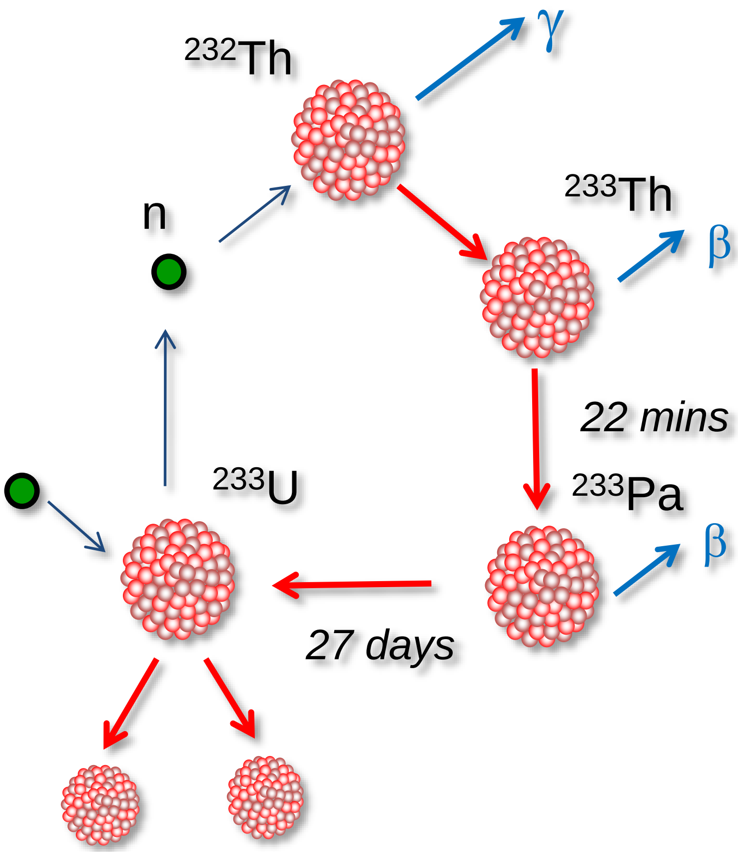
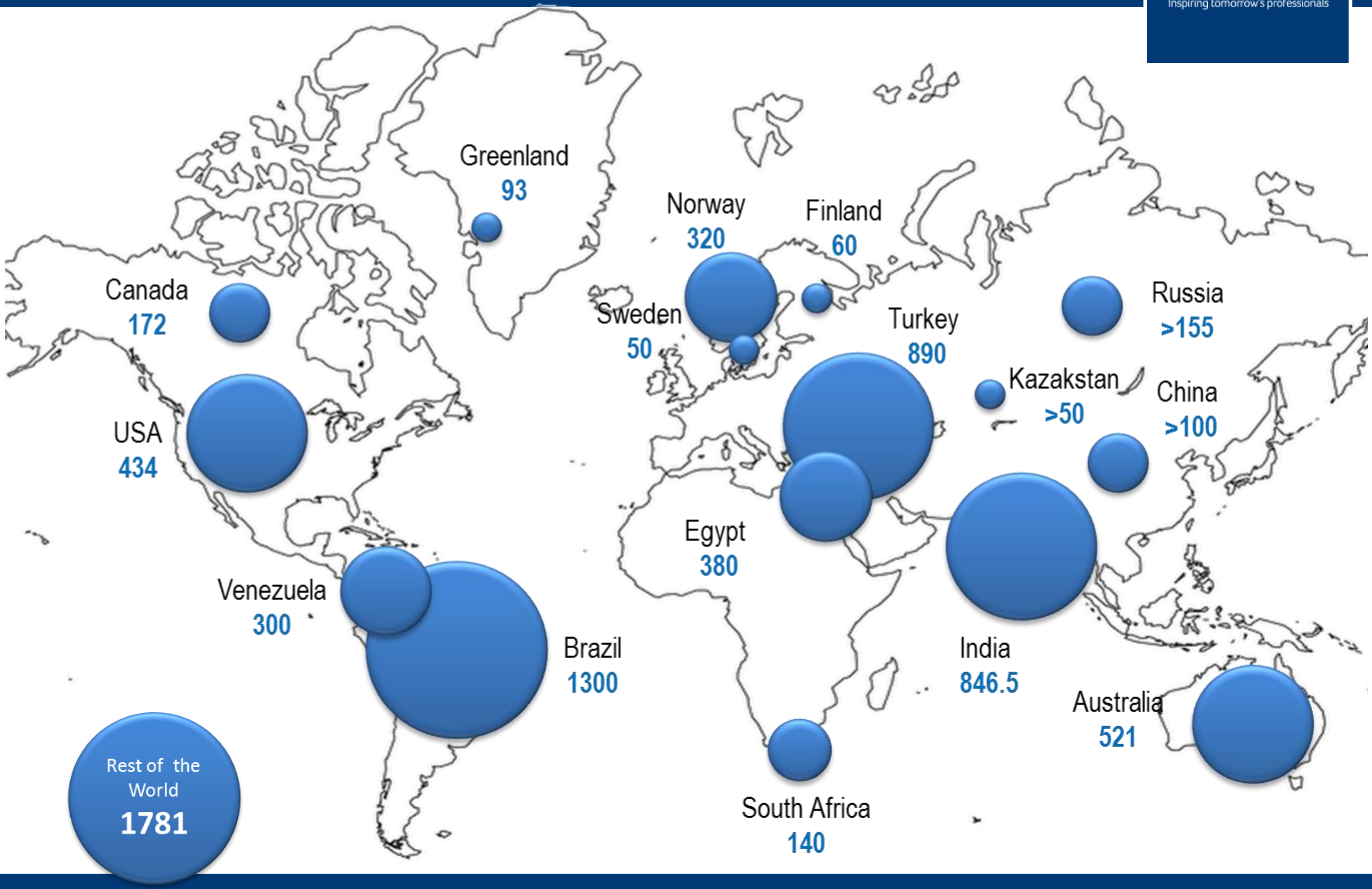
Thorium power: where are we now?

Bob Cywinski
Professor Emeritus
International Institute for Accelerator Applications
University of Huddersfield, UK

Thorium



Known thorium resources (ktonnes)



Fighting ignorance……

“There is little chance that thorium-fuelled nuclear reactors will play a major role in meeting the UK’s future energy requirements......

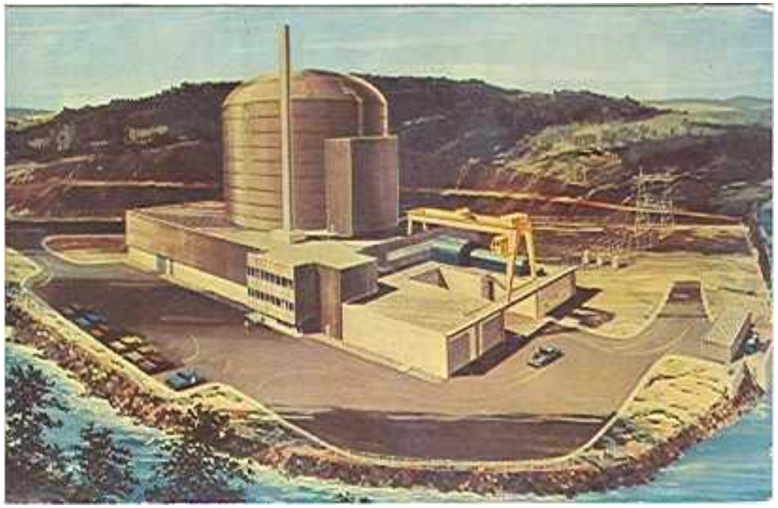
.........No thorium reactor design has been implemented beyond relatively small, experimental systems”

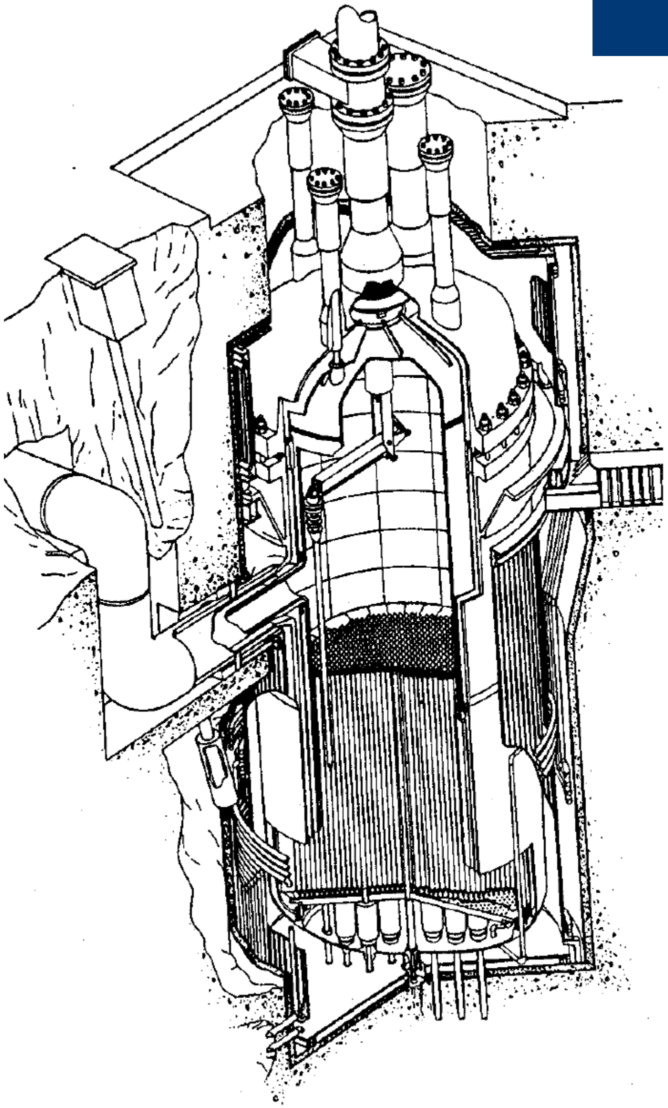
Baroness Tina Stowell,
Government spokesman on energy and climate change
House of Lords
November 2011

Where were we then….

Country	Name	Type	Power	Operation	Fuel
Germany	AVR THTR	HTGR HTGR	15 MW_e 300 MW_e	1967-1988 1985-1989	Th+U235, coated particles
UK (OECD/ Euratom)	Dragon	HTGR	20 MW_{th}	1966-1973	Th+U235, coated particles
USA	Peach Bottom Fort St Vrain	HTGR HTGR	40 MW_e 330 MW_e	1967-1974 1976-1989	Th+U235, coated particles
USA	Shippingport Indian Point 1	LWBR PWR LWBR PWR	100 MW_e 285 MW_e	1977-1982 1962-1980	Th+U233 Oxide pellets
India	Kamini Cirus Dhruva	MTR (LWR) MTR MTR	30 kW_{th} 40 MW_{th} 100 MW_{th}	In operation In operation In operation	Al+U233, J-rod of Th&ThO_2

Peach Bottom, USA - HTGR

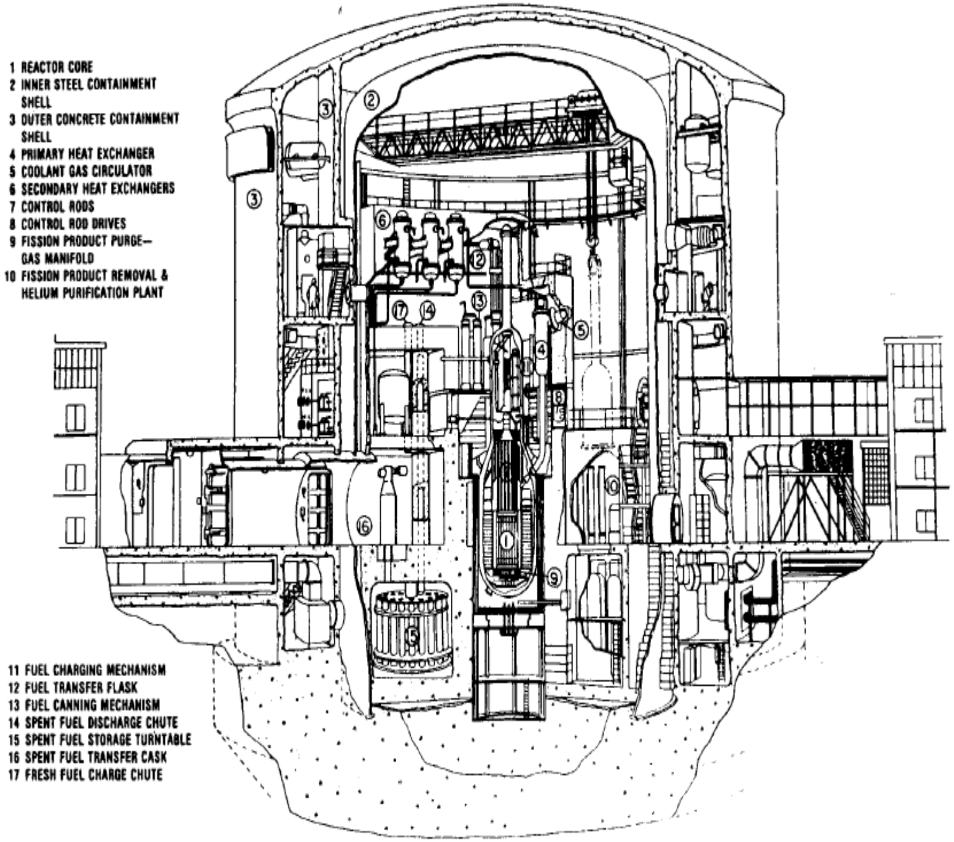




General Atomics' Peach Bottom high-temperature, graphite-moderated, helium-cooled reactor in the USA operated between 1967 and 1974 at 110 MW_{th}.

Fuel particles were highly-enriched uranium /thorium in PyC (Briso) shells

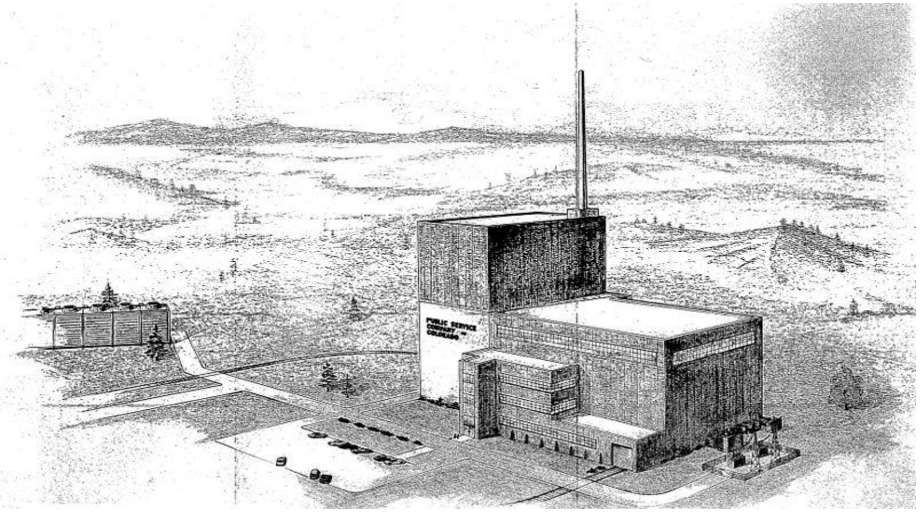
Dragon, UK (OECD/Euratom) - HTGR



Thorium fuel elements with a 10:1 Th/U (HEU) ratio were irradiated in the 20 MWth Dragon reactor at Winfrith, UK, for 741 full power days between 1964 and 1973

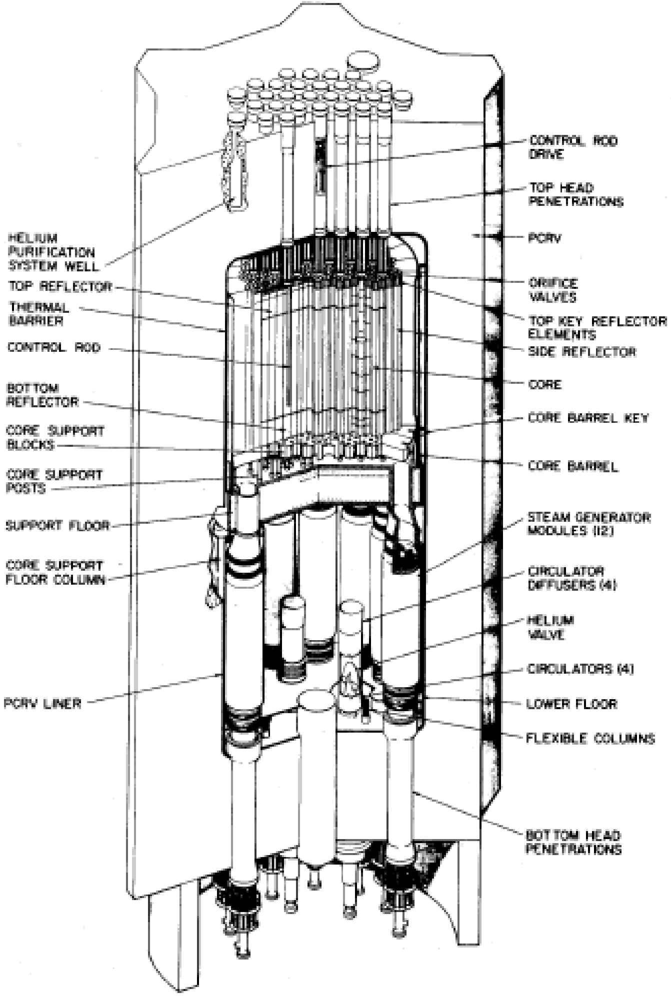
The Th/U fuel was used to 'breed and feed', so that the U-233 created replaced the burnt U-235 at the same rate, and fuel could be left in the reactor for about six years.

Fort St Vrain (US) - HTGR



Fort St Vrain operated between 1974-1989 as a high-temperature (700°C), graphite-moderated, helium-cooled 842 MWth (330 MWe)

~25 tonnes of thorium was used in fuel for the reactor in prismatic configuration, achieving 170,000 MWd/t burn-up.

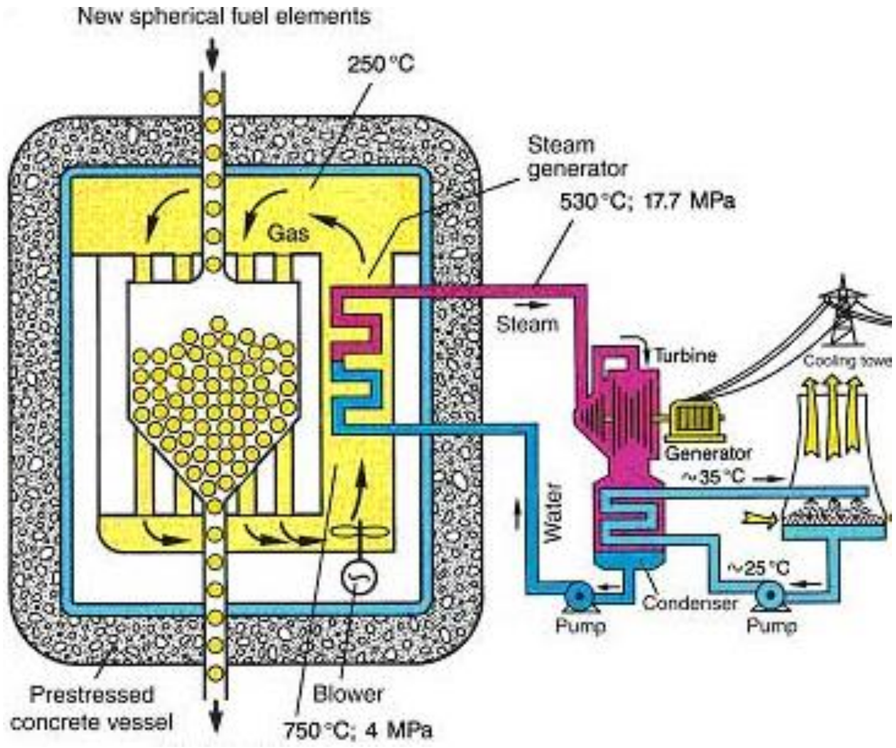


AVR (Germany) - HTGR

The Helium cooled AVR (Atom Versuchs Reaktor) experimental pebble bed reactor at Jülich, Germany, operated between 1967 and 1988, for over 750 weeks at 15 MWe, about 95% of the time with thorium-based fuel.

Approximately 100,000 billiard ball-sized fuel elements were used.

Overall a total of 1360 kg of thorium was used, mixed with high-enriched uranium (HEU). Burnups of 150,000 MWd/t were achieved.

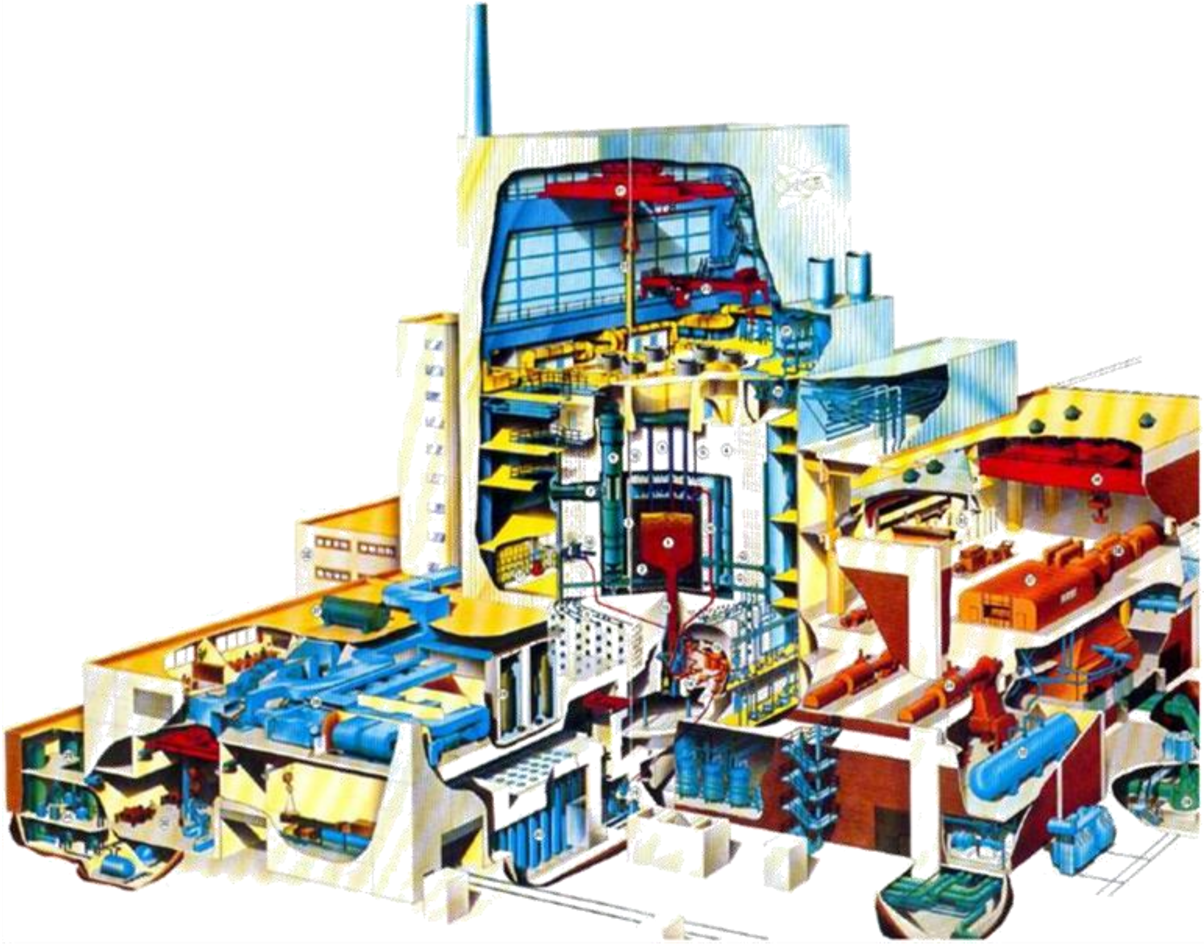


Thorium HTR (Germany) - HTGR

The 300 MWe THTR (Thorium High Temperature Reactor) operated between 1983 and 1989.

THTR was fuelled with 674,000 pebbles, over half containing Th/HEU fuel (the rest graphite moderator and some neutron absorbers).

The fuel pellets were continuously recycled with the fuel passing through the core an average of six times.



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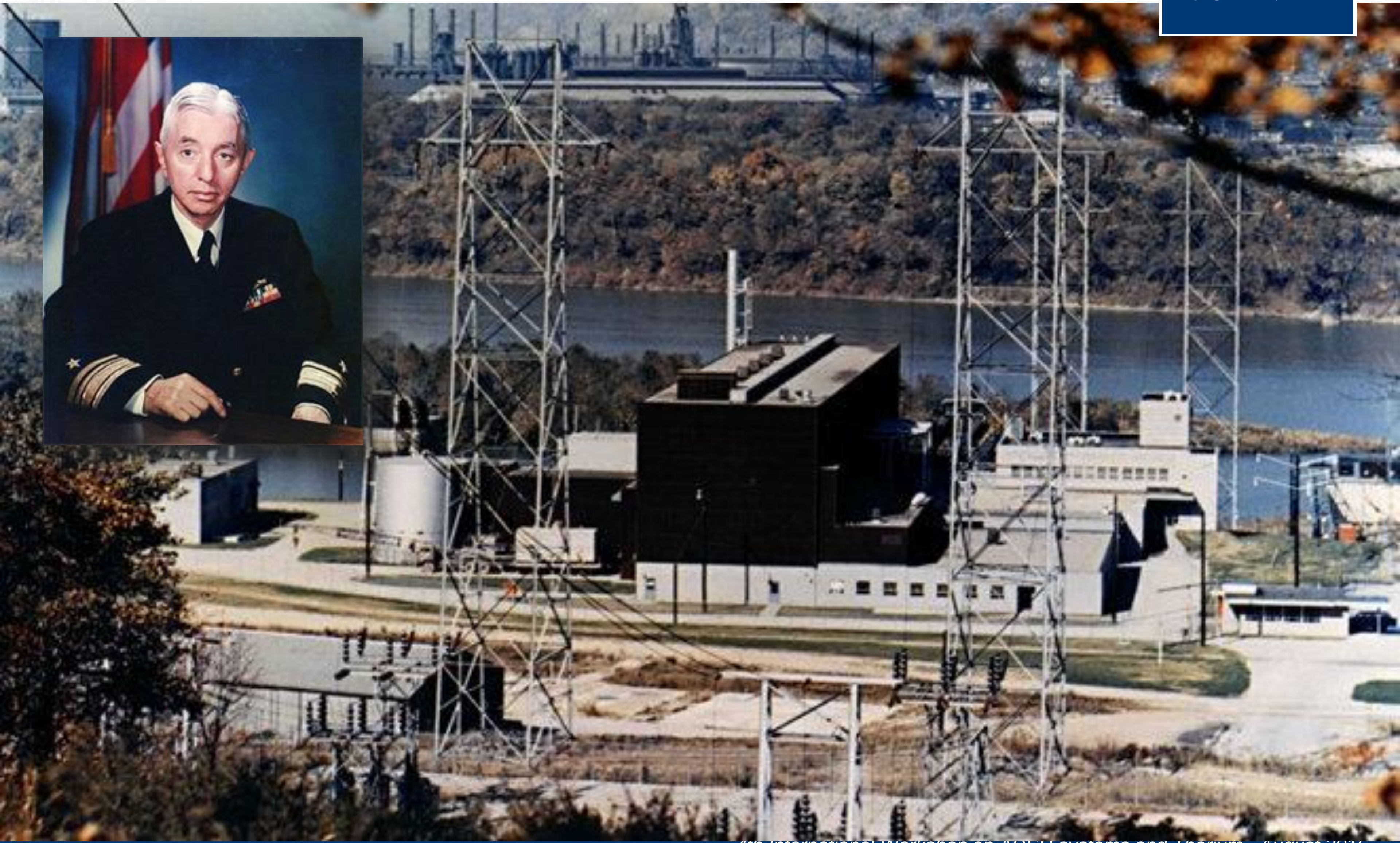
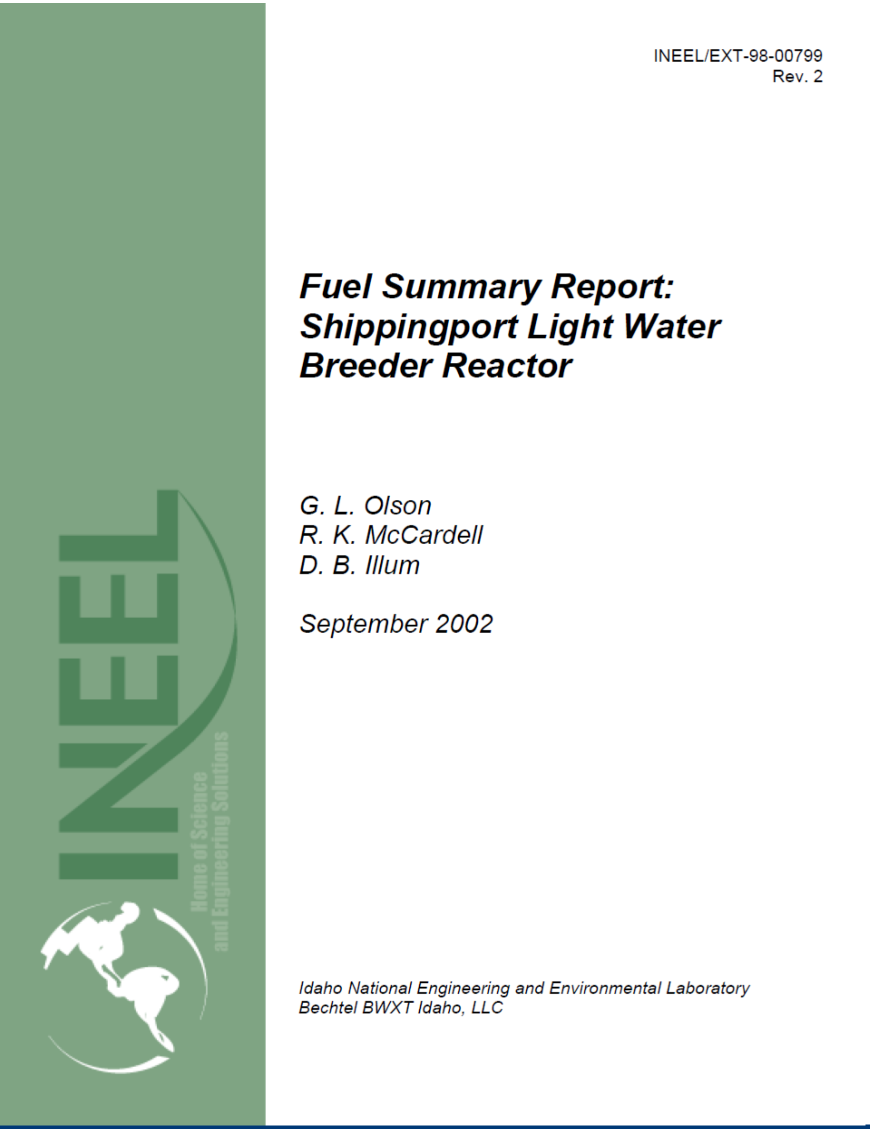
Shippingport LWBR



Shippingport LWBR



INEEL/EXT-98-00799
Rev. 2

Fuel Summary Report: Shippingport Light Water Breeder Reactor

G. L. Olson
R. K. McCardell
D. B. Illum

September 2002

Idaho National Engineering and Environmental Laboratory
Bechtel BWXT Idaho, LLC

The Shippingport 100MW$_e$ Light Water Breeder Reactor (LWBR) was developed by Bettis Atomic Power Laboratory to demonstrate the potential of a water-cooled, thorium oxide fuel cycle breeder reactor.

The LWBR core operated for 29,000 full power hours between 1977–1982 The fuel and fuel components suffered minimal damage during operation, and the reactor testing was deemed successful.

Extensive destructive and nondestructive postirradiation examinations confirmed that the fuel *was in good condition with minimal amounts of cladding deformities and fuel pellet cracks*.

Shippingport LWBR

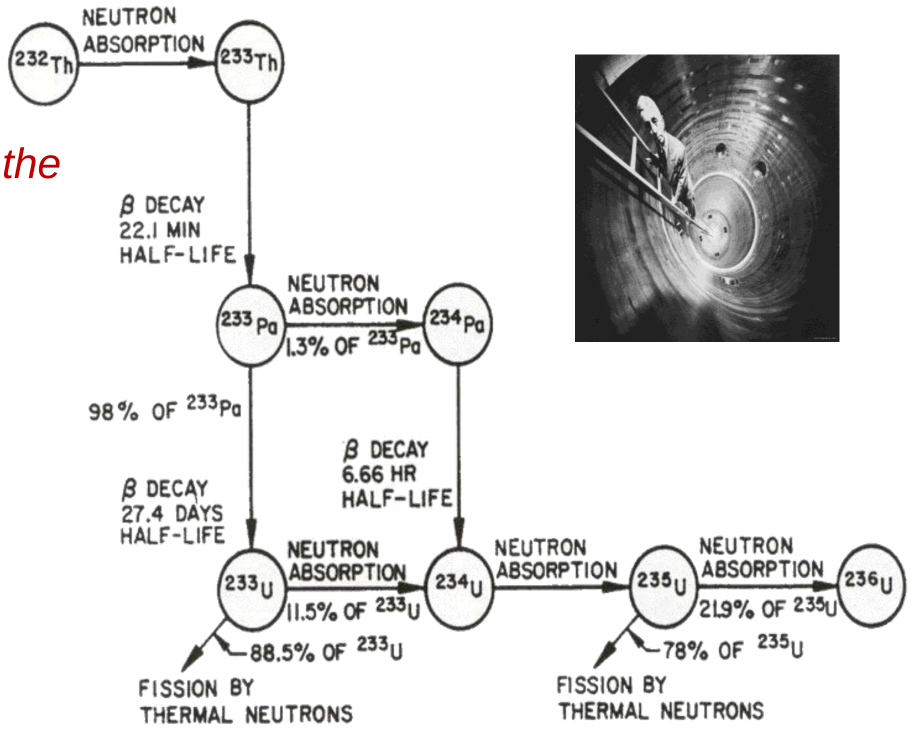
The Shippingport LWBR project was deemed a technical success:

After 5 years and 2.5×10^9 kWh of electrical power it showed no sign of reaching the end of its useful life, but was closed in 1982 because of budgetary constraints and the need to determine whether breeding occurred

Approximately 1.3% more fissile material than at the start of operation was found in the core

But …..there was no follow through:

- There was little effort to promote the technology.
- The assembly of the core modules required excessive manual labour implying a high production cost
- No effort to develop other U/Th reactors in an effort to help spread the fixed costs
- The program was seen as Admiral Rickover's pet project.



Shippingport LWBR

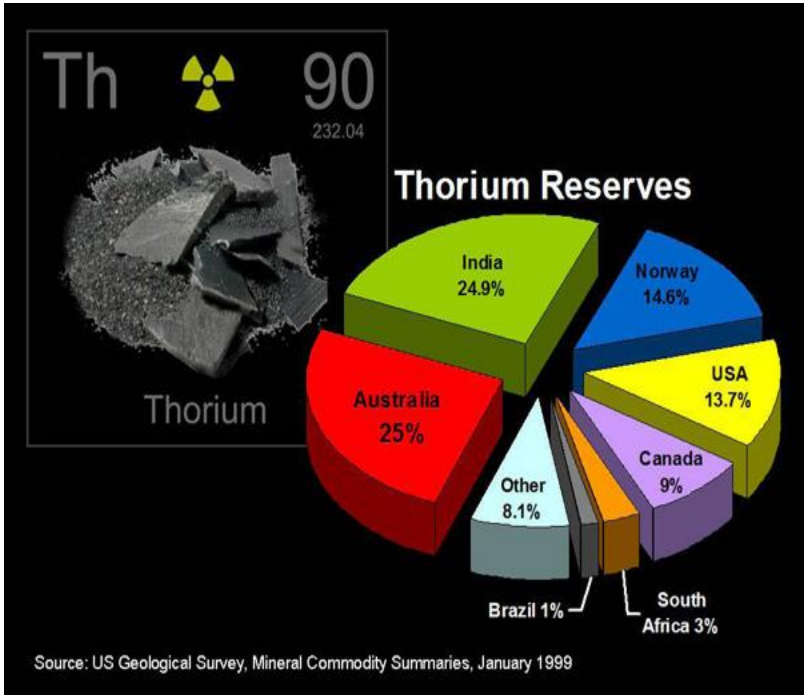
"Uranium-233/thorium cores can be designed and built, can be operated in existing LWR plants to produce electricity, and can breed enough fissile fuel to overcome modest losses in reprocessing and refabrication.

For the United States in particular, this means that the plentiful domestic supply of thorium, a material with no other significant use, can become an important energy source.

This resource can provide about 50 times as much energy as the domestic supply of uranium used in current LWRs. The light-water breeder thus has an energy potential that could meet the entire electrical needs of the United States for centuries."

J. C. CLAYTON
WESTINGHOUSE ELECTRIC CORPORATION
1993

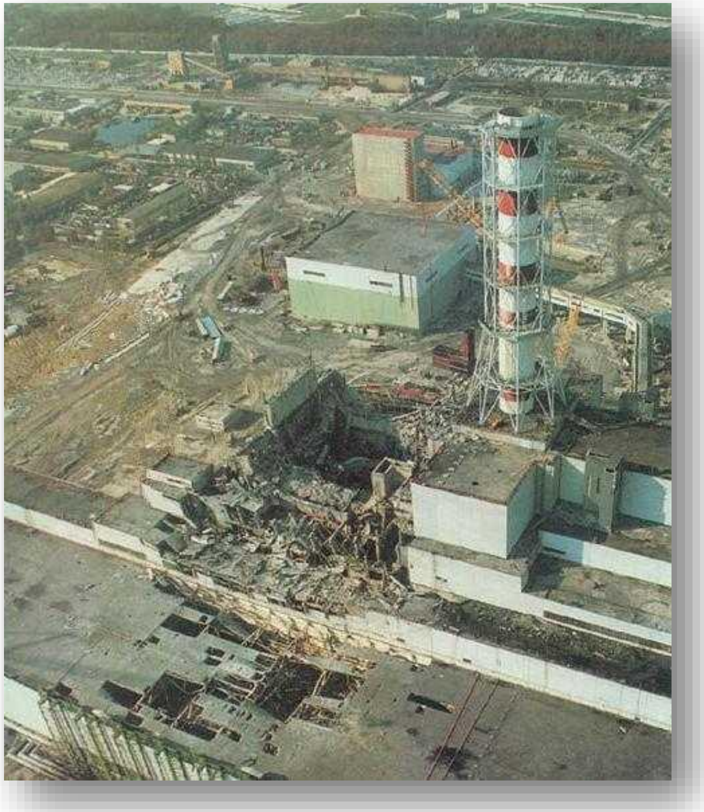
Initial drivers for thorium deployment (60s, 70s)



Source: US Geological Survey, Mineral Commodity Summaries, January 1999

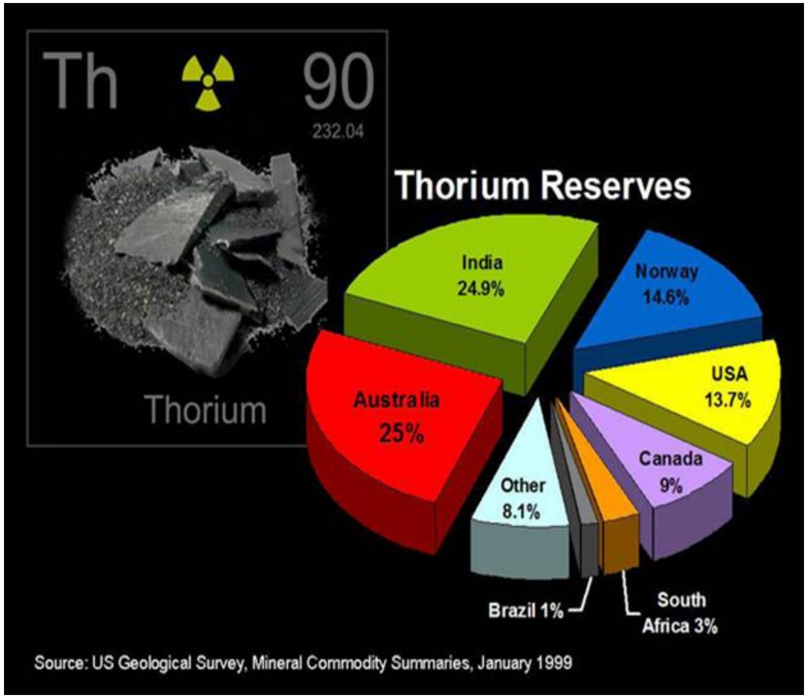
- An alternative fuel cycle in anticipation of a projected rapid growth in nuclear power and possible shortage of natural uranium.
- Thorium's abundance in nature
- The price for uranium reached \$40.00/pound by the mid-1970s
- The absence of uranium resources but large amounts of identified thorium resources in some countries having an ambitious civil nuclear program
- A good in-core neutronic and physical behaviour of thorium fuel
- A lower initial excess reactivity requirement (higher thermal conversion factor) of thorium based cores with particular configurations.

Brakes on thorium deployment (80’s)



- Interest in the nuclear option waned significantly, and public support for nuclear power dramatically declined following TMI and Chernobyl.
- Low priced uranium was available in the early 1980s and for over two decades,
- introduction to the market of down-blended uranium obtained from nuclear weapon disarmament programs
- The absence of reprocessing capability in the U.S for recovery and recycling of fissile U233 (stopped by Carter and Ford)
- Proliferation concerns with a HEU thorium cycle: HEU chemically separable from thorium

Current drivers for thorium deployment

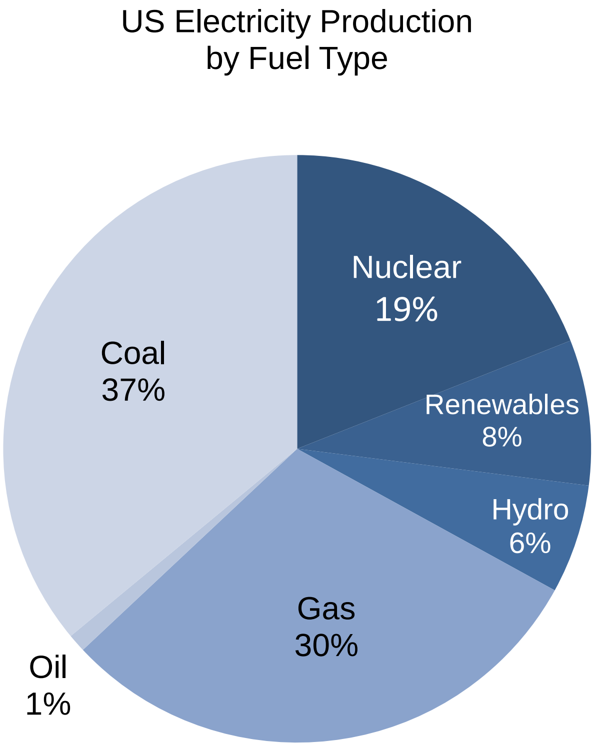


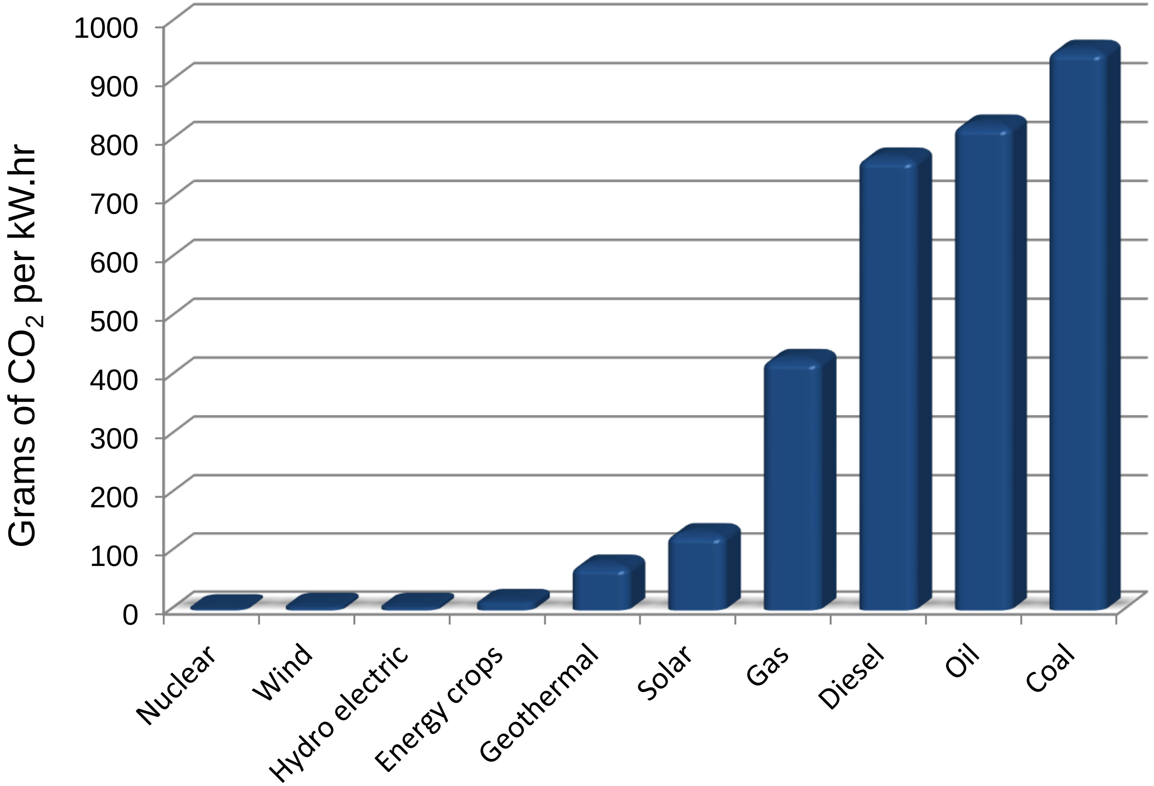
Source: US Geological Survey, Mineral Commodity Summaries, January 1999

All the drivers from the 60s and 70s plus

- The potential for the low production of Pu and minor actinides in thorium based-fuel cycles
- The capability of destroying plutonium by fissioning it in a plutonium/thorium cycle in thermal reactors. (LWRs, HTRs, MSRs, ADS)
- The transmutation of higher actinides and destruction of legacy waste
- The possibility of breeding fissile isotopes
- More recently, the dramatic increase in the price of uranium that is tied to the perceived shortage

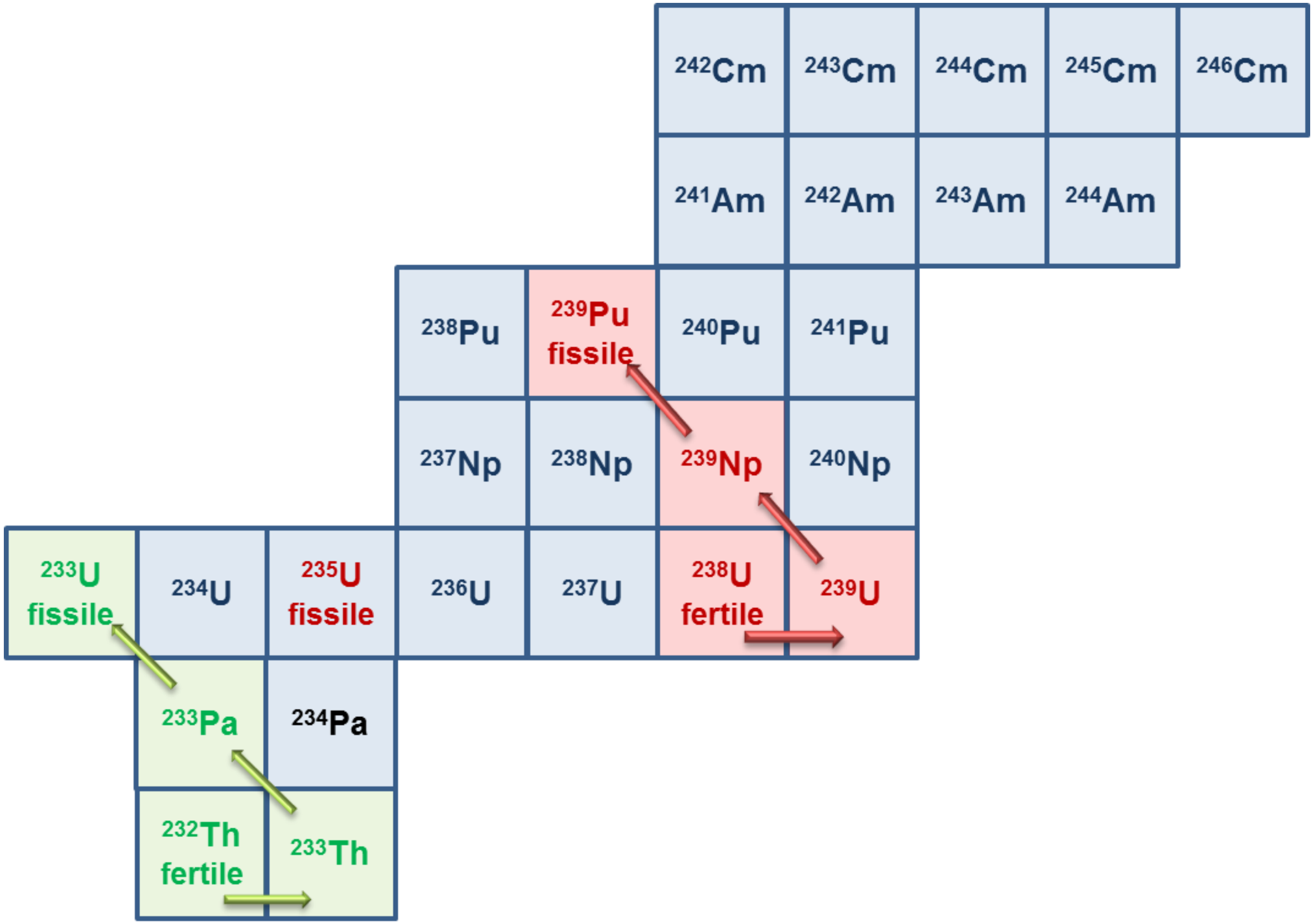
CO_2 emissions and electricity production





Average of ~500g CO_2 per kW.hr

Uranium and Thorium fuel cycles



^{242}Cm ^{243}Cm ^{244}Cm ^{245}Cm ^{246}Cm

^{241}Am ^{242}Am ^{243}Am ^{244}Am

^{238}Pu
^{239}Pu fissile
^{240}Pu
^{241}Pu

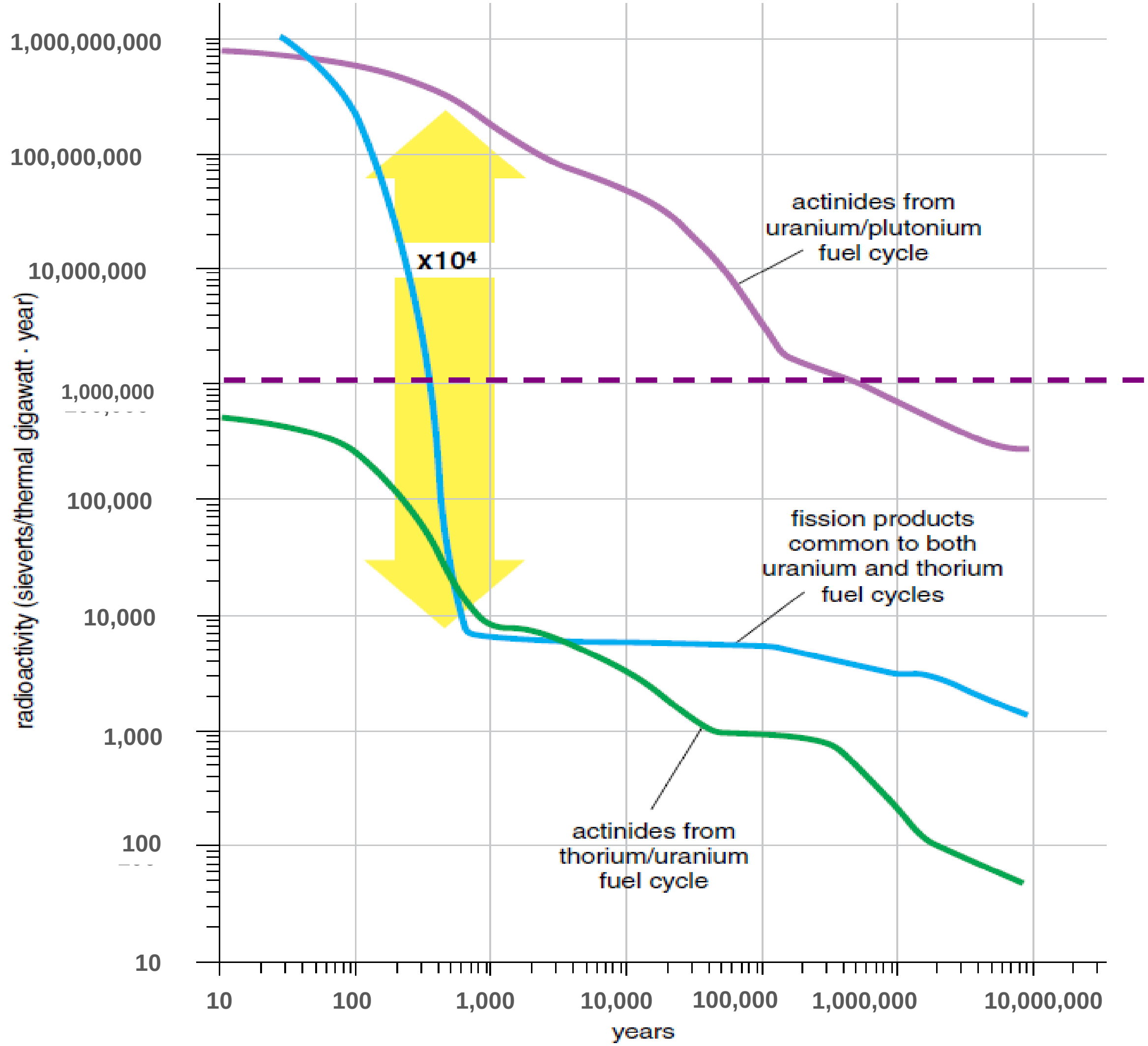
^{237}Np ^{238}Np ^{239}Np ^{240}Np

^{233}U fissile
^{234}U
^{235}U fissile
^{236}U
^{237}U
^{238}U fertile
^{239}U

^{233}Pa ^{234}Pa

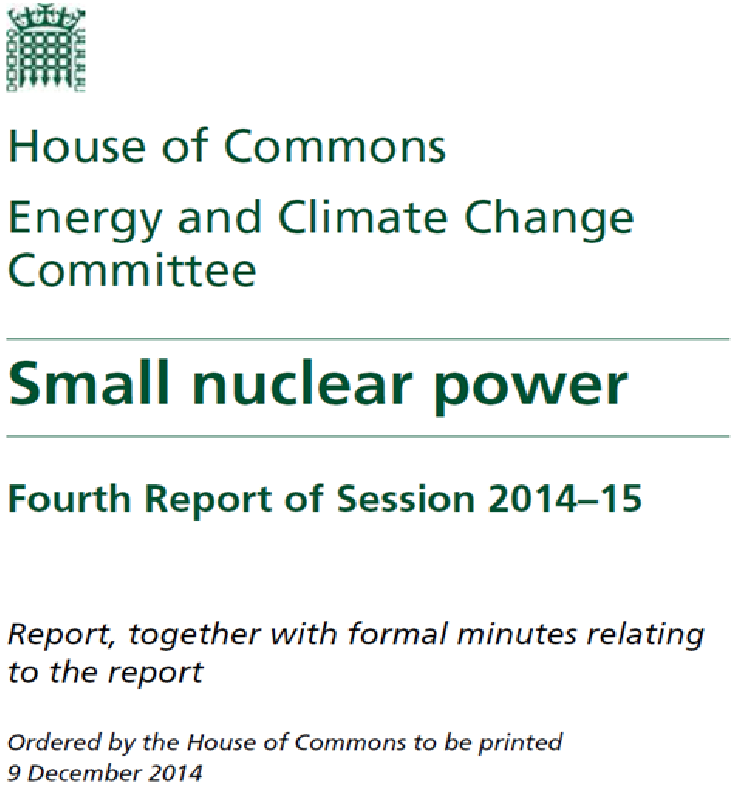
^{232}Th fertile
^{233}Th

Nuclear waste: U and Th fuel cycles



Current industrial global interest

Political interest



House of Commons

Energy and Climate Change Committee

Small nuclear power

Fourth Report of Session 2014–15

Report, together with formal minutes relating to the report

Ordered by the House of Commons to be printed 9 December 2014

“In the future, new technologies may bring with them the possibility of improved technical features in nuclear reactors, for example through enhanced safety or through use of waste materials.

We heard that there are a number of advantages of switching to a thorium fuel cycle.

The UK must remain an active participant in thorium research and development

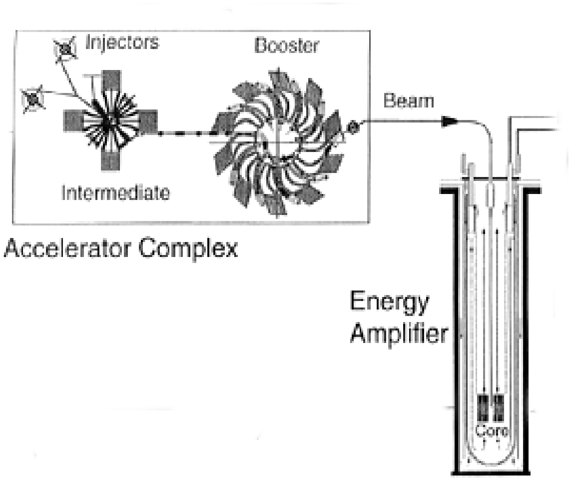
We recommend that the Government commission a study to confirm the potential benefits of thorium in the longer-term and how potential barriers to its use might be overcome”

Thorium deployment

1.
Conventional Systems
(LWR, PWR, HTGR)

2.
Molten Salt Reactors
After Weinberg's
Oak Ridge MSRE

3.
Accelerator Driven Subcritical Reactors (ADSRs)
After Rubbia's Energy Amplifier Concept



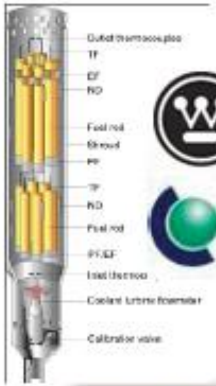
1. Conventional reactors

Thor Energy & The International Thorium Consortium

Los Alamos

The OECD Halden Reactor Project

- **5-year Thorium fuel test program initiated**
- 2-year Feasibility Study together with nuclear utility Vattenfall completed
- 2-year detail fuel design completed
- Completed design of unique Thorium test program in the Halden test reactor in Norway
- Fuel & test rig in production, loading into reactor in Q3 2012
- International Consortium of utilities, industry, R&D-organizations participating in this first step towards commercial use of Thorium.

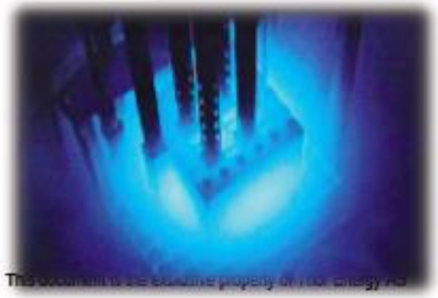


Westinghouse

Fortum

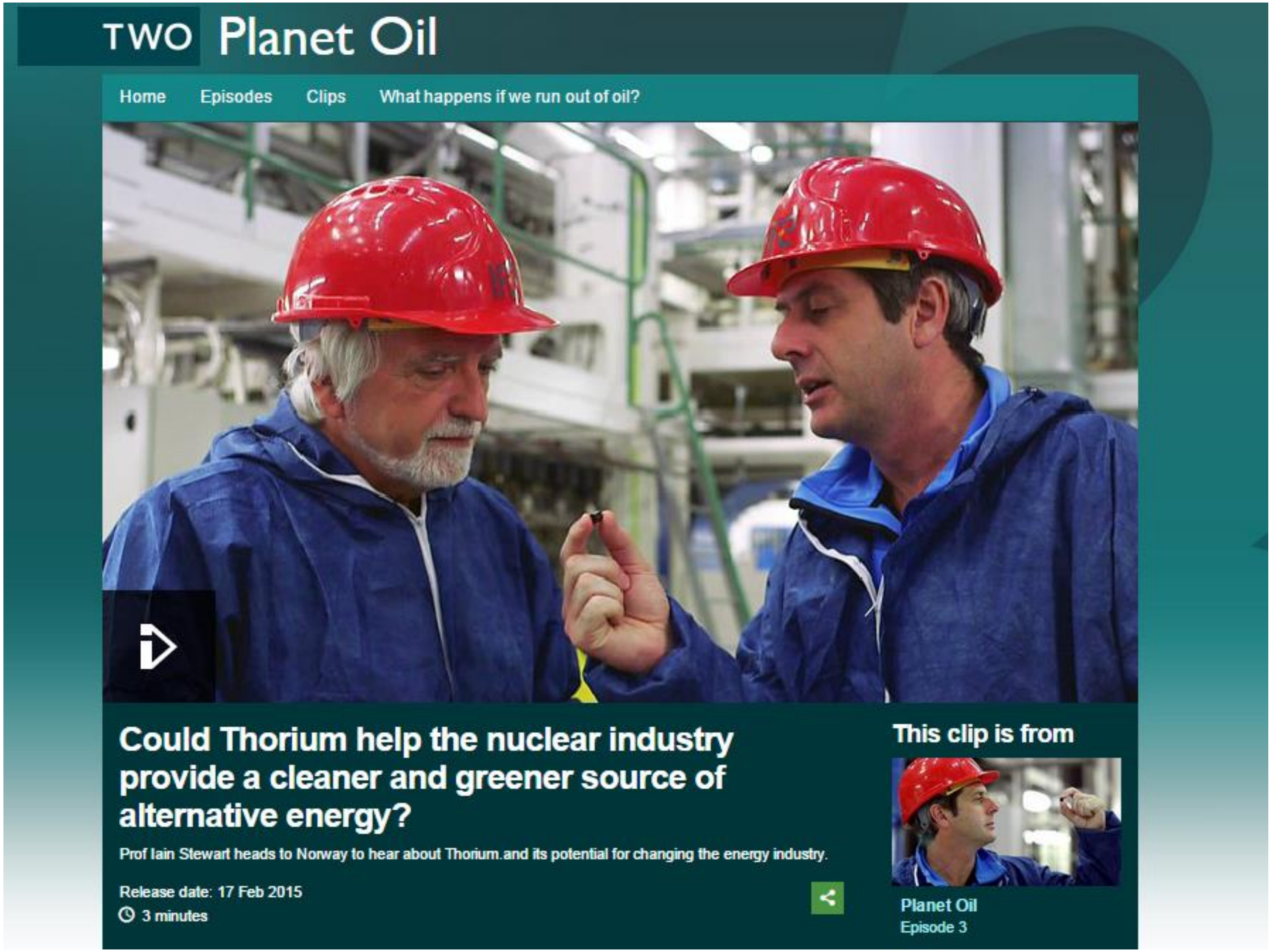
Thor Energy

IFE Institutt for energiteknikk



Thorium in the 25MW BWR Halden Reactor

Thorium in the 25MW BWR Halden Reactor



Could Thorium help the nuclear industry provide a cleaner and greener source of alternative energy?

Prof Iain Stewart heads to Norway to hear about Thorium.and its potential for changing the energy industry.

Release date: 17 Feb 2015

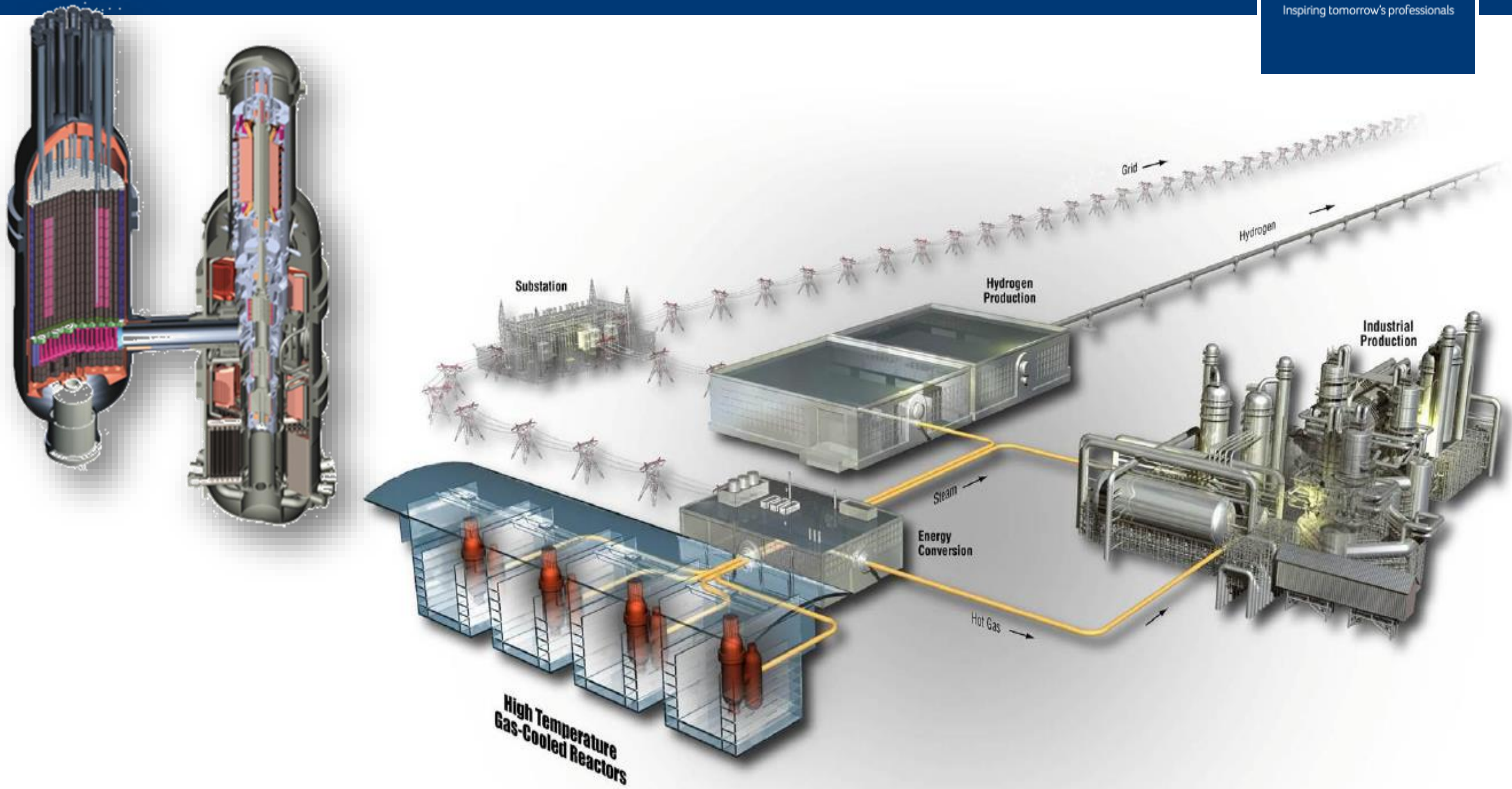
3 minutes

This clip is from

Planet Oil
Episode 3

BBC2
“Planet Oil”
with
Professor
Iain
Stewart

The future: Th-fuelled HTG modular reactors?



eg Areva's Antares HTGR system

2. Molten salt reactors

Oak Ridge National Laboratory explored both 2-fluid and 1-fluid molten salt reactors in the 1960s

An $8MW_{th}$ thorium single fluid molten salt reactor, MRSE, was demonstrated at ORNL, running successfully for 5 years to 1970

Fuel:
$71\%LiF-16\%BeF_2-12\%ThF_4-0.3\%UF_4$

A follow-up programme to design and build a $1000\ MW_e$ breeder reactor using the Th/U cycle (MSBR) was abandoned in 1976

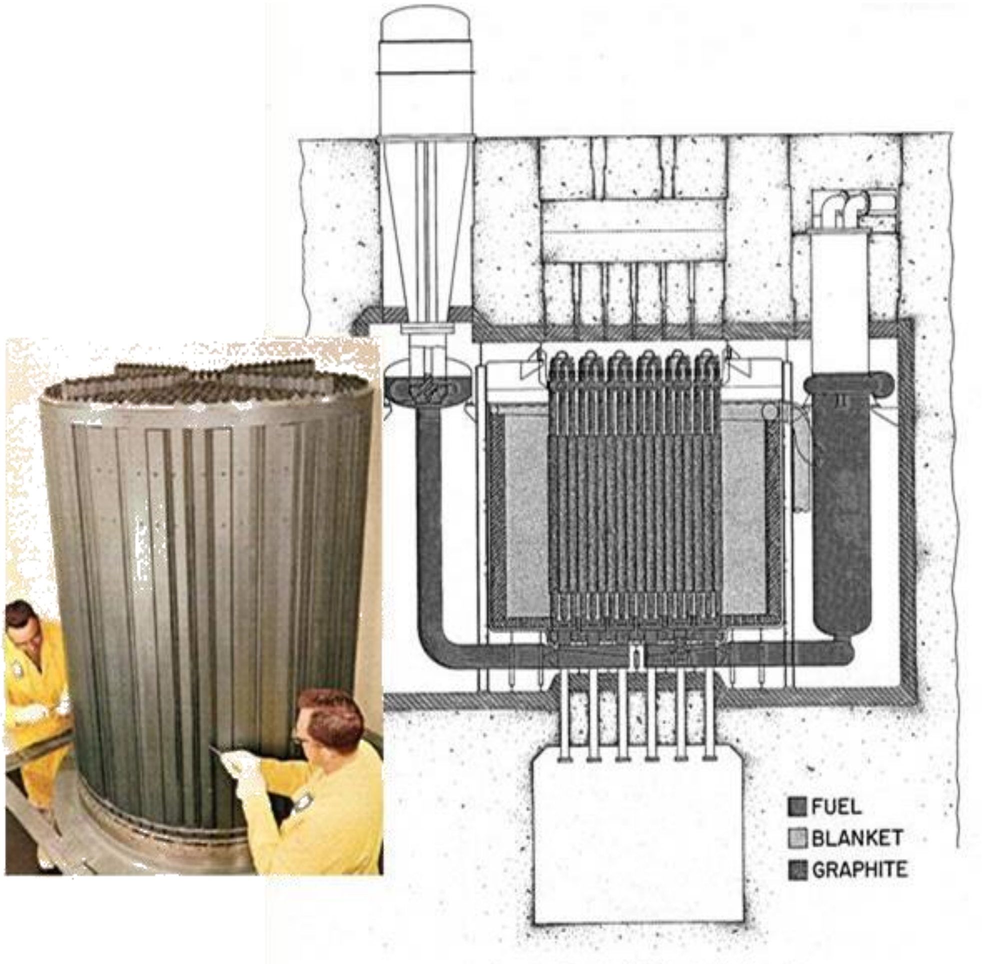
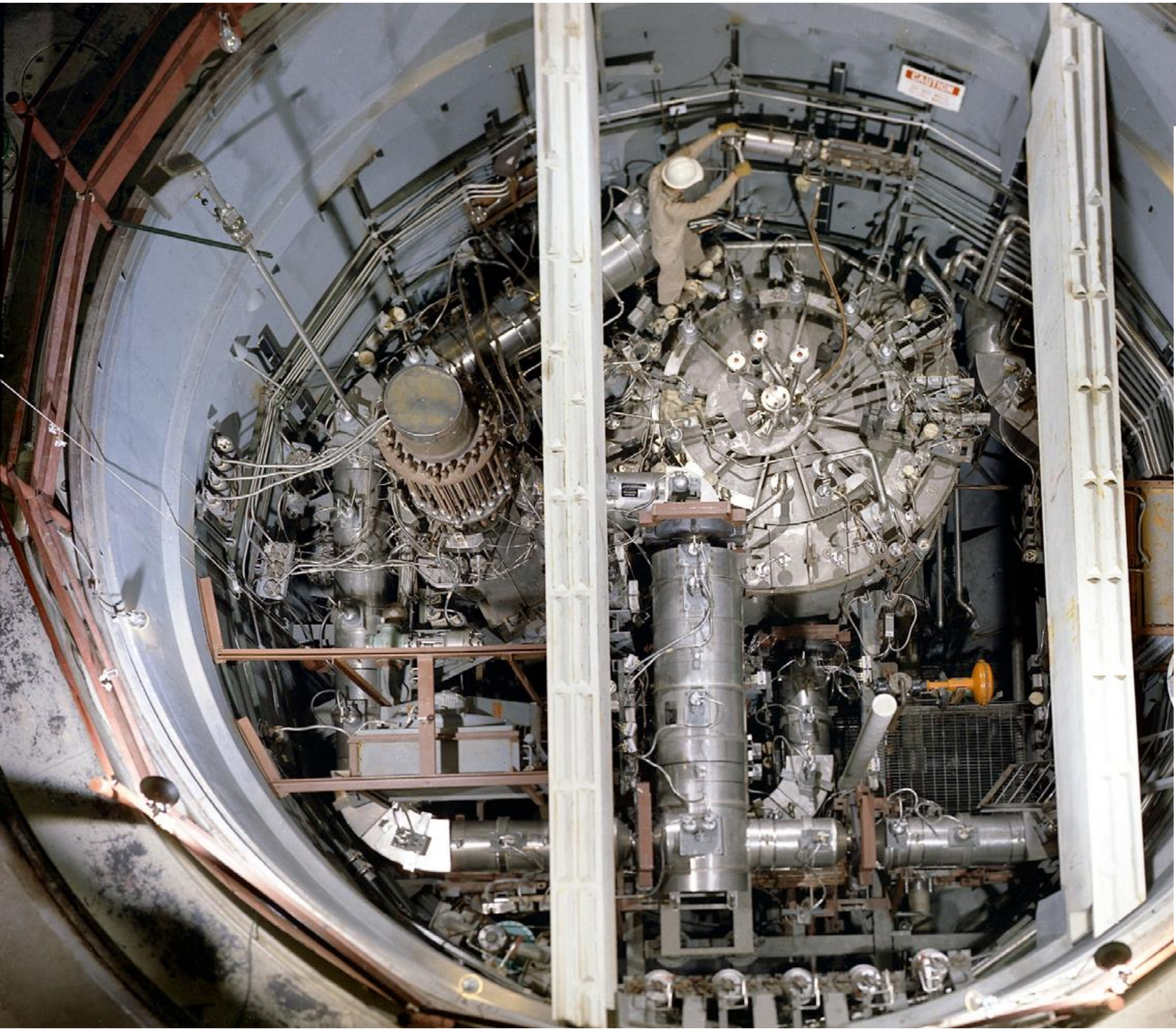
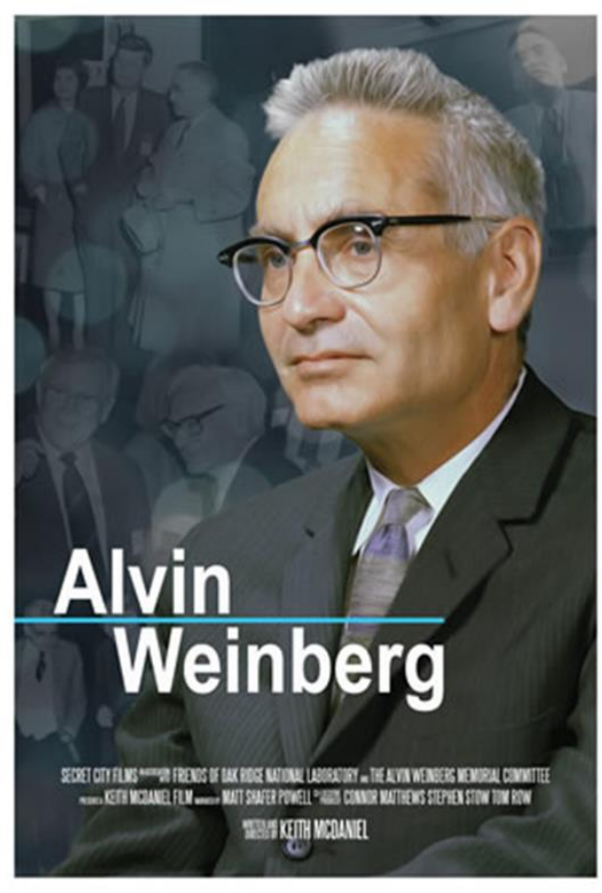


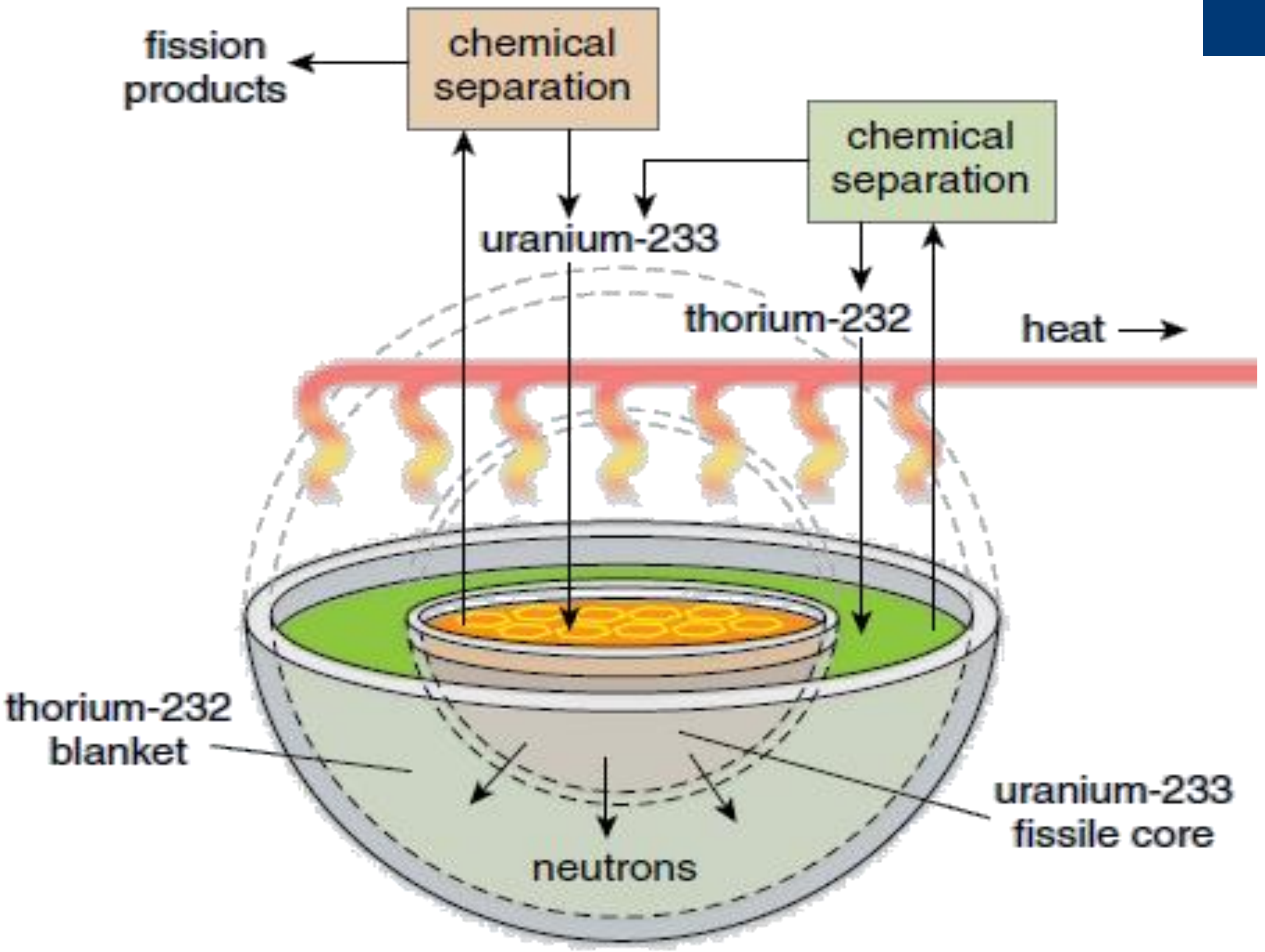
Fig. 2. Two-Region Molten-Salt Breeder.

Weinberg’s MSR

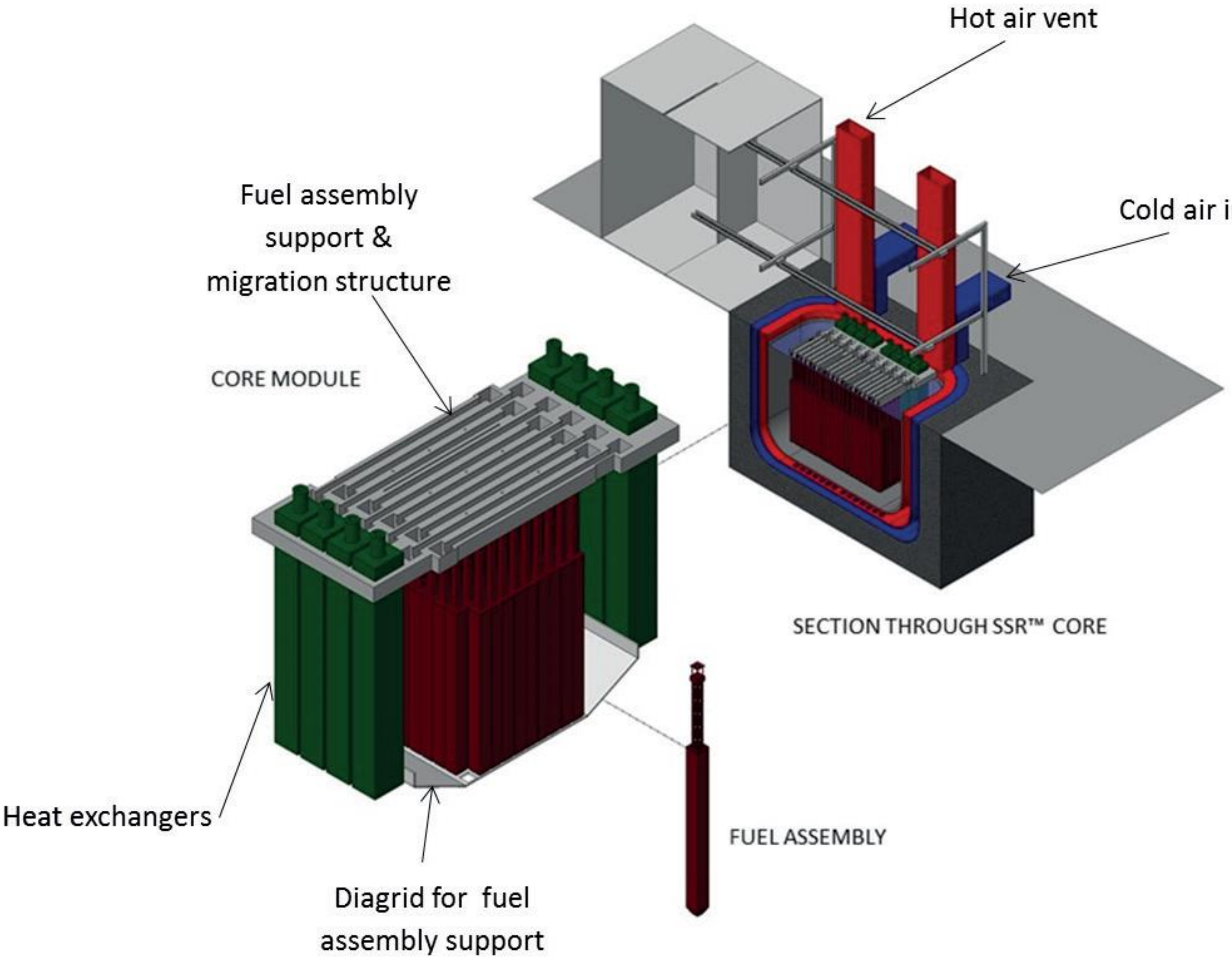




A two fluid MSR



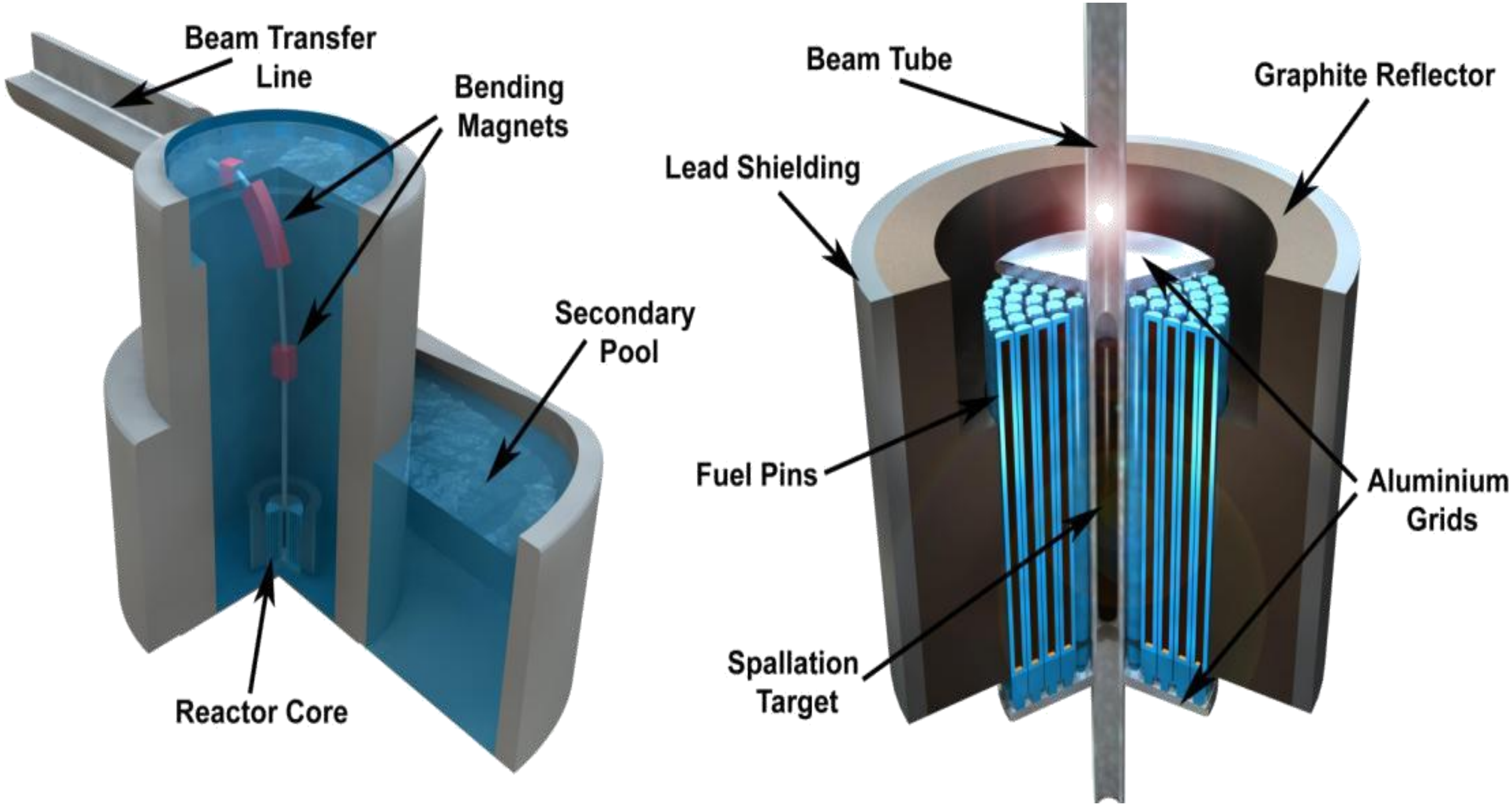
Moltex 150MW modular Stable Salt Reactor



safer, cheaper, nuclear

Fuel salt composition	NaCl/UCl3/PuCl3 (60/20/20)
Fissile content fresh assembly	20mol% reactor grade plutonium
Fuel salt M. Pt.	487°C
Fuel salt operating temp	500-1121°C
Fuel salt redox control	Sacrificial zirconium
Fuel salt power density	150kW/l
Coolant composition	ZrF4/KF/NaF (42/48/10)
Coolant melting point	385°C
Coolant operating temp	450-650°C
Coolant redox control	ZrF2/ZrF4 couple
Coolant flow velocity in core	1.7m/s
Reactor pressure	Atmospheric pressure
Coolant pump pressure	0.25-0.5 bar

3. Accelerator driven subcritical reactors



The Energy Amplifier

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

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

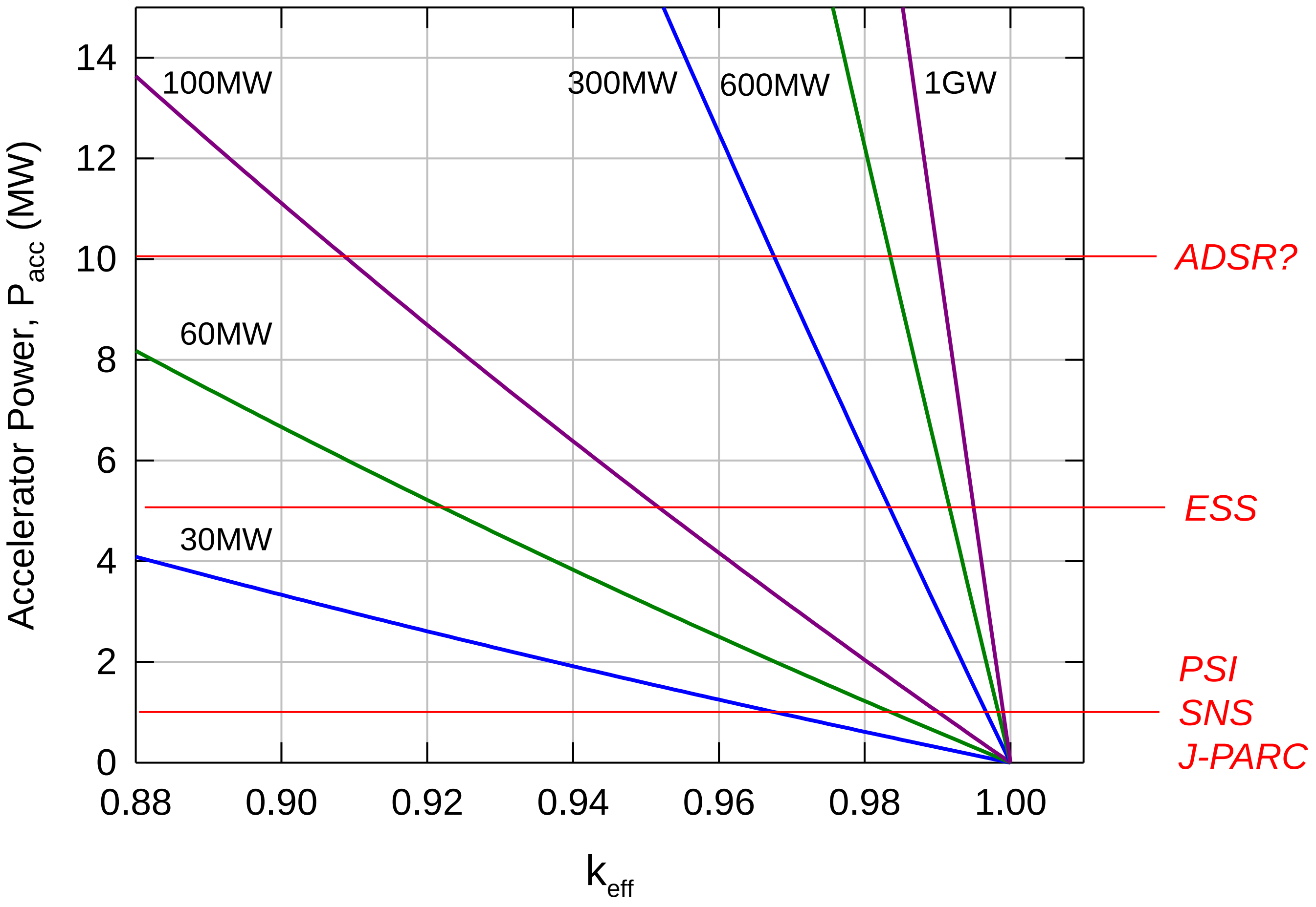
with N = number of spallation neutrons/sec
E_f = energy released/fission (~200MeV)
ν = mean number of neutrons released per fission (~2)
k_{eff} = criticality factor for the reactor core (<1 for ADSR)

Remembering that N varies approximately linearly with energy of the protons, delivering ~24 neutrons per proton at 1 GeV for a lead spallation target, and noting

P_{acc} (MW) = I_P (mA) x E_p (GeV) and $P_{el} \approx 0.4 \times P_{th}$

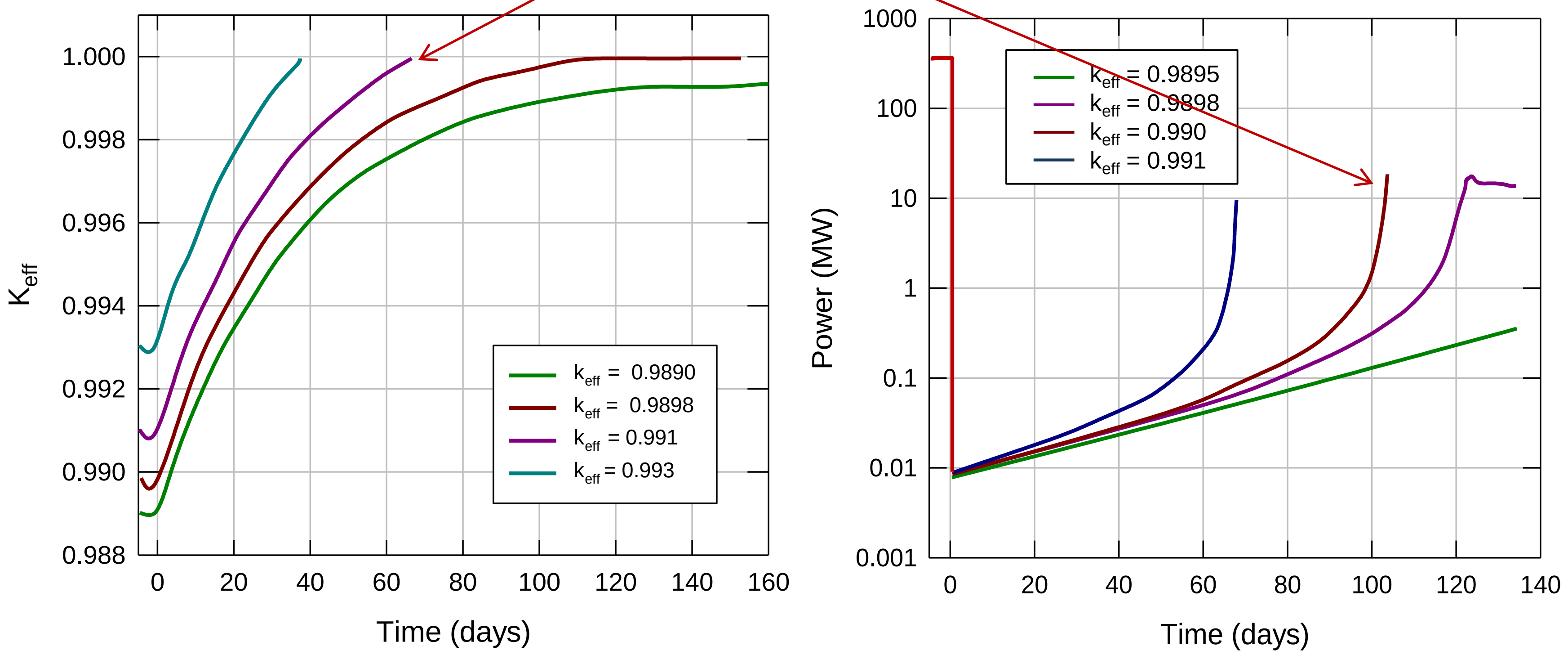
$$P_{acc} \approx P_{el} \cdot \frac{1 - k_{eff}}{k_{eff}} \quad \text{or} \quad G = \frac{P_{el}}{P_{acc}} \approx \frac{k_{eff}}{1 - k_{eff}}$$

ADSRs : accelerator power



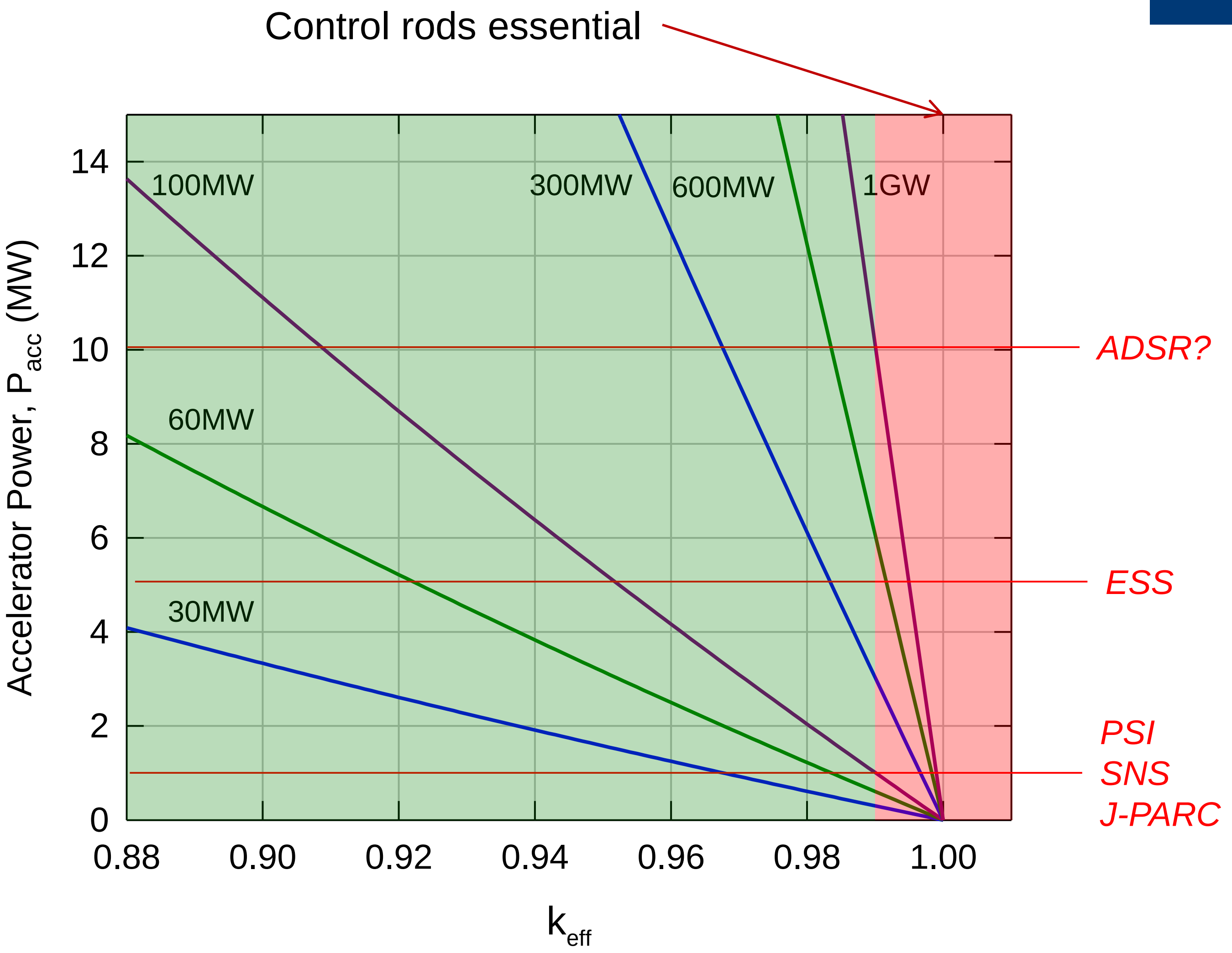
Time dependence of k_{eff}

decay of ^{233}Pa to fissile ^{233}U



After G.Parks et al, Cambridge

Subcritical ADSR operation


Control rods essential

ADSR?

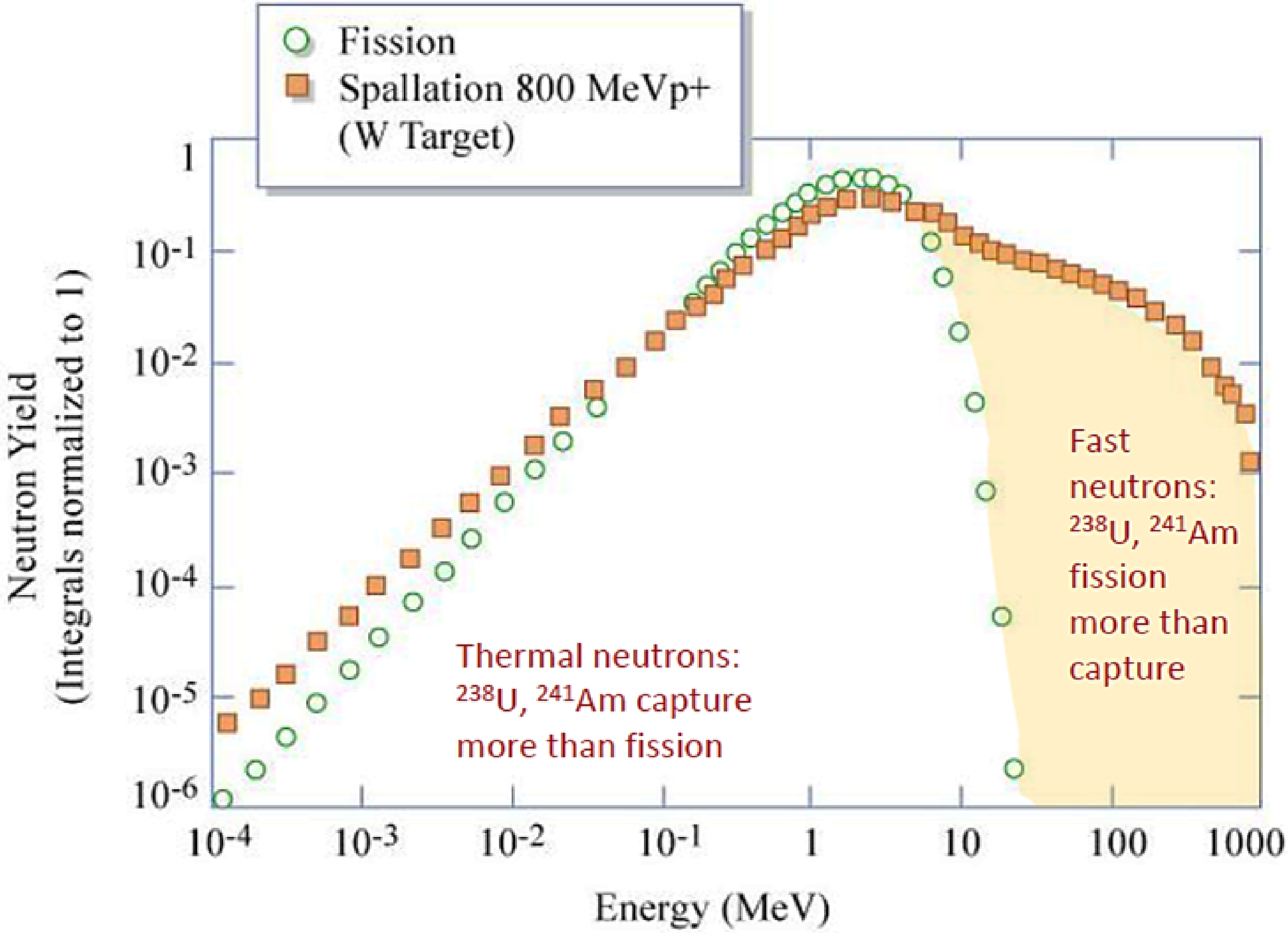
ESS

PSI
SNS
J-PARC

Delayed neutrons

Fissile nucleus	ν_d (neutrons/100 fissions)
^{233}U (thermal)	0.667±0.003
^{235}U (thermal)	1.621±0.05
^{238}U (fast)	4.39±0.10
^{239}Pu (thermal)	0.628±0.038
^{240}Pu (fast)	0.95±0.08
^{241}Pu (thermal)	1.52±0.11
^{242}Pu (fast)	2.21±0.26

Spallation neutron vs fission neutrons

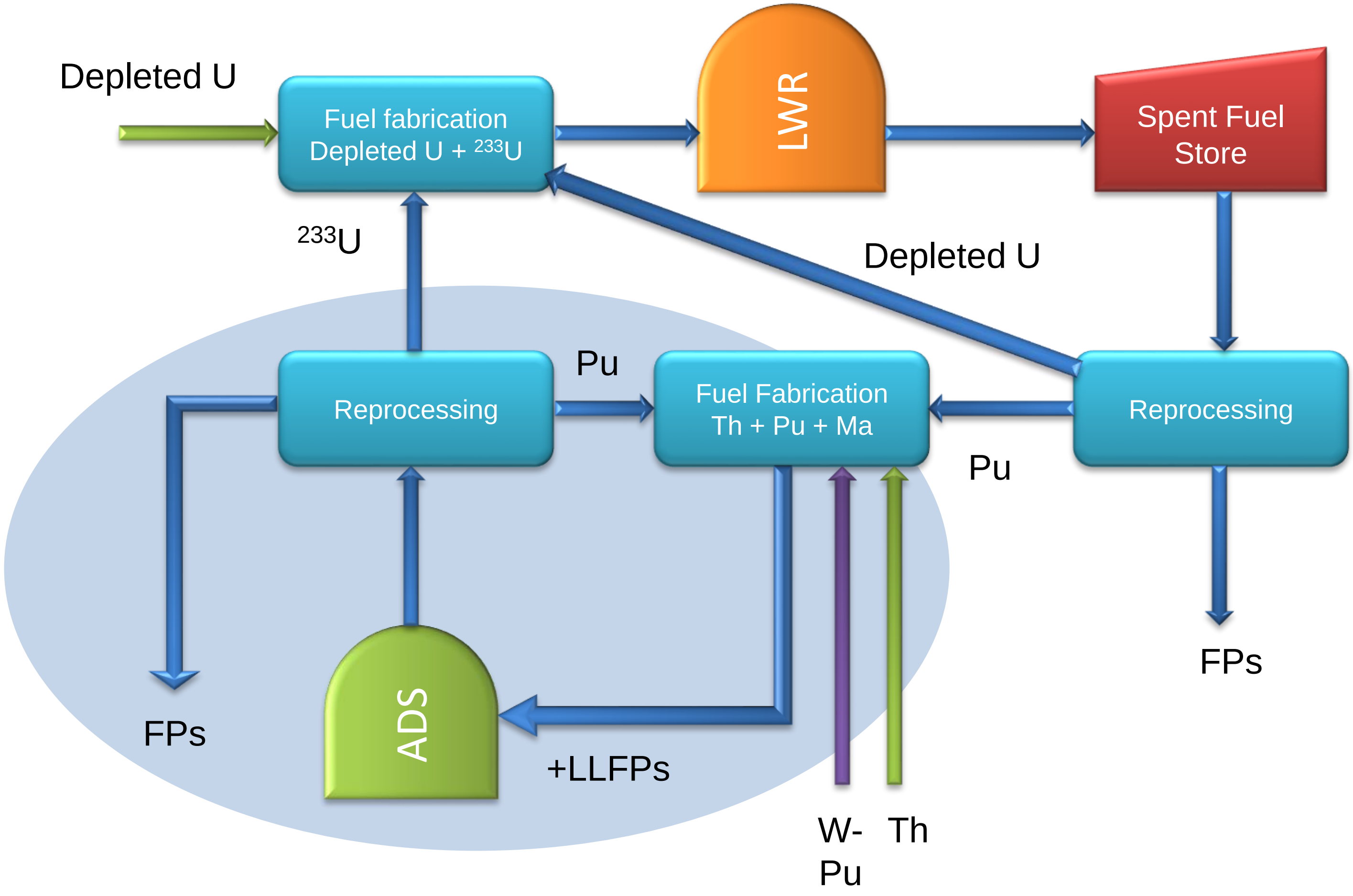


Thermal neutrons: ^{238}U, ^{241}Am capture more than fission

Fast neutrons: ^{238}U, ^{241}Am fission more than capture

Nuclide	fiss/abs Thermal	fiss/abs Fast
^{239}Pu	63%	79%
^{240}Pu	0.34%	43%
^{241}Pu	23%	82%
^{242}Pu	1.4%	36%
^{237}Np	1.9%	17%
^{238}Np	91%	84%
^{239}Np	3.9%	19%
^{241}Am	1.3%	12%
^{242}Am	83%	84%
^{242}Cm	8.9%	33%
^{244}Cm	6.0%	32%
^{246}Cm	18%	53%

Cross-Progeny



Transmutation of LLFPs

The energy required to transmute a fraction of long lived fission products (ie ^{99}Tc, ^{129}I, ^{135}Cs, ^{126}Sn…) q_{fp}, in an ADSR is given by

$$E_{fp} = \frac{N_p \dfrac{k_{eff}}{\nu(1-k_{eff})} E_f - \dfrac{E_p}{\eta_b \eta_T}}{N_p . \left[\left(1 - \dfrac{k_{eff}}{\nu}\right)\eta_{fp} + \dfrac{k_{eff}}{1-k_{eff}} \left(\left(1 - \dfrac{k_{eff}}{\nu}\right)\eta_{fp} - \dfrac{q_{fp}}{\nu} \right) \right]} \quad (\mathrm{MW})$$

with

$$\eta_{fp} = \frac{\Sigma_a(\mathrm{FP})}{\Sigma_a(\mathrm{FP}+\mathrm{Fuel}+\mathrm{Struct.Mat})}$$

and η_b and η_T are the efficiencies of converting electricity into the proton beam (~0.5) and converting heat into electricity (~0.4) respectively. N_p is the number of spallation neutrons emitted by a proton of energy E_P

For a positive energy balance we therefore require:

$$k_{eff} \geq \frac{1}{1 + \dfrac{N_p E_f \eta_b \eta_T}{\nu . E_p}} \cong 0.7 \qquad \textit{(for a lead target)}$$

. Takahashi, H. and Rief, H, (1992) The energy requirement for transmuting fission products, *OECD/NEA Second General Meeting of the International Information Exchange Programme on Actinide and fission Product Separation and Transmutation*, ANL.

Fertile to fissile conversion ?

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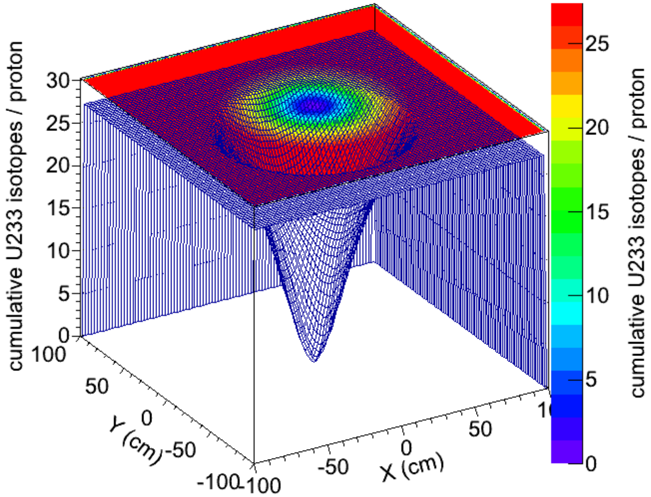
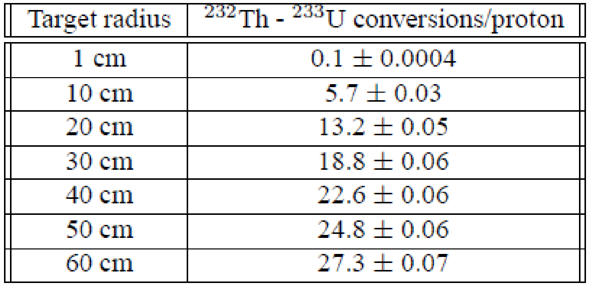
Our GEANT4 calculations show that conversion of ^{232}Th to ^{233}U directly by spallation is possible:





Target radius	^{232}Th - ^{233}U conversions/proton
1 cm	0.1 ± 0.0004
10 cm	5.7 ± 0.03
20 cm	13.2 ± 0.05
30 cm	18.8 ± 0.06
40 cm	22.6 ± 0.06
50 cm	24.8 ± 0.06
60 cm	27.3 ± 0.07

- 1 GeV protons incident on a large (60cm diameter 120cm long) cylinder of ^{232}Th will generate up to 27 ^{233}U nuclei per proton

- After 300 days of irradiation with a 1mA, 1 GeV proton beam the mass fraction of ^{233}U is 0.2% (1.8% needed for criticality)

- This is unlikely to be an economic process for producing ^{233}U for conventional reactor systems

- "*Cross-Progeny*" may be a more appropriate and cost effective route

Bungau, Cywinski, Barlow, Bungau

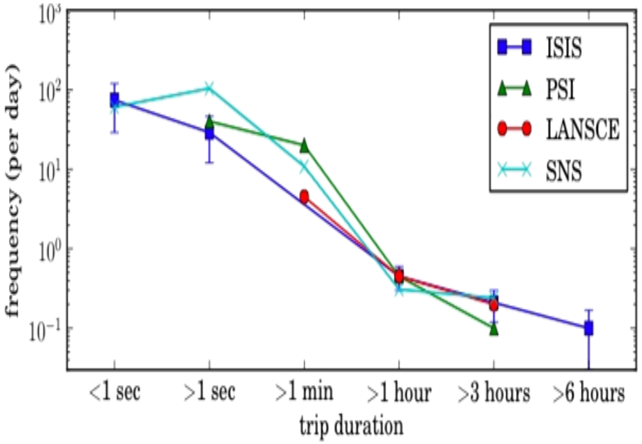
But……

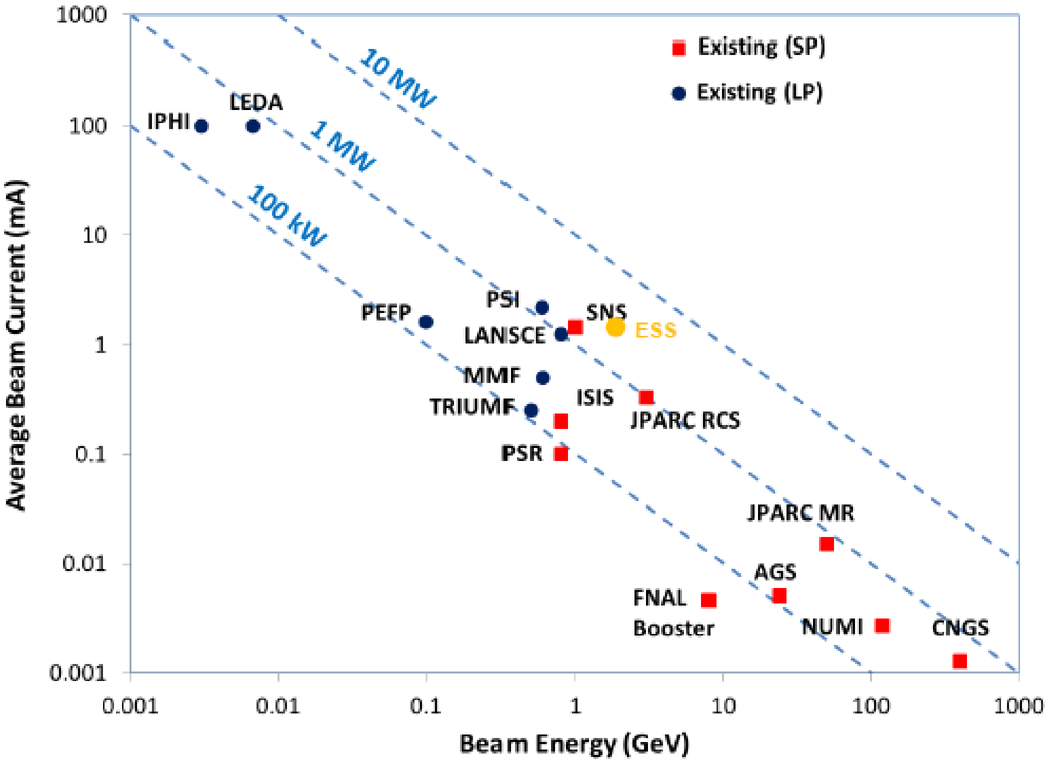
….do we have the appropriate accelerator technology to drive an ADSR for power generation and/or cross progeny and FP transmutation in terms of

(a) *Capital cost*?

(b) Energy, current and footprint?

(c) Reliability?





New ns-ffag accelerator technology

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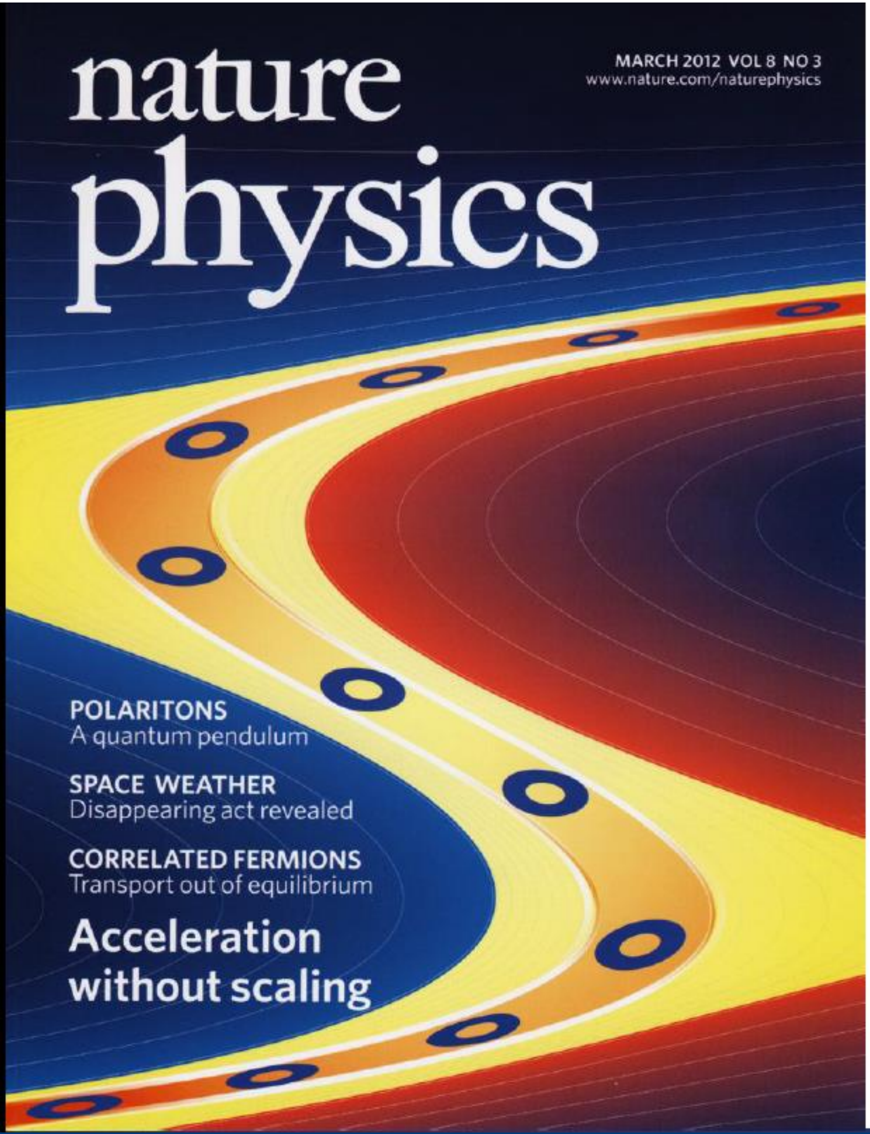
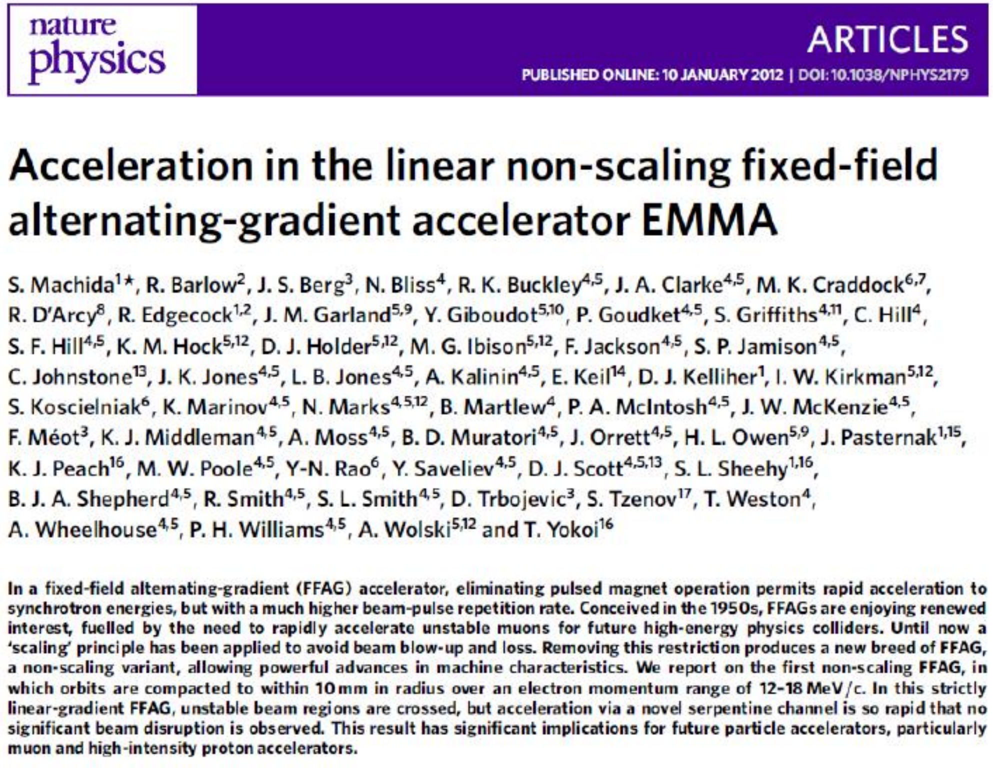
THE AWARDS
UNIVERSITY OF THE YEAR



Huddersfield led the international £7.5M ns-ffag project to develop and build a new type of particle accelerator

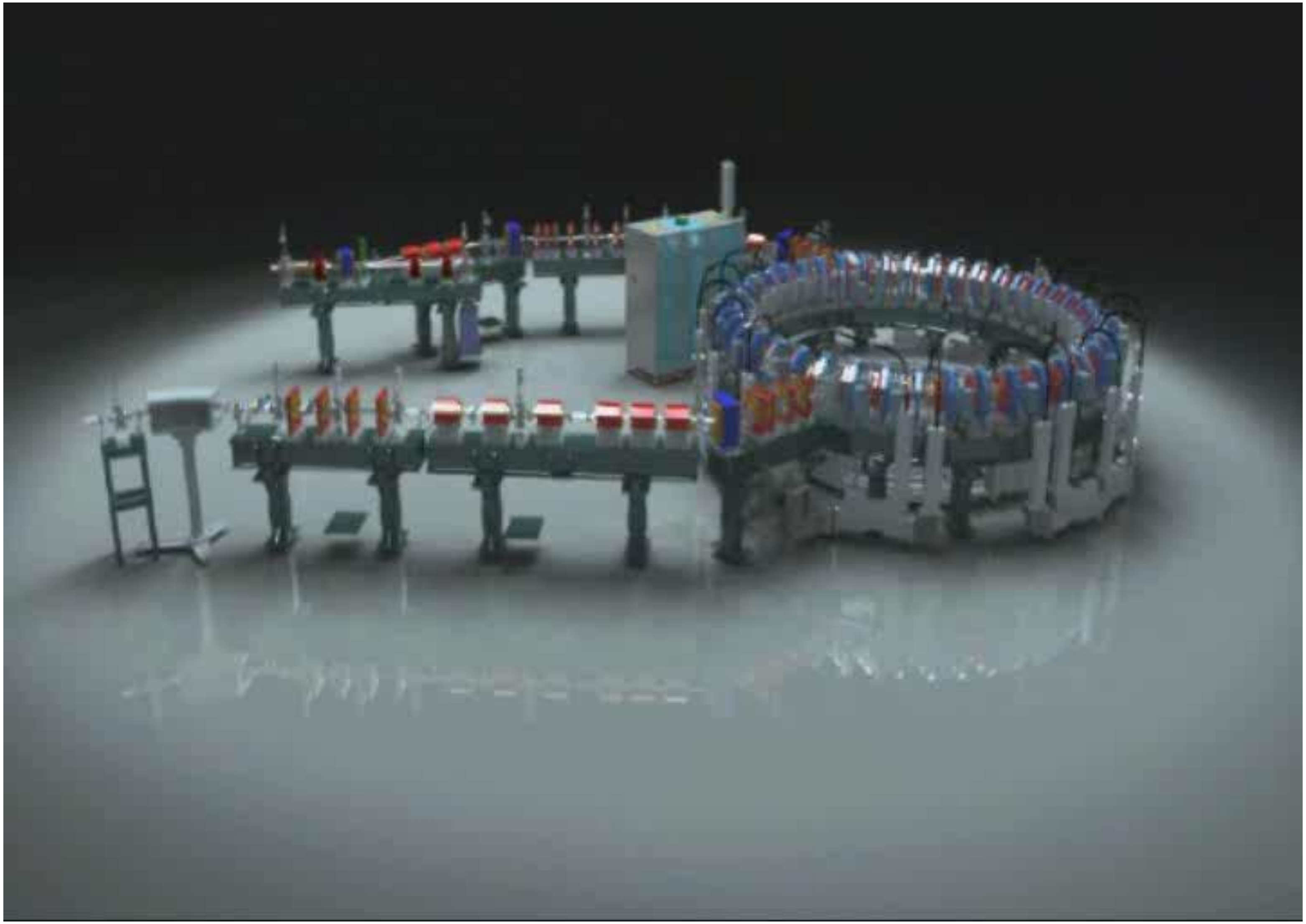

nature physics ARTICLES
PUBLISHED ONLINE: 10 JANUARY 2012 | DOI: 10.1038/NPHYS2179

Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA

S. Machida[1]*, R. Barlow[2], J. S. Berg[3], N. Bliss[4], R. K. Buckley[4,5], J. A. Clarke[4,5], M. K. Craddock[6,7], R. D'Arcy[8], R. Edgecock[1,2], J. M. Garland[5,9], Y. Giboudot[5,10], P. Goudket[4,5], S. Griffiths[4,11], C. Hill[4], S. F. Hill[4,5], K. M. Hock[5,12], D. J. Holder[5,12], M. G. Ibison[5,12], F. Jackson[4,5], S. P. Jamison[4,5], C. Johnstone[13], J. K. Jones[4,5], L. B. Jones[4,5], A. Kalinin[4,5], E. Keil[14], D. J. Kelliher[1], I. W. Kirkman[5,12], S. Koscielniak[6], K. Marinov[4,5], N. Marks[4,5,12], B. Martlew[4], P. A. McIntosh[4,5], J. W. McKenzie[4,5], F. Méot[3], K. J. Middleman[4,5], A. Moss[4,5], B. D. Muratori[4,5], J. Orrett[4,5], H. L. Owen[5,9], J. Pasternak[1,15], K. J. Peach[16], M. W. Poole[4,5], Y-N. Rao[6], Y. Saveliev[4,5], D. J. Scott[4,5,13], S. L. Sheehy[1,16], B. J. A. Shepherd[4,5], R. Smith[4,5], S. L. Smith[4,5], D. Trbojevic[3], S. Tzenov[17], T. Weston[4], A. Wheelhouse[4,5], P. H. Williams[4,5], A. Wolski[5,12] and T. Yokoi[16]

In a fixed-field alternating-gradient (FFAG) accelerator, eliminating pulsed magnet operation permits rapid acceleration to synchrotron energies, but with a much higher beam-pulse repetition rate. Conceived in the 1950s, FFAGs are enjoying renewed interest, fuelled by the need to rapidly accelerate unstable muons for future high-energy physics colliders. Until now a 'scaling' principle has been applied to avoid beam blow-up and loss. Removing this restriction produces a new breed of FFAG, a non-scaling variant, allowing powerful advances in machine characteristics. We report on the first non-scaling FFAG, in which orbits are compacted to within 10 mm in radius over an electron momentum range of 12–18 MeV/c. In this strictly linear-gradient FFAG, unstable beam regions are crossed, but acceleration via a novel serpentine channel is so rapid that no significant beam disruption is observed. This result has significant implications for future particle accelerators, particularly muon and high-intensity proton accelerators.

EMMA – world's first electron ns-ffag



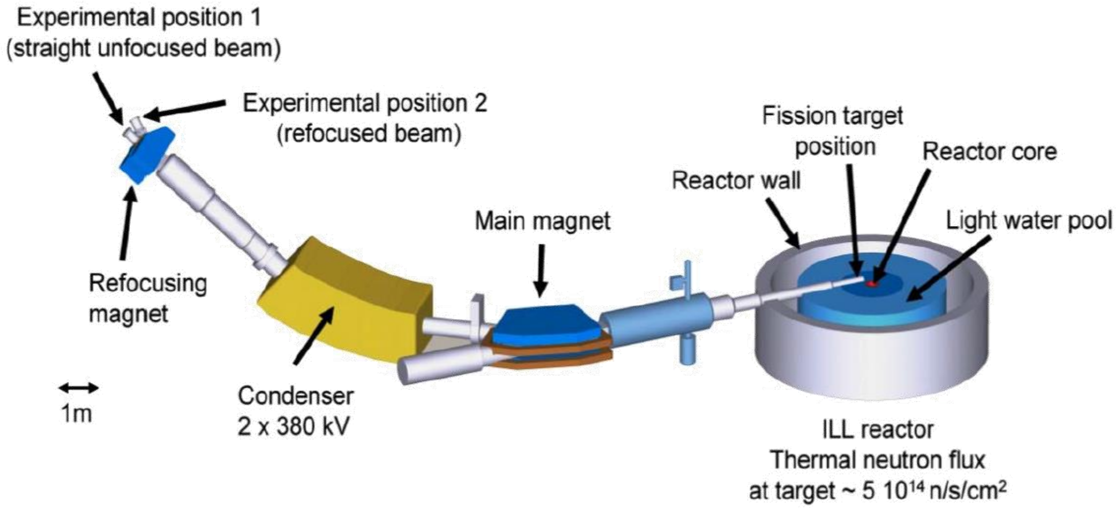
^{233}U Fission Cross-sections

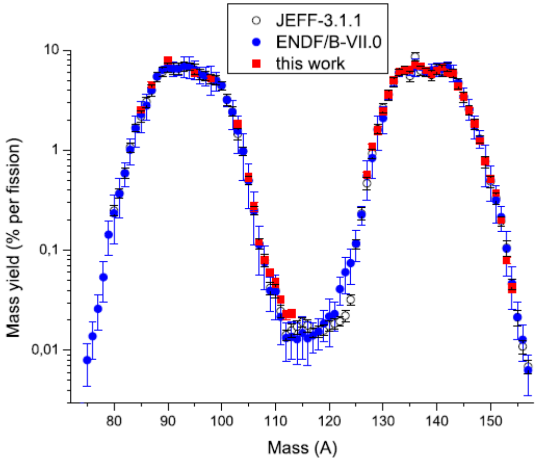
Measurement of the mass and isotopic yields of the ^{233}U(n_{th},f) rection at the Lohengrin Spectrometer (ILL, Grenoble)

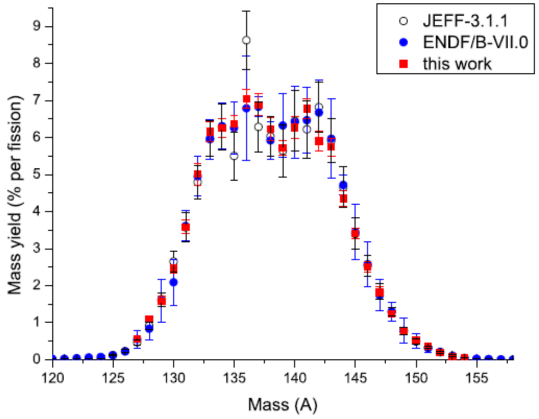
Fission fragments deflected electrically and magnetically (to give A/Q and E/Q)

International team led by Kessedjian (Grenoble)

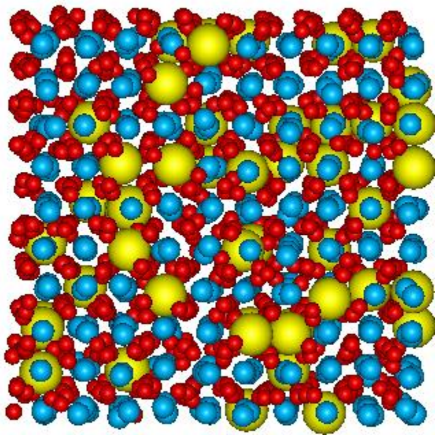
Published in :
Advancements in Nuclear Instrumentation Measurement Methods and their Applications (ANIMMA), 2011
DOI:10.1109/ANIMMA.2011.6172920

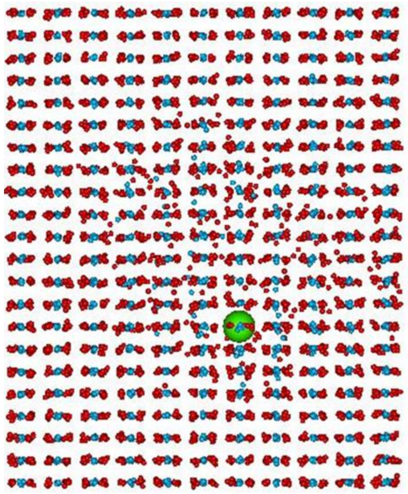






Molecular dynamics simulations





- Molecular dynamics have been used to investigate the thermal expansion, oxygen diffusion, and heat capacity of pure thoria and uranium doped (1-10%) thoria between 1500 K and 3600 K.

- Effects of radiation damage, oxygen vacancies and U substitution have been simulated

- Results indicate that the thermal performance of the thoria matrix, even when doped with 10%U, is comparable to, and possibly better than, that of UO_2

- Simulations are now being extended to molten thorium salts (LiF, BeF_2 and ThF_4 with ThF_4 content of 10% - 20%) to better understand MSR fuels.

Martin, Cooke and Cywinski, Journal of Applied Physics 112, 073507 (2012)

Conclusions

Thorium has been used successfully in the past and could now provide an alternative, sustainable, safe, low waste and proliferation-resistant fuel for nuclear power generation

Thorium has been used successfully for many years for power generation in HTGR and LWBR reactors. We have the technology to deploy it now

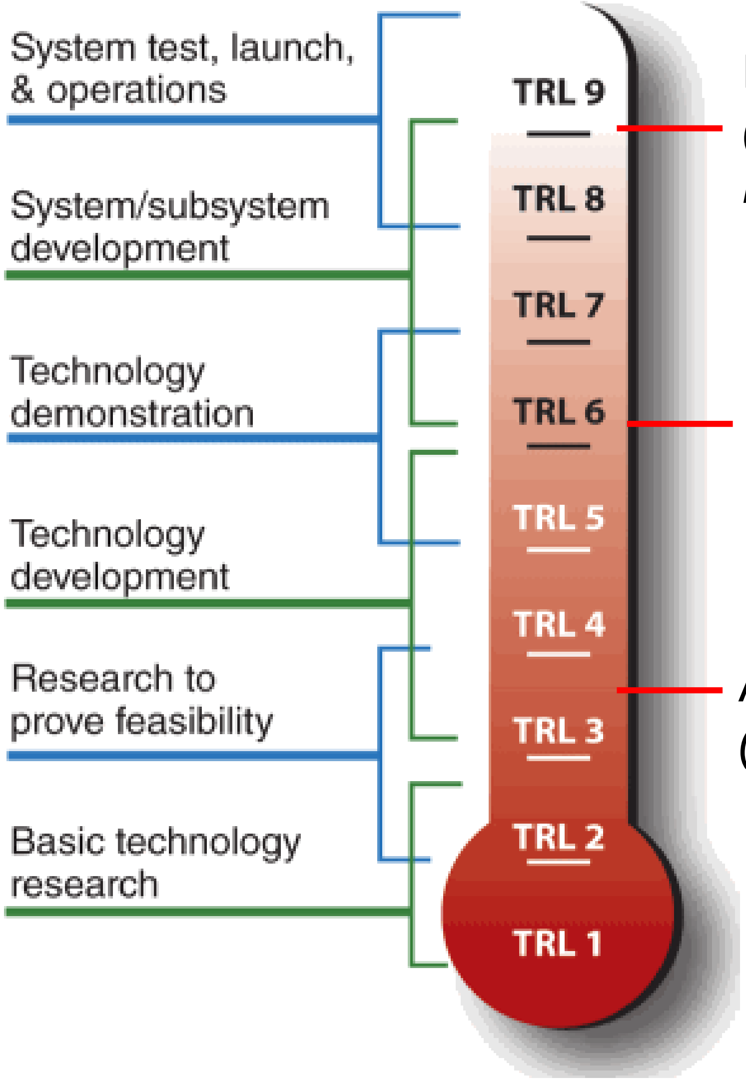
Thorium could be the fuel of choice in next generation modular reactor systems

There is a resurgence of interest in molten salt reactors which are well suited to the deployment of thorium-based fuel

MAs and Pu can be mixed with thorium and burnt as fuel, reducing radiotoxicity by orders of magnitude and turning a liability into an asset in reactors and MSRs, but particularly in ADS systems

Thorium fuelled ADSRs can also efficiently transmute fission products

Thorium technology readiness levels



System test, launch, & operations

System/subsystem development

Technology demonstration

Technology development

Research to prove feasibility

Basic technology research

TRL 9

TRL 8

TRL 7

TRL 6

TRL 5

TRL 4

TRL 3

TRL 2

TRL 1

LWBR, HTGR
(eg Shippingport, Fort St Vrain)

MSR
(eg Oak Ridge)

ADS
(eg KURRI)

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Thank you