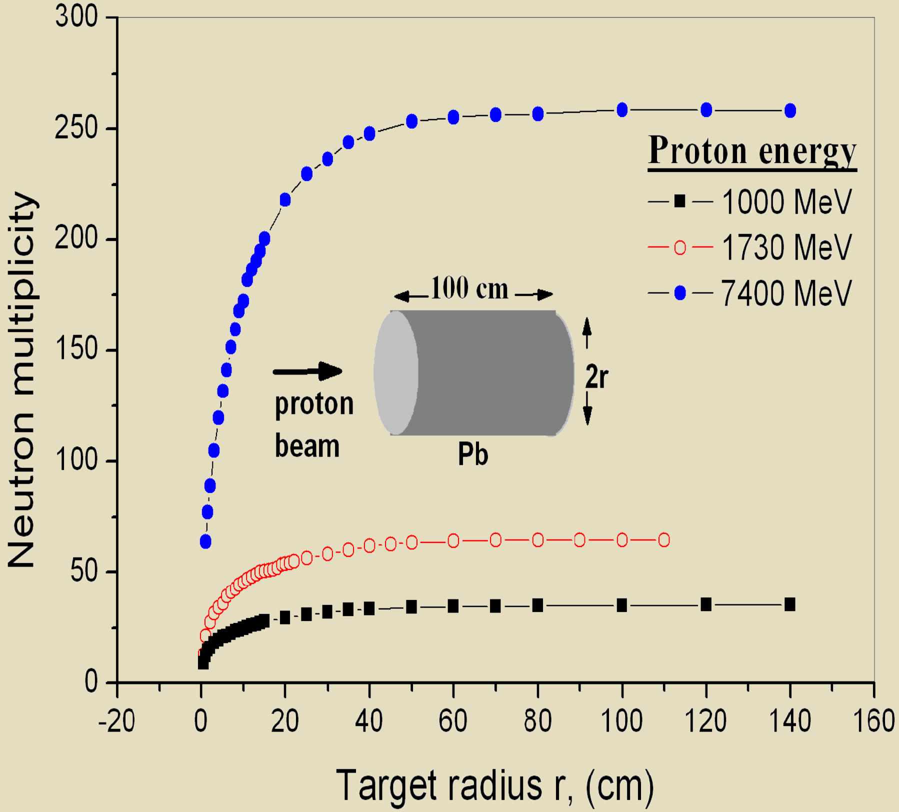
Spallation

......for example by utilising spallation, rather than fission, neutrons...

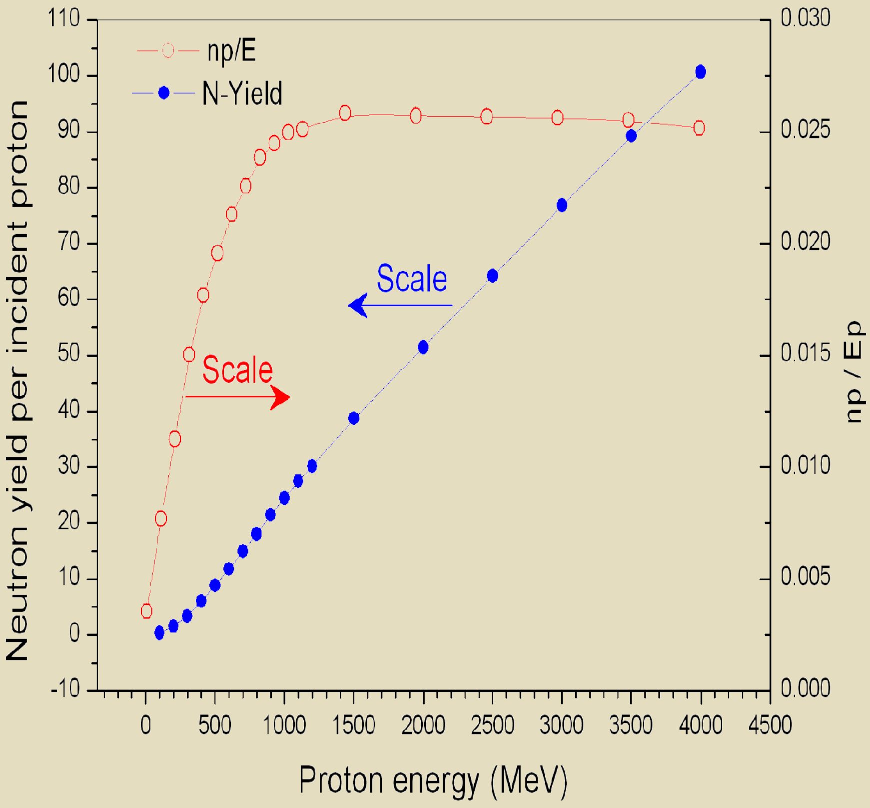


......and we know a lot about spallation (ISIS, PSI, SNS, J-PARC, ESS

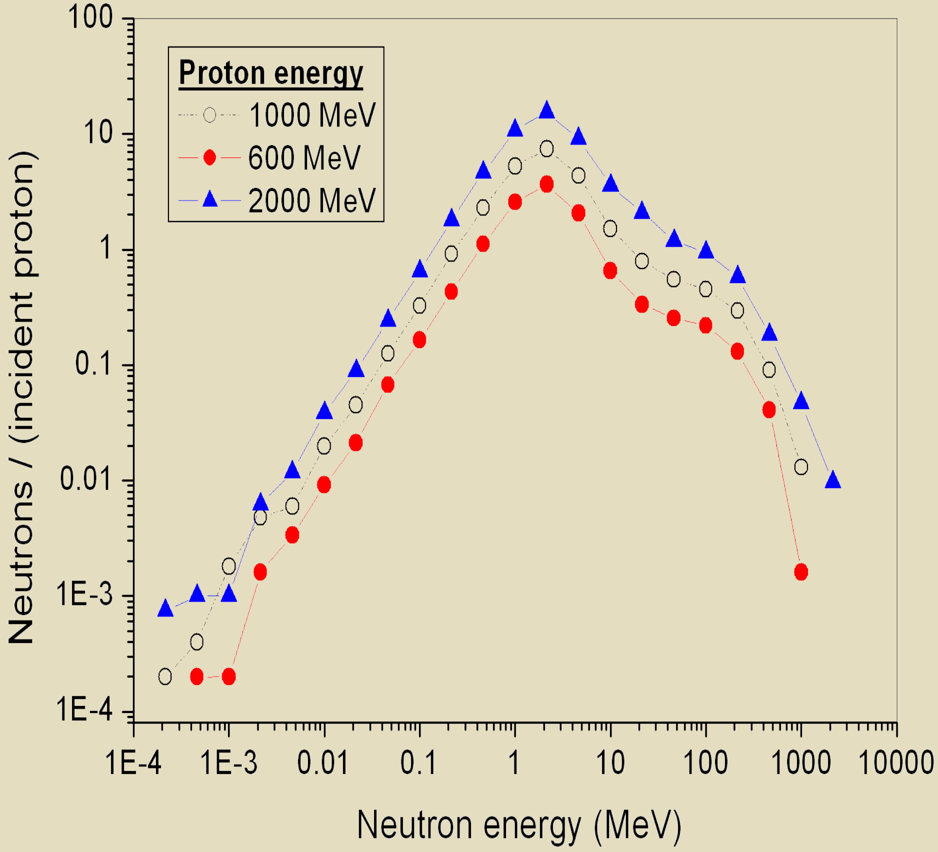
Target size



Proton energy



Neutron energies

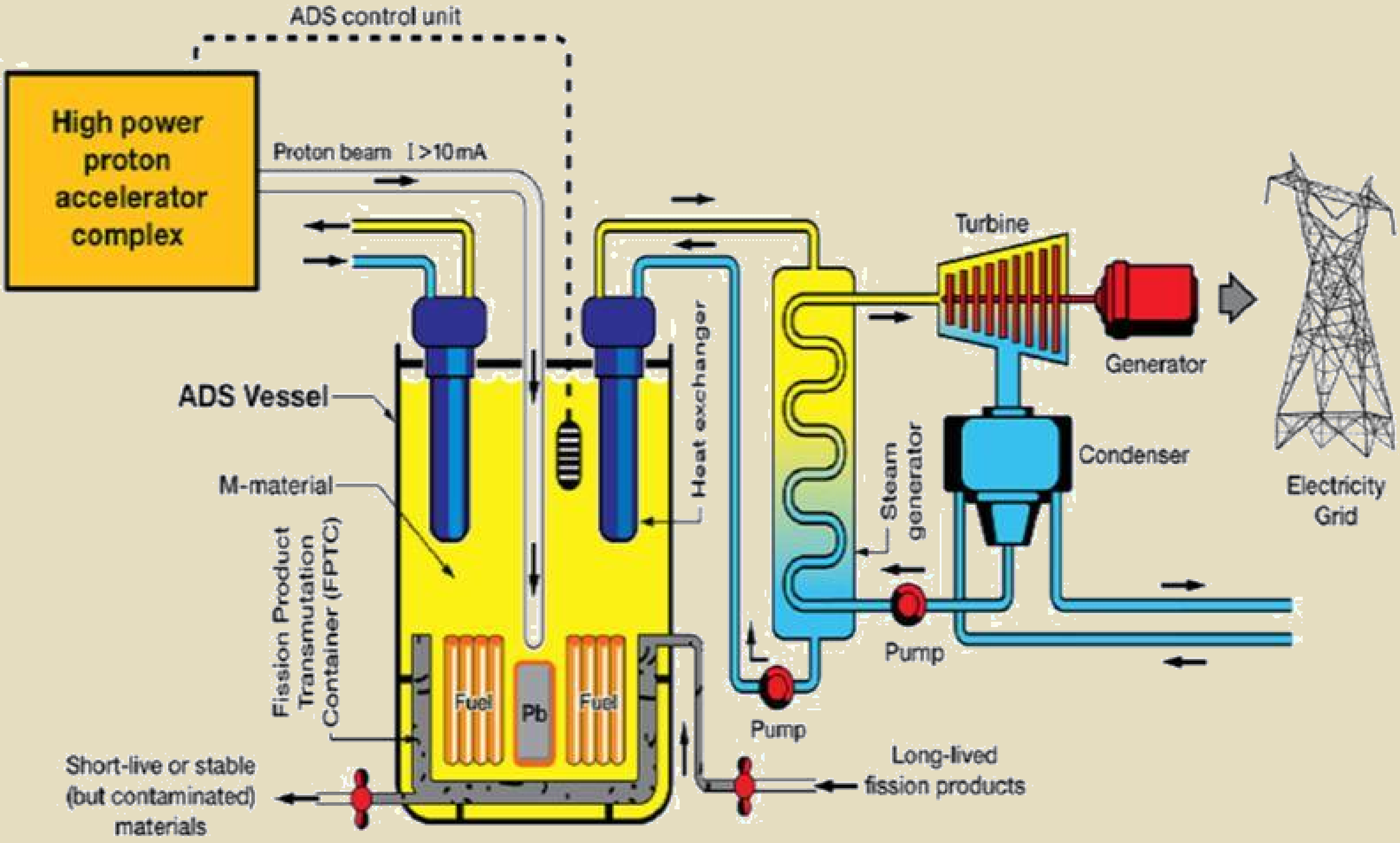


The energy spectrum of the spallation neutrons at different incident proton energies.

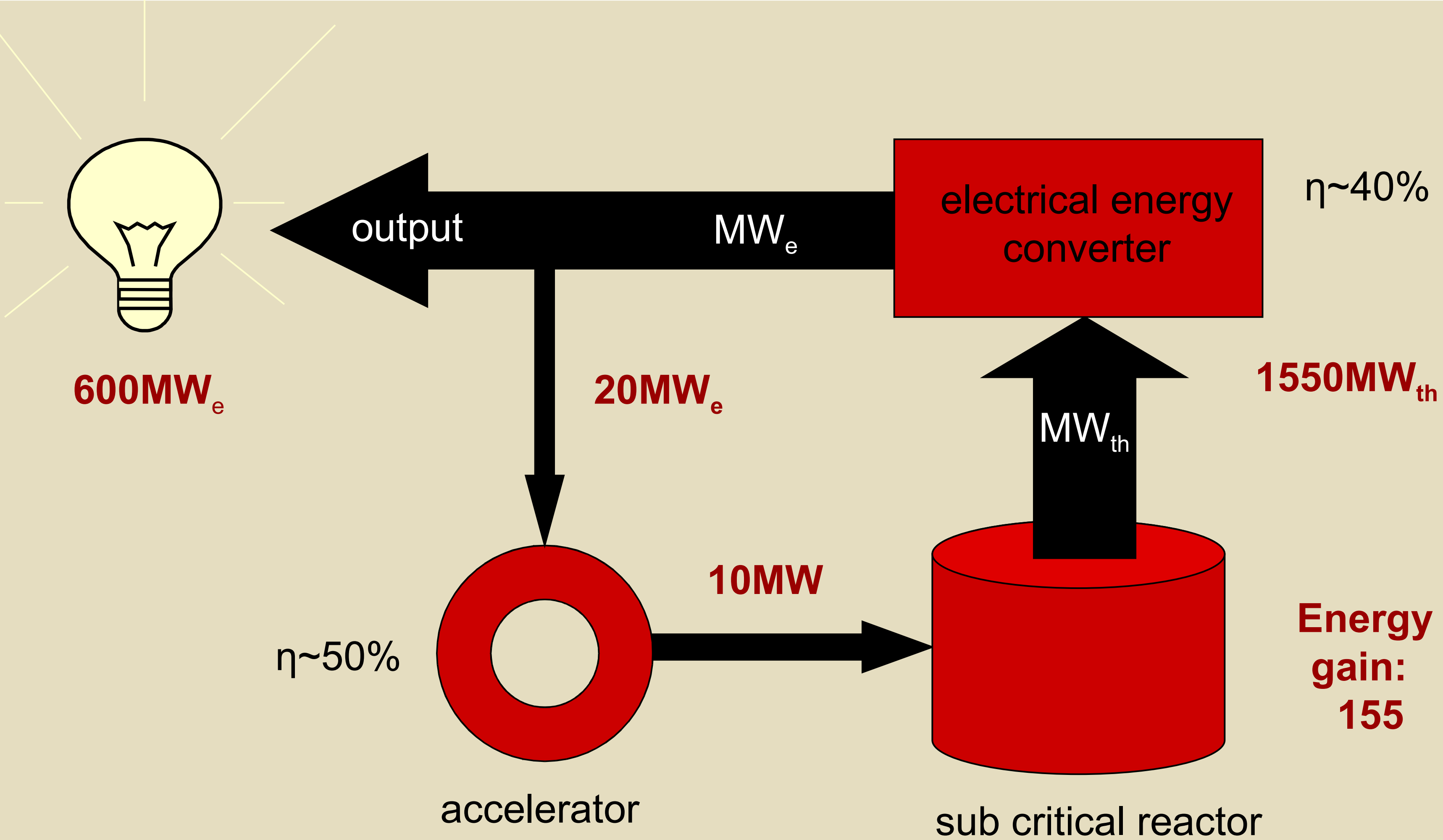
The target is a lead cylinder of diameter 20 cm

At 1 Gev, approximately 24 neutrons per proton are produced

The Energy Amplifier/ADSR Concept



The Energy Amplifier/ADSR energy balance



$^{232}Th + n \rightarrow {}^{233}Th \rightarrow {}^{233}Pa\ (27d) \rightarrow {}^{233}U$

Proton beam requirements for EA/ADSR

The (thermal) power output of an ADSR is given by

$$P_{th} = \frac{N \times E_f}{\nu} \cdot \frac{k_{eff}}{1 - k_{eff}}$$

with
- N = number of spallation neutrons/sec
- E_f = energy released/fission (~200MeV)
- v = mean number of neutrons released per fission (~2)
- k_{eff} = criticality factor (<1 for ADSR)

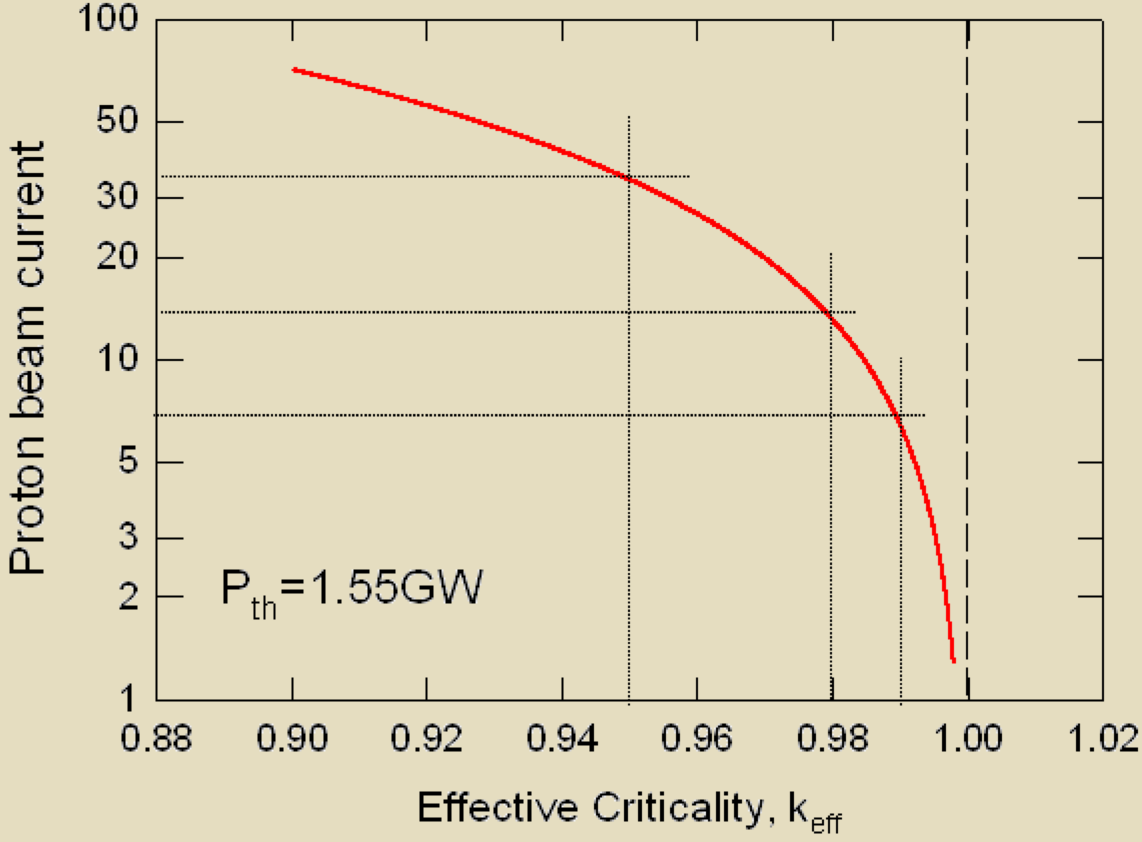
So, for a thermal power of 1550MW we require

$$N = 9.6 \times 10^{19} \times \frac{1 - k_{eff}}{k_{eff}} \text{ neutrons.s}^{-1}$$

Given that a 1 Gev proton produces 24 neutrons (in lead) this corresponds to a proton current of

$$i = \frac{9.6 \times 10^{19}}{24} \times 1.6 \times 10^{-19} \times \frac{1 - k_{eff}}{k_{eff}} \text{ amps} = 640 \times \frac{1 - k_{eff}}{k_{eff}} \text{ mA}$$

Proton beam requirements



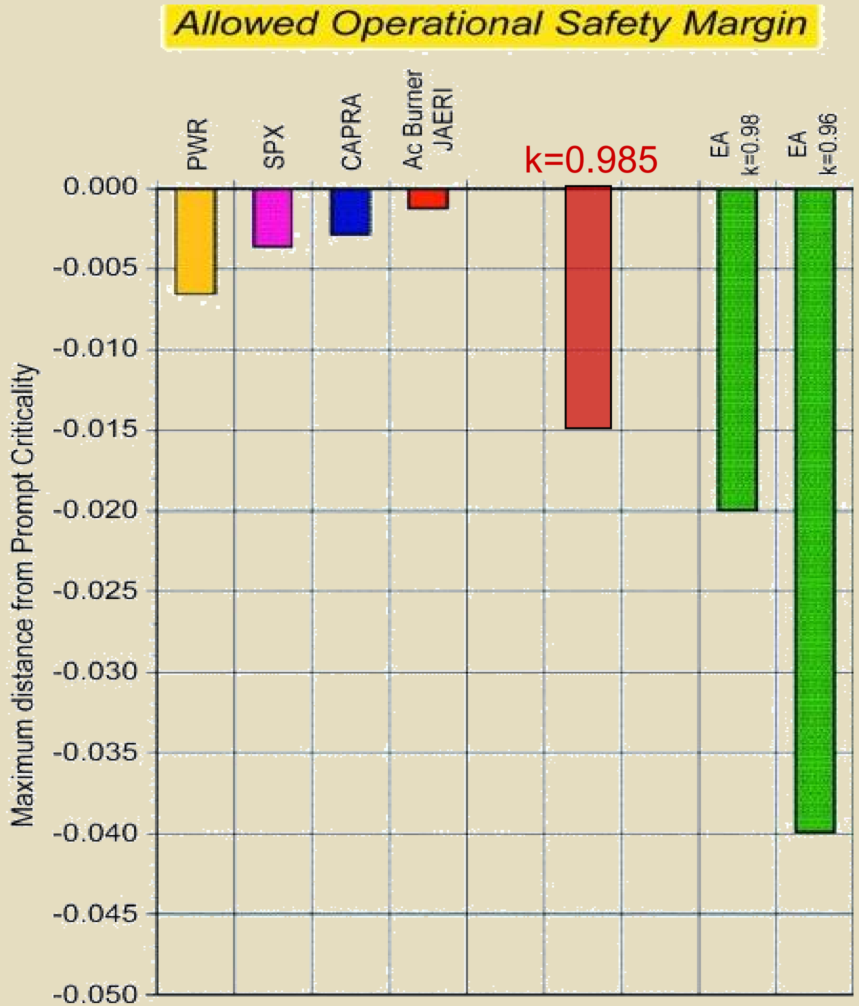
k_{eff}=0.95, i=33.7mA

k_{eff}=0.98, i=13.1mA

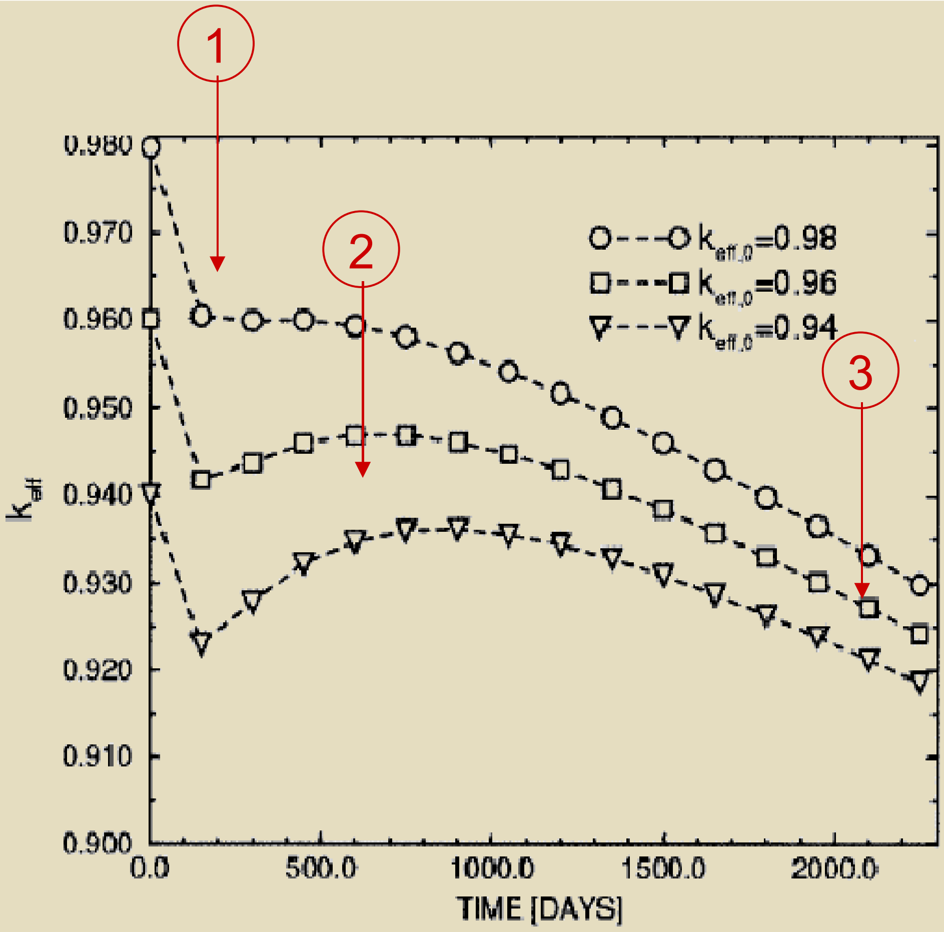
k_{eff}=0.99, i=6.5mA

To meet the constraint of a 10MW proton accelerator we need k_{eff}=0.985

Safety margins



Time evolution of k_{eff} for a Th-fuelled ADSR



H.M. Broeders, I. Broeders :
Nuclear Engineering and Design 202 (2000) 209–218

Evolution of the criticality value, k_{eff}, over 6 years for lead-cooled Th/U^{233} ADSRs

1. Initial loss due to build-up of absorbing Pa^{233} and decrease of U^{233} enrichment by neutron absorption and fission

2. Increase due to increasing U^{233} enrichment from subsequent β-decay of Pa^{233}

3. Long term decrease due to build up of neutron absorbing fission products

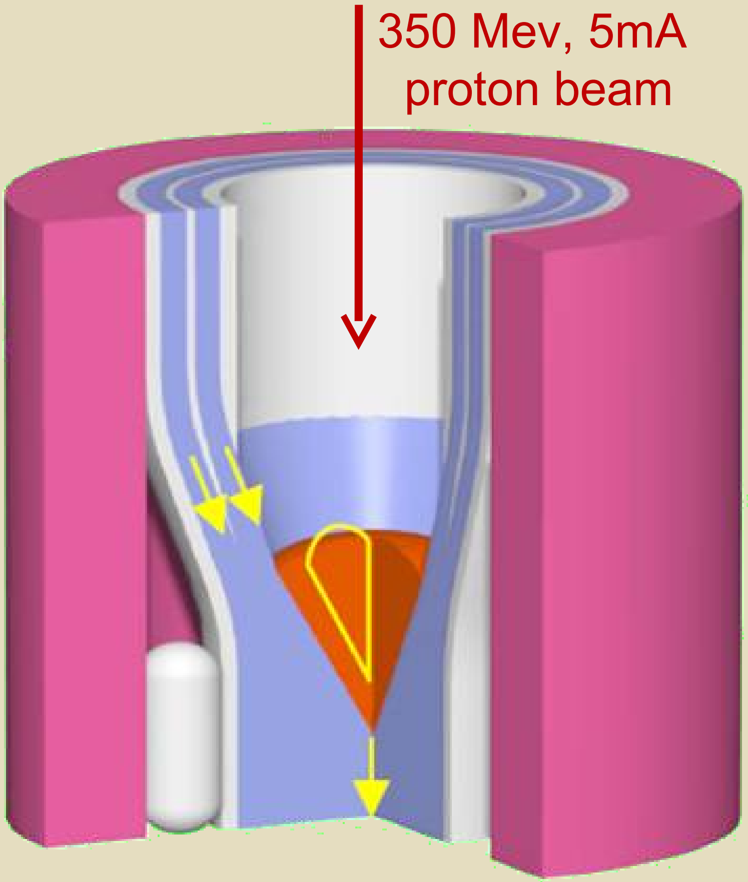
MYRRHA: an ADSR transmutation proposal

The MYRRHA design proposes a windowless Pb-Bi target:

The target surface results from the vertical co-axial confluent Pb-Bi liquid metal flow

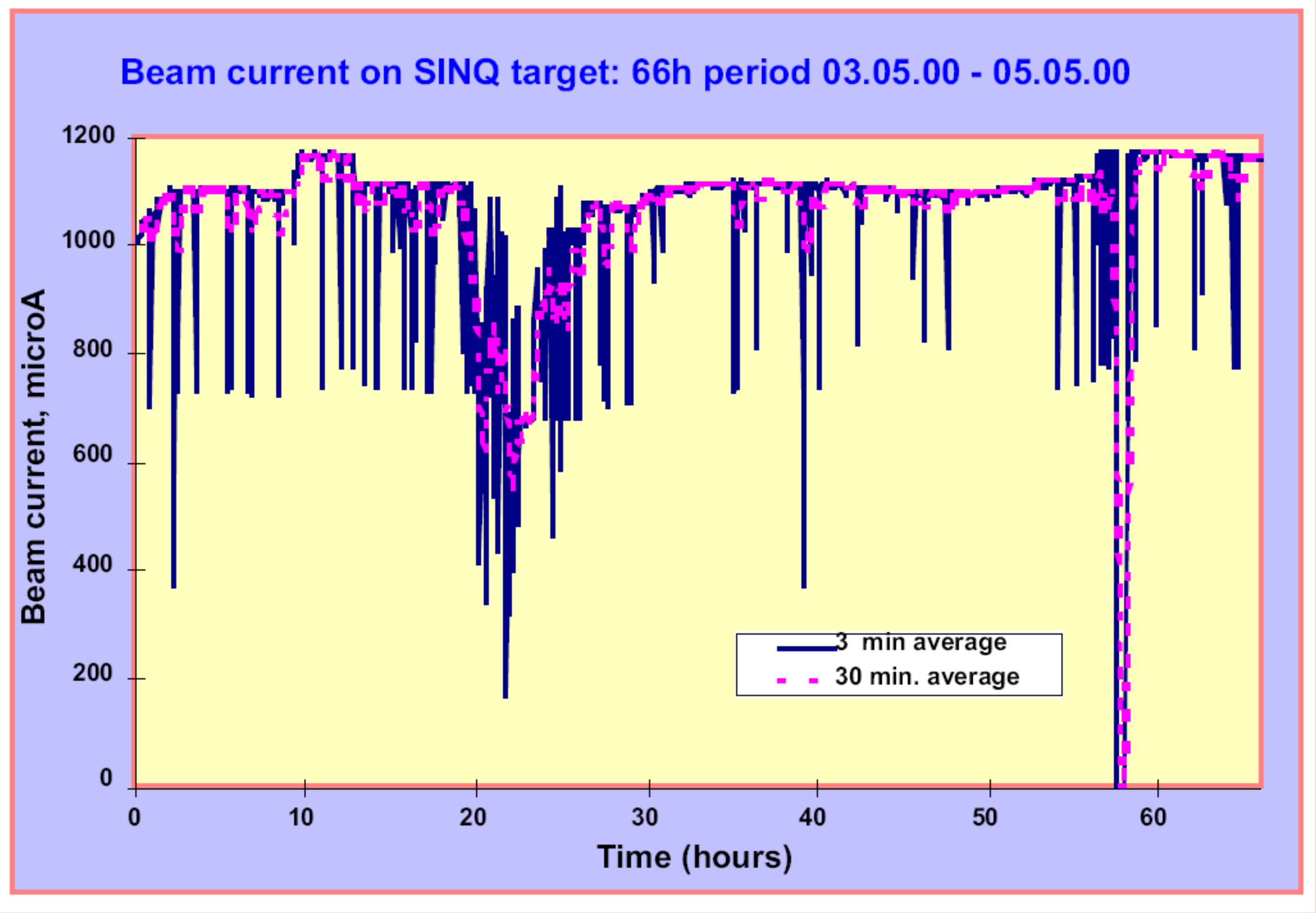
The beam impacts the target vertically from above

MYRRHA is being designed to transmute Pu waste

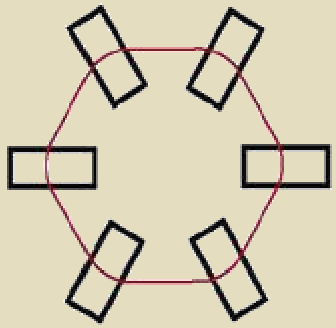


But no ADSR prototype has ever been built ....why not?

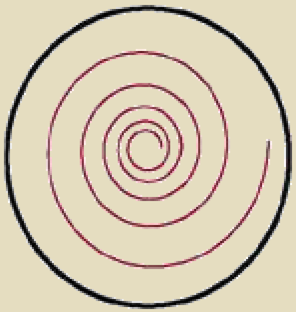
...because existing accelerators are not stable



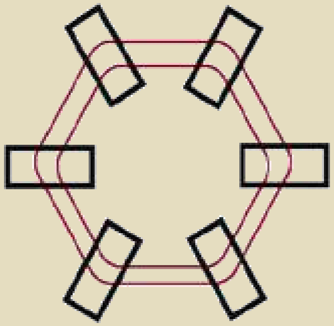
FFAGs: Fixed Field Alternating Gradient accelerators



Synchrotron
constant closed orbit
varying magnetic field



Cyclotron
isochronous
orbit



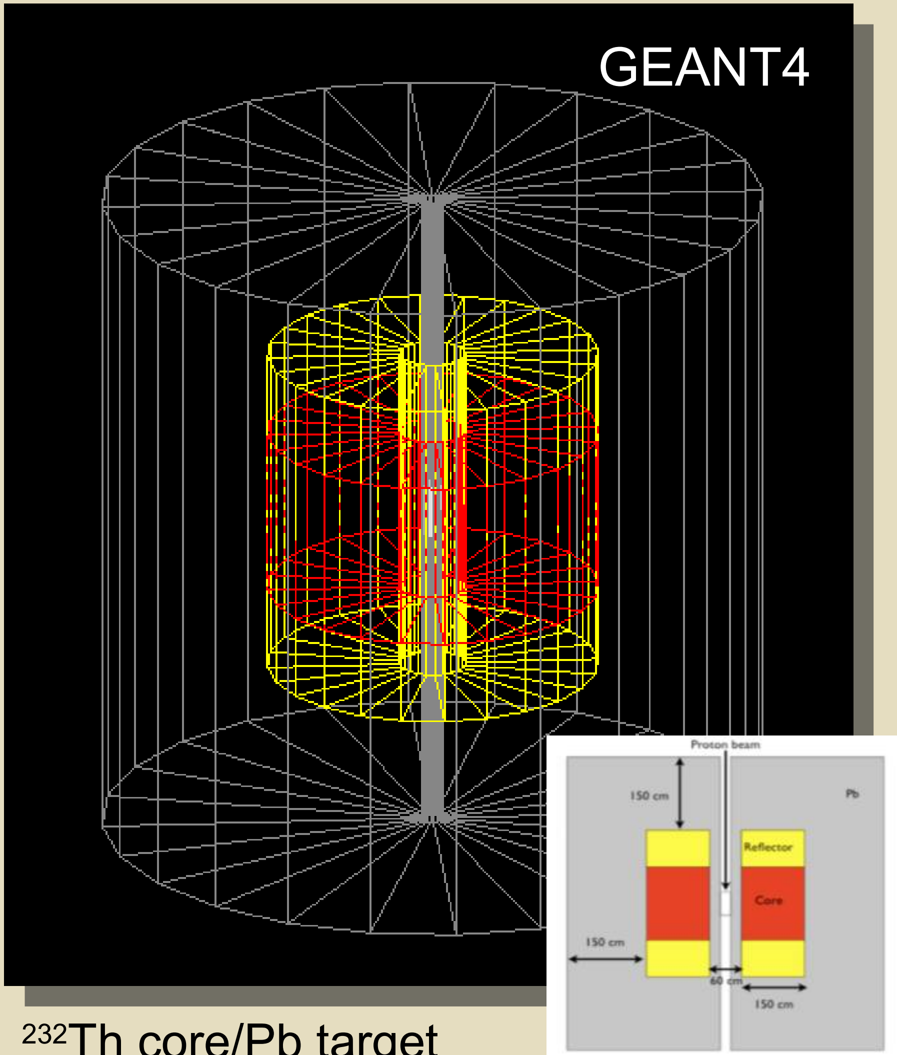
FFAG
varying closed orbit
fixed magnetic field

- Synchrotron-like proton energies with cyclotron –like currents
- Significantly more compact – and therefore cheaper to construct
- Simpler (fixed fields) - and hence more reliable?

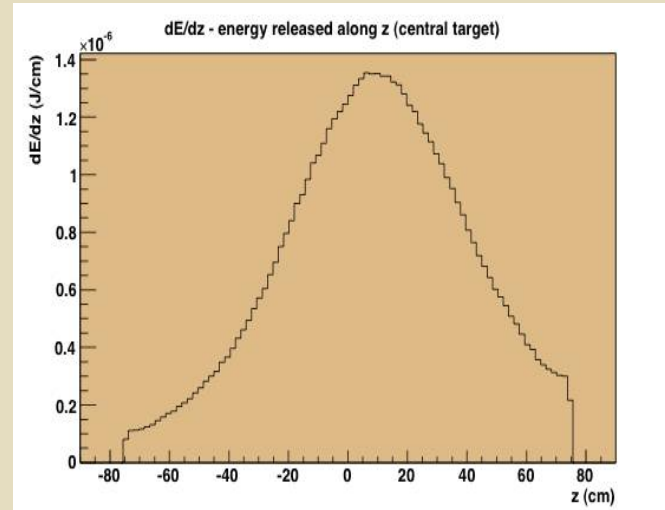
Innovative non-scaling FFAGs are currently being developed as part of the BASROC CONFORM RCUK Technology programme

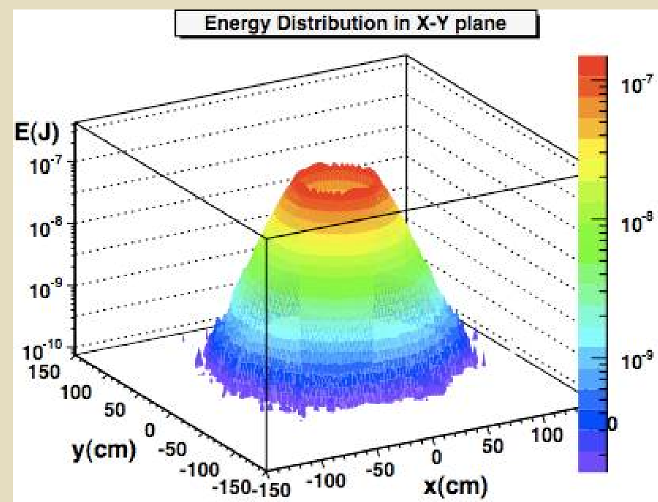
BASROC

ADSR geometry -single spallation target

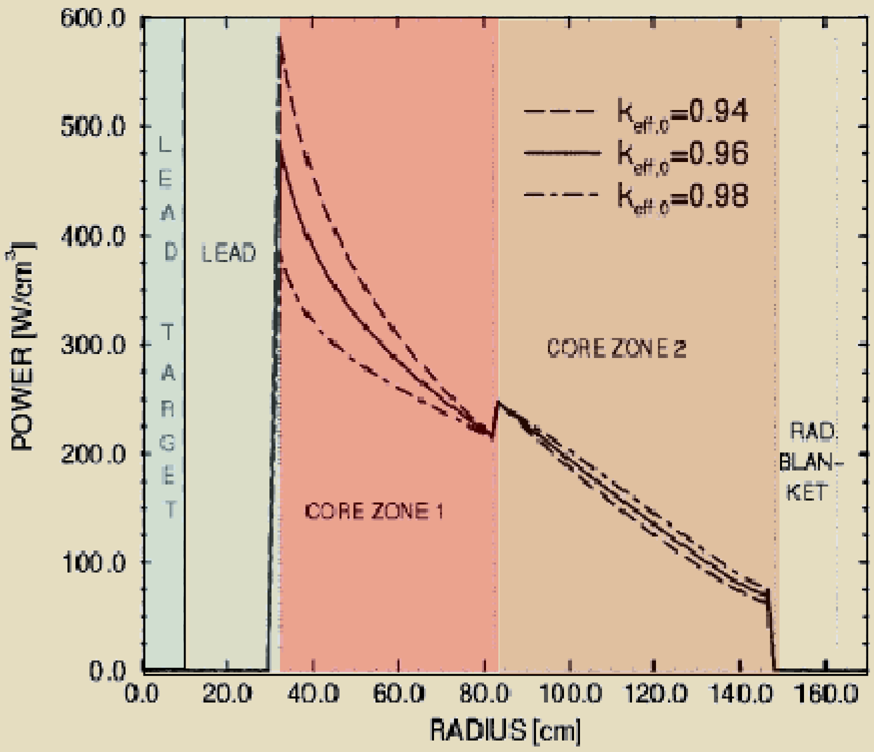


^{232}Th core/Pb target





Flux distribution in ADSR core



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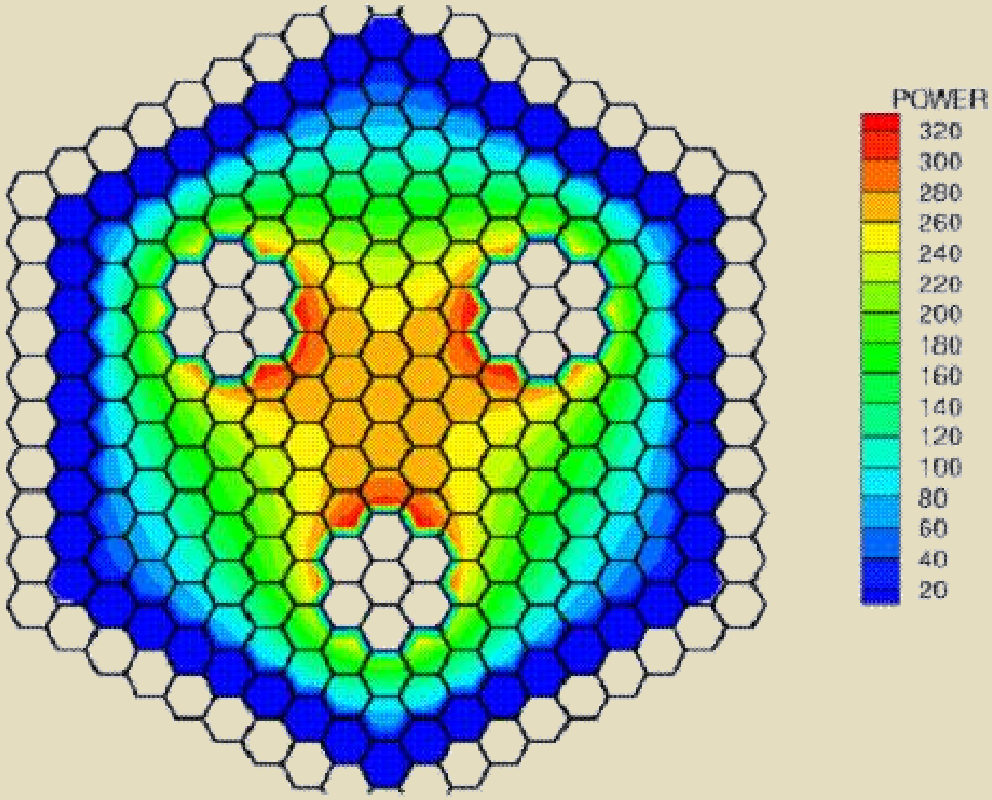
Power density distribution improves with k_{eff} but remains non-optimal

Solution is generally to increase fissile enrichment in several core zones (eg see step at zone boundary on left)

A better solution might be to use several proton beams and spallation targets

Multiple beams/targets should also alleviate accelerator stability problems

Triple target ADSR

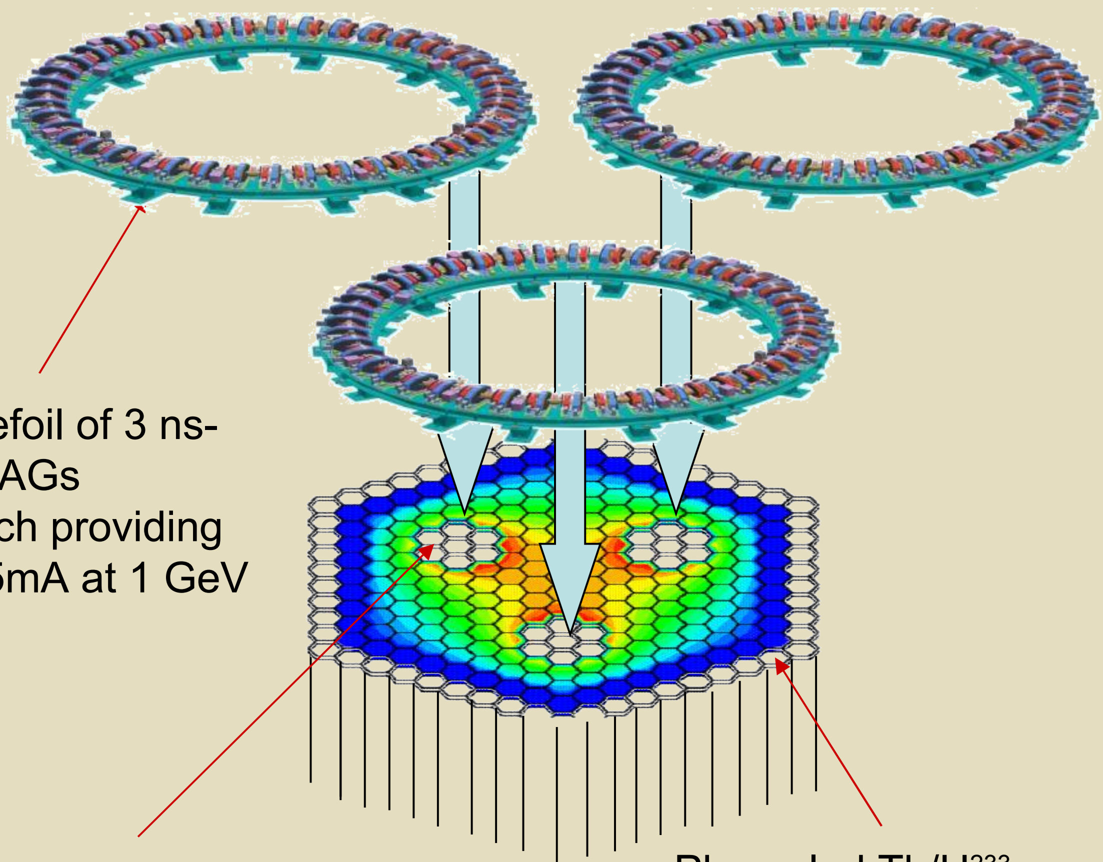


Power density distribution ($W:cm^3$) in a lead-cooled ADSR with $Th:U^{233}$ fuel.

The three beams with buffer zones are described by seven lead-filled fuel element positions.

The over-all power distribution is satisfactory.

Triple target FFAG-driven ADSR



Trefoil of 3 ns-FFAGs each providing 3.5mA at 1 GeV

Molten lead is both core coolant and spallation target

Pb-cooled Th/U^{233} subcritical core with:
k_{eff}=0.985
P_{th}=1550MW_{th}

Power density distribution ($W:cm^3$) in a lead-cooled ADSR with Th:U^{233} fuel.

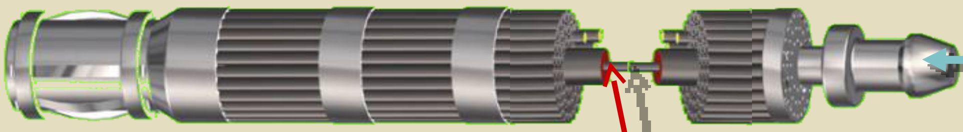
The three beams with buffer zones are described by seven lead-filled fuel element positions.

The over-all power distribution is satisfactory.

Three ns-FFAG drivers should be no more expensive than a singe conventional driver....

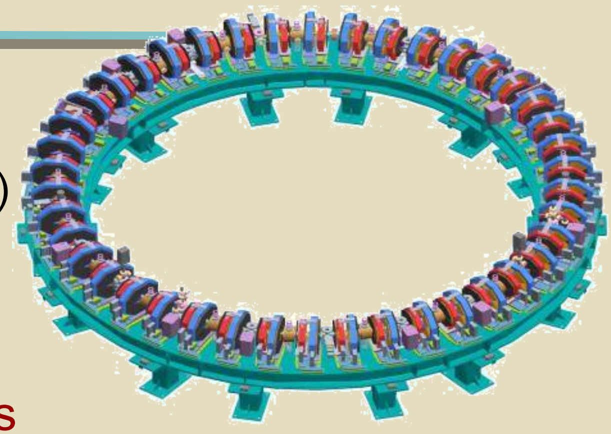
.....and will provide the required reliability margin

Can thorium fuel be used in conventional reactors?



Miniature spallation target in central bore of fuel element assembly

High power (MW) proton beam



Spallation charging of Th fuel rods

- ^{232}Th to ^{233}U conversion can be better optimised, with mitigation against detrimental neutron absorption by ^{233}Th and ^{233}Pa
- Modifications to existing reactors are not necessary
- Wider global exploitation of nuclear technology is possible
- Fuel preparation and burn cycles are decoupled

Fuel types

Thorium Metal

Ductile, can be shaped. High conductivity
Problem with diffusion of Fe and Ni at T> 500ºC forming brittle phases. Th diffuses into Zr at about 800ºC.

Thoria -ThO_2

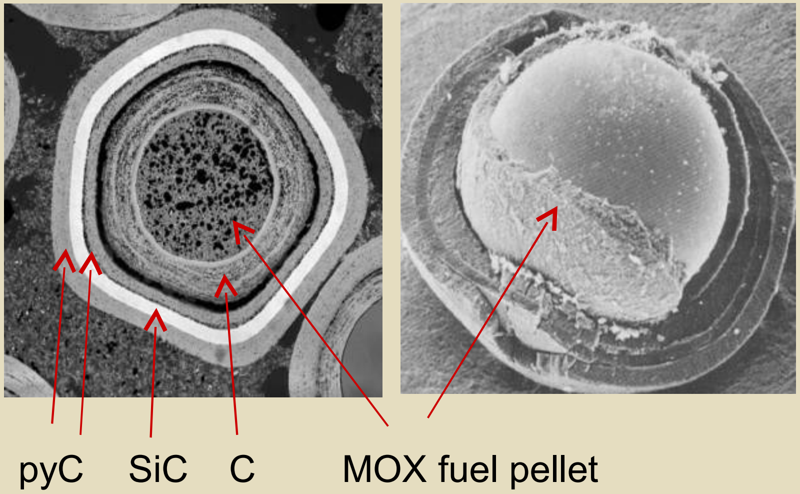
High melting point, most stable oxide known. Powder can be prepared by sol-gel methods then pelletised.
MOX fuels are made by combining ThO_2 with UO_2 or PuO_2

Thorium Nitrides and Carbides

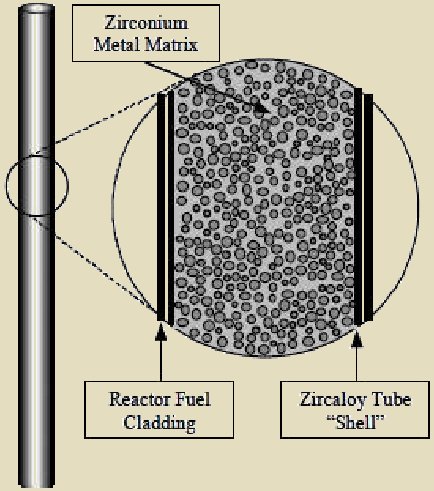
Carbides ($(ThU)C_2$) have already been successfully used. The use of nitrides is also possible

Cermet

Fine oxide partilcles embedded in a metallic host.



TRISO fuel (ORNL)

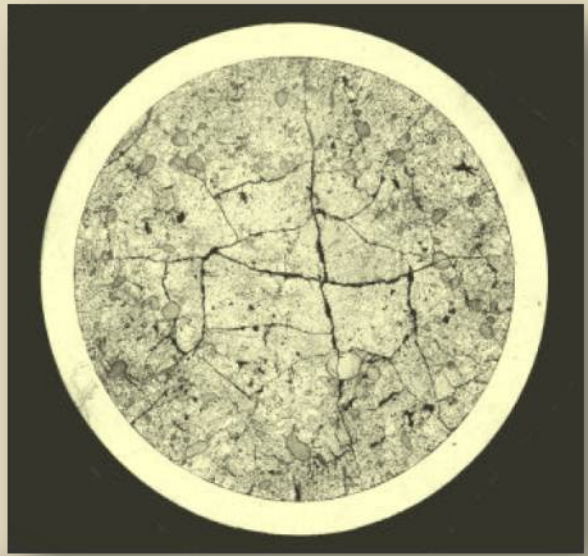


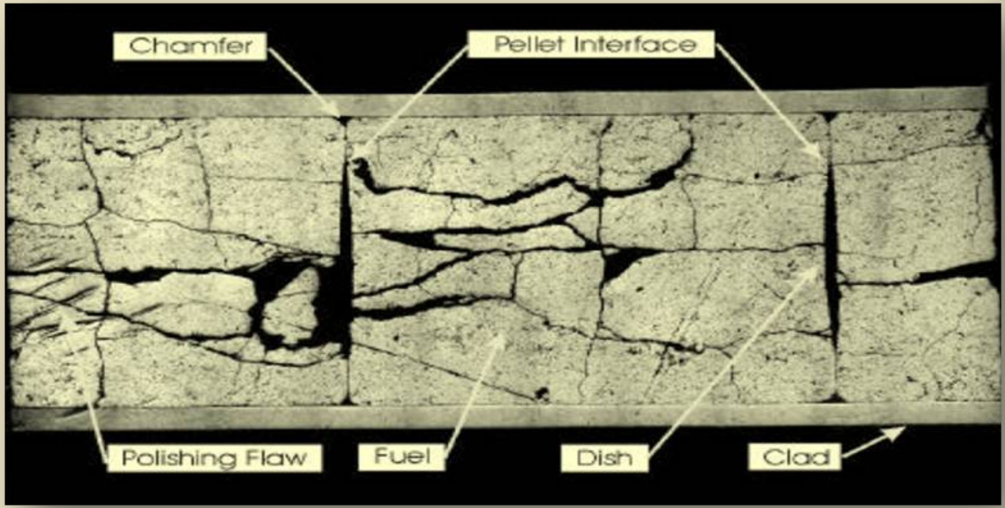
Cermet fuel element

Materials Physics

LWR fuel rod element

- Crack formation
- Substantial grain growth in centre (ie in hotter region)
- Small gap at pellet-cladding interface





Effects of irradiation and thermal cycling on thorium fuel assemblies must be studied and characterised - thorium fuel rods may be deployed for several years

Summary

- Thorium is an underexploited fuel resource that could meet all our power generation requirements for many centuries
- Thorium fuel is proliferation resistant and produces relatively low level radiotoxic waste
- Although thorium is fertile, not fissile, it may be possible to construct safe and reliable EA/ADSR power systems, using spallation neutrons to drive the transmutation/fission process
- Similar processes could provide thorium fuel elements for conventional power reactors
- The key to both technologies is the development of compact, cheap and reliable accelerators: We believe ns-FFAGs may fit the bill
- Significant materials research on thorium and thorium compounds is still required

Thorium might just save the planet!!

Acknowledgements

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Dr Bill Nuttall and Dr Geoff Parks (Cambridge)

ThorEA
the thorium energy amplifier association

RCUK/EPSRC (£7.5M) EPSRC(£150K) STFC (£500K)?

ThorEA Workshop, University of Huddersfield, 17 April 2009