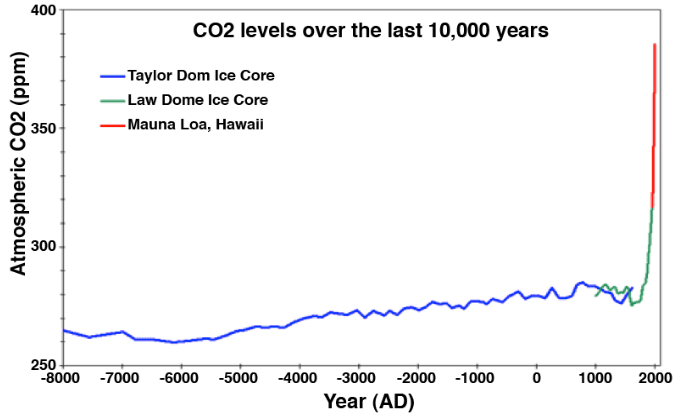
Prospects for Accelerator-Driven Thorium Systems

LINAC14, 27th Linear Accelerator Conference
CICG, Geneva, Switzerland
September 5, 2014

Jean-Pierre Revol
Centro Fermi, Roma, Italy
iThEC, Geneva, Switzerland

Burning fossil fuel till the end?

- **Global warming?** Atmospheric CO_2 level higher than ever in the past 15 million years, increasing faster than ever before (IPCC report, March 2014 > 2˚C more likely than ≤ 2˚C)



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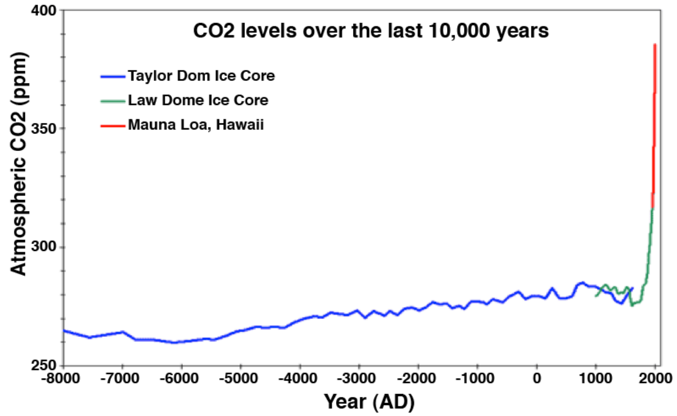
  - The ambient air pollution caused the premature deaths of > 400 000 Chinese in 2013
  - WHO: in 2012, 1 in 8 of total global deaths was the result of air pollution exposure
- **Ocean water pollution?** From air pollution (SO_2, NOx) and CO_2 in the atmosphere



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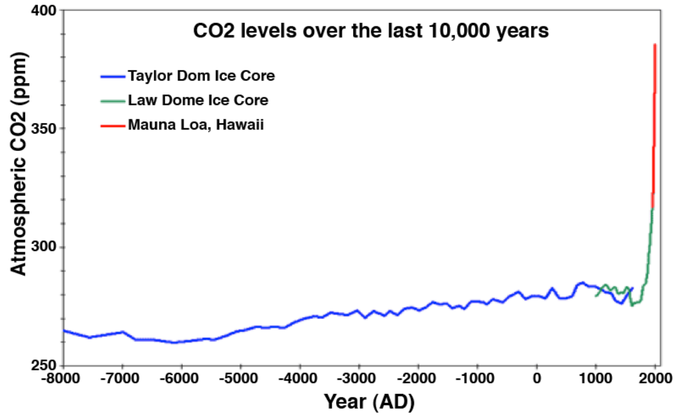


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- **Way out?**

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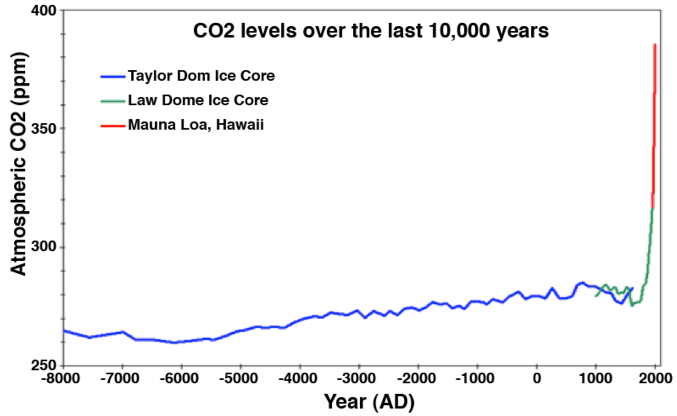

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- **Way out? We must innovate!**

Energy R&D

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  - No CO_2, no air pollution (SOx, NOx, etc.)
  - Potential to produce abundant and base load type of electric energy
  - Nuclear fission technology exists and is well understood
  - Breeding can make it essentially "sustainable" on the human time scale

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  - Waste management (storage over ≤ one million years, the only option developed so far)
  - Proliferation of nuclear weapons (uranium ≈ military)
  - Sustainability (< 100 yr at present rate)

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- **Question: Can one make nuclear energy acceptable to Society?**

Answer: Yes with thorium!

- ThEC13 Conference organized by the **international Thorium Energy Committee** (iThEC: http://www.ithec.org) – 32 countries, 47 speakers, including prestigious personalities

CERN DG

Claude Haegi*, Hans Blix

Pascal Couchepin, Carlo Rubbia

- Representatives of **India and China cited energy issues as their prime concern** and announced strong motivations to do R&D on thorium http://indico.cern.ch/event/thec13
- **Europe is not representative of the world:**
  - Population expected to decrease
  - Little economic growth
  - Highest standard of living

Europe should play the leading role in this type of R&D as Europe masters the know-how

*President of Foundation for the Economy and sustainable Development of the Regions of Europe

Thorium and nuclear industry?

- **Little interest in thorium until now**; however, the increasing worldwide pressure is finally having some small effect. For the first time, thorium was officially mentioned by a main French nuclear actor.
- At ThEC13, AREVA and SOLVAY announced an agreement on thorium:

AREVA and SOLVAY join their know-how to add value to thorium's entire life cycle

Luc van den Durpel
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- However, AREVA is only considering thorium for the very long term (80-100 years). A few thorium fuel elements inserted in a uranium reactor (Halden research reactor in Norway).

Thorium ($^{232}Th_{90}$)

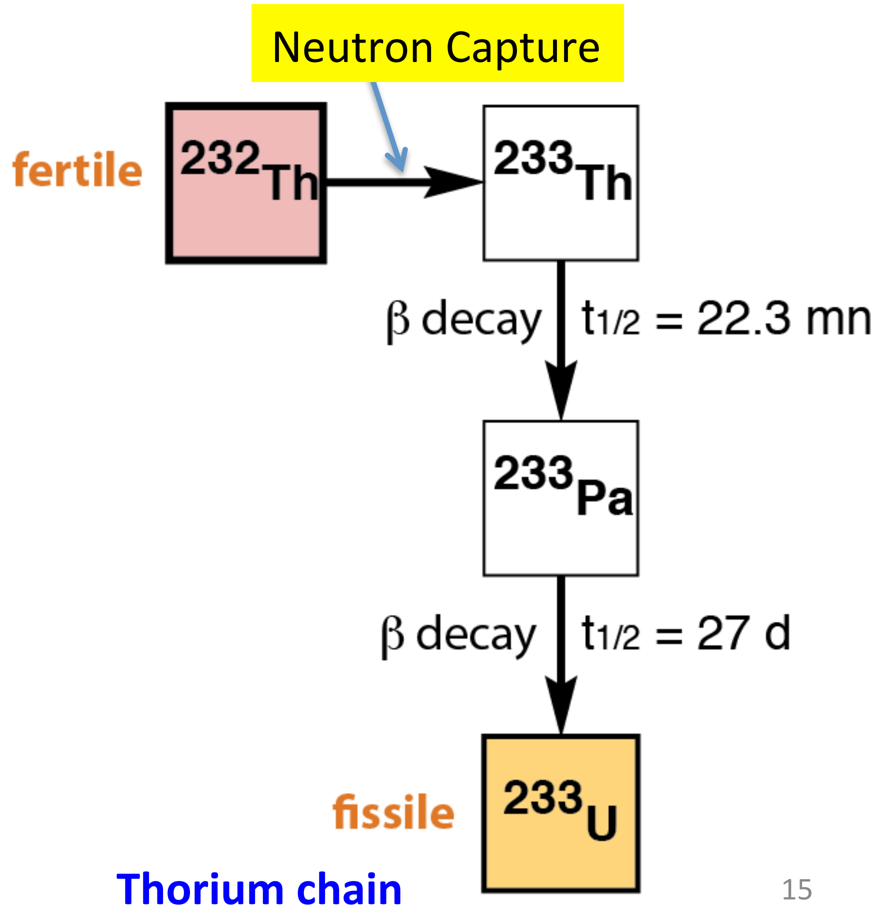
- **Natural thorium is isotopically pure**, α-decay with a half-life of 14 billion years (almost stable, no enrichment)
- **Abundant (1.2x10^{14} tons in the Earth's crust)**, as much as lead, and three to four times more than uranium:
  - Recovering only one part per million, that is 1.2x10^{8} tons, would provide the present world power consumption of 15 TW, for 18'000 years. "Thorium is a source of energy essentially sustainable on the human time scale" C. Rubbia @ ThEC13
- **Known and estimated resources ≈7x10^{6} tons** (IAEA); probably a poor indicator because not searched for systematically (≈1000 years at present world energy consumption)
- Thorium occurs in several minerals including thorite ($ThSiO_4$), thorianite (ThO_2 + UO_2) and monazite (**Ce, La, Nd, Th)PO_4**). **Often a by-product of mining for rare earths** (lanthanides + scandium and yttrium), tin, coal and uranium tailings

Monazite sample containing 2 to 3% of thorium mixed with rare earths (from the Steenkamp-skraal mine, South Africa – Trevor Blench)

- Thorium dioxide (ThO_2) has the **highest melting** point (3300 °C compared to 2865 °C for UO_2) of all oxides and is one of the best refractory materials
- Metallic thorium has a melting point of 1750˚C compared to 1130˚C for metallic uranium

Fission energy from $^{232}Th_{90}$

- Thorium is **fertile**, not fissile, so it can **ONLY** be used in breeding mode, by producing ^{233}U, which is fissile
- However, this gives a potential factor 140 gain compared to ^{235}U in PWR (in addition to the factor 3 to 4 in abundance)



Thorium chain

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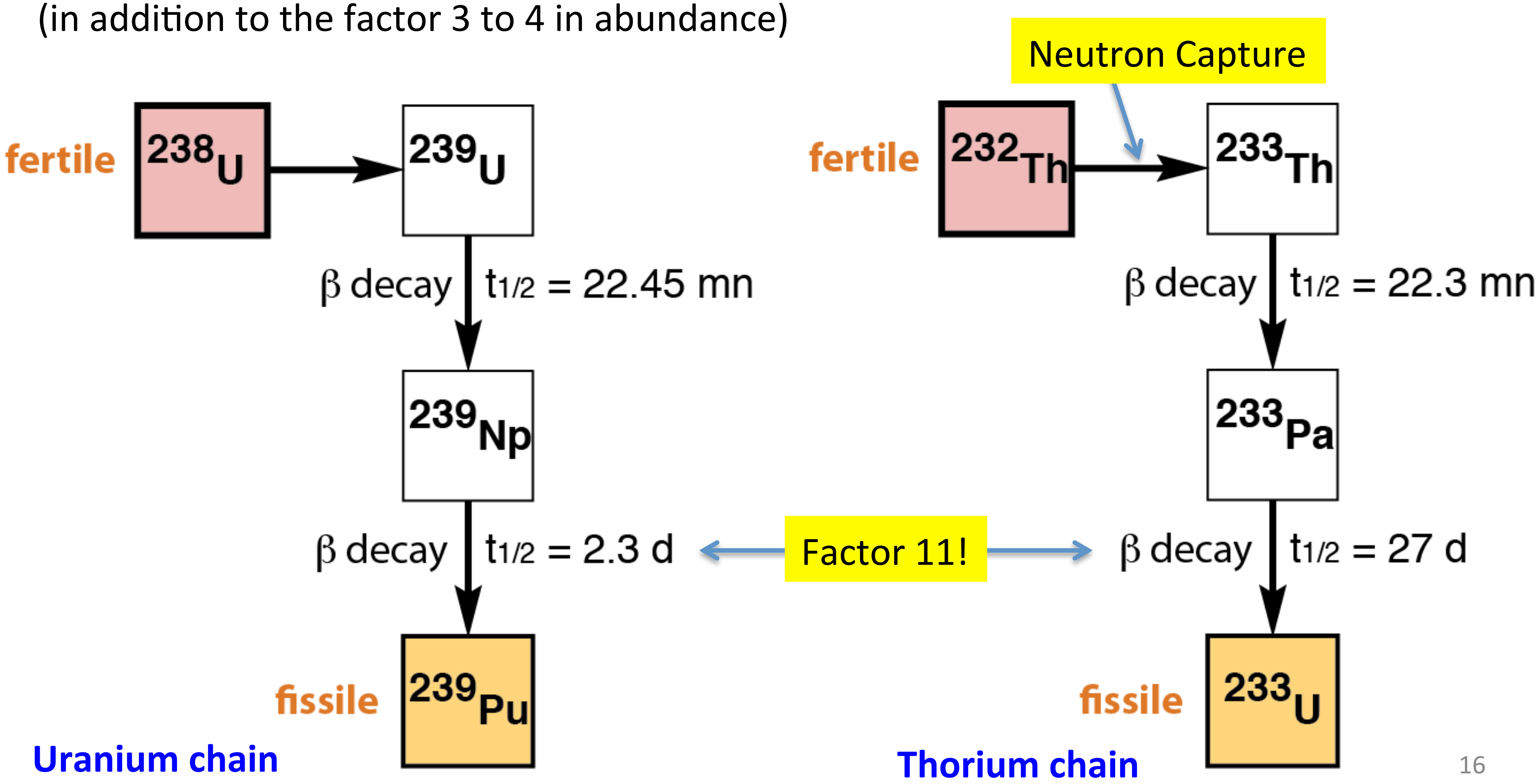

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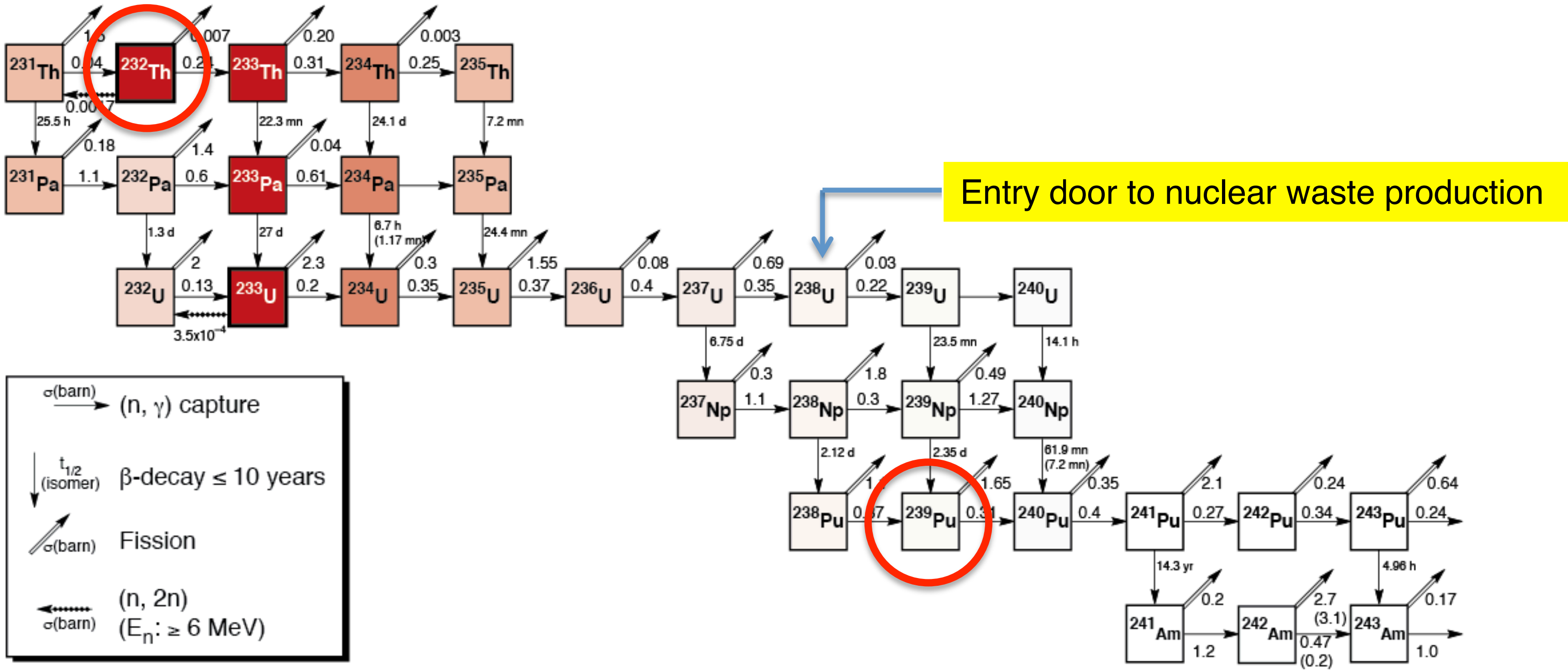
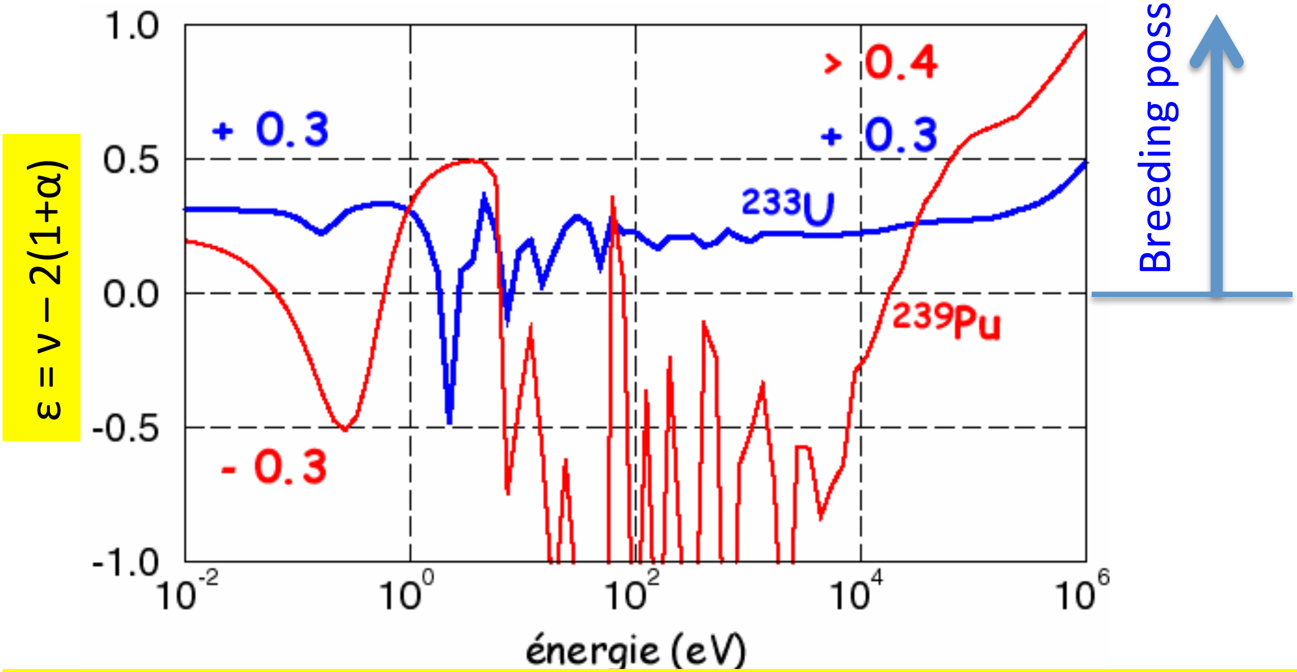
- However, this gives a potential factor 140 gain compared to ^{235}U in PWR (in addition to the factor 3 to 4 in abundance)
- Minimizes nuclear waste production, as it is 7 neutron captures away from ^{239}Pu
- **Can be used to destroy existing nuclear waste, if used in a fast neutron system**



Fission energy from $^{232}Th_{90}$

- For fast neutron breeder reactors ^{233}U is not as good as ^{239}Pu



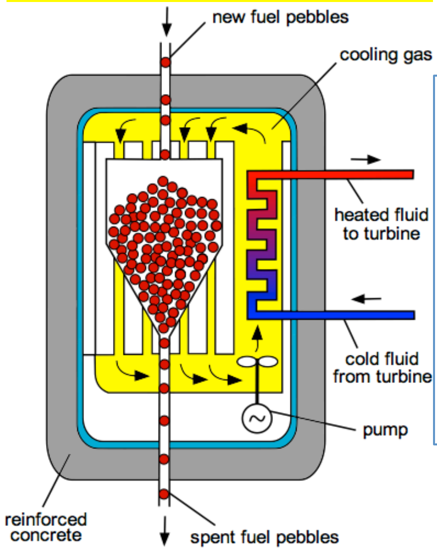
ε = Average number of neutrons in excess of the 2 neutrons needed to run the fission chain

- As thorium has a higher capture cross section than ^{238}U, and it takes much longer to breed the fuel (^{233}U) because of the long half-life of ^{233}Pa), **one cannot simply replace ^{238}U by ^{232}Th in current reactors.**

How to use thorium in practice?

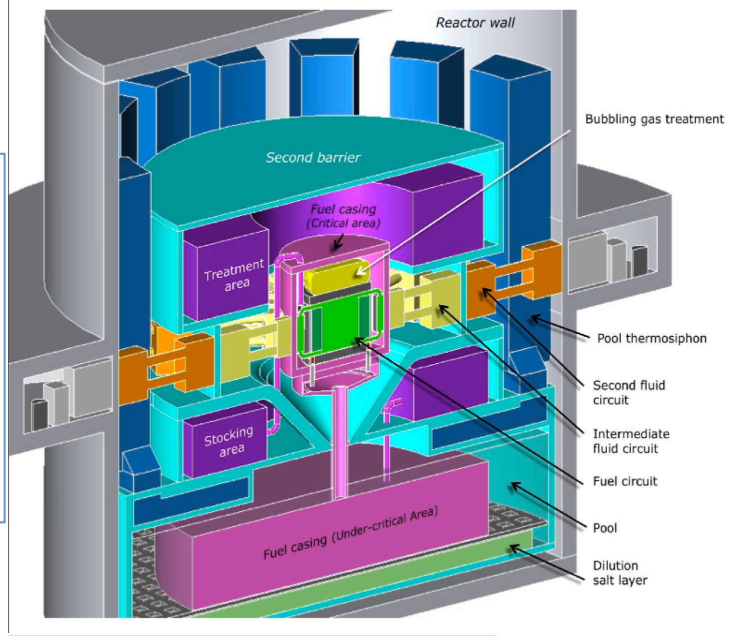
- **Thorium blankets around fast critical reactors to breed ^{233}U**: the Indian approach, at the cost of maintaining three different nuclear reactor technologies
- **Continuously circulating fuel to always have fresh fuel in the core**
  Pebble bed or molten salt critical reactors (MSR)
- **Provide extra neutrons with an accelerator: ADS**

Pebble bed Scheme



Pebble –bed and Molten salt reactors both systems have severe issues to be resolved, mainly in terms of safety, in addition to the fact that they do not provide a fast neutron flux

MSR Scheme



China taking the lead

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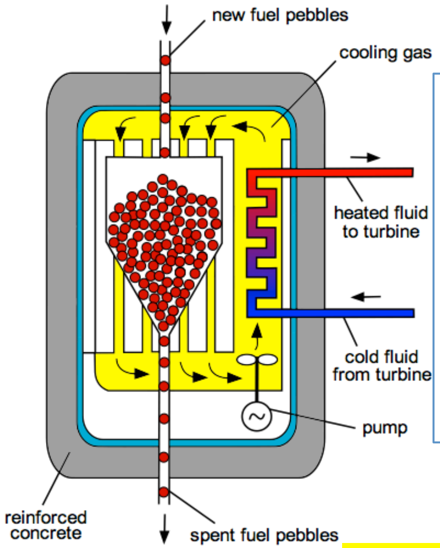

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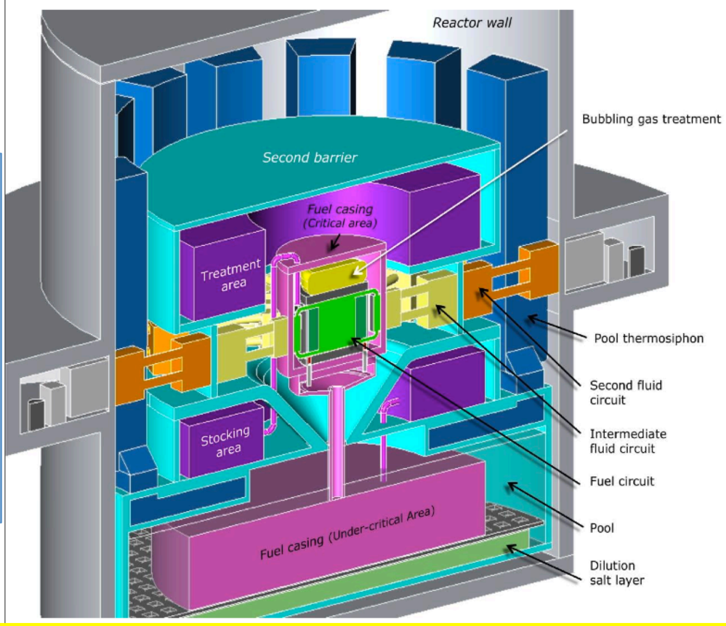
MSR Scheme



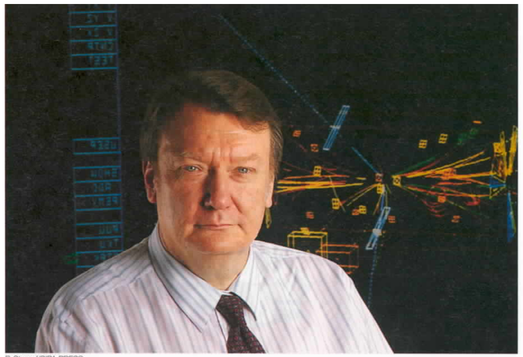
Last March, the Chinese government decided that the first fully-functioning thorium MSR reactor should be built within 10 years, instead of 25 years, as originally planned (Shanghai Institute of Applied Physics)

A short history of ADS

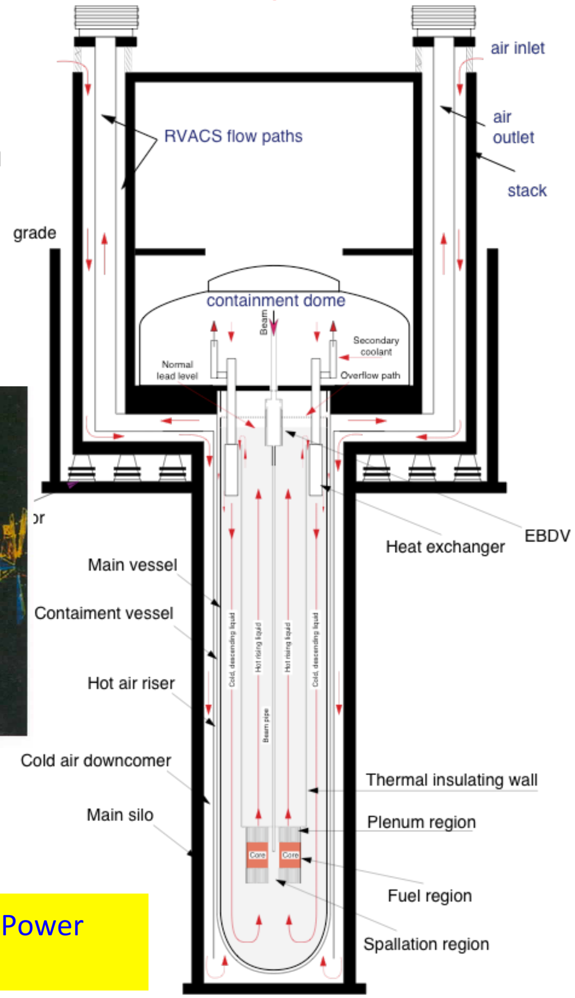
- **The basic process in ADS is nuclear transmutation**
  - 1919 Rutherford ($^{14}N_7 + ^{4}He_2 \rightarrow ^{17}O_8 + ^{1}p_1$) **^{210}Po accelerator!**
  - 1940 E.O. Lawrence/USA and W.N. Semenov/USSR proposed to use a **particle accelerator as a neutron source**
  - 1942 G. Seaborg produced the **first µg of ^{239}Pu** with the Berkeley 60 inch cyclotron
  - 1950 E.O. Lawrence proposed the **Materials Testing Accelerator (MTA)** at the Lawrence Livermore Radiation Lab, to produce ^{239}Pu from Oak Ridge depleted uranium
  - 1952 W.B. Lewis in Canada proposed to use an accelerator to produce **^{233}U from thorium** for CANDU reactors (electro-breeder concept)

A short history of ADS

- **1980s**: Renewed interest in ADS as the USA decided to slow the development of fast critical reactors (Fast Flux Test Facility @ ANL):
  - **H. Takahashi** at BNL: several proposals of ADS systems (PHOENIX), including the **idea of burning minor actinides**;
  - **Ch. D. Bowman** at Los Alamos: thermal neutron ADS (**ATW**) with thorium;
  - **Japan** launched the **OMEGA** at JAERI (now JAEA).
- **1990s**: Big push to ADS by C. Rubbia through a vigorous research programme at CERN:
  - Development of **innovative simulation** of nuclear systems
  - Specific **experiments to test basic concepts** (FEAT, TARC)
  - Construction of **advanced neutron Time of Flight facility** (n_TOF)
- Accelerator driven **subcritical ADS:**
  - **Fast neutrons**
  - **Thorium** rather than uranium
  - **Lead** as spallation target, moderator and coolant
  - **Deterministic safety** with passive cooling elements



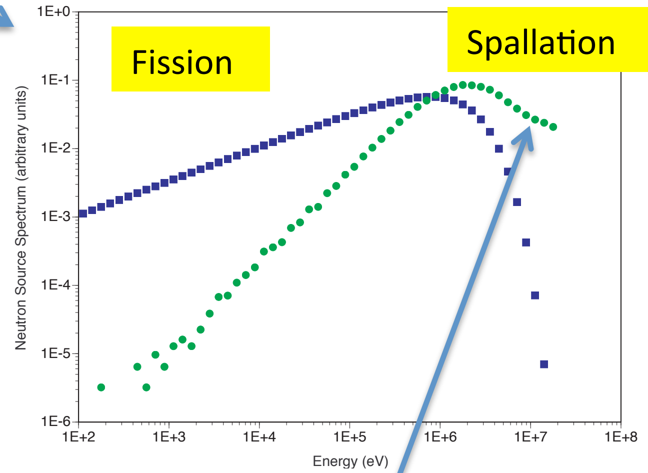
P. Stumpf/SIPA PRESS



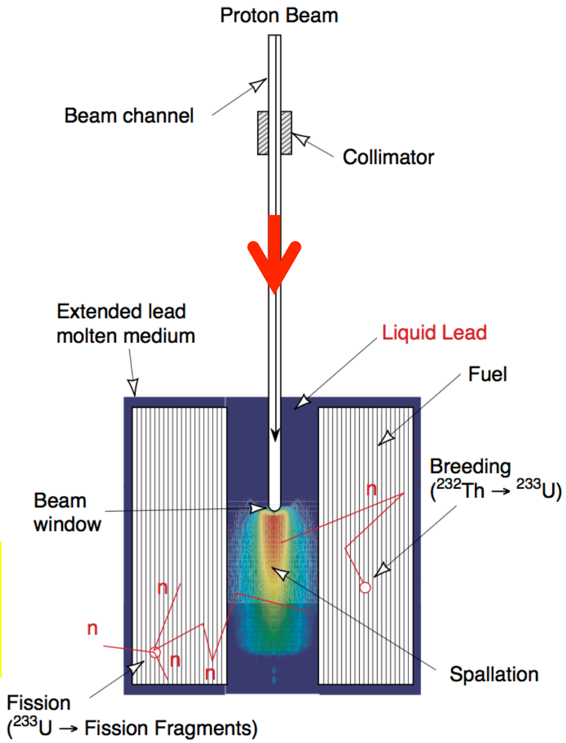
C. Rubbia, et al., « Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier », CERN/AT/95-44 (ET)

ADS: the subcritical approach

- A particle **accelerator** to provide a **neutron source through spallation**
- A **core** in which both source neutrons and fission neutrons are at work – with a **moderator least moderating** to allow for a fast neutron spectrum



Non negligible contribution from the high energy tail (n,xn) reactions on Pb. See later the effect on k_S



Turning off the accelerator turns off the chain reaction

Theory of subcritical systems

- **Theory of subcritical systems** interesting in itself. Properties are quite different from those of critical systems (*C. Rubbia, CERN/AT/ET/Internal Note 94-036*)
- MC simulations are needed for quantitive properties. Neutron flux geometry important to determine the generated power distribution and the uniformity of fuel burnup
- Analytical approach to get insight into the physics. The basic equation similar to that of a critical reactor, but **with an external neutron source term in addition, allows to obtain the** qualitative properties of the system:

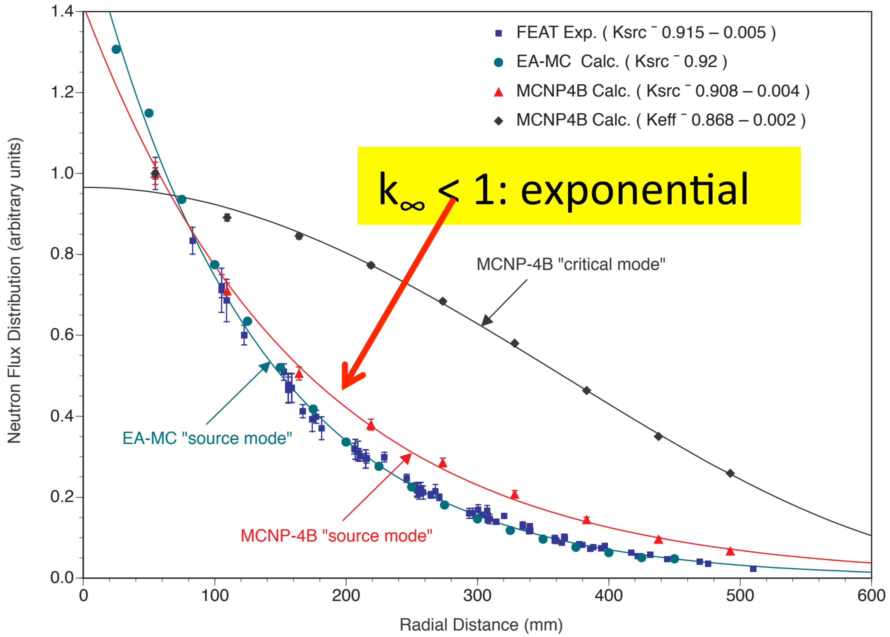
$$\frac{\partial n(\vec{r},t)}{\partial t} = \nu \Sigma_f \Phi(\vec{r},t) + C(\vec{r},t) - \Sigma_a \Phi(\vec{r},t) + D\nabla^2 \Phi(\vec{r},t)$$

Fission | **Source** | Absorption | Leakage

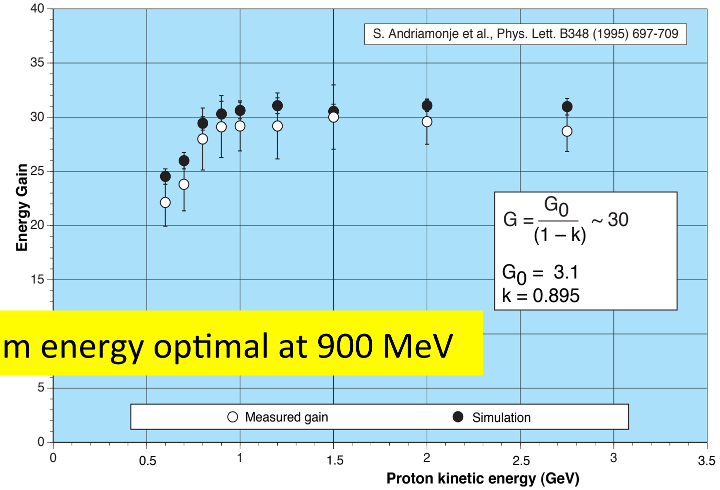
$$k_s \approx \frac{\nu' \Sigma_f \Phi(\vec{r},t) + C(\vec{r},t)}{\Sigma_a \Phi(\vec{r},t) - D\nabla^2 \Phi(\vec{r},t)} > k_{eff}$$

Switching off the neutron source not only stops the main power generation, but also moves the system further away from prompt criticality, k_s to k_{eff}.

FEAT and TARC experiments at CERN



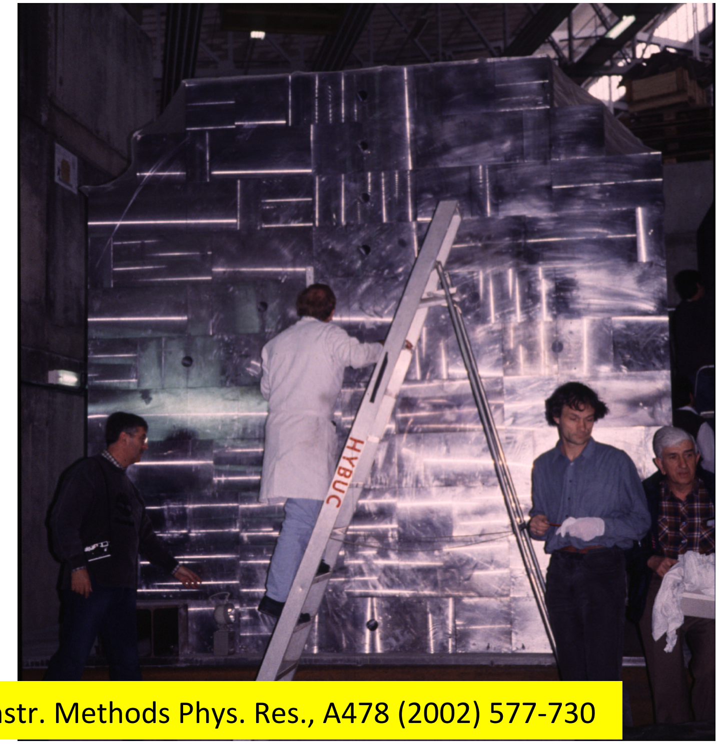
$k_\infty < 1$: exponential



$$G = \frac{G_0}{(1-k)} \sim 30$$

$G_0 = 3.1$
$k = 0.895$

Beam energy optimal at 900 MeV



3.62 t of natural uranium at CERN PS; k_{eff} ~ 0.9

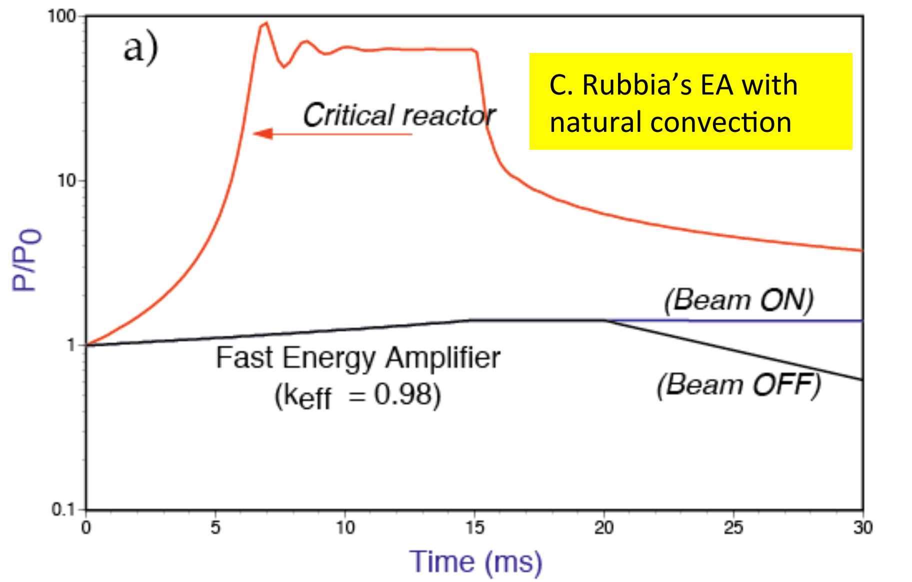
Nucl. Instr. Methods Phys. Res., A478 (2002) 577-730

Physics of subcritical systems

- Subcritical systems are insensitive to delayed neutron fraction (β); **safety margin** (distance from prompt criticality) **is a design choice**, it is not imposed by Nature!

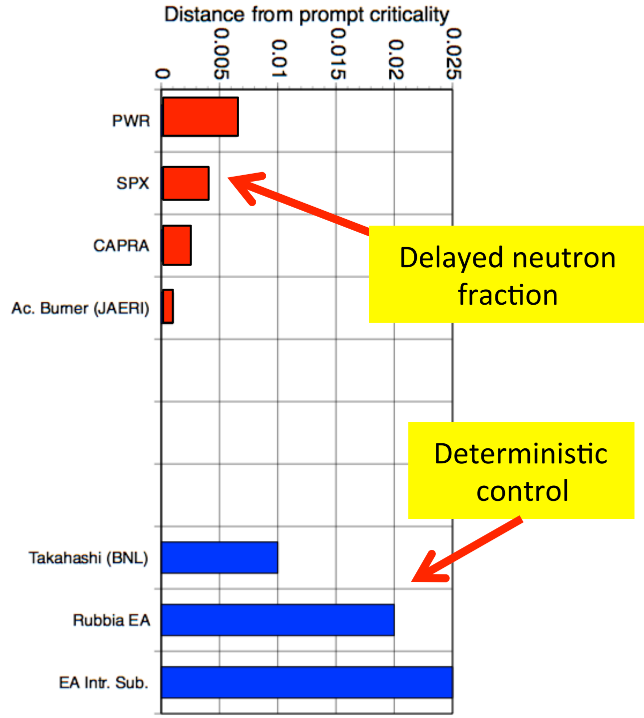
- The reactivity changes only very slowly; the beam can be switched off very quickly, reducing k_s to k_{eff}. It is possible to choose a higher k_s in order to reduce the load on the accelerator (Takahashi at BNL, k_s = 0.99)

Comparative response to reactivity insertion



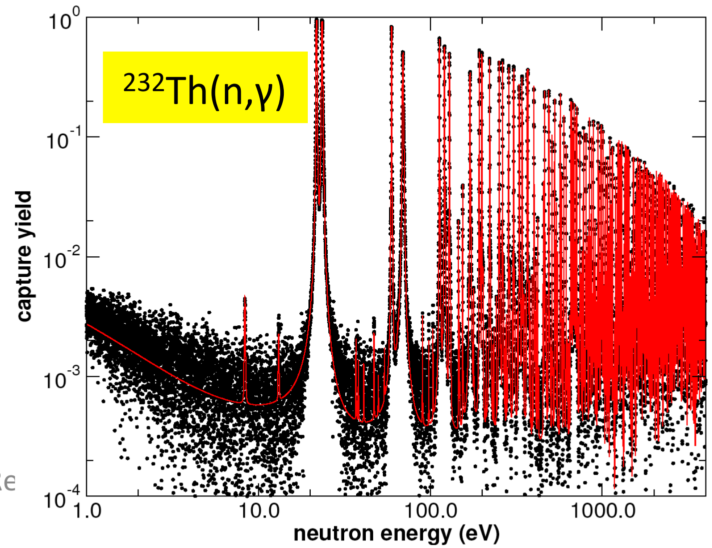
There is enough time for the natural convection to adapt

The CERN LHC beam can be switched off in 270µs, the CERN SPS in 46 µs, and a smaller accelerator for ADS, even much faster.

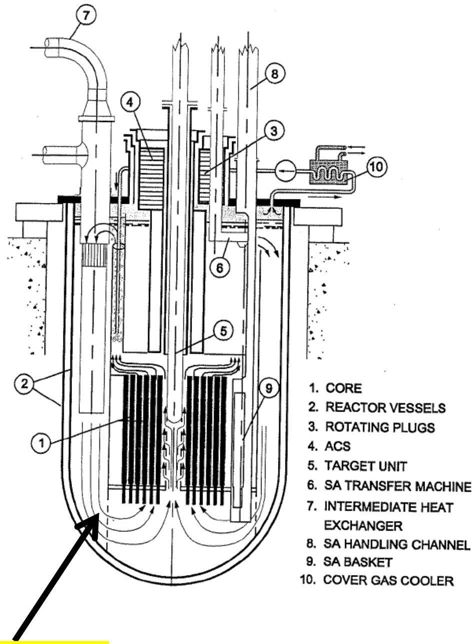


ADS demonstrator

- The next step for ADS today is a demonstrator of significant power. This is much more a political issue (funding) than a scientific one.
- **The technology for a demonstrator or prototype with power of ≈ 100 MWth is ready** – the goal is to validate technological solutions and to learn how to run such system
- The basic physics is well known, and simulation is available and presumably reliable – Impressive measurements at CERN n_TOF

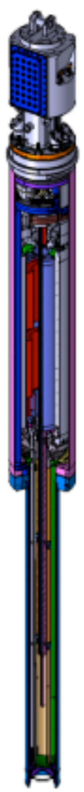


First proposal by C. Rubbia et al., in 1999
Ansaldo engineering design for the Energy Amplifier Demonstration Facility
EA B0.00 1 200 (Jan. 1999)



Forced convection

MEGAPIE TARGET



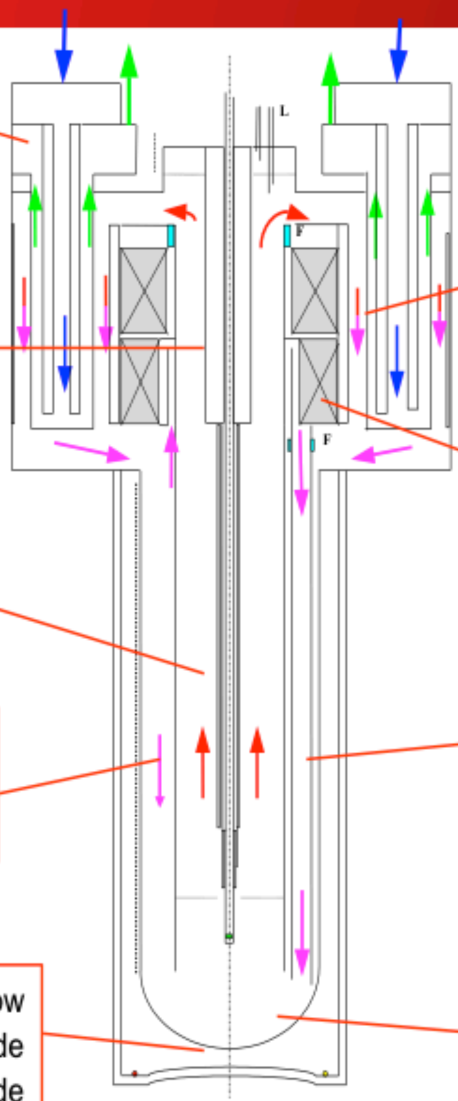
Heat Exchanger (Oil)
10 l/s, 5.5 m/s
140-175°C inside

Main Pump
4 l/s, 1.2 m/s
380°C

Guide Tube
4 l/s, 0.33 m/s
380°C

Downcomer
3.75 l/s, 0.33 m/s
230-240°C

Beam Window
380°C outside
330°C inside



Heat Exchanger
4 l/s, 0.33 l/s/pin
0.46 m/s
380-230°C inside

Bypass Pump
0.25 l/s, 0.2 m/s
230°C

Bypass Tube
0.25 l/s, 1m/s
230-240°C

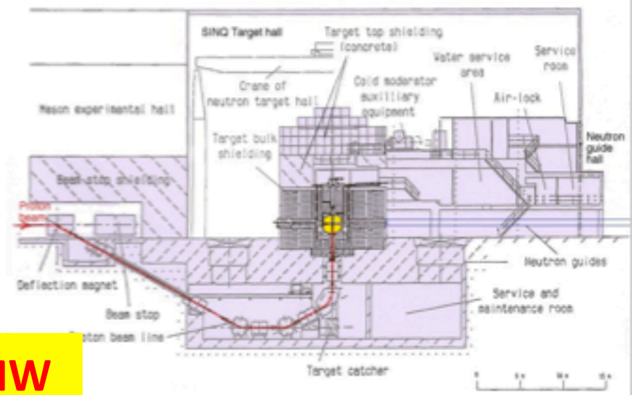
Nozzle 1.2 m/s
Beam Window 1 m/s

Design parameters

p-beam energy:	575 MeV
p-current:	1.74 mA
Heat removal:	650 kW
Design pressure:	16/10 bar
Design temp.:	400°C
Cover gas press:	3.2 bar
Operation:	1 year
with max 6000 mAh	
Radiation damage:	20-25 dpa

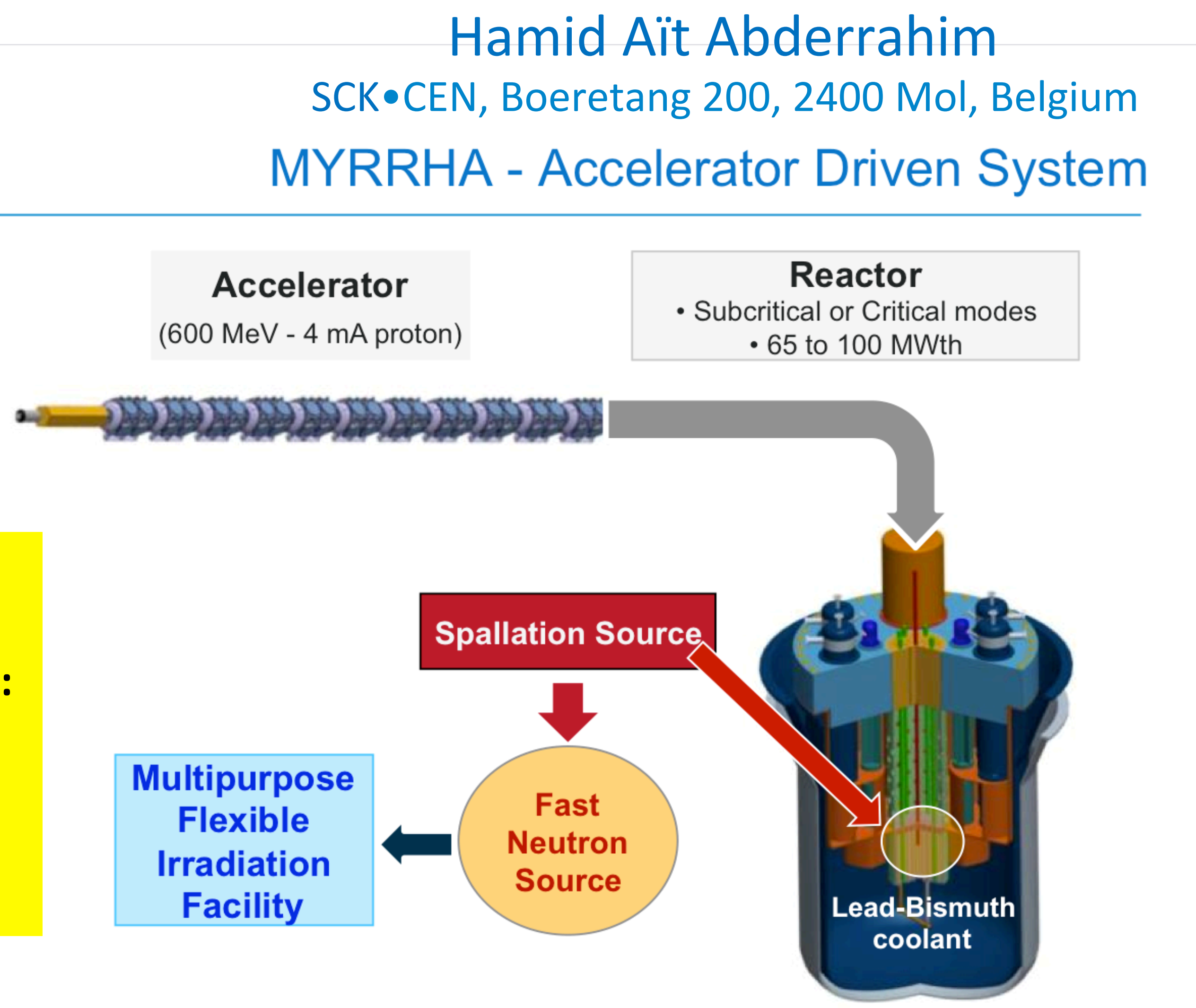
Dimensions

Length:	5.35 m
Weight:	1.5 t
LBE-Volume:	89 l



Successful 4 month run at PSI in 2006, 1 MW

ADS demonstrator: MYRRHA



Most important project in Europe, with strong support from the Belgian government:
– partially funded
– no thorium
– will not remain an ADS,
will turn into a critical reactor

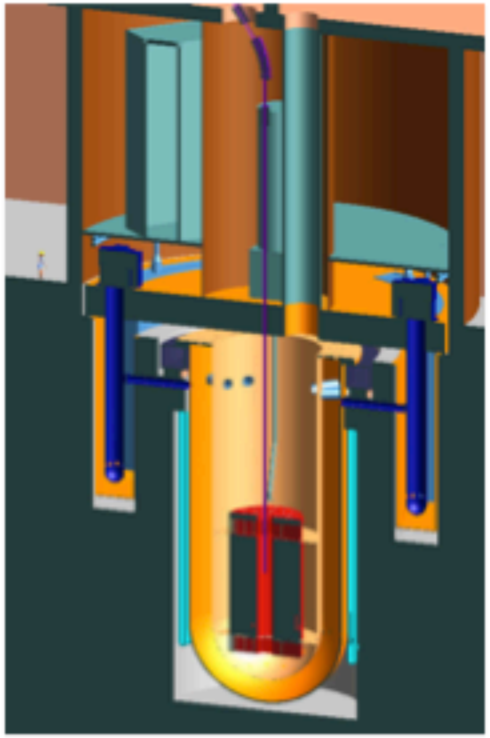
Industrialized ADS

EA Feasibility Study: Aker ASA and Aker Solutions ASA (2010)

AkerSolutions

- 1500MWTh/600MWe
- Sub-critical core
- Thorium oxide fuel
- Accelerator driven via central beam tube
- Molten lead coolant
- Coolant temp 400-540°C
- 2 Axial flow pumps
- 4 Annular heat exchangers
- Direct lead/water heat exchange

- *It may be modified to a Minor Actinide burner (ADS)*



A Thorium fuelled reactor for power generation

Carlo Rubbia

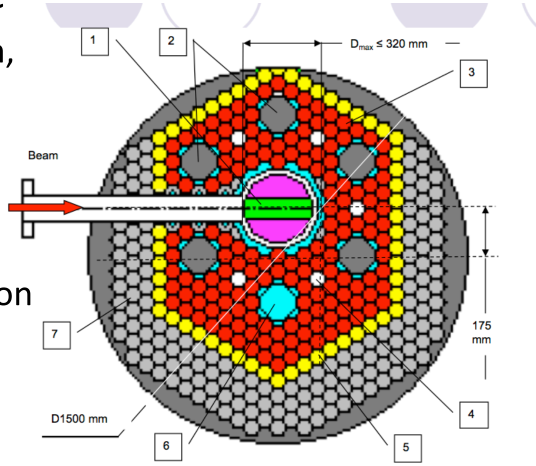
CERN_Oct_2013

Slide# : 23

Other ADS projects

S. Sidorkin, Russia

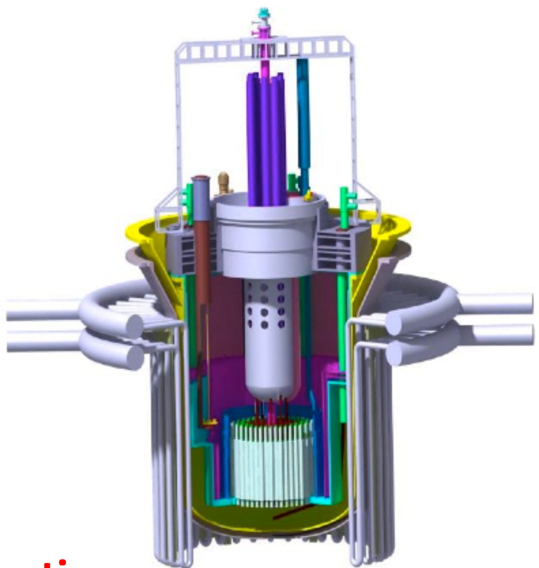
- China, Japan, Korea, Russia, USA, Venezuela and Ukraine
  - 200 kW uranium-based ADS prototype, driven by an electron beam, due for completion in 2014 at the Karkhov Institute of Physics and Technology (**KIPT**)
  - 10 MW **TROISKS** ADS, 300 kW proton beam, rearranging existing elements (accelerator, neutron source, etc.)
  - Virginia Nuclear Energy Consortium Authority associated to Jefferson Lab, in the USA, with a view to create a "Science & Technology Center (STC) for the Application of High-Power Accelerators for the Advancement of Innovative Multidisciplinary Science"

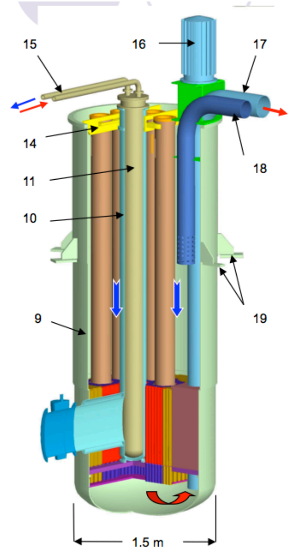


1 –target module;
2 – hermetical PbBi capsules with high enriched fuel and minor actinides;
3 – the cassettes of the water-cooled part of blanket with MOX fuel (~ 25% enr.);
4 – the module of controlled systems;
5 – decoupler (if it is required);
6 – traps of thermal neutrons (moderator) can construct in any place ;
7 – reflector.

Next ADS Conference

Lack of coordination





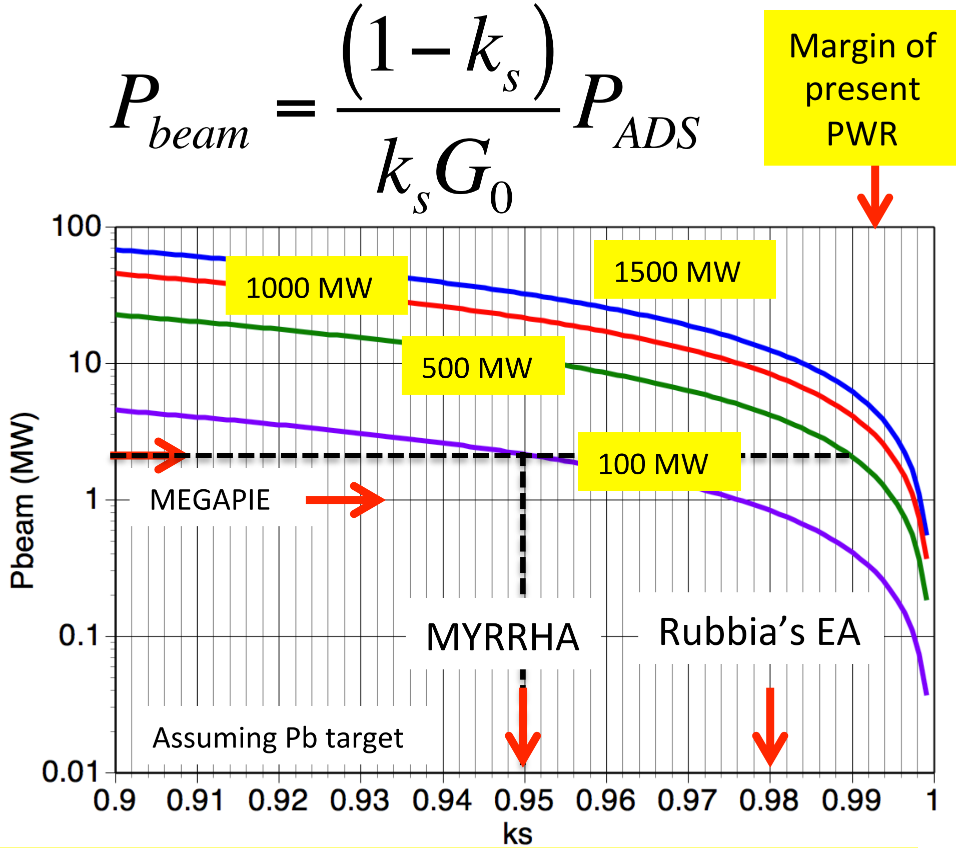
Lei Yang, IMP, China

Required accelerator power

$$P_{beam} = \frac{(1-k_s)}{k_s G_0} P_{ADS}$$

- For a given power output, the energy gain (choice of k_s and G_0) determines the accelerator power
  Trade-off between accelerator power and criticality margin

- Possibility of modulating the beam intensity to allow variations in the power output (**complementary with a fluctuating renewable energy source**)

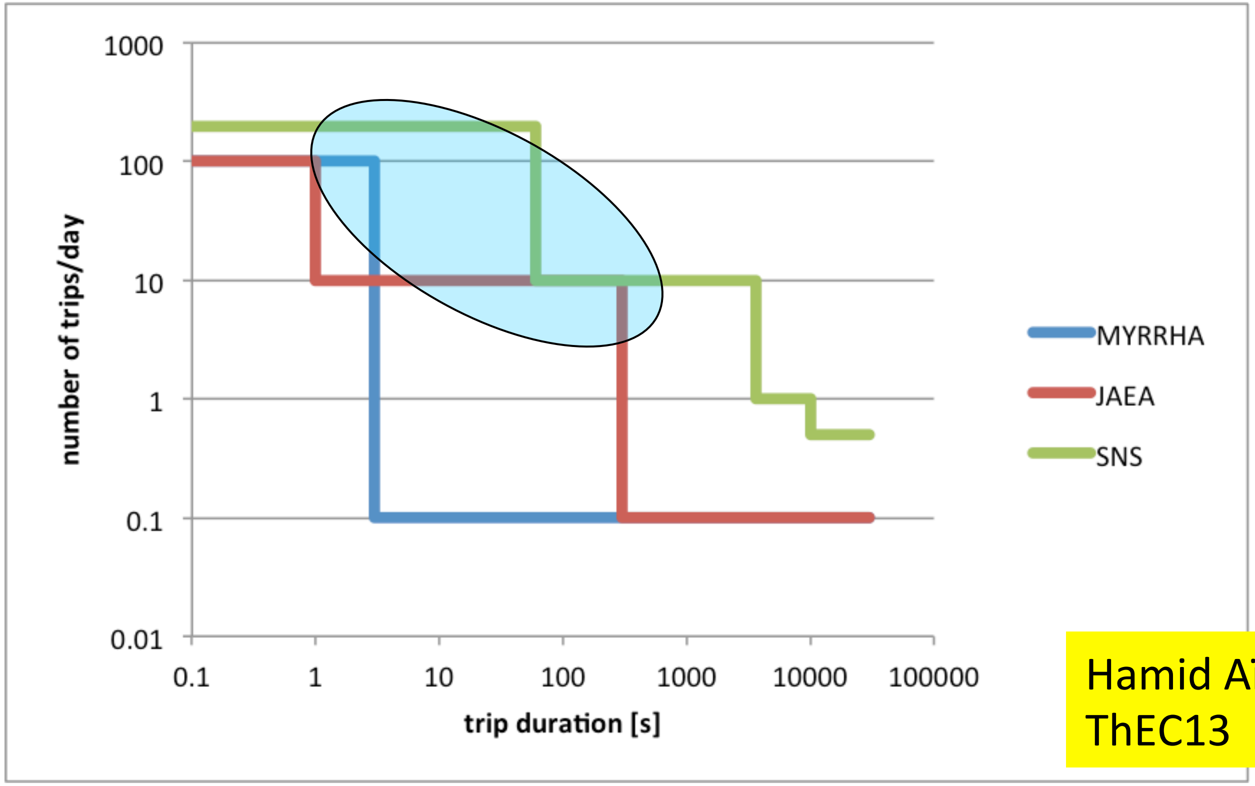


PSI separate turns cyclotron
(2.4 mA and 1.4 MW, with 0.59 GeV protons).
P_{ADS} = 210 MW_{th} with k = 0.98
MYRRHA LINAC
(≤ 1 to 4 mA and ≤ 2.4 MW, with 0.6 GeV protons)
P_{ADS} = 50-100 MW_{th} with k = 0.95

Accelerator requirements

- In principle, it does not matter how the external neutron source is provided. In practice, for industrial applications, there are a number of well-defined requirements for the accelerator:
  - **Beam particle**: **protons**
  - **Beam Energy**: **$E_{beam} \geq$ 900 MeV**
  - **Beam power**: **a few to ≈ 10 MW** depending on choice of k_s value, and required power. Large operational range to follow demand (factor 10?)
  - **Beam spot size (footprint)**: large on impact on window (studies at JAEA → OK ≤ 0.1-0.2 mA/cm^2), MYRRHA has 0.07mA/cm^2
  - **Beam losses**: minimize irradiation of the accelerator and of the environment (main issue for any high power beam, not only for ADS); impact on the maintenance and repair (figure of merit ≤ 1W/m for LINACS, for cyclotrons losses are localized)
  - **Reliability**: The limitation comes mainly from thermal stress inducing fatigue in fuel structure. minimize beam trips (multiple sources); For instance, for MYRRHA:
    - No limit for trips for $T_{trip} < 0.1$ s
    - Not more than 100 trips per day 0.1 s $< T_{trip} < 3$ s
    - Not more than 10 in three months for $T_{trip} > 3$ s
    - Administrative limit if SCRAM event (discovered by MYRRHA Collaboration!)

Data on Beam trips



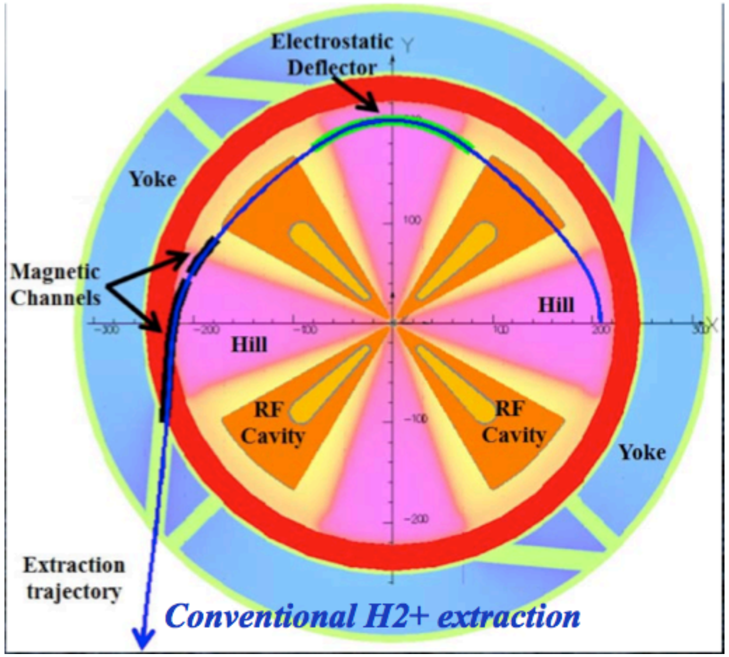
Hamid Aït Abderrahim
ThEC13

- In the Beznau nuclear reactor (KKB) in Germany, for instance, which has been running for 40 years, they were initially counting on 10 trips per year, and nowadays, they hardly get one trip per year. Technology is evolving …

Accelerator requirements

- **Beam power stability and control**: 1% fluctuation on beam intensity is 1% fluctuation on the thermal power
- **Energy efficiency**: maximize fraction of electric grid power stored in the beam. Relevant to overall energy efficiency of system
- **Size of accelerator**: for waste elimination, people might want to fit it on the site of a standard nuclear power plant
- **Cost:** This is very important.
  One main criticism of ADS has been that "the accelerator does not exist and will be too expensive"

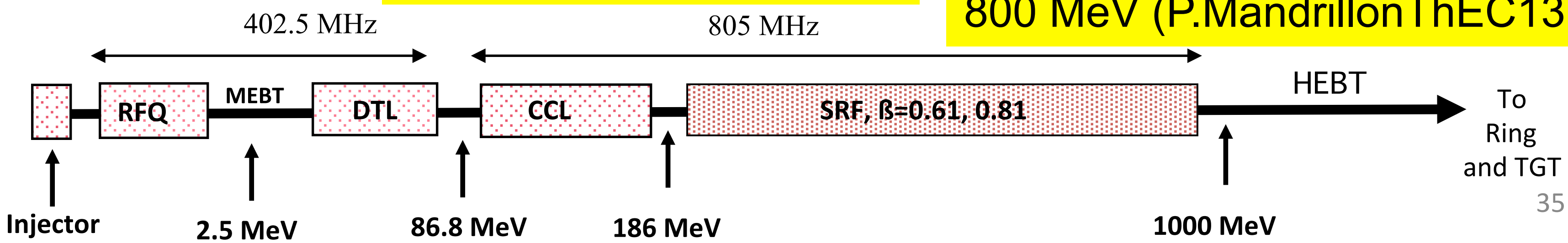
Cyclotron



- In the end, the solution chosen among LINAC, Cyclotron or FFAG, will be the one best fulfilling these requirements

H_2^+ AIMA Cyclotron w reverse bend and multiple injection, 1.6 MW at 800 MeV (P.MandrillonThEC13)

Superconducting SNS LINAC



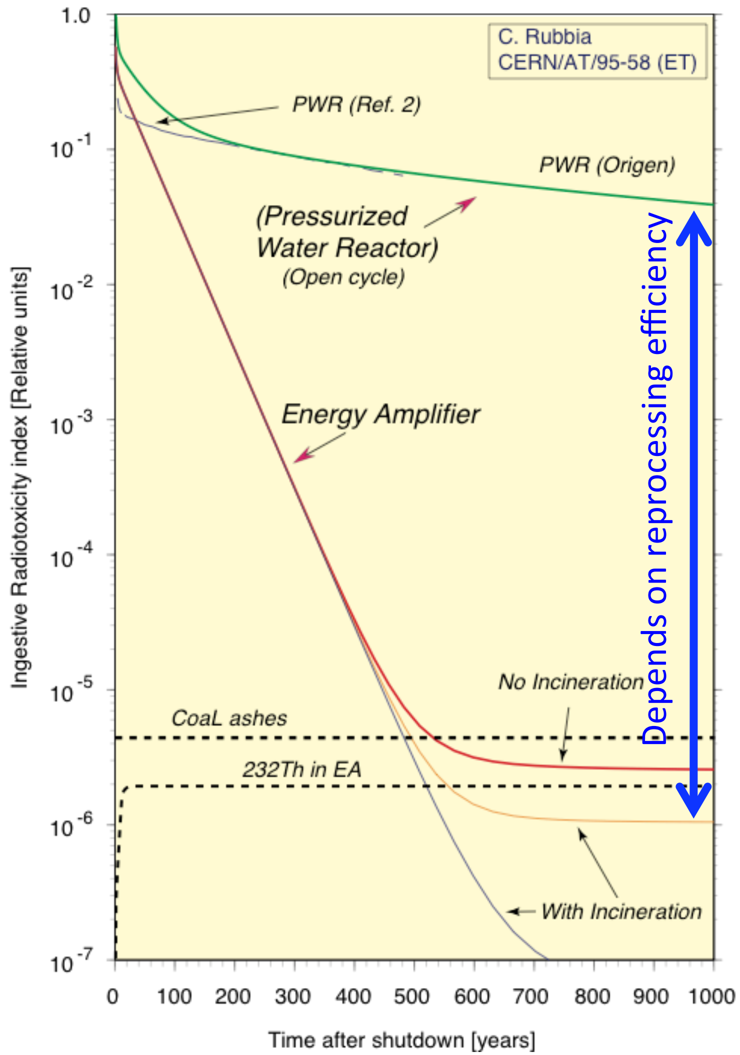
Transmutation performance of ADS

- **C. Rubbia's EA can destroy** 36 kg of TRU/TW_{th}.h (A PWR **produces** 14 kg of TRU/TW_{th}.h)

- Calculations of specific transmutation rates (Y. Kadi)

Transmutation rates (kg/TW_{th}h) of plutonium and minor actinides and LLFPs

Nuclides	EADF (ThPuO2) ENDF/B-VI	EADF (UPuO2) ENDF/B-VI	EADF (UPuO2) JENDL-3.2	PWR (UO2)
^{233}U	+ 31.0			
Pu	– 42.8	– 7.39	– 5.55	+ 11.0
Np	+ 0.03	+ 0.25	+ 0.24	+ 0.57
Am	+ 0.24	+ 0.17	+ 0.14	+ 0.54
Cm	+ 0.007	+ 0.017	+ 0.020	+ 0.044
^{99}Tc prod	+ 0.99	+ 1.07	+1.22	+ 0.99
^{99}Tc trans	– 3.77	– 3.77		
^{129}I prod	+ 0.30	+ 0.31		+ 0.17
^{129}I trans	– 3.01	– 3.01		



Conclusion

- There is no reason to keep thorium, hence ADS, out of the energy R&D effort.
- Developed countries which have the know-how should lead the R&D effort.
- **The physics of Accelerator-Driven Systems is well understood, conceptual designs exist.**
- When taking into account the need for safety, waste management and non-proliferation, thorium in a fast neutron ADS is a most interesting option for energy production and nuclear waste elimination.
- ADS is a challenging innovation but there is no show stopper. **The ball is in the camp of the accelerator community.**

RESERVE

Abstract

- ***Title***: **Prospects for Accelerator-Driven Thorium Reactors**

- ***Abstract***: To meet the tremendous world energy needs, systematic R&D has to be pursued to replace fossil fuels. Nuclear energy, which produces no green house gases and no air pollution, should be a leading candidate. How nuclear energy, based on thorium rather than uranium, could be an acceptable solution is discussed. Thorium can be used both to produce energy or to destroy nuclear waste. The thorium conference, organized by iThEC at CERN in October 2013, has shown that thorium is seriously considered by developing countries as a key element of their energy strategy. However, developed countries do not seem to move in that direction, while global cooperation is highly desirable in this domain. As thorium is not fissile, an elegant option is to use a proton accelerator to drive an "Accelerator Driven System (ADS)", as suggested by Nobel Prize laureate Carlo Rubbia. Therefore, the accelerator community has an important challenge to meet: provide the required proton beam for ADS.

Choice of the accelerator type: Linac versus cyclotron

In principle both accelerator types can deliver the required proton beam for ADS applications. However, the nature of each — one compact unit for an isochronous cyclotron, a sequential modular structure for the linac — brings both advantages and disadvantages.

Due to its recirculation nature, a cyclotron is compact and cost effective. However, it lacks every form of redundancy which is crucial for fault tolerance. Hence, a cyclotron will not reach the wanted level of availability, and furthermore an upgrade of its beam energy is not a realistic option.

Linacs on the other hand, can be built as a sequence of many independent accelerating structures (RF cavities), which is a highly modular situation. It is this modularity that makes such a linac particularly well suited to tackle the availability issue. In case of failure of a single accelerating module, independently controlling the RF amplitude and phase of the adjacent modules creates the conceptual possibility of recovering the beam within a short time. Furthermore, increasing the final beam energy is obtained by merely adding accelerating modules.

For these reasons **MYRRHA favours the linac option**.

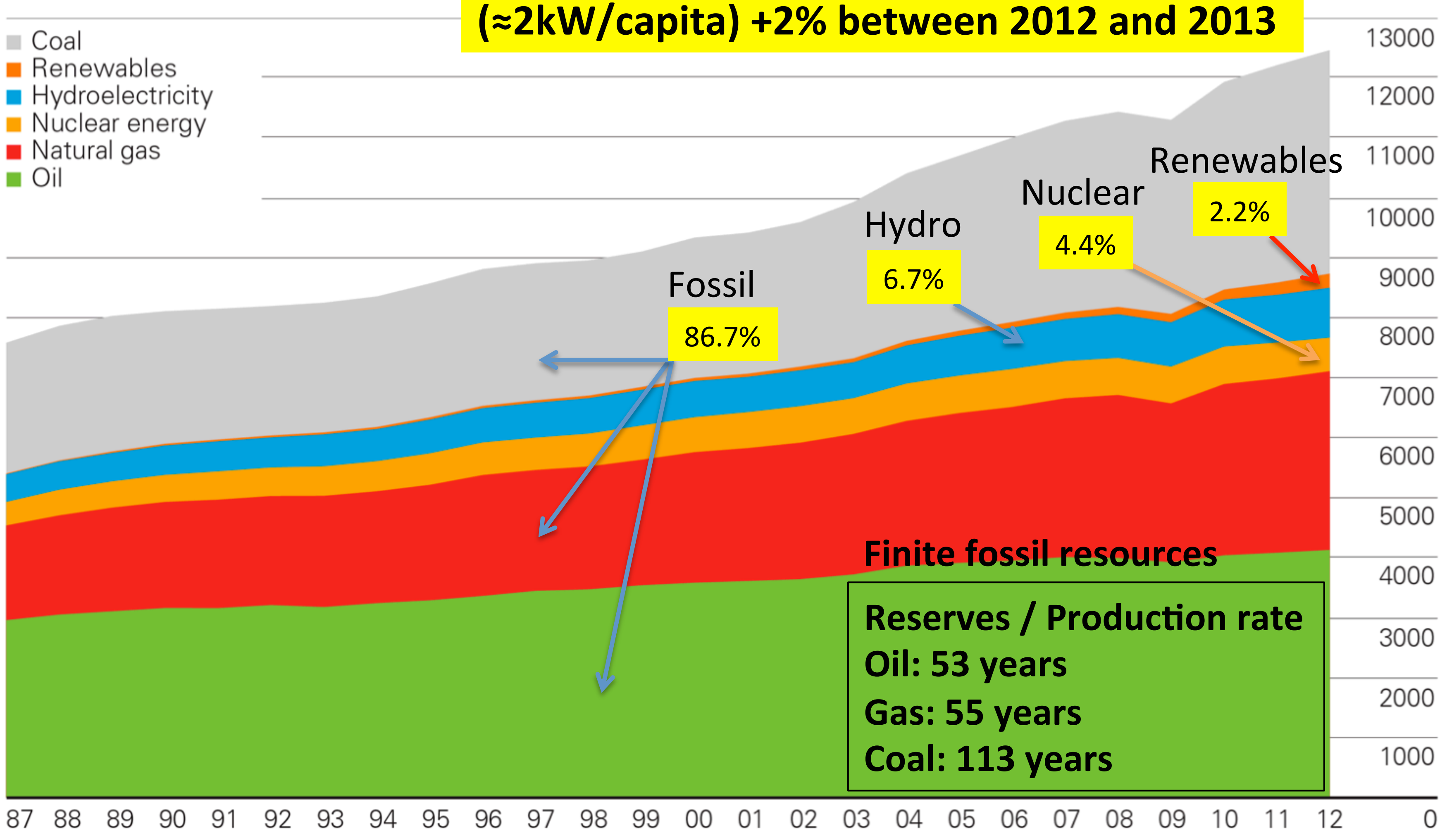
Linac versus cyclotron

LINAC	CYCLOTRON
Large space requirement (few hundred m long) but light	**Compact but heavy**
Expensive	**Cheaper in construction**
Less efficient power conversion	**More efficient power conversion**
Modularity provides redundancy	**No intrinsic redundancy**
Upgradable in energy	Difficult to upgrade in energy
Straightforward beam extraction	Difficult extraction and related beam losses
Capable of high beam current (100 mA)	Modest beam current capability (5 mA)

Primary energy world consumption

Million tonnes oil equivalent

Today the world behaves as a 15 TW engine (≈2kW/capita) +2% between 2012 and 2013



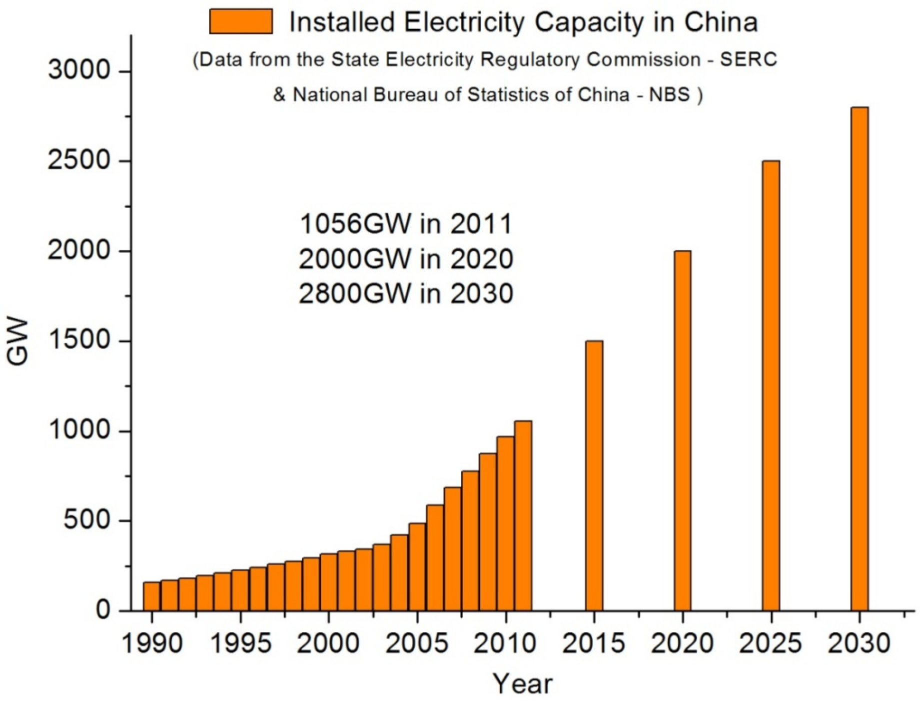
BP Statistical review of World Energy 2014

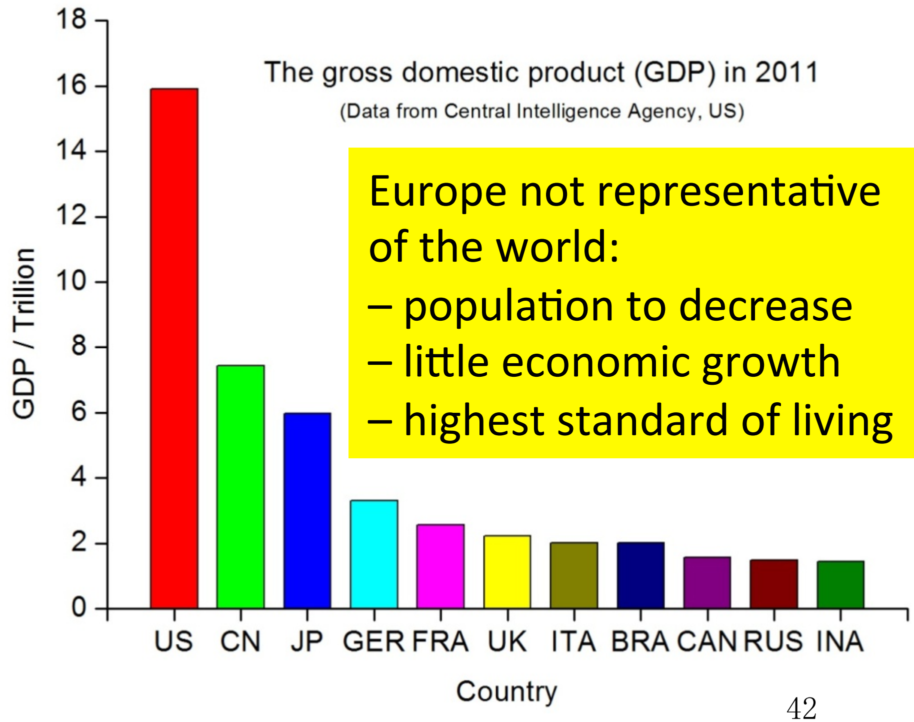
If, by end of 21st century, **people in developing countries are allowed to live as well as we do in Europe today,** then, the world power consumption will have to increase by a factor 3 or more.

Xu Hongjie

China's Energy Challenge

- Analysis and forecast on national electric power in China: In 2030, the electricity demand of per person will be about 2KW, total generation capacity will reach about 3000GW, the MW -level power stations will need 3000.





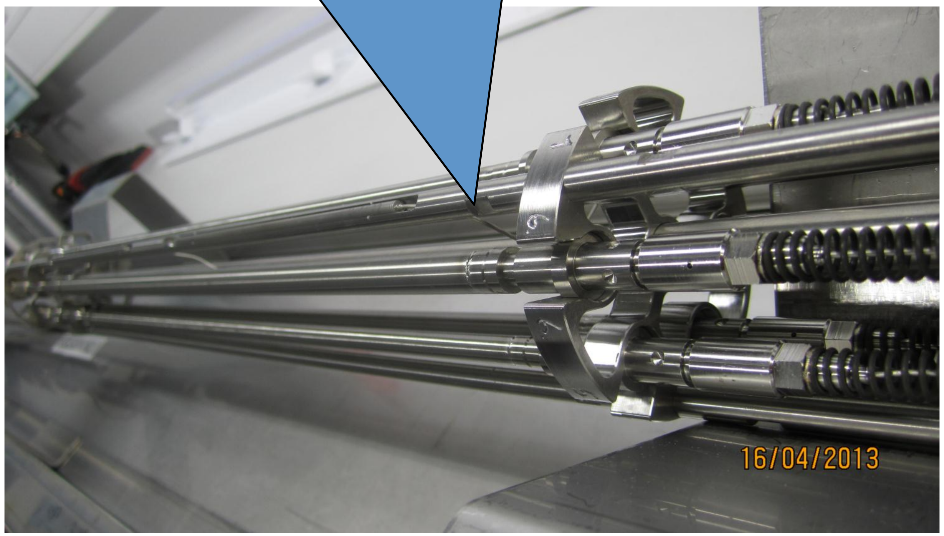
Europe not representative of the world:
– population to decrease
– little economic growth
– highest standard of living

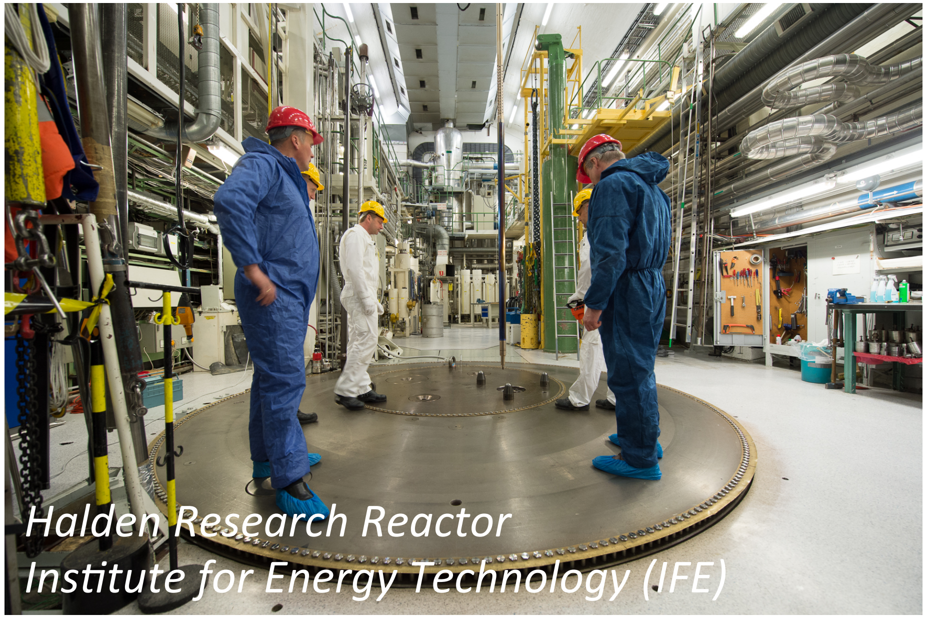
Revol/LINAC14

Thorium in Light Water Reactors

Thor Energy (The Norwegian Thorium Initiative) collaborates with Westinghouse to carry out **thorium fuel tests** in the Halden research reactor.

- 2 Rods 85%Th - 15%Pu pellets, ITU, Germany
- 2 Rods 7%Th – 93%UOX, IFE, Norway
- 1 Rod 65%Th – 35%UOX, IFE, Norway
- 1 UOX Reference rod

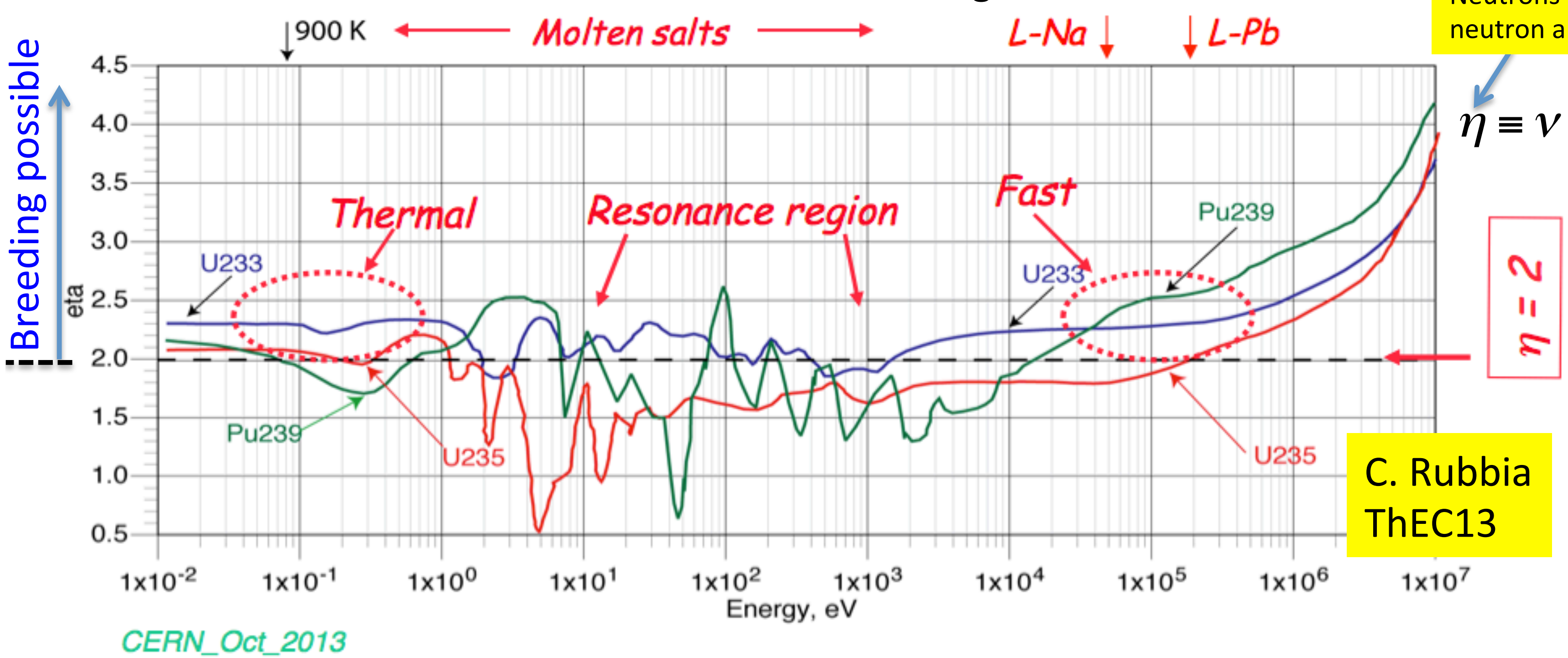




Halden Research Reactor
Institute for Energy Technology (IFE)

Fission energy from $^{232}Th_{90}$

- For fast neutron breeder reactors ^{233}U is not as good as ^{239}Pu

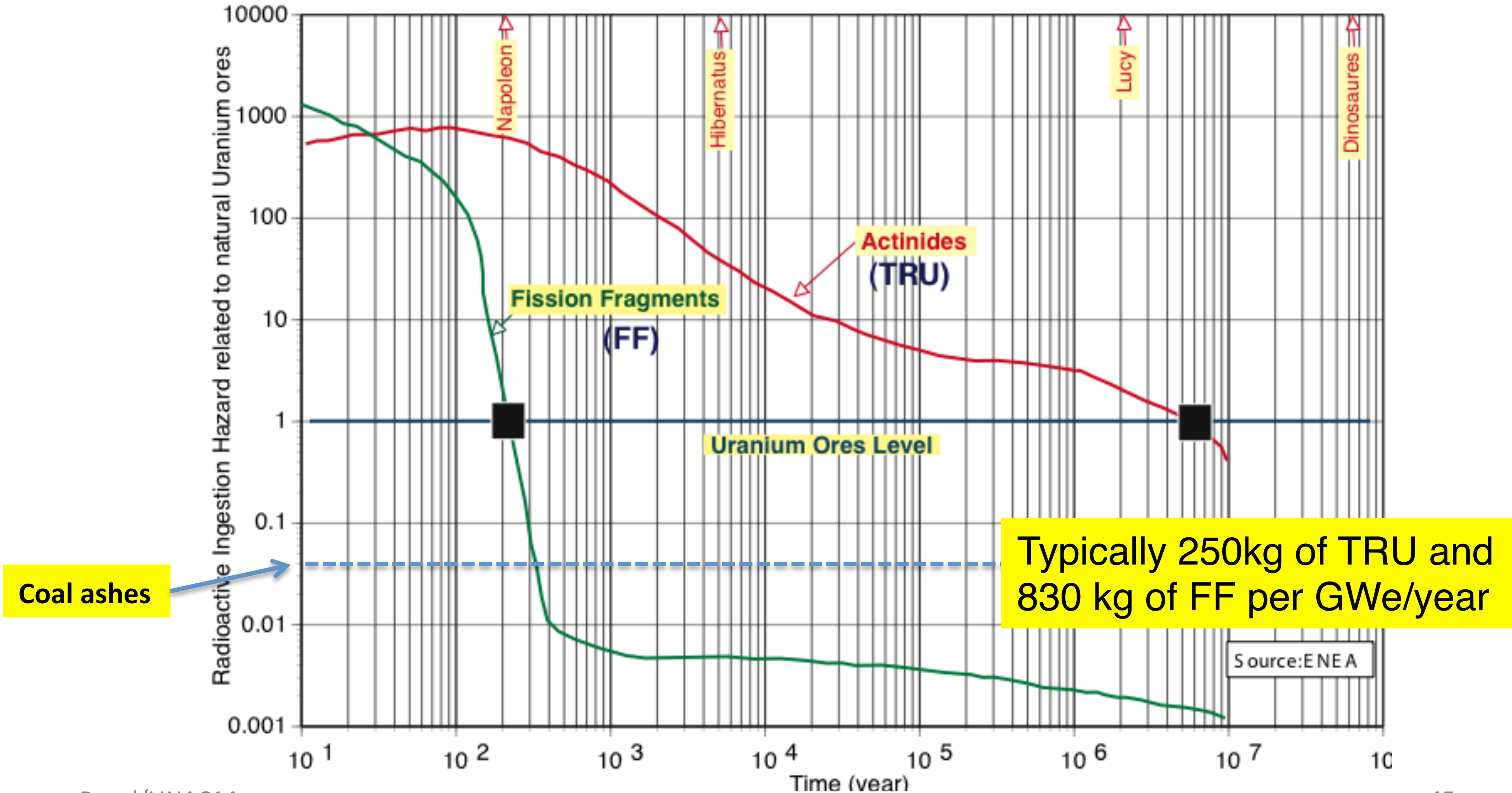


$$\eta \equiv \nu \frac{\sigma_f}{\sigma_f + \sigma_c}$$

- In addition, Thorium has a higher capture cross section than ^{238}U, and it takes much longer to breed the fuel (^{233}U) because of the long half-life of ^{233}Pa), so one cannot simply replace ^{238}U by ^{232}Th in current reactors.

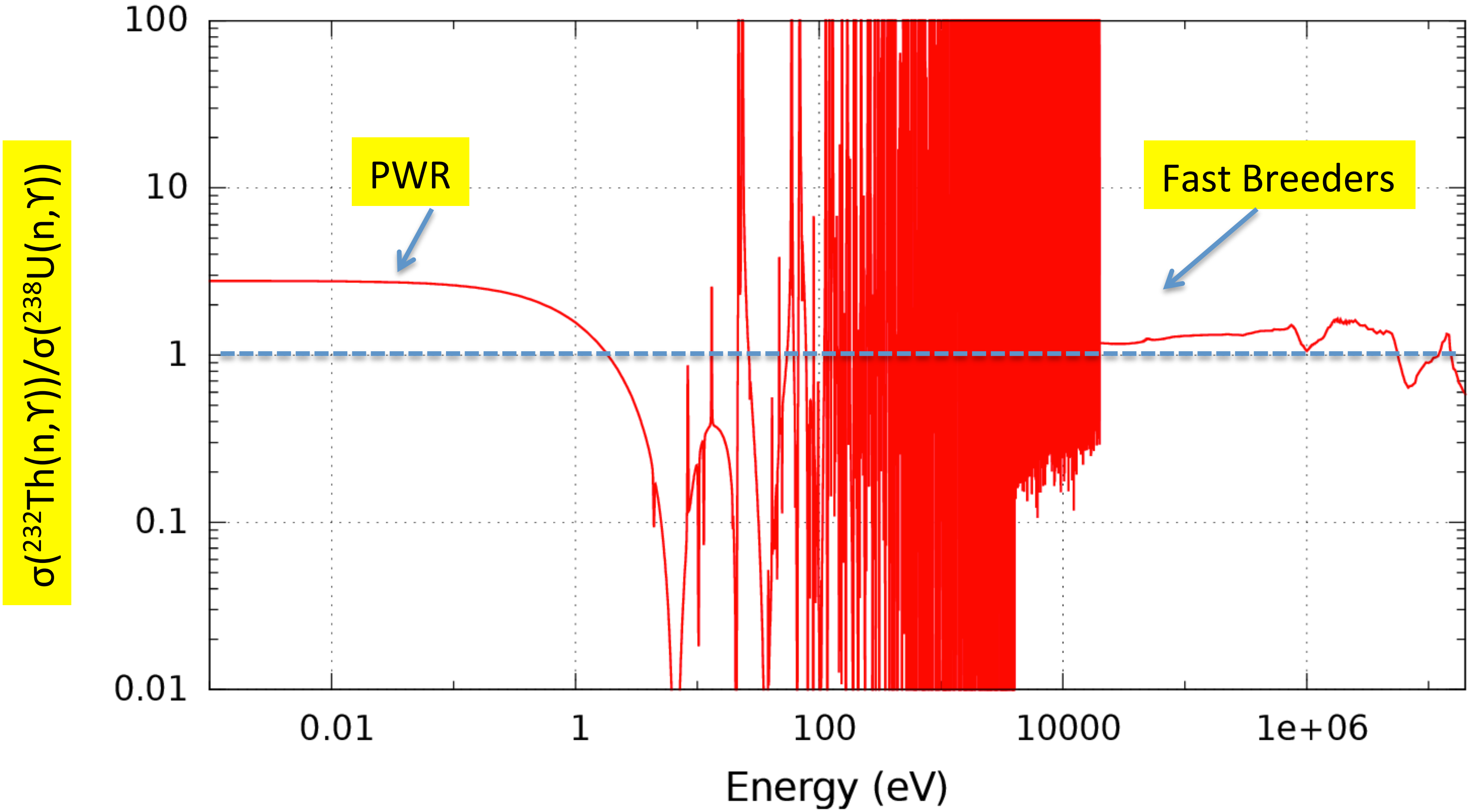
Nuclear Waste

- TRU produced by neutron capture and β-decays constitute the main problem, because of their long life time

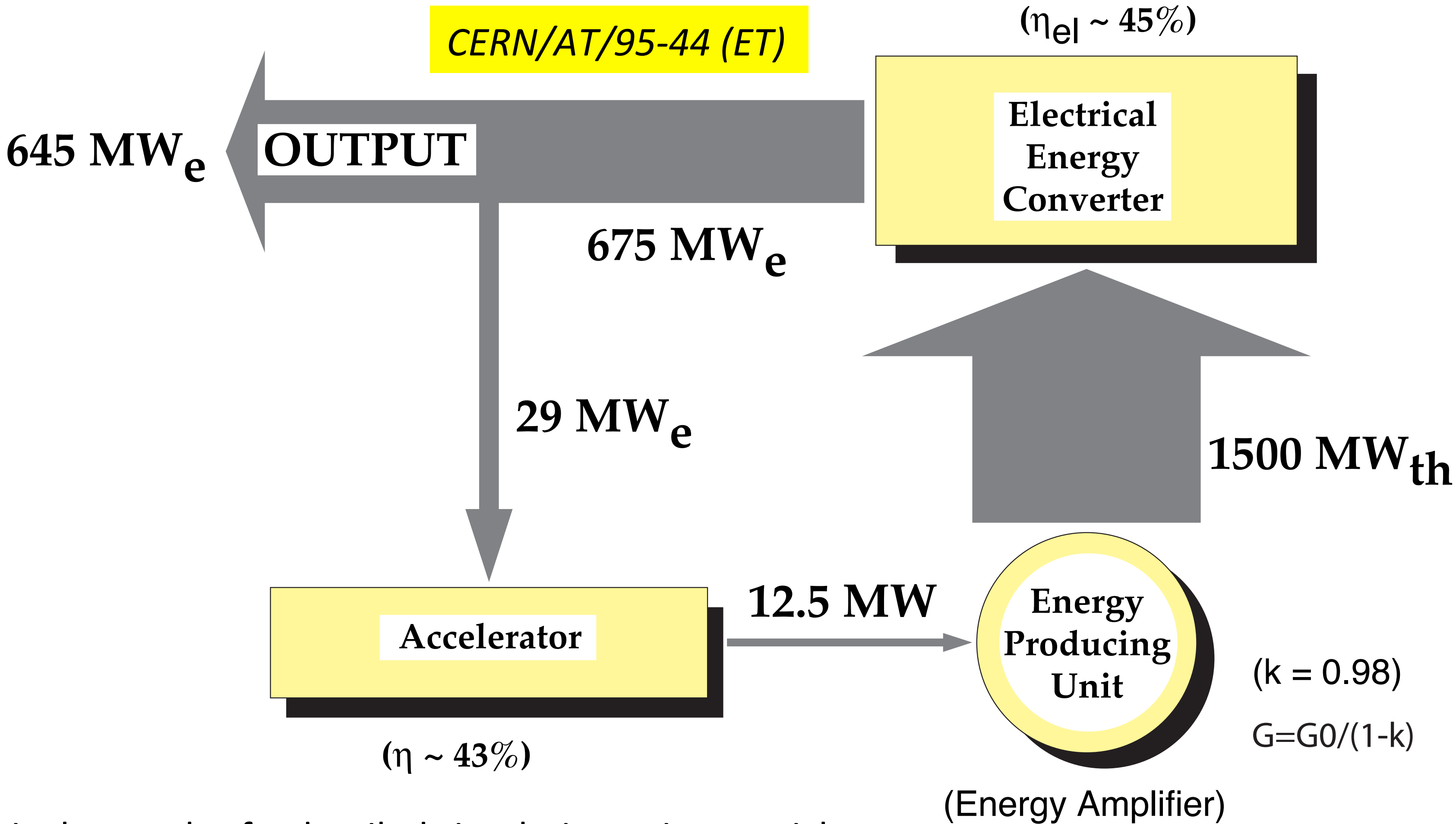


Neutron Captures

- Thorium has a higher capture cross section than ^{238}U, and it takes longer to breed the fuel (^{233}U), so one cannot simply replace ^{238}U by ^{232}Th in current reactors.



Energy flow in EA



This is the result of a detailed simulation using particle physics methods, starting from single protons in the beam

Thorium blanket: Indian strategy

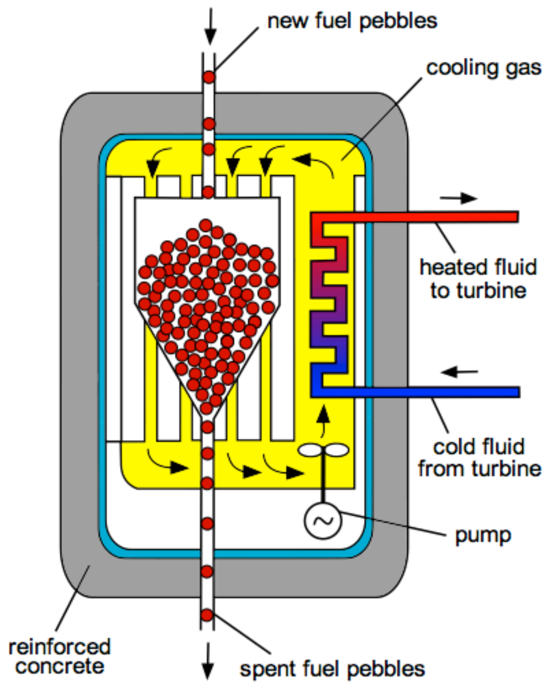
- India, with little uranium resources but a lot of thorium, has the most advanced practical scheme for using thorium (including front-end and back-end of the fuel cycle):
  - Use **heavy water reactors** (CANDU) or **LWR** to produce **plutonium**
  - Use **sodium cooled U-Pu fast reactors** with a thorium blanket to breed **^{233}U**
  - Reprocess blankets and manufacture **^{233}U-Th fuel** for **advanced fast reactors or heavy water reactors**

- The Indian scheme works. However, several issues remain concerning the **complexity** (three technologies), the **sustainability** and **nuclear waste management**.

Pebble bed critical reactors

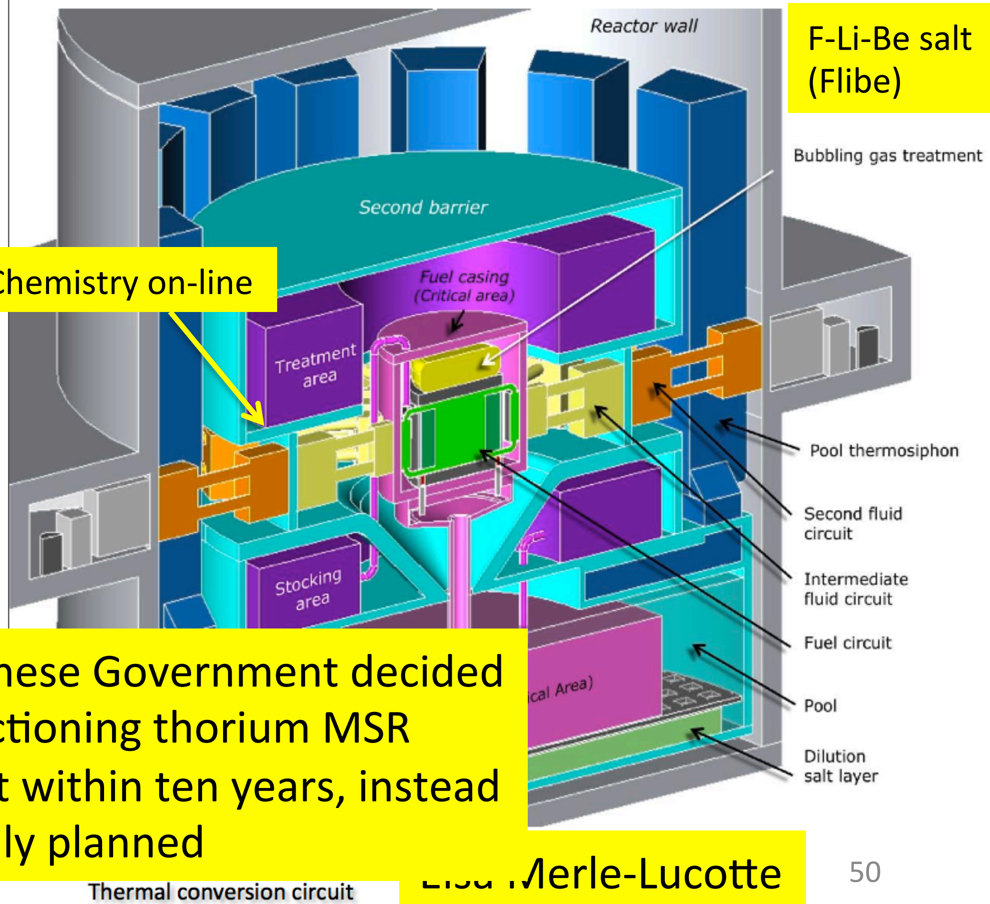
- Proposed by Farrington Daniels at Oakridge, in the 1940s. Initial developments in Germany (AVR Jülich), followed by THTR-300MW (1983-1989). New developments in South Africa, now in the United States and Turkey.
  - Presented as passively safe, because high temperature systems can be cooled by natural air convection
  - Not discussed at ThEC13
- Several severe issues to be resolved:
  - No containment building if cooling by natural air convection
  - Uses flammable graphite as moderator
  - Produces more high-level nuclear waste than current nuclear reactor designs
  - Relies heavily on pebble integrity and fuel handling (pebble accident in THTR-300)
  - Water ingress is a danger
  - Reprocessing of spent fuel virtually impossible

Pebble Bed Reactor scheme



Molten salt critical reactors

- This is clearly a technology that is concentrating industry's interest (10 talks related to the subject at ThEC13): China, India, UK, USA, Czech Republic, France, Switzerland
- Pioneered at Oakridge in 1960 (Molten Salt Reactor Experiment, UF4, 7.4MWth)
- Advantages:
  - Liquid fuel allows extending burnup indefinitely, because of reprocessing on-line
  - High temperature (500˚C – 600˚C), heat produced directly in heat transfer fluid
  - Passive cooling for decay heat removal
- **Several severe issues**: neutron emission outside core, on-line chemistry failure, corrosion, licencing issues, etc.
- Presently not using a fast neutron spectrum (R&D should be extended to other salts – $PbCl_3$, to minimize waste)
- There is a particular most ambitious effo Shanghai Institute o

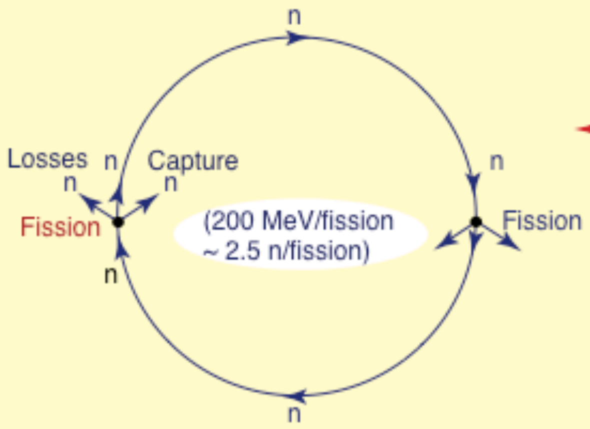


End of March, the Chinese Government decided that the first fully-functioning thorium MSR reactor should be built within ten years, instead of 25 years, as originally planned

Elsa Merle-Lucotte

Critical versus Subcritical Systems

Chain Reaction



Critical Reactor ⟷ **Energy Amplifier**

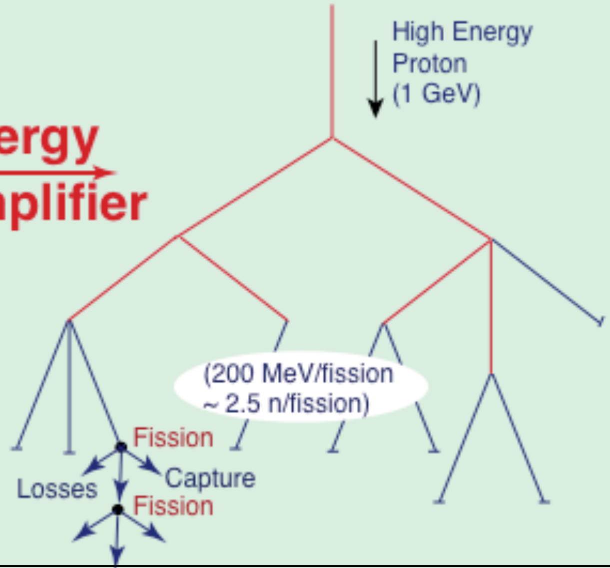
Effective neutron multiplication factor

$$k = \frac{\text{Production}}{\text{Absorption + Losses}}$$

Self-sustained process:
k = 1
(if k < 1 the Reactor stops
if k > 1 the Reactor is supercritical)

⇒ The time derivative of the power kept equal to zero by control

Nuclear Cascade



$$\text{Energy gain}(G) \equiv \frac{\text{Energy produced by EA}}{\text{Energy provided by beam}} = \frac{G_0}{(1-k)}$$

Externally driven process:
k < 1 (k = 0.98)

$$E_{tot} = G \times E_p$$

Energy Produced — Beam Energy

⇒ Constant Energy Gain

$$N_0\left(1 + k + k^2 + k^3 + k^4 + \dots + k^n\right) = N_0 \frac{k^{n+1} - 1}{k - 1} \approx \frac{N_0}{1-k}$$

Organizational Overview

The Chinese Academy of Sciences (CAS) and U.S. Department of Energy (DOE) Nuclear Energy Cooperation Memorandum of Understanding (MOU)

MOU Executive Committee Co-Chairs

China – Mianheng Jiang (CAS) 江绵恒
U.S. – Peter Lyons (DOE)

Technical Coordination Co-Chairs

China – Zhiyuan Zhu (CAS) 朱志远
U.S. – Stephen Kung (DOE)

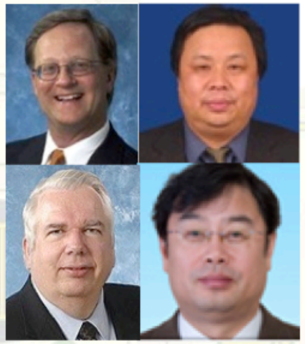
Nuclear Hybrid Energy Systems *

- Zhiyuan Zhu (CAS) 朱志远
  Yuhan Sun (SARI,CAS) 孙予罕
- Steven Aumeier (INL)

* Work scope governed by DOE-CAS Science Protocol Agreement

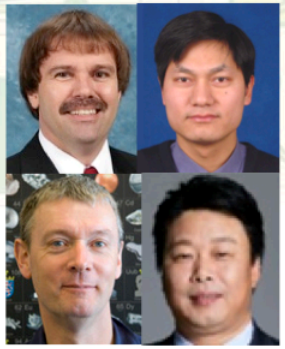
Molten Salt Coolant Systems

- Hongjie Xu (SINAP, CAS) 徐洪杰
  Weiguang Huang (SARI,CAS) 黄伟光
- Cecil Parks (ORNL)
  Charles Forsberg (MIT)



Nuclear Fuel Resources

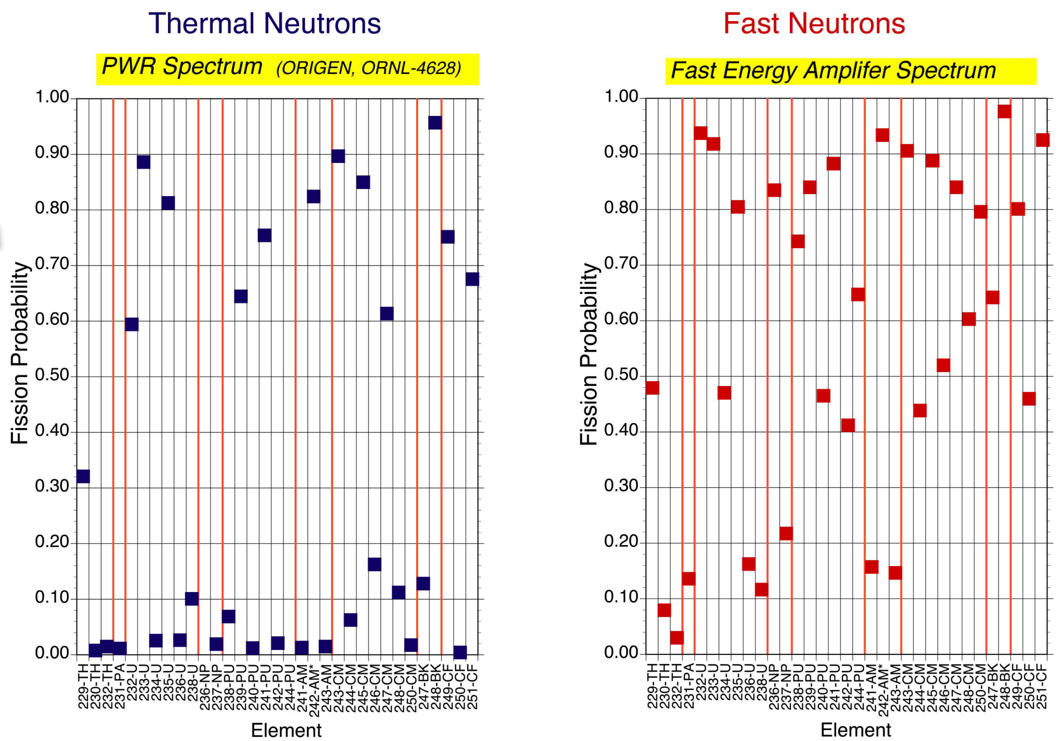
- Zhimin Dai (SINAP, CAS) 戴志敏
  Biao Jiang (SARI,CAS) 姜标
- Phil Britt (ORNL)
  John Arnold (UC-Berkeley)

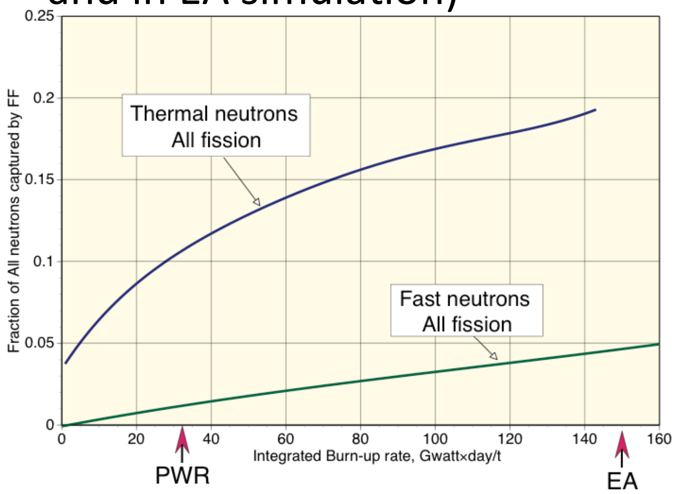


SINAP :Shanghai Institute of Applied Physics
SARI: Shanghai Advanced Research Institute
ORNL: Oak Ridge National Laboratory
INL: Idaho National Laboratory
MIT: Massachusetts Institute of Technology
UC-Berkeley: University of California at Berkeley

Why fast neutrons?

- **Advantages of fast neutrons**:
  - Favourable to breeding
  - Enhances TRU fission probability
  - No need to separate out Pu! **simplifies reprocessing** (Pyro-Electro)
  - Reduces captures on FF, **extends burnup (better use of fuel)** (120 GW.day/t achieved in fast electro-breeder at Argonne N.L., and in EA simulation)





- Fast spectrum, implies as little **moderation** as possible:
  - Sodium or gas used in GENERATION IV
  - Molten salts in MSR
  - Pb or Pb-Bi eutectic in ADS systems

ADS @ ThEC13

- **Largest number of talks at ThEC13 (17 talks)**
- **Status of readiness of technologies**:
  - Accelerator(s) (cyclotrons, linacs, Fixed Field Alternating Gradient)
  - Spallation targets
  - Core designs
- **Presentation of systems**:
  - MYRRHA (SCK•CEN, Mol, Belgium)
  - Troitsk (Russia) & CADS (China) for burning minor actinides, and a discussion in India to use ADS to simplify the present thorium utilization scheme
  - Molten Salt ADS (C. Rubbia, Japan, Korea)
- **Concrete tests**:
  - PSI cyclotron beam (1.4 MW proton beam – 2.4 mA x 590 MeV)
  - 0.8 MW LBE spallation target (MEGAPIE@SINQ (Swiss Spallation Neutron Source), SNS (1.4 mA x 1 GeV, 1.4 MW Spallation Neutron Source at Oakridge N.L.), etc.)
  - Reactivity measurement by beam pulses (Cheol Ho Pyeon, from Korea)
  - Corrosion, material compatibility, etc.

ADS energy gain

- A source neutron is multiplied by fissions and (n,xn) reactions. Since $k_s<1$, neutron production stops after a limited number of generations:

$$N_0\left(1+k_s+k_s^2+k_s^3+k_s^4+\ldots+k_s^n\right)=N_0M=N_0\frac{k_s^{n+1}-1}{k_s-1}\approx\frac{N_0}{\left(1-k_s\right)}$$

- The energy gain G is a characteristic of ADS:

Energy/fission; n/p; n/fission; Beam energy

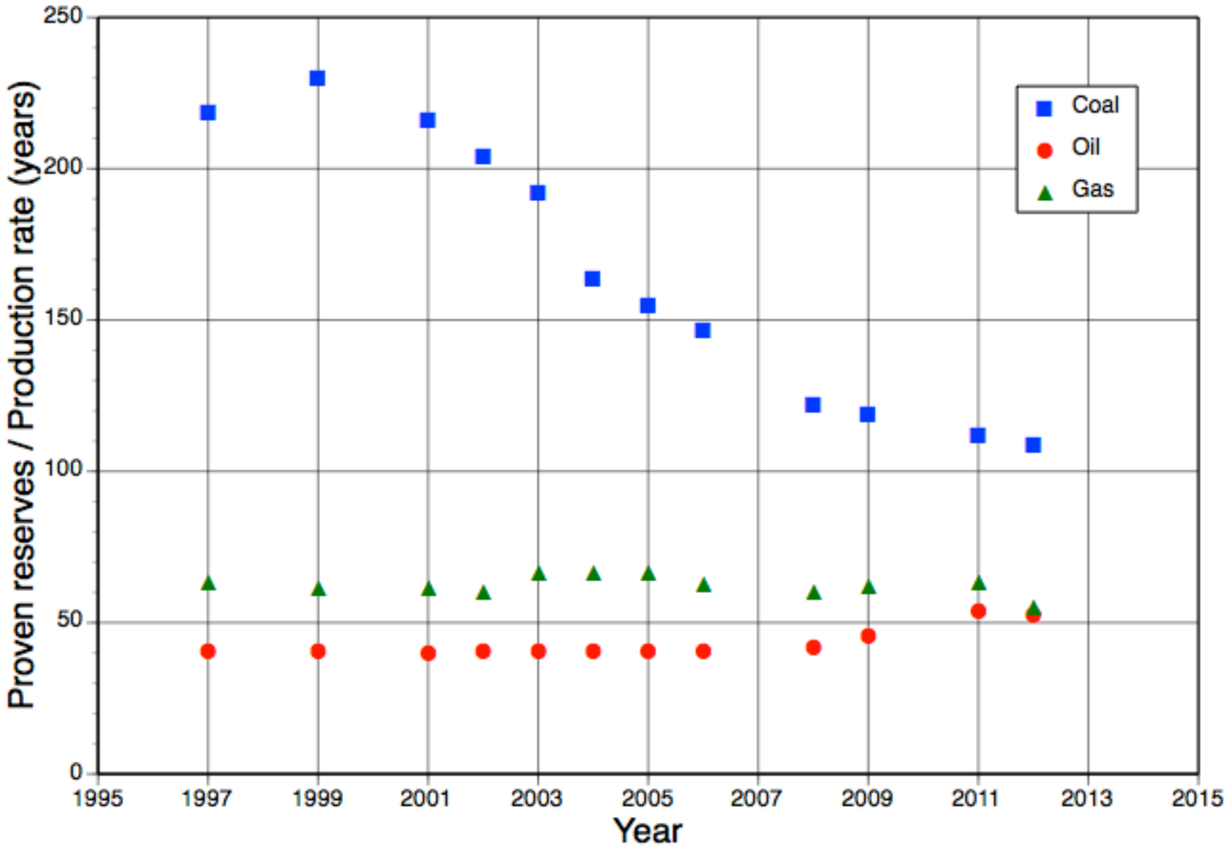
$$G\equiv\frac{Energy\ produced\ in\ EA}{Energy\ injected\ by\ the\ beam}=\frac{0.18k_sN_0}{\nu\left(1-k_s\right)E_b}=\frac{G_0k_s}{\left(1-k_s\right)}\approx\frac{G_0}{\left(1-k_s\right)}$$

- G_0 includes information from the spallation process (G_0 ~ 3 for uranium; G_0 ~ 2.7 for lead, etc.)

$$G=\frac{G_0\left(E_b,Material,Geometry\right)}{1-k_s}$$

Fossil Fuel Proven Reserves

- Newly discovered resources are also getting more expensive to extract



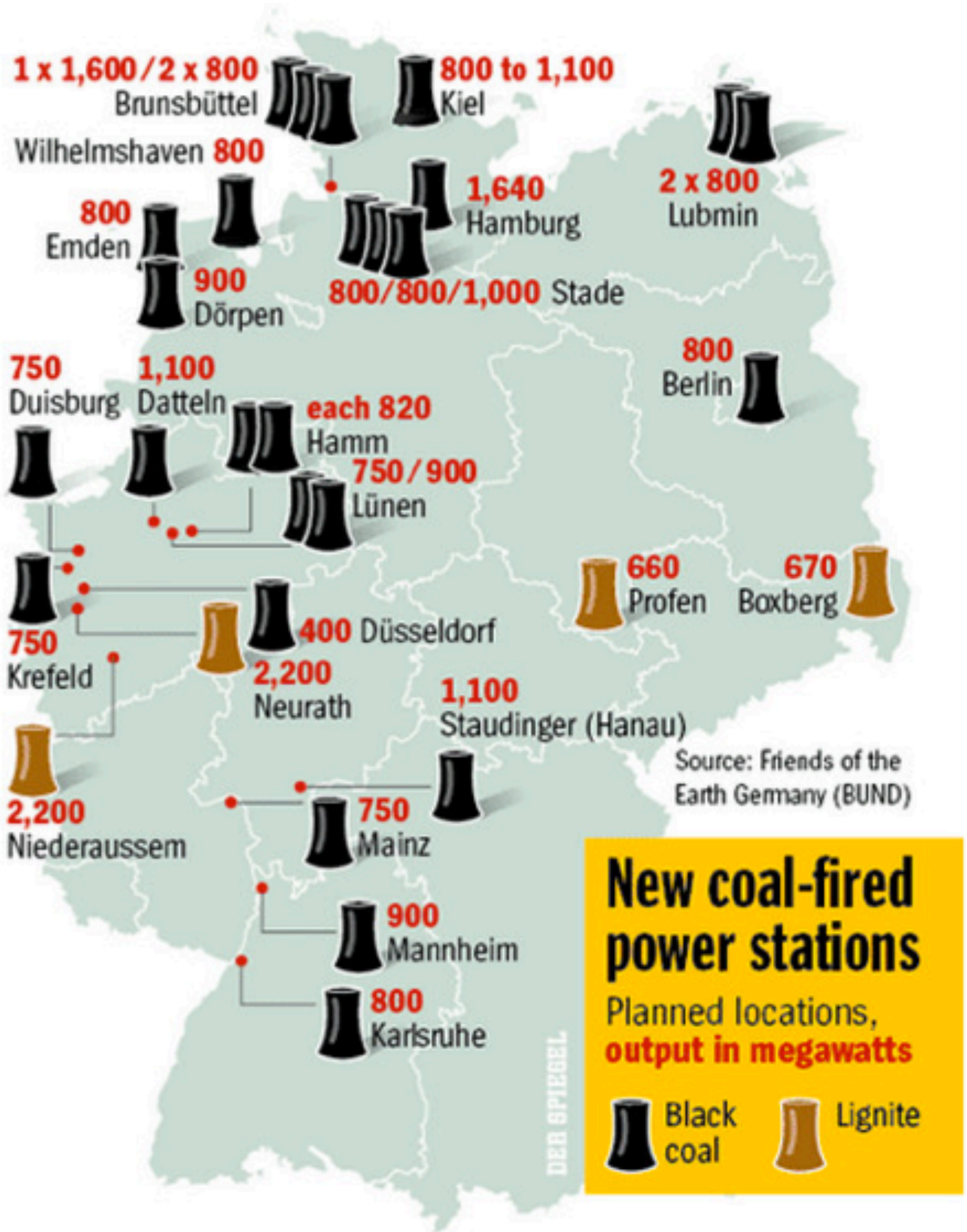
Energy and pollution in China

- Even though coal accounts for 70% of China's total energy consumption, China is doing better than most European countries, in terms of CO_2 emissions: no point telling China to stop burning coal …

Country	ton of CO_2 per capita
USA	16.94
Germany	9.14
Denmark	7.48
➔ China	5.92
France	5.04
World	**4.50**

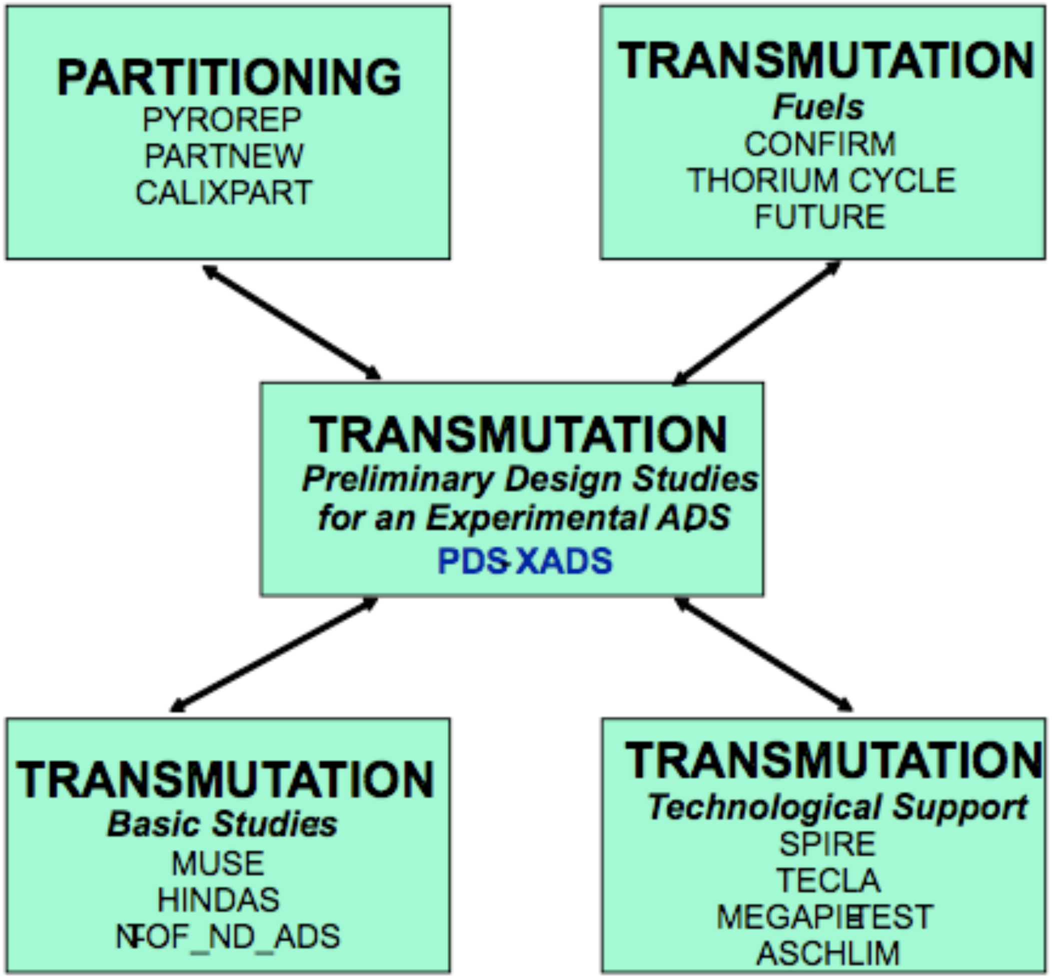
Source:
IEA 2013
Key World
Energy Statistics

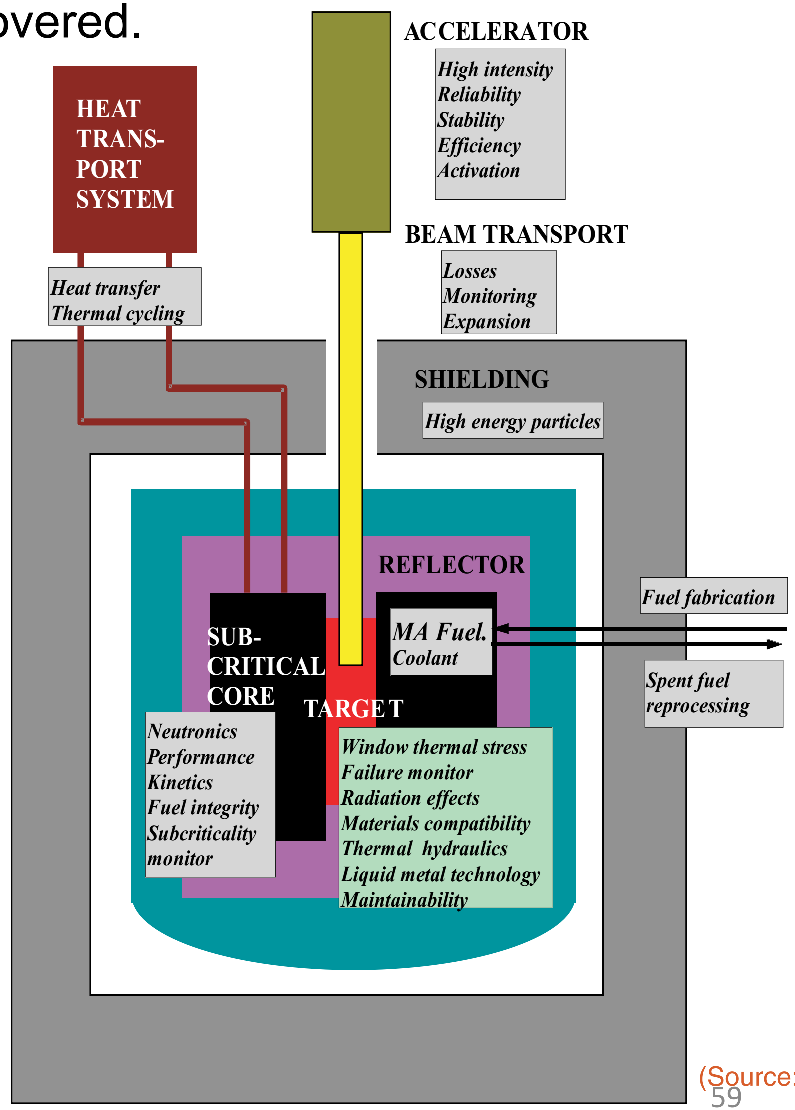
- Germany to open 10 new coal-fired power stations in the next two years (Bloomberg, Nov. 2013), while at the same time exporting subsidized green electricity (Netherland)


1 x 1,600/2 x 800
Brunsbüttel
800 to 1,100
Kiel
Wilhelmshaven 800
2 x 800
Lubmin
800
Emden
1,640
Hamburg
900
Dörpen
800/800/1,000 Stade
800
Berlin
750
Duisburg
1,100
Datteln
each 820
Hamm
750/900
Lünen
660
Profen
670
Boxberg
400 Düsseldorf
750
Krefeld
2,200
Neurath
1,100
Staudinger (Hanau)
Source: Friends of the Earth Germany (BUND)
2,200
Niederaussem
750
Mainz
900
Mannheim
800
Karlsruhe
DER SPIEGEL
New coal-fired power stations
Planned locations, output in megawatts
Black coal
Lignite

R&D in Europe

Many projects carried out since the EU FP5 and FP6 (Eurotrans) in the field of partitioning and transmutation. All aspects covered.





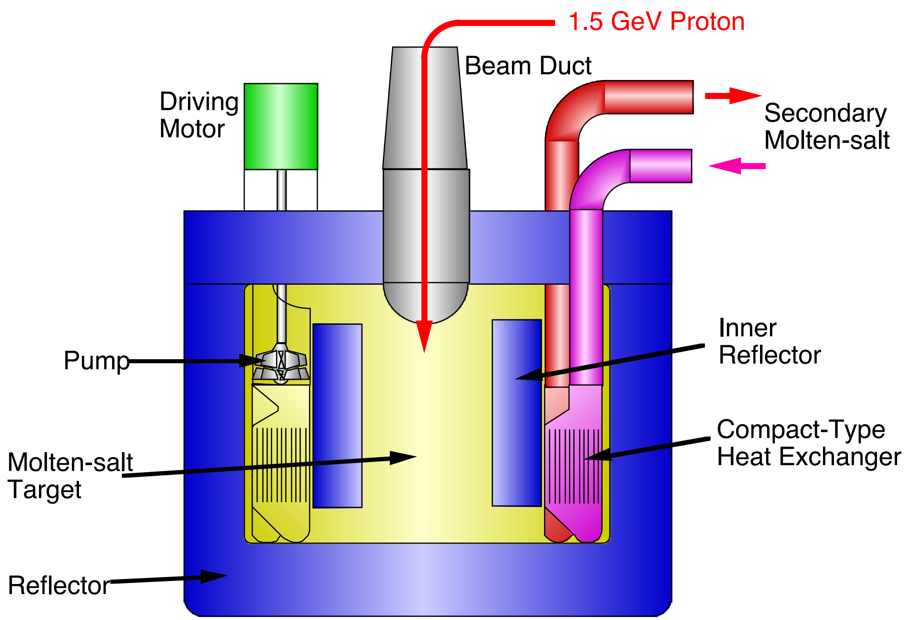
(Source:PSI)

Molten salt ADS

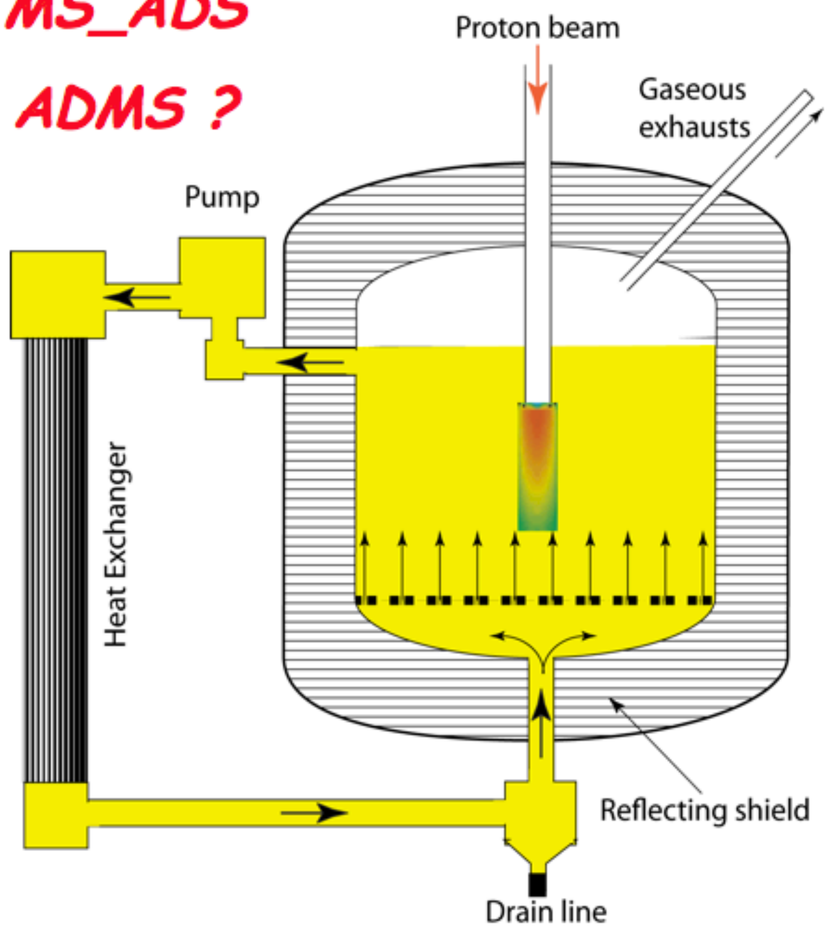
- Several **Molten Salt ADS concepts** were discussed: Carlo Rubbia, Toshinobu Sasa and Laszlo Sajo-Bohus.

MS_ADS

ADMS ?



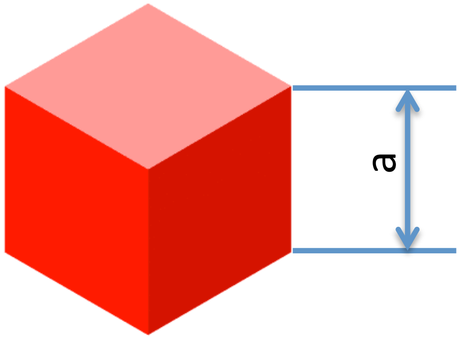
Toshinobu Sasa



Carlo Rubbia

Thorium for 1 GWexYear

- 645 GWe for one year requires **0.679 ton** of thorium in C. Rubbia's Energy Amplifier, hence for **producing 1 GWe during one year takes 1.05 ton of thorium**
- Note that to produce **1 GW of thermal energy during one year requires only 0.453 ton of thorium (6.79 kt of thorium per year for the entire world power consumption of 15 TW)**
- Given that the density of thorium is 11.7 g/cm^3, it takes a cube of thorium of side **a = 33.8 cm** to produce 1 GWth during one year!



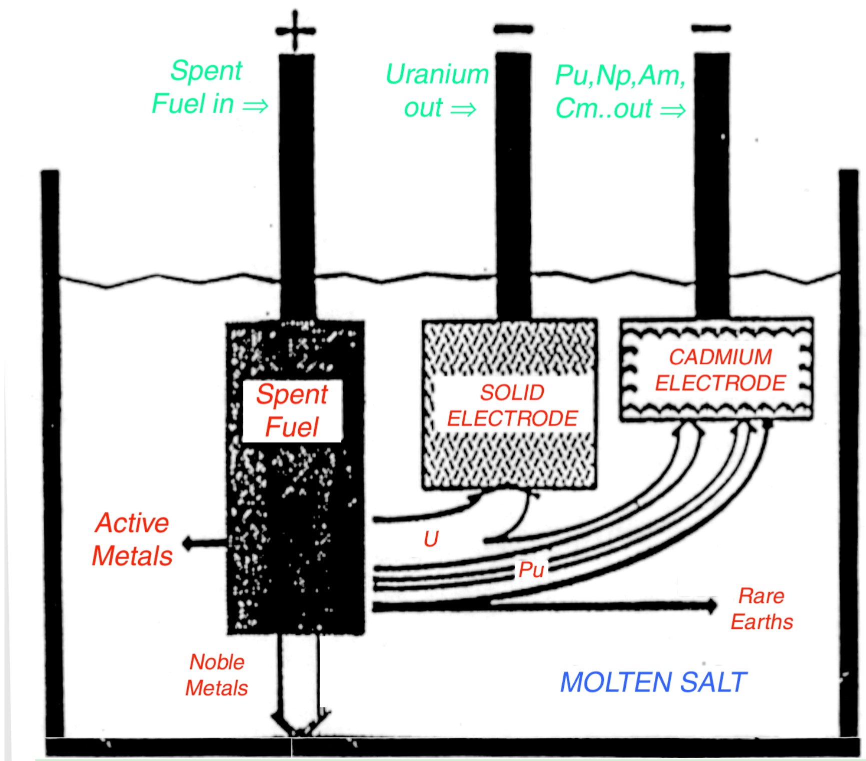
Annual production of a 900MWe PWR

On suppose un rendement de 33% et un facteur de charge de 70% (7,9 TWh → 5,5 TWh); typiquement 225kg de TRU et 745 kg de FF.

Electricité	**5,5 milliards de kWh**
Combustible usagé (à 33,000 MWd/t)	**21,5 t de UO_2**
Actinides	**20 620 kg**
Uranium ^{238}U (avec 1,1% de ^{235}U)	**20 400 kg**
Plutonium ^{239}Pu, ^{241}Pu (71%)	**209 kg**
Actinides mineurs (Np, Am, Cm, etc.)	**16 kg**
Fragments de fission (total)	**745 kg**
Fragments de fissions à vie longue	**50 kg**
Déchets de classe A (Gaines, matériaux structurels, etc.)	**100 – 200 m^3**

Pyro-electric reprocessing

- Electrolysis of molten salt solution. Actinides are separated out. Method already tested in the case of Uranium at Argonne National Lab (99.99% efficiency achieved). Plutonium remains combined with minor actinides (Np, Am, Cm, etc.). Simpler, nothing goes to the environment (no water) unlike Purex, small dimensions, not proliferating.



Transmutation of LLFF

^{99}Tc ($t_{1/2} = 2.1\times10^{5}$ ans) + n → ^{100}Tc ($t_{1/2} = 15.8$ s) + γ prompts

→ $^{100}Ru^{*} \rightarrow {}^{100}Ru$ (stable) + γ's

ARC maximise le taux de capture de neutrons