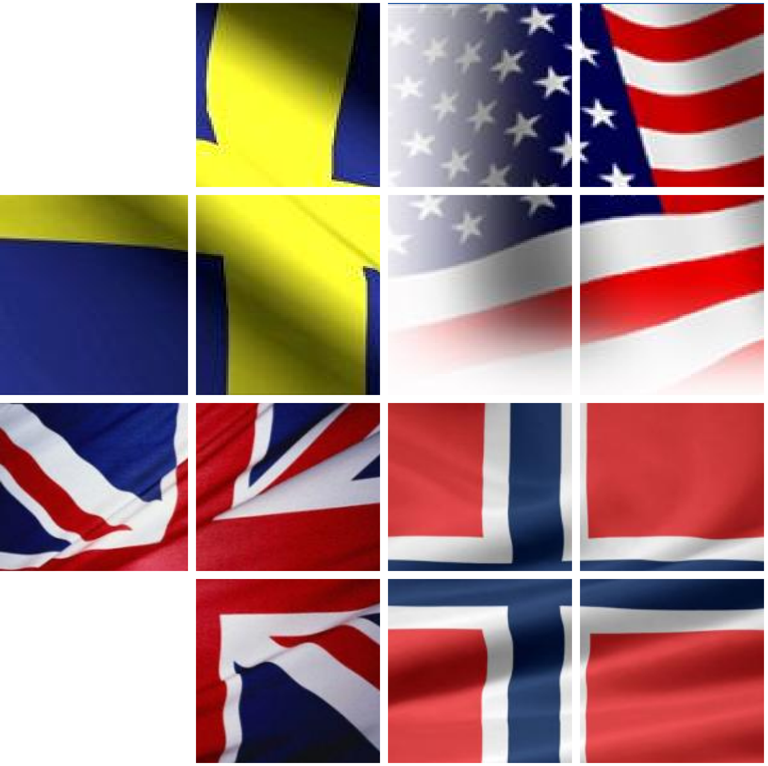
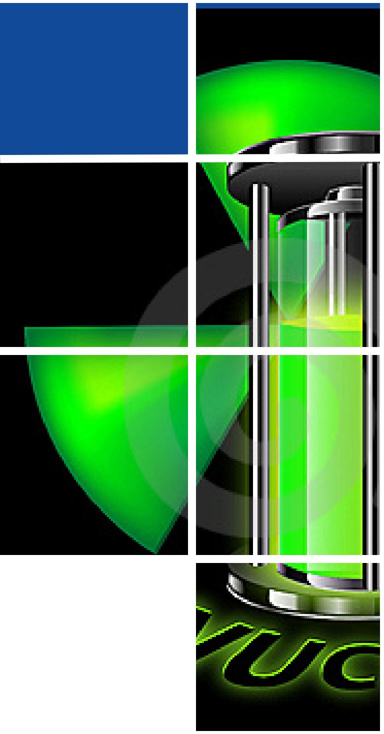
IPAC 2012
21 May 2012
New Orleans



Thorium Energy Futures

S. Peggs (*BNL/ESS*), W. Horak, T. Roser (*BNL*)
G. Parks (Cambridge U.), M. Lindroos (*ESS*)
R. Seviour (*ESS/Huddersfield U.*)
R. Barlow, **R. Cywinski** (*Huddersfield U.*)
S. Henderson (*FNAL*),J.-L. Biarrotte (*IPN*)
A. Norlin (*IThEO*)
V. Ashley, R. Ashworth (*Jacobs*),
A. Hutton (*JLab*), H. Owen (*Manchester U.*),
P. McIntyre (*TAMU*), J. Kelly (*Thor Energy/WNA*).

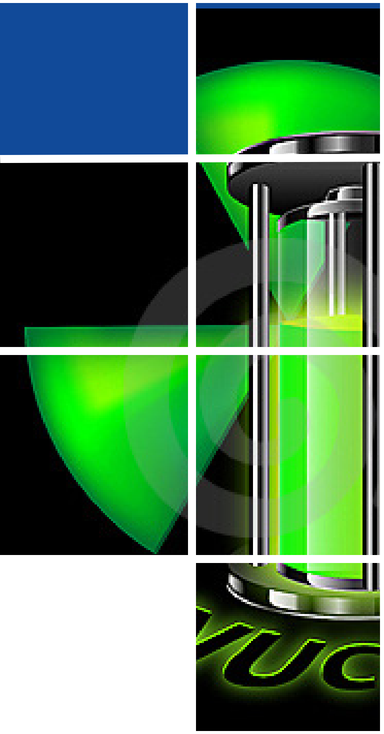
Pre-Fukushima nuclear capacity



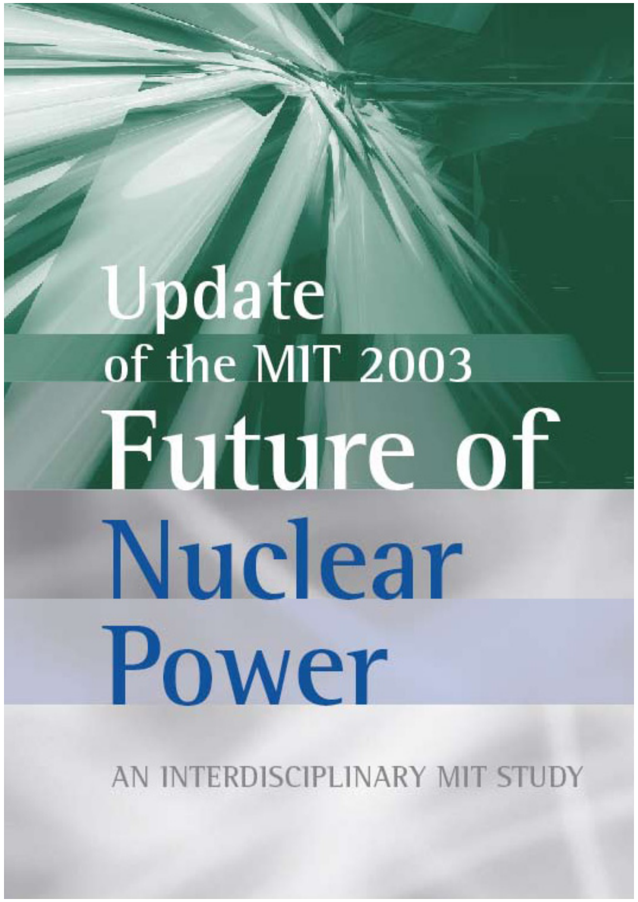
Country	Nº. Reactors	GW capacity	% Total Electricity
France	58	63	75
Sweden	10	9	37
South Korea	21	19	31
Japan	55	47	29
Germany	17	20	26
United States	104	101	20
Russia	32	23	18
United Kingdom	19	11	17
Canada	18	13	15
India	20	5	3
21 Others	87	69	
Totals:	**441**	**380**	**14**

.... this represents only 5% of global energy provision

Increasing capacity by x4 would cut carbon emissions by 20%



Retaining the nuclear option



"...... the nuclear option should be retained precisely because it is an important carbon-free source of power…."

....but there are four unresolved problems:

- *high relative costs*
- *perceived adverse safety, environmental, and health effects*
- *potential security risks stemming from proliferation*
- *unresolved challenges in long-term management of nuclear wastes*.

Annual global use of energy resources

5×10^9
tonnes of coal

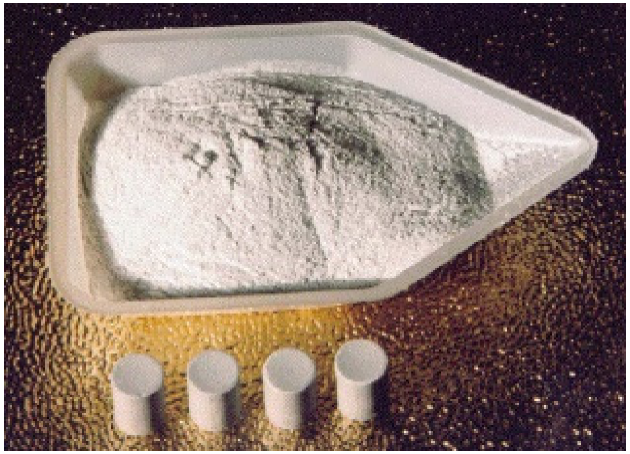
27×10^9
barrels of oil

2.5×10^{12} m^3
natural gas

65×10^3
tonnes of uranium

=

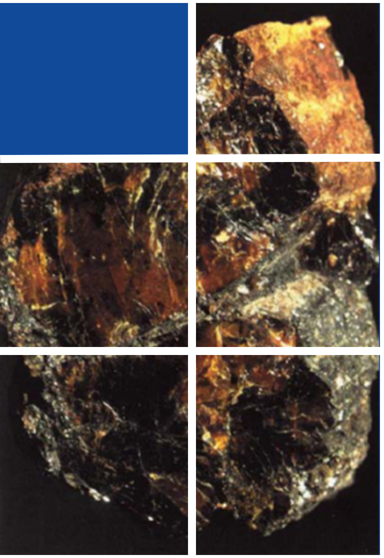
An alternative fuel?

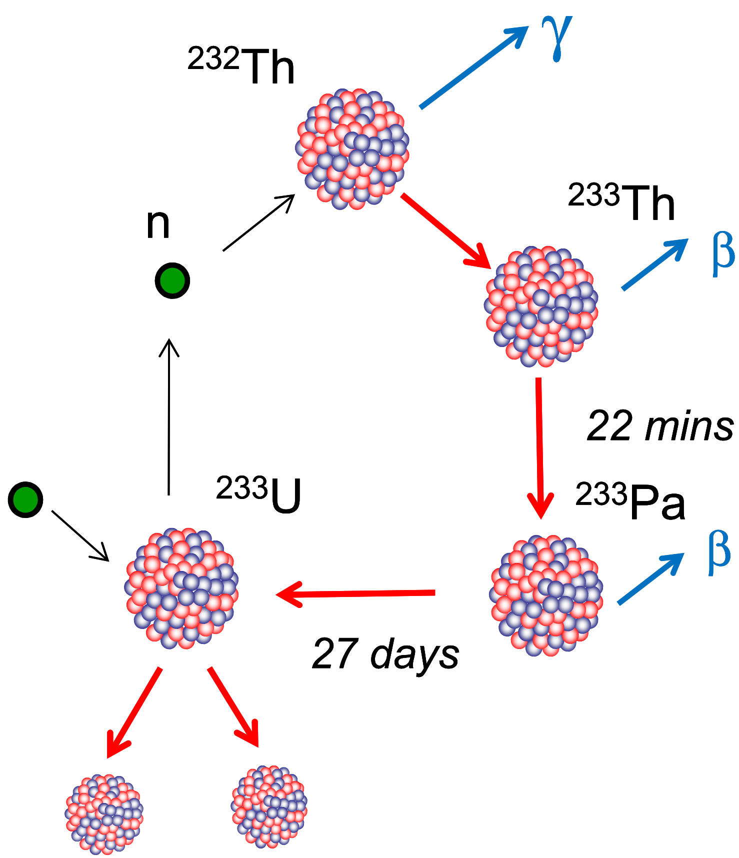


5×10^3 tonnes of thorium

4x more plentiful than U
10,000 years supply

Breeding fuel from thorium





Advantages

Does not need processing

Generates virtually no plutonium and less higher actinides

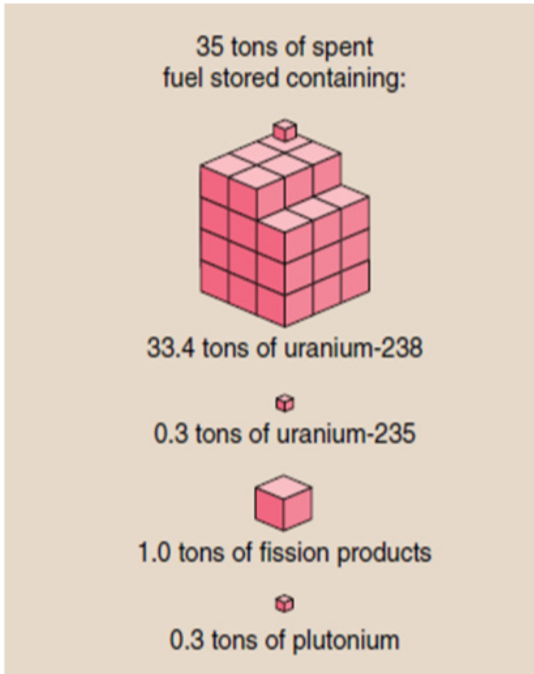
^{233}U has superior fissile properties

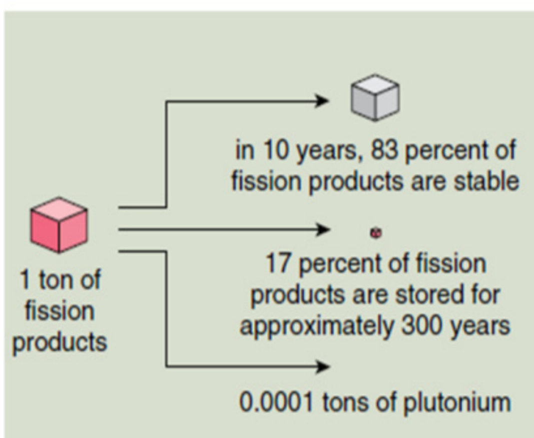
Disadvantages

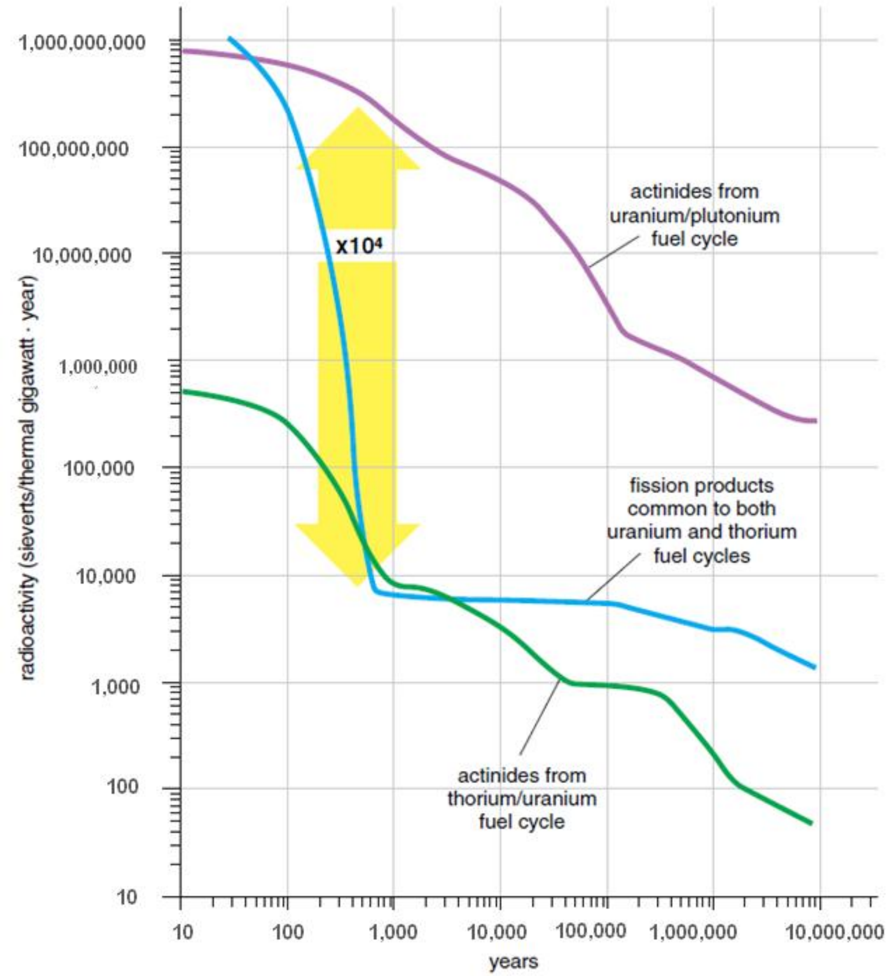
Requires introduction of fissile seed (^{235}U or Pu)

The decay of parasitic ^{232}U results in high gamma activity from ^{208}Tl.

Advantages of thorium: waste



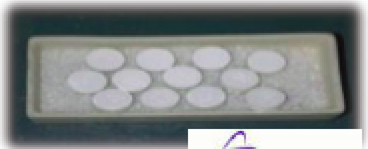




1. Thorium as fuel in conventional reactors

Thor Energy & The International Thorium Consortium

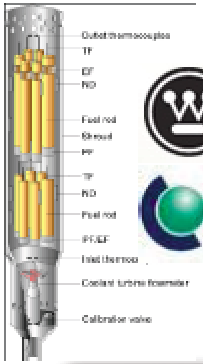
Feasibility study → Fuel design → Irradiation → Test rods → Full bundle



The OECD Halden Reactor Project

Los Alamos

- **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.

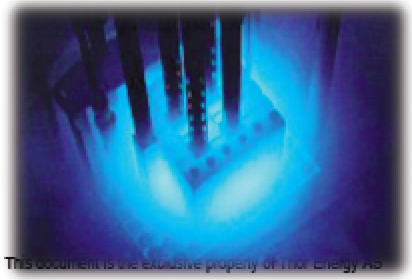


Westinghouse

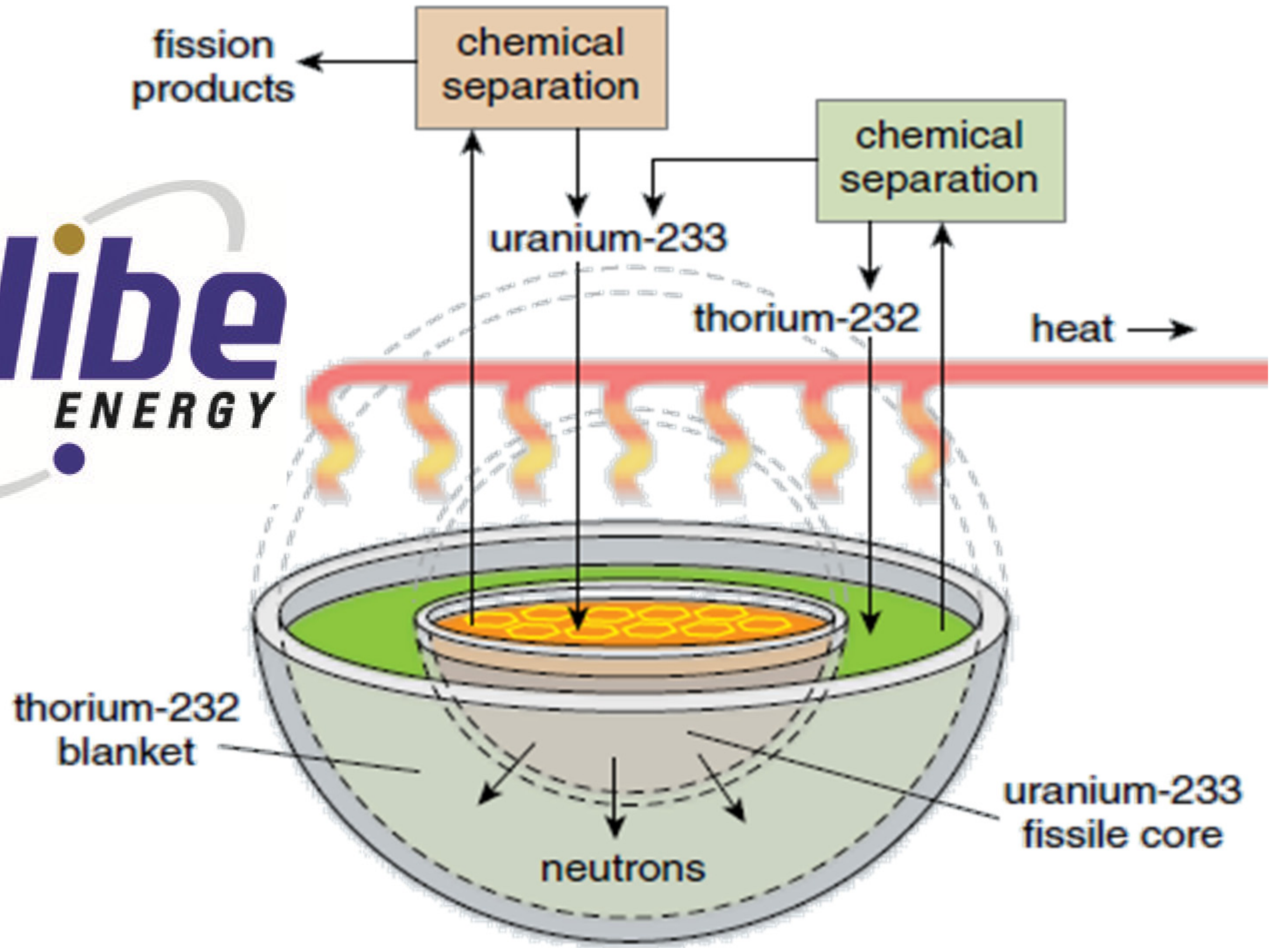
Fortum

Thor Energy

IFE Institutt for energiteknikk

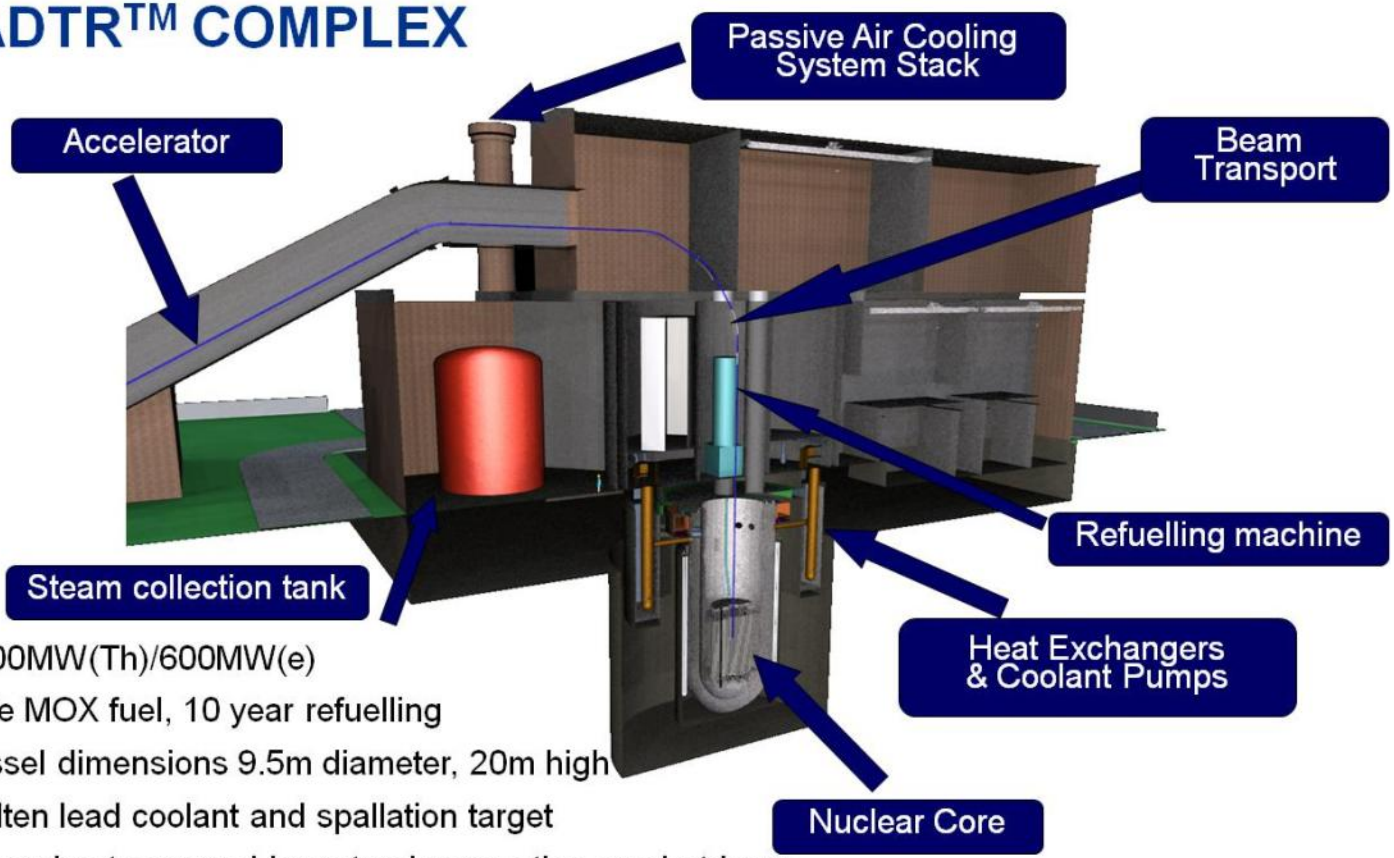


2. Thorium as fuel in molten salt reactors:



UK ADSR Projects: Jacobs

Jacobs Engineering's ADTR^{TM} COMPLEX



- 1500MW(Th)/600MW(e)
- 59te MOX fuel, 10 year refuelling
- Vessel dimensions 9.5m diameter, 20m high
- Molten lead coolant and spallation target
- Decay heat removed by natural convection on shutdown
- System operates at atmospheric pressure

Accelerator requirements

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 (<1 for ADSR)

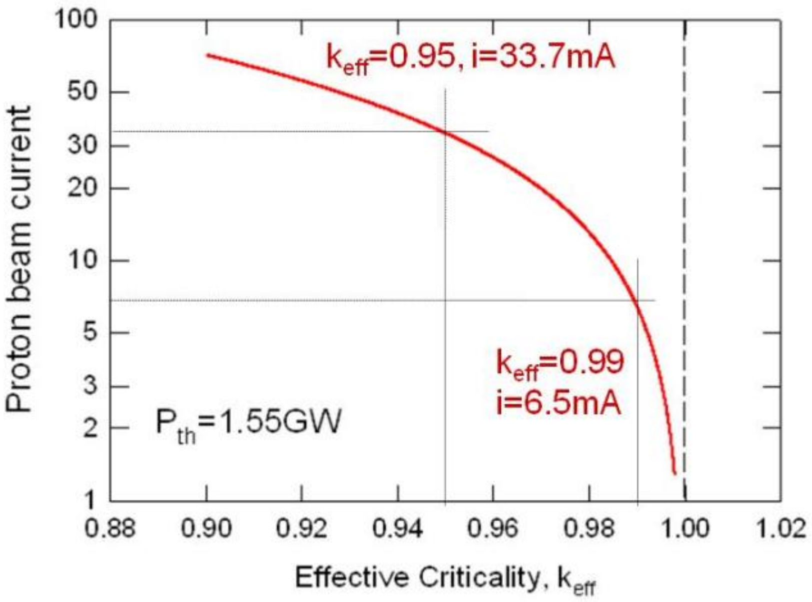
Assuming:

P_{th} = 1550MW

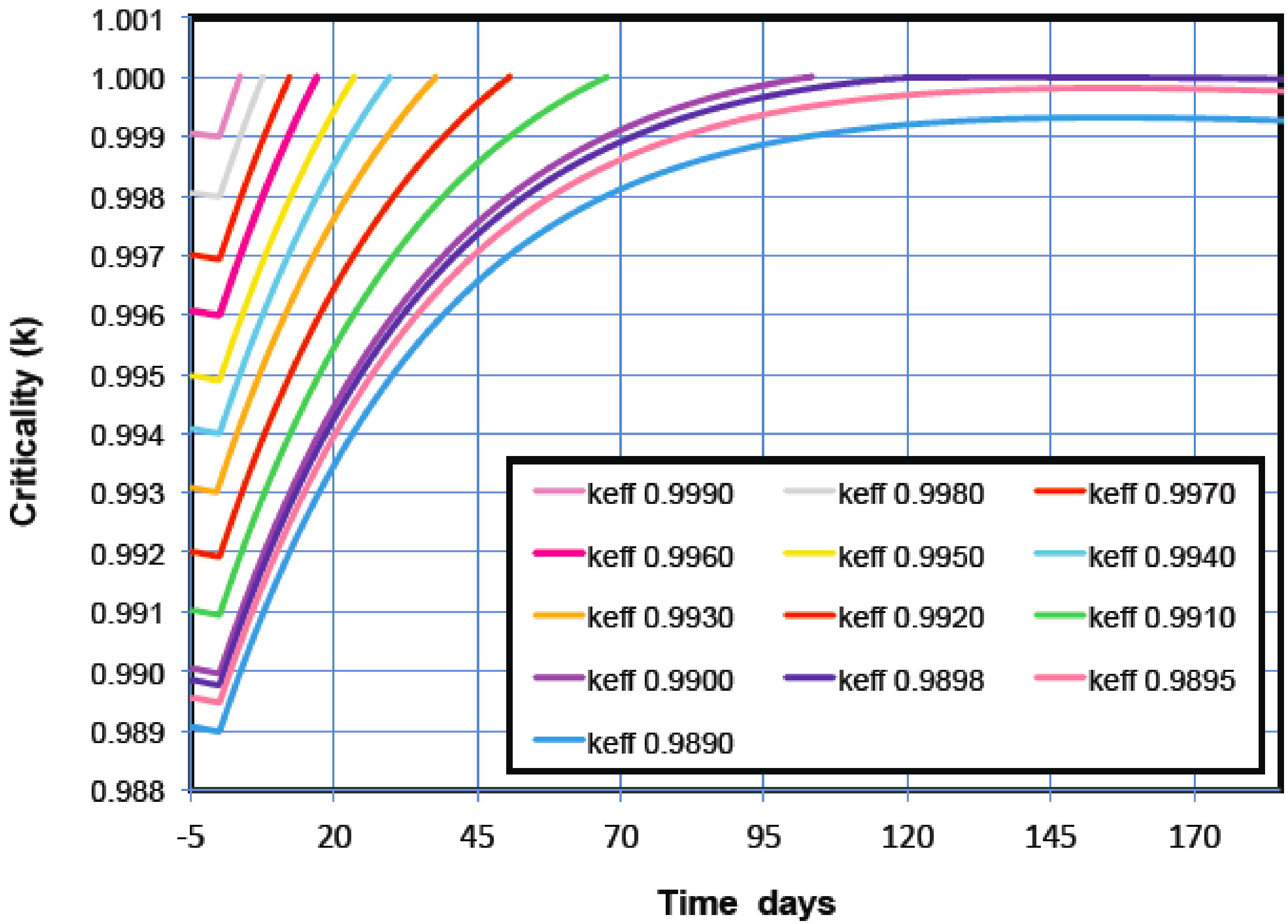
1 GeV proton beam (producing 24 spallation neutrons per proton)

Then:

k_{eff} = 0.985 requires 10mA of beam current

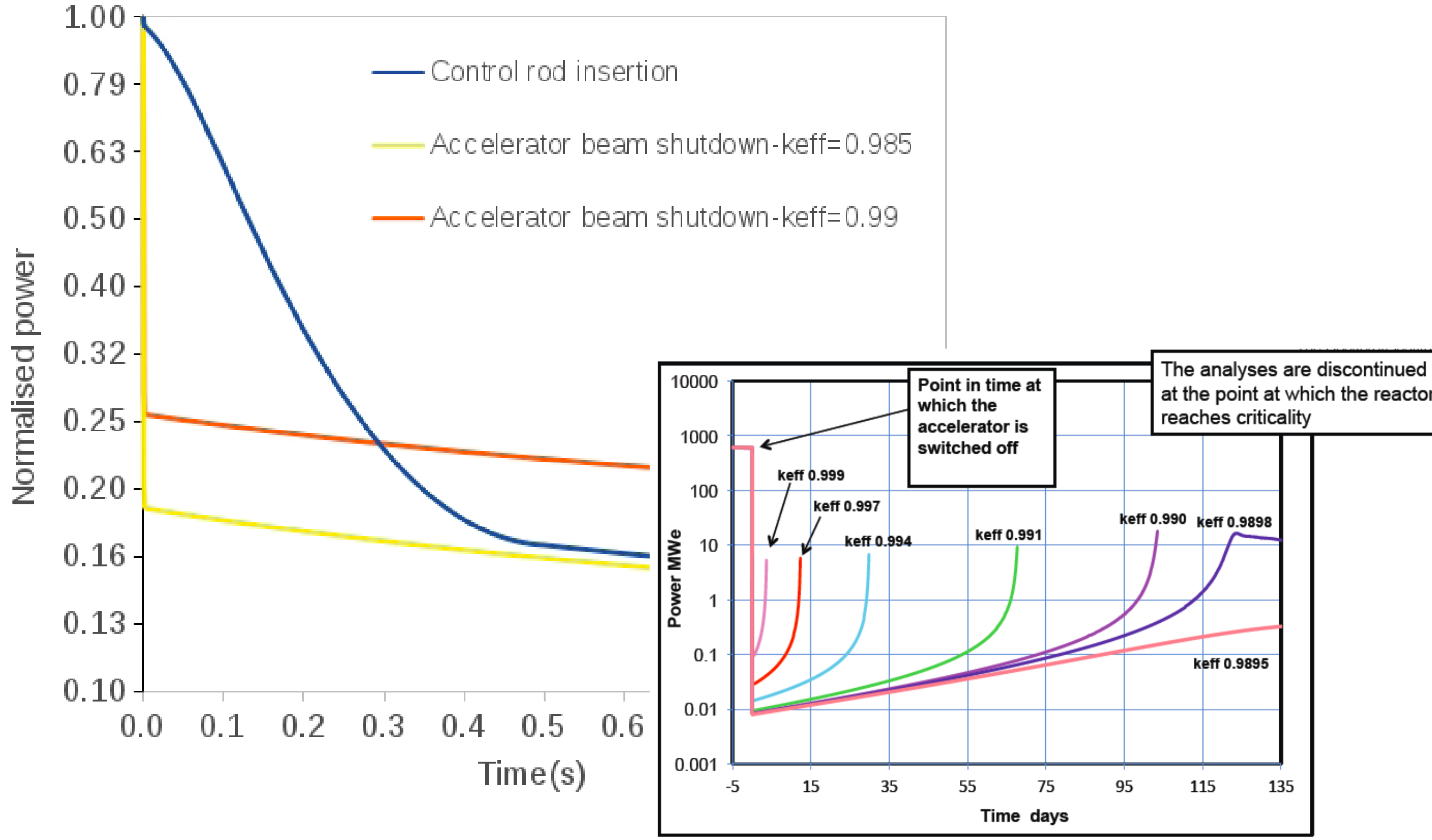


Evolution of the criticality value, k_{eff}



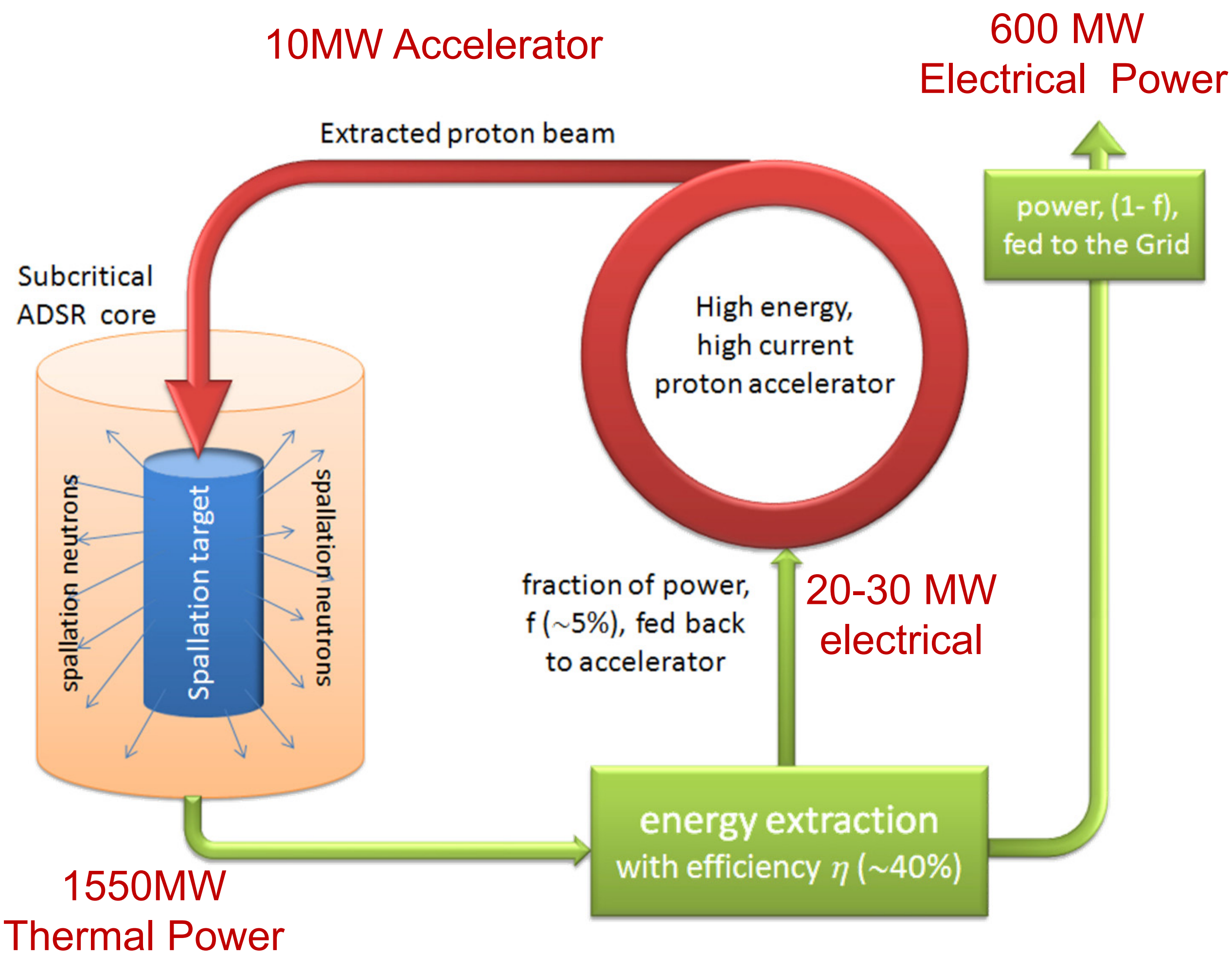
Coates, Parks (Cambridge)

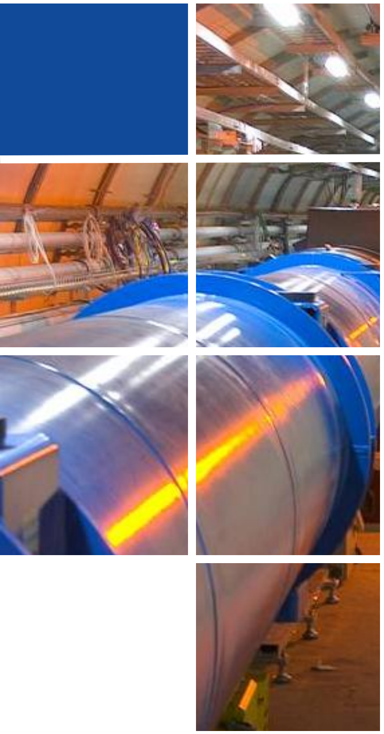
ADSR Shutdown



Parks et al (Cambridge)

The ADSR as an energy amplifier





Technology readiness assessment (US)

		Transmutation Demonstration	Industrial-Scale Transmutation	Power Generation
Front-End System	Performance	Green	Green	Green
	Reliability	Yellow	Yellow	Red
Accelerating System	RF Structure Development and Performance	Green	Green	Green
	Linac Cost Optimization	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Yellow
RF Plant	Performance	Green	Green	Green
	Cost Optimization	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Red
Beam Delivery	Performance	Green	Green	Green
Target Systems	Performance	Green	Yellow	Yellow
	Reliability	Yellow	Yellow	Yellow
Instrumentation and Control	Performance	Green	Yellow	Yellow
Beam Dynamics	Emittance/halo growth/beamloss	Green	Yellow	Yellow
	Lattice design	Green	Yellow	Yellow
Reliability	Rapid SCL Fault Recovery	Yellow	Red	Red
	System Reliability Engineering Analysis	Yellow	Red	Red

Green: “ready”, Yellow: “may be ready, but demonstration or further analysis is required”, Red: “more development is required”.

Proton drivers?

Cyclotrons

High Current (<A) Low Energy (600MeV)
Continuous beam

Synchrotrons

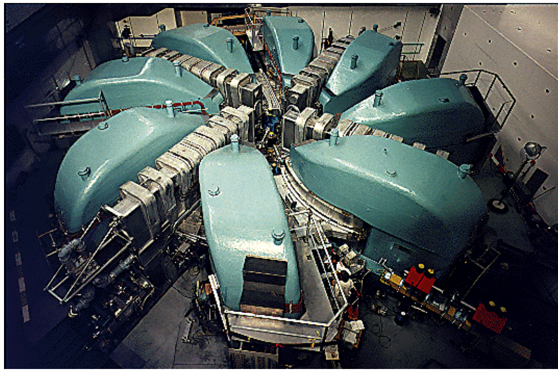
Low Current (<mA) High Energy (TeV)
Pulsed Beam

Linacs

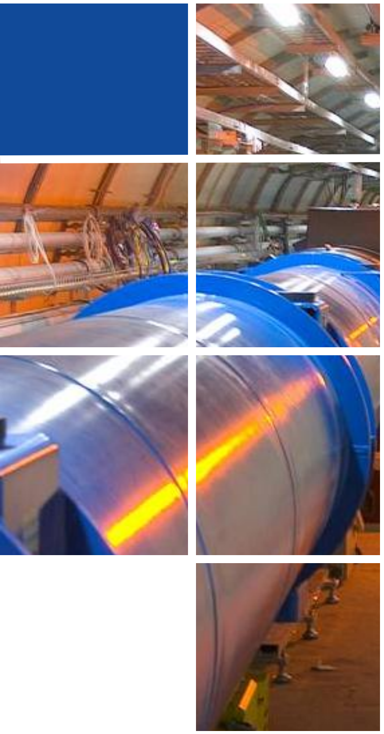
High Current, High Energy
Pulsed or continuous beam
Large and relatively expensive

FFAGs

Still at prototyping stage

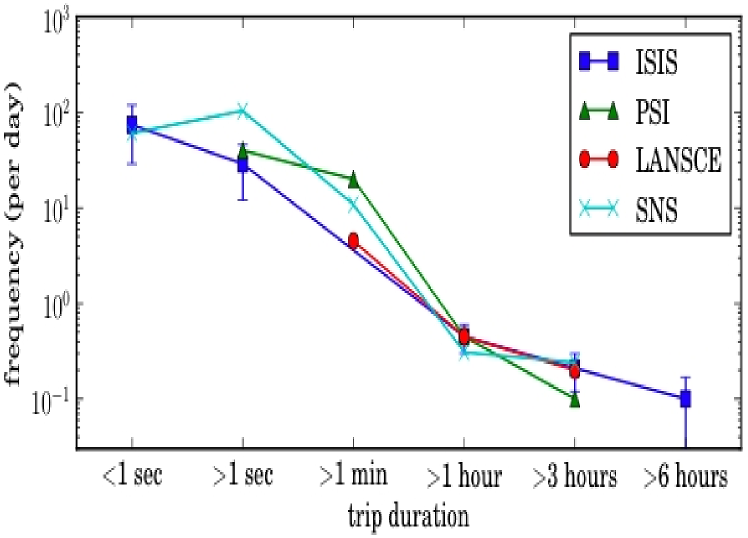


Addressing Reliability



There is a need for:

1. development and demonstration of highly reliable high-current proton injector systems;
2. advancing the state-of-the-art in accelerator systems, including linacs, FFAGs and RF systems
3. improved understanding of beam loss mechanisms, emittance and halo growth;
4. development of highly reliable and fault tolerant accelerator systems and accelerator components.



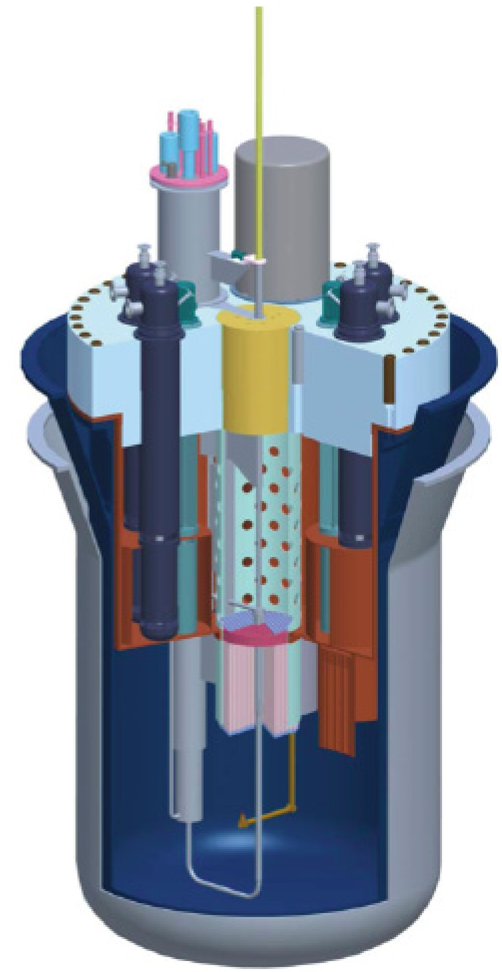
MYRRHA: Transmutation

The MYRRHA Project

SCK•CEN
THE BELGIAN NUCLEAR RESEARCH CENTRE

1b€ European project to build an ADSR for transmutation and waste management (2015)

SC Linac, 600 MeV, 2.5 mA
57 MWth reactor
Pb-Bi eutectic target/coolant
Fuel (MOX) loading from underneath
Examine transmutation of waste



Abderrahim et al., *Nuclear Physics News, Vol. 20, No. 1, 2010*

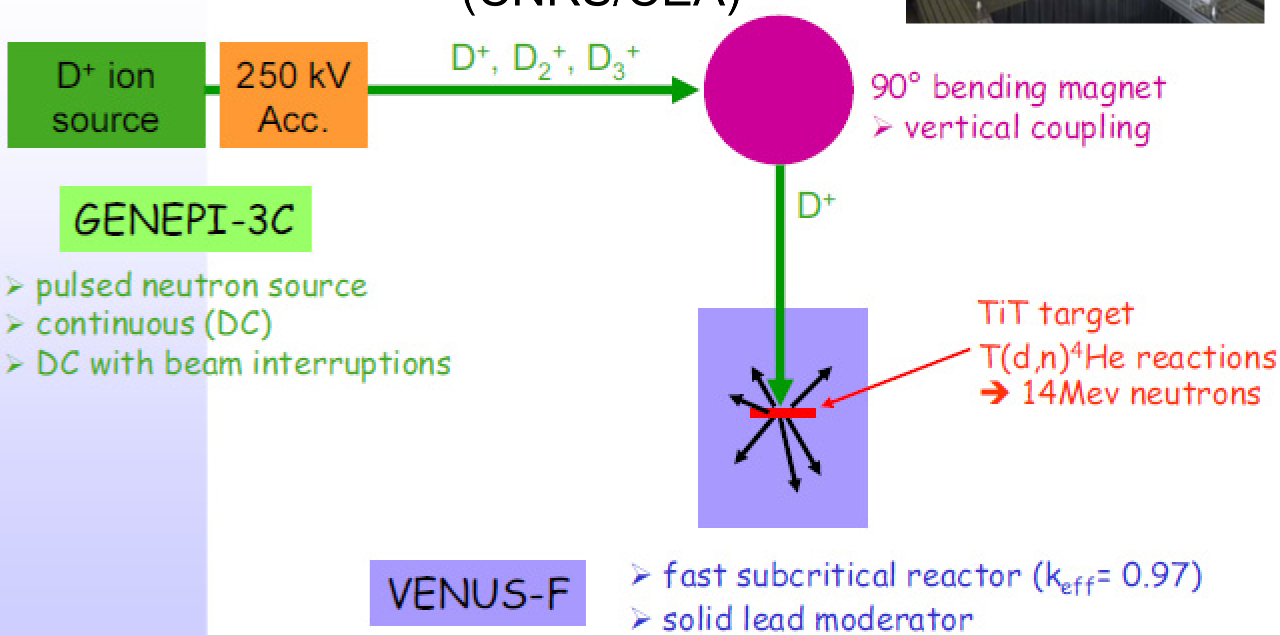
GUINEVERE

January 2012

SCK • CEN
THE BELGIAN NUCLEAR RESEARCH CENTRE

World's first operation of an accelerator driven Pb-cooled fast subcritical reactor (zero power)

(CNRS/CEA)



KURRI

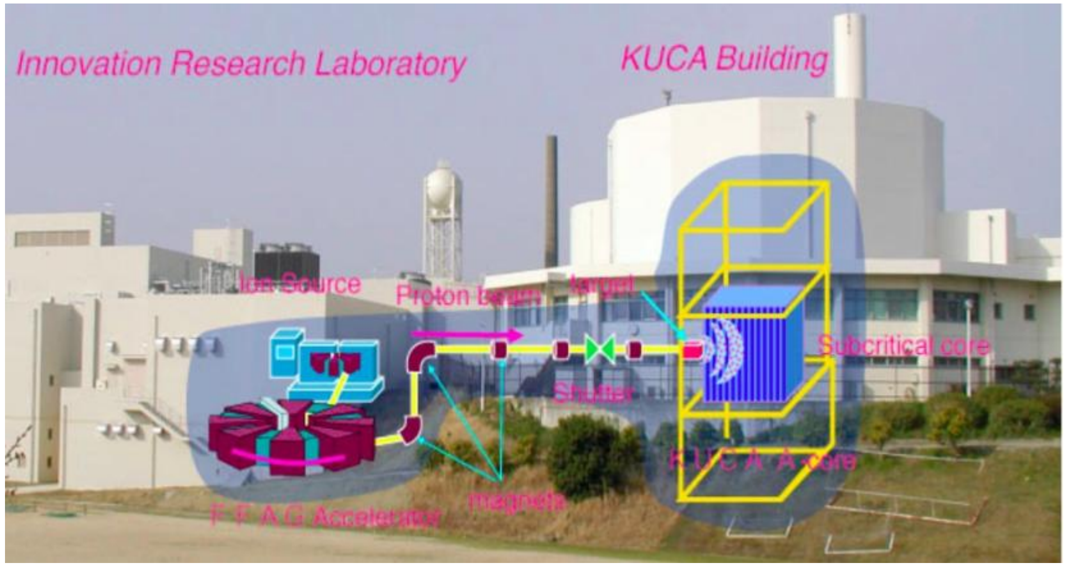
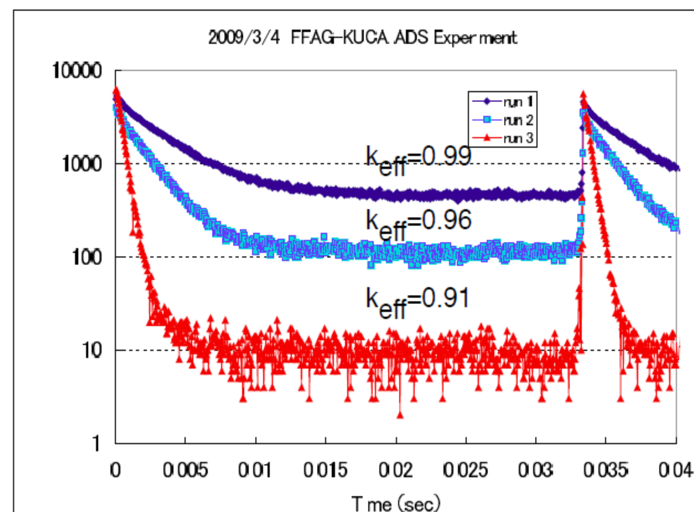


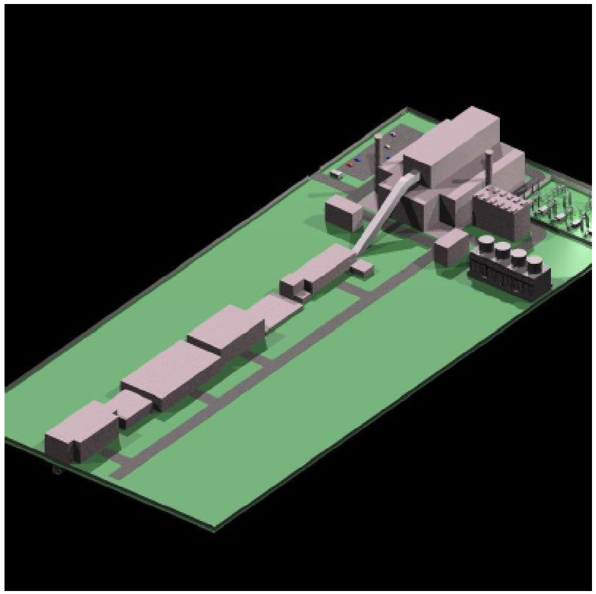
Table 1: The basic parameters for ADSR experiment.

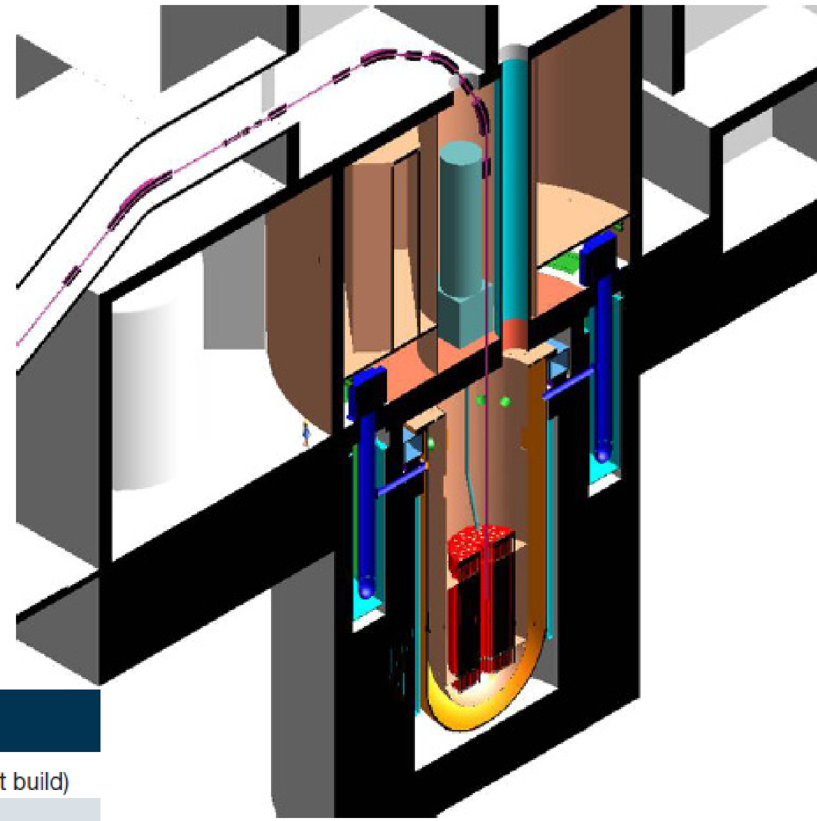
Reactor output power	~10 W
Neutron multiplication factor	≤ 100
Beam power	≤ 0.1 W
Beam energy	100 - 150 MeV
Beam current	≤ 1 nA

Results show prompt and delayed neutrons, the latter from stimulated fission.



Th-fuelled ADSR Design: Jacobs





Key features:	
Cost to build equivalent to conventional	(per kW for first build)
Applies existing technology	
Thorium is cheaper than uranium	
No need for expensive enrichment	
Lower operational costs	
Meets Gen IV timescales	
600MW niche market	

K_{eff}	0.995
Accelerator	3MW
ADSR	600MW

Conclusions

Thorium offers a safe, sustainable, low waste alternative to the uranium/plutonium fuel cycle

Thorium can be deployed in:

- conventional reactors
- Molten Salt Recators (MSR)
- Accelerator Driven Subcritical Reactors (ADSR)
- hybrid MSR/ADSR reactors

Thorium systems provide means of burning existing legacy waste and/or generating electricity

But......

Significant R&D has to be carried out on**:**

- Materials research (particularly for MSR systems)
- Improving accelerator reliability (for ADSR and hybrids)
- Beam, spallation target and blanket interfaces (for ADSR and hybrids)

IPAC 2012
21 May 2012
New Orleans

Thank You!