ADS and its potential

Applications of High Intensity Proton Accelerators
Oct 19-21, 2009 Fermilab
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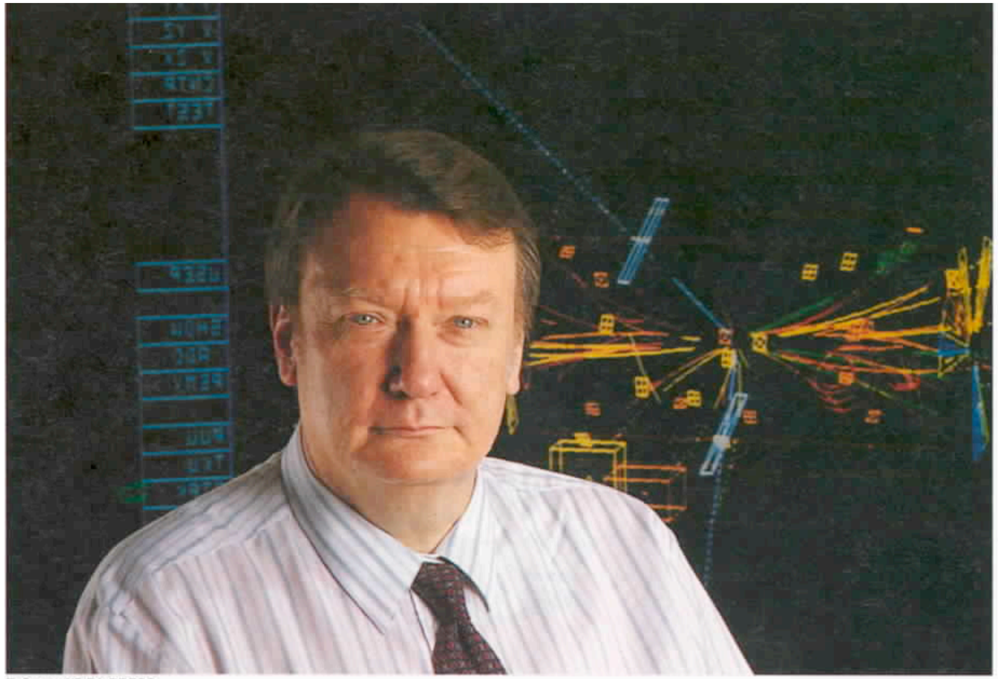
- The basic process in ADS is nuclear transmutation:
  - 1919 Rutherford ($^{14}N_7 + {}^{4}He_2 \rightarrow {}^{17}O_8 + {}^{1}p_1$) **^{210}Po accelerator!**
  - 1929 Major step for particle accelerators: Ernest O. Lawrence invention of the cyclotron (+Leo Szilard & Rolf Wideröe)
  - 1940 E.O. Lawrence/USA and W.N. Semenov/USSR propose to use a particle accelerator as neutron source
  - 1941 with 6 MeV deuteron on ^{238}U, G. Seaborg produces the first μg of ^{239}Pu
  - 1950 E.O. Lawrence proposes the Materials Testing Accelerator at the Lawrence Livermore Radiation Lab, to produce ^{239}Pu from Oak Ridge depleted uranium
  - 1952 W.B. Lewis in Canada proposes to use an accelerator to produce ^{233}U from thorium for CANDU reactors (electro-breeder concept)

- MTA and Lewis' projects dropped or slowed down when (a) rich uranium deposits were discovered in the USA, and (b) it was realized that it required several hundred mA of beam intensity, several hundred MW to produce the beam! [*Pu, no amplification*]

  This workshop: what can we do today with a 10 MW beam?
- Renewed interest in ADS in the 1980's, when the USA decide to slow the development of fast critical reactors (Fast Flux Test Facility @ Argone) and when it is realized that accelerator technology has made significant progress:
  - H. Takahashi at Brookhaven National Lab submits several proposals of ADS systems (PHOENIX), including the **idea of burning minor actinides** (Fast neutrons – k~0.99);
  - Ch.D. Bowman at Los Alamos proposes a thermal neutron ADS (**ATW**) with thorium & chemistry on-line for ^{233}Pa extraction;
  - Japan launches **Options for Making Extra Gains from Actinides** (OMEGA now JPARC) at JAERI (now JAEA).

- In the 1990s, Carlo Rubbia becomes convinced that the accelerator technology is indeed mature for a realistic exploitation of the ADS idea. He launches a vigorous research programme at CERN based on:
  - development of **innovative simulation** of nuclear systems
  - specific **experiments to test basic concepts** (FEAT, TARC)
  - construction of an **advanced neutron Time of Flight facility** (n_TOF) to acquire basic neutron cross-section data, crucial to simulate reliably any configuration with new materials (see talk by E. Gonzalez)

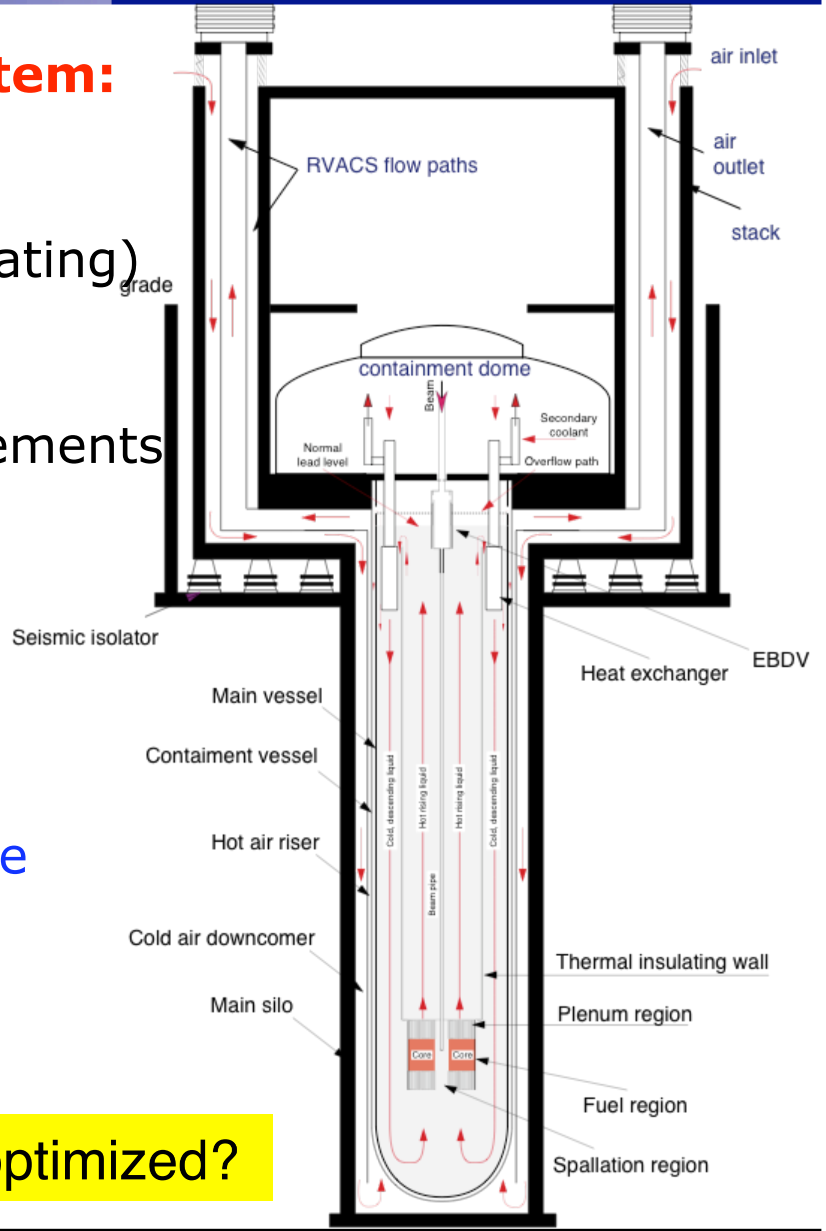


P. Stumpf/SIPA PRESS

CR triggered a major R&D effort on ADS in Europe, and in the world

The Energy Amplifier

- Proton accelerator driven **subcritical system:**
  - **Fast neutrons** (10^4 to 10^6 eV range)
  - Fuel based on **thorium** rather than uranium (minimize waste, less proliferating)
  - **Lead** as spallation target, moderator and coolant
  - **Deterministic safety** with passive elements



- C. Rubbia, et al.
  « Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier »,
  CERN/AT/95-44 (ET)
- C. Rubbia et al.,
  « A Realistic Plutonium Elimination Scheme with Fast Energy Amplifiers and Thorium-Plutonium Fuel »,
  CERN/AT/95-53 (ET)

How were the options chosen & parameters optimized?

Guidelines for ADS parameters choice

- **Safety**:
  - No criticality accident: make the system subcritical (void coef., T coef., β_{eff} no longer "critical" parameters)
    This requires an external proton source!
  - Operate system with passive safety elements to avoid core melting or limit its consequences, borrowing features from US advanced fast critical reactor designs;
  - Avoid dangerous coolants such as liquid sodium (use lead) Generation IV?
- **Waste management**:
  - Use (1) fast neutrons, (2) thorium fuel, and (3) recycle long -lived transuranic actinides (TRU) to minimize production.
- **Military proliferation**:
  - Use thorium fuel (small Pu prod., ^{233}U more difficult mixture)
  - Avoid Pu extraction (Purex), use pyroelectric reprocessing instead (developed for uranium at Argone N.L.)

- Basic equation similar to that of a critical reactor, but with external neutron source in addition:

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

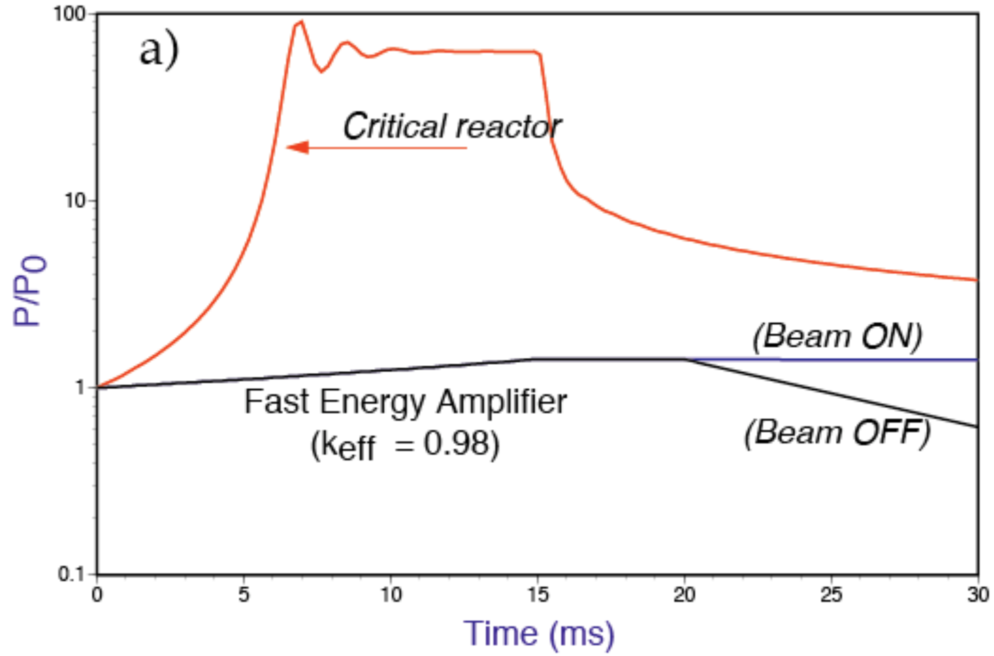
Fission | **Spallation** | Absorption | Leakage

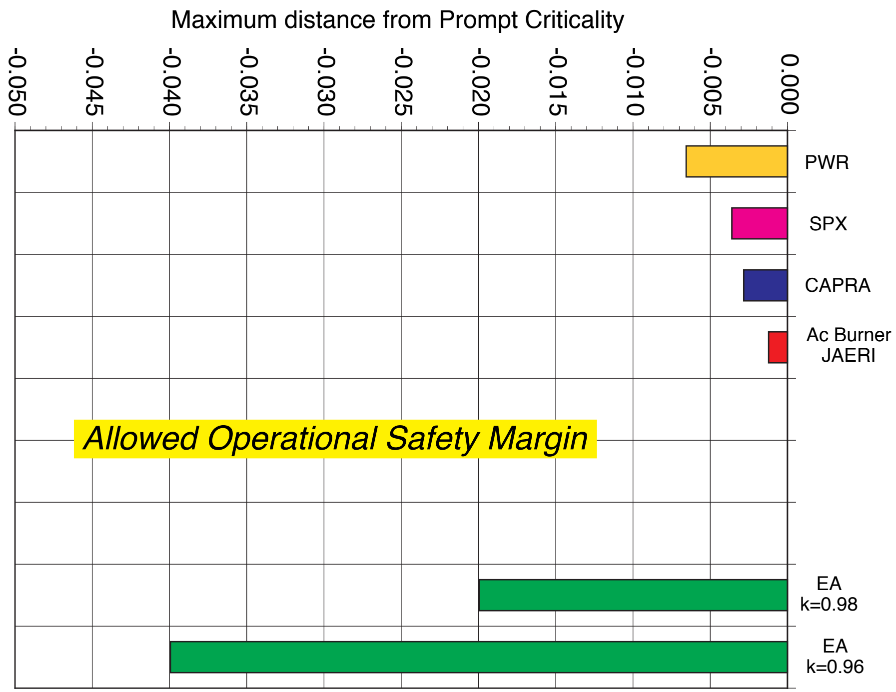
- **Theory of subcritical systems** interesting in itself, to get insights into the physics of such systems which is quite different from that of critical systems. (*C. Rubbia, CERN/AT/ET/Internal Note 94-036*)
- Example of finite system at equilibrium, with $k_\infty > 1$:
  - All modes excited;
  - Theorem: $k_1 > k_n$;
  - Relation between k_{source} and k_{eff}
  - etc.

$$\Phi(\vec{x}) = L^2 \sum_{l,m,n} \frac{C_{l,m,n}}{1 + B^2_{l,m,n} L^2_c} \times \frac{\Psi_{l,m,n}(\vec{x})}{1 - k_{l,m,n}}$$

- Nowadays, Monte Carlo methods allow to simulate all details of a real system (LHC detectors: 30M nodes!)

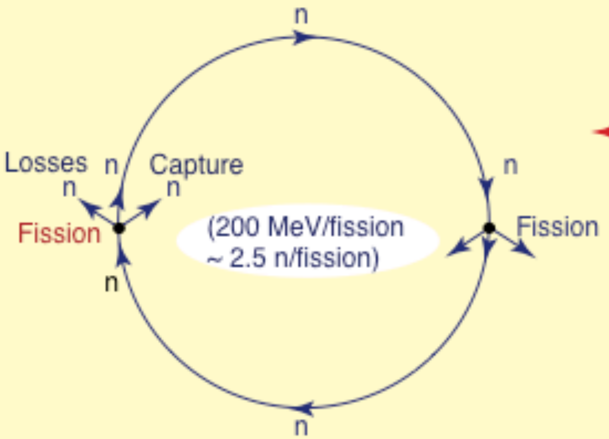
- Insensitive to delayed neutron fraction (β), distance from prompt criticality; **safety margin is a choice**, it is not imposed by Nature!





Critical versus Subcritical Systems

Chain Reaction



Critical Reactor ⟷ **Energy Amplifier**

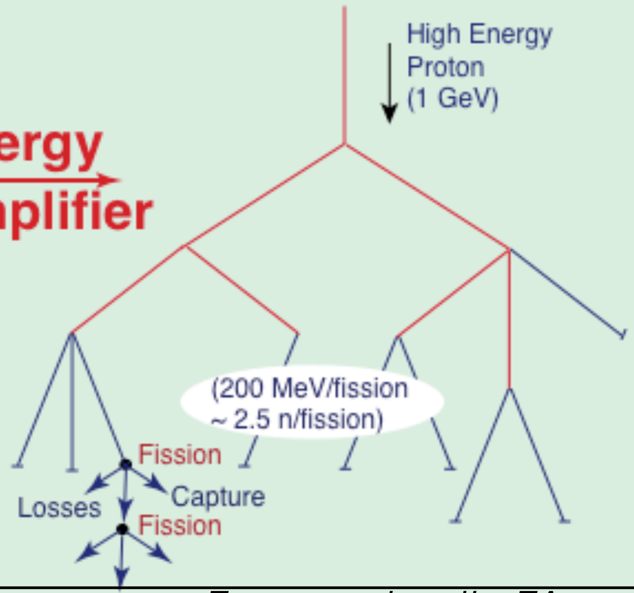
Effective neutron multiplication factor

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

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



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

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

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

Energy Produced   Beam Energy

⇒ Constant Energy Gain

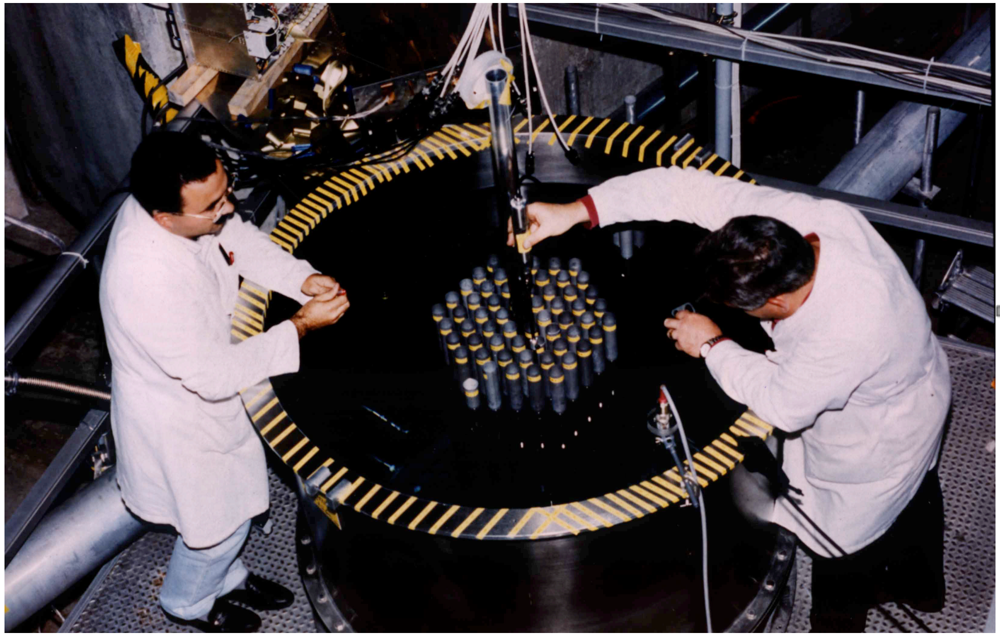
$$N_0\left(1+k+k^2+k^3+k^4+...+k^n\right) = N_0\frac{k^{n+1}-1}{k-1} \approx \frac{N_0}{1-k}$$

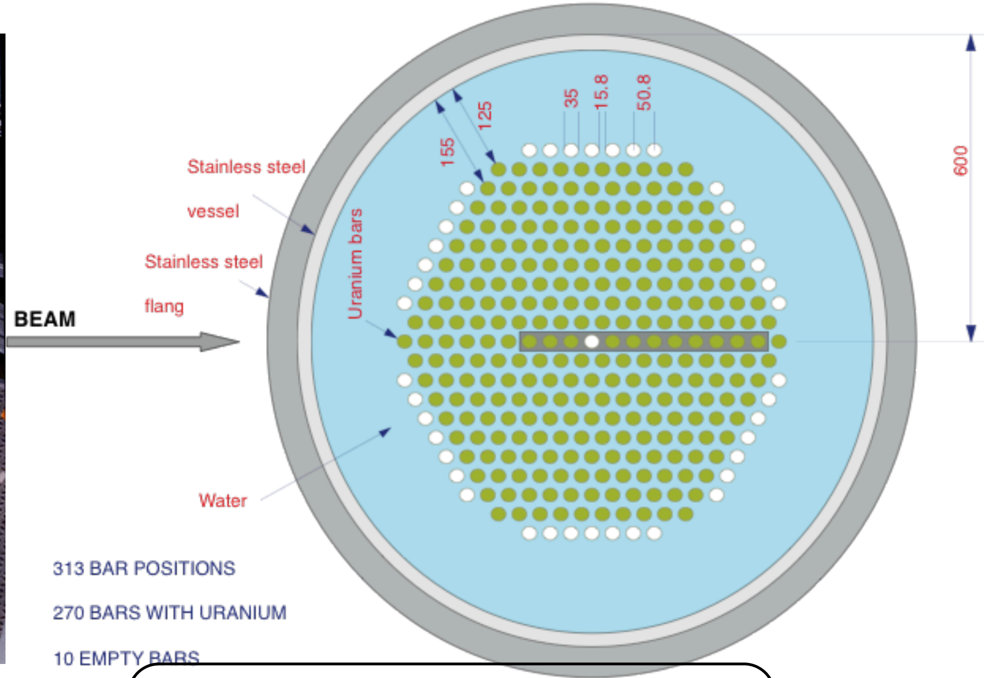
Energy gain in ADS systems

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

- For a given power output, the energy gain (choice of k and G_0) determines the required accelerator power. **Trade-off between accelerator power and criticality margin**
- Modulating the beam intensity allows variations in the power output, unlike in the case of critical reactors (complementary with a fluctuating renewable energy source, such as wind or solar!) **Neutronics with thorium very favourable compared to uranium $t_{1/2}$ (^{233}Pa) ~ 27d; $t_{1/2}$ (^{239}Np) ~ 2.3d!**

- The goal of the **F**irst **E**nergy **A**mplifier **T**est (**FEAT**) at the CERN PS was to check the **basic concept of energy gain**, and **validate the innovative simulation** developed by C. Rubbia and his group.



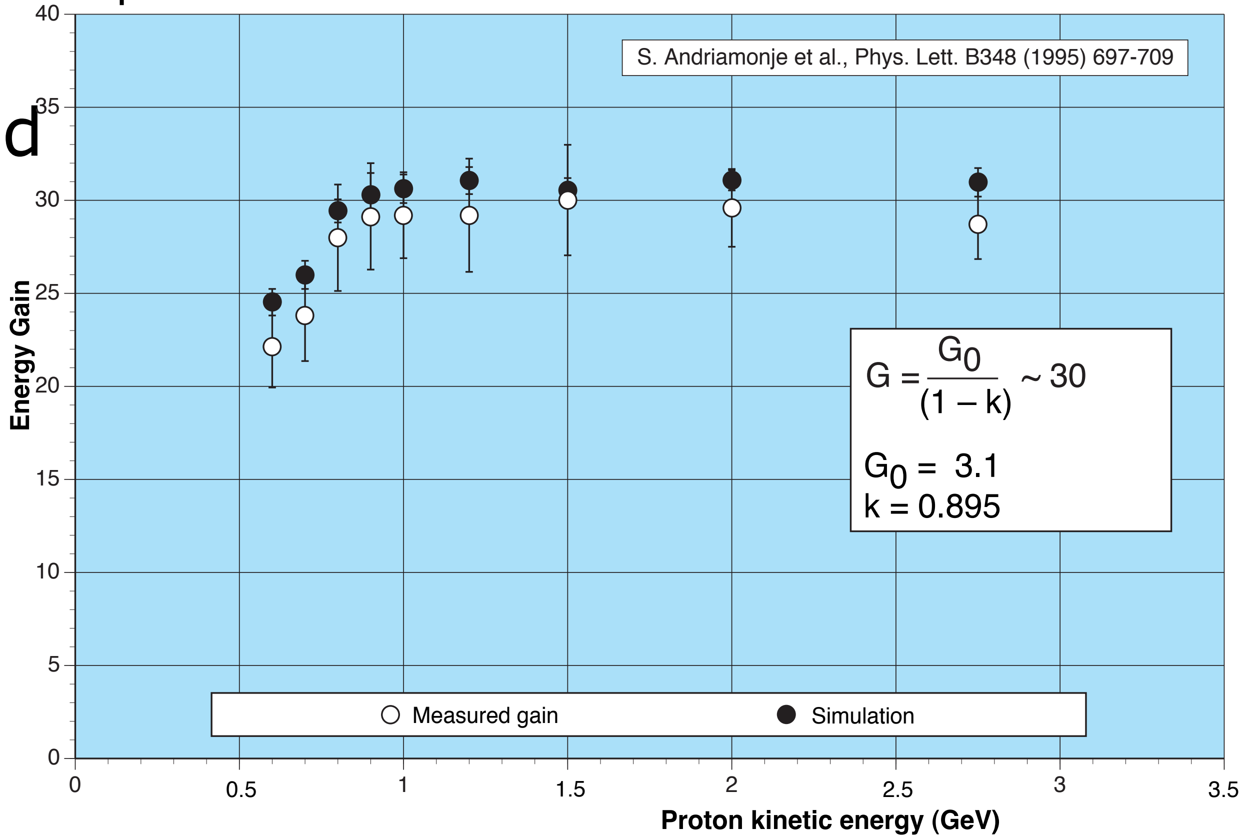


3.62 t of natural uranium; $k_{eff} \sim 0.9$

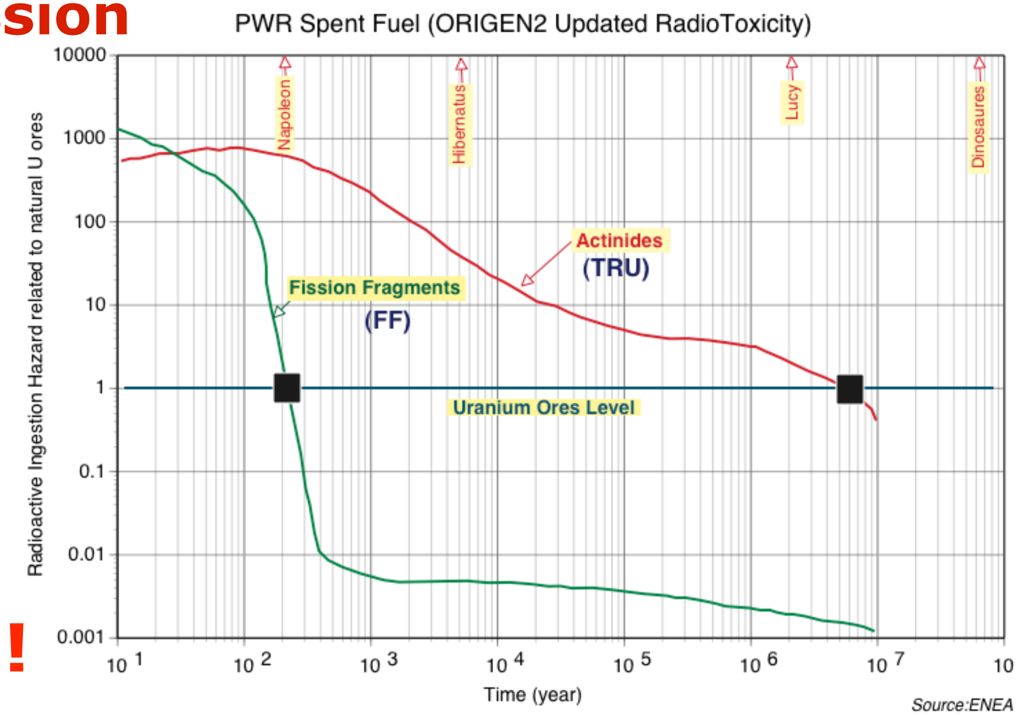
– Count fissions
– Measure temperature

- Optimum beam energy reached at 900 MeV, with slow decrease at higher energies (ionization vs nuclear cascade production): neutron yield scales with proton energy (E_p)

- Simulation validated from spallation to heat production



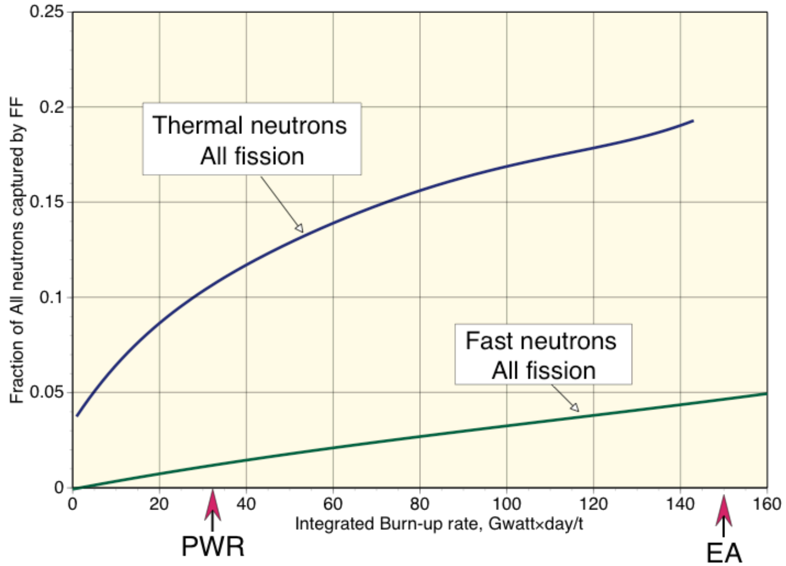
- The two components of radioactive waste require different strategies:
  - **TRansUranic elements** (**TRU, 1.1 %**: Np, Pu, Am, Cm, Bk, etc.) result from neutron capture in the fuel and subsequent decays. (**~100 t/y of ^{239}Pu produced in the World + Military Pu**):
    ⇒ eliminated through fission producing energy!
  - **Fission Fragments** (**FF, 4%**: produced in the fission process):
    ⇒ eliminated through neutron capture (only long-lived part)

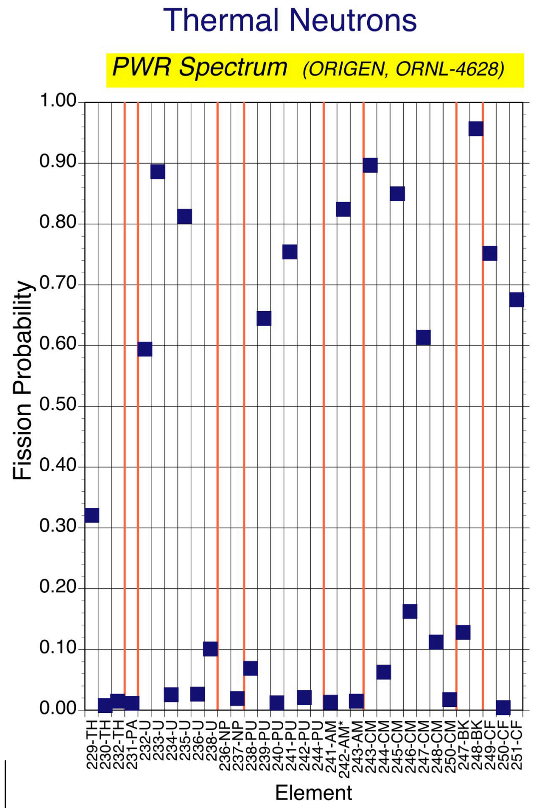


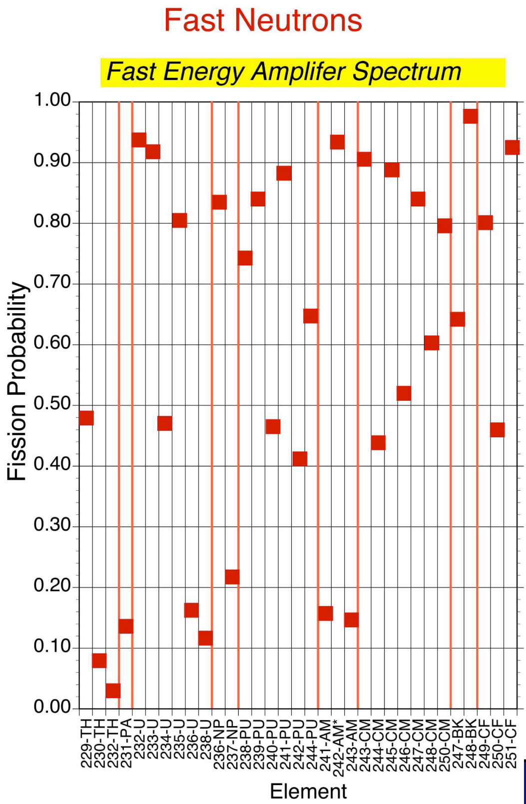
Priority: TRU elimination!

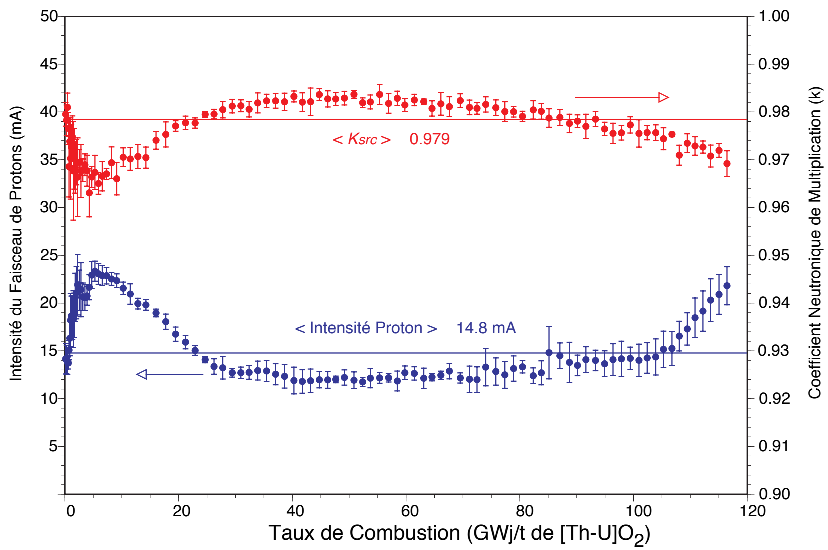
Use fast neutrons:

- Enhances TRU fission probability
- No need to separate out Pu!
- Allows extended burnups (Realised both in electro-breeder at Argonne and in EA simulation)



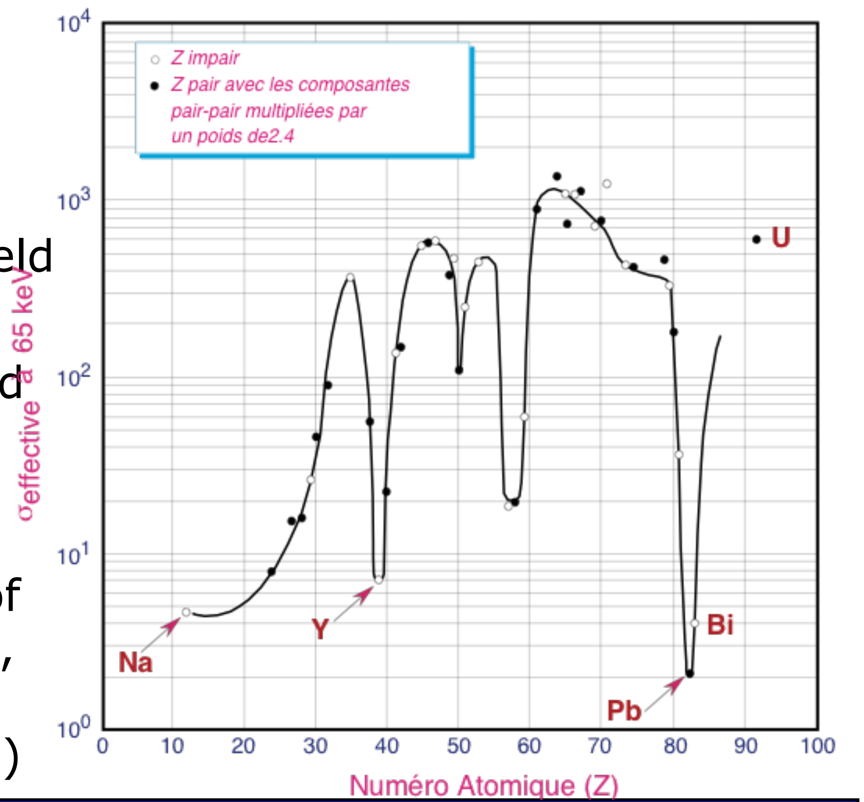




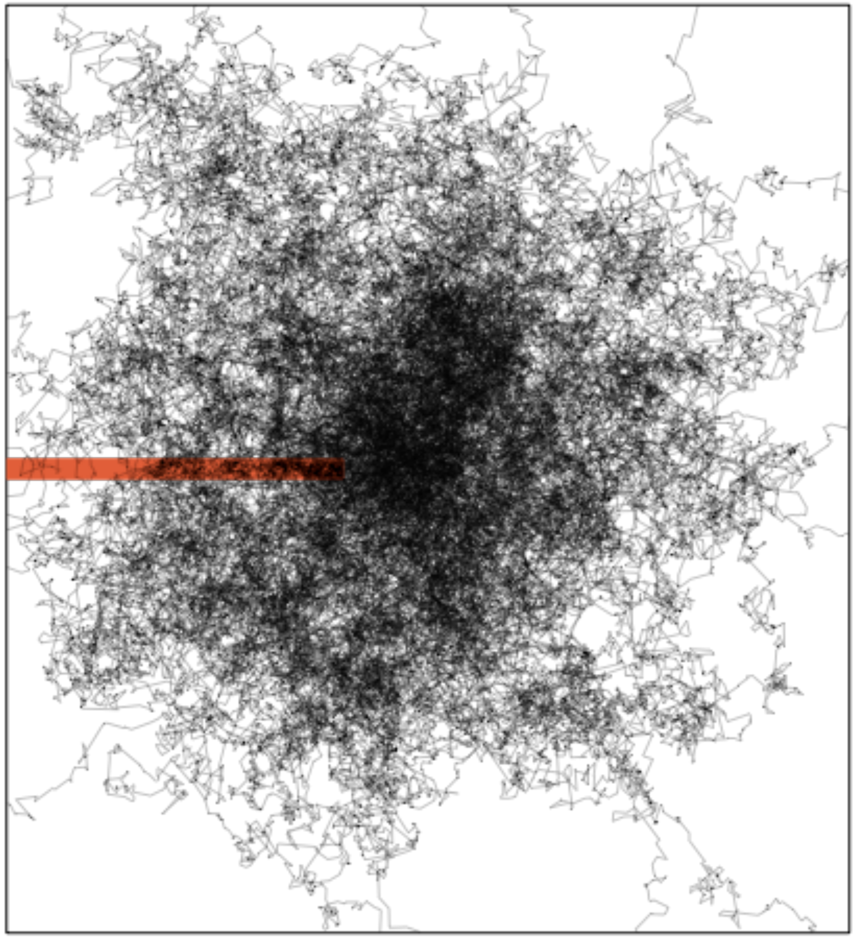


Practical strategy (1)

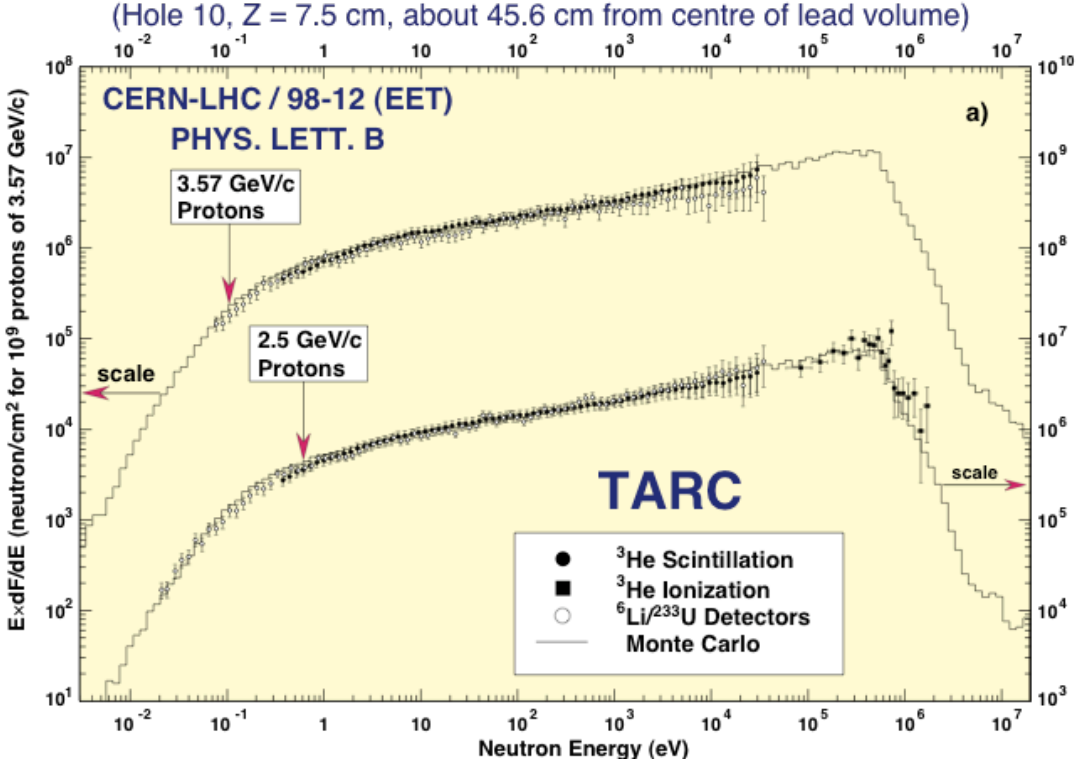
- **Use lead as moderator**: in order to have fast neutrons, moderate neutrons as little as possible (sodium, gas, lead)
- Lead (or Pb-Bi eutectic for prototype) is the choice for the EA: spallation target, moderator, heat removal agent, containment medium. It is the heavy element most transparent to neutrons.
  - Spallation target: neutron yield almost as good as for uranium;
  - Safety: Lead less dangerous than sodium. Boiling temperature well separated from fusion point (unlike sodium); radiation shield
  - Excellent coolant;
  - ***Drawbacks***: **corrosion** at high T but rapid progressin new materials (lead loops, Eurofer), and use of Super critical CO_2 Brayton power cycle achieving 45% thermal efficiency with inlet temperature of only 550˚C (53% at 700˚C) MIT V. Dostal, M.J. Driscoll, P. Hejzlar.
    Po production (Pure Pb better than Pb-Bi)



- Neutron phenomenology studied in great details in the TARC experiment at the CERN PS.

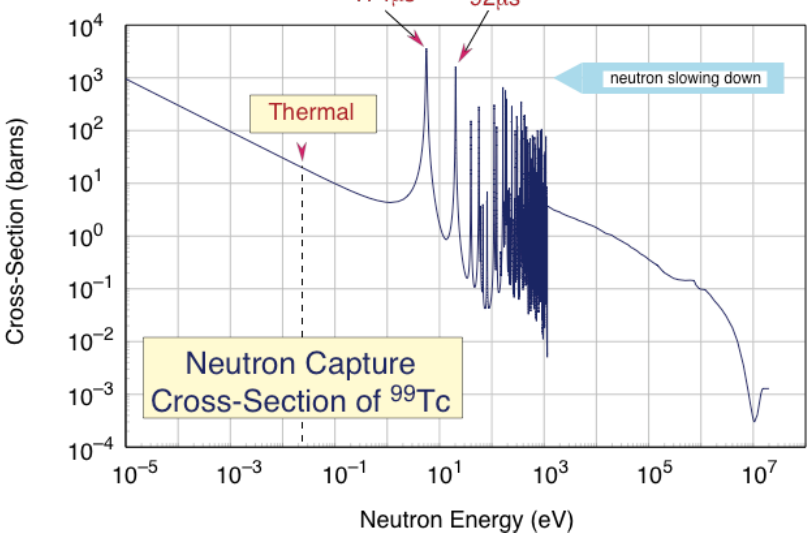


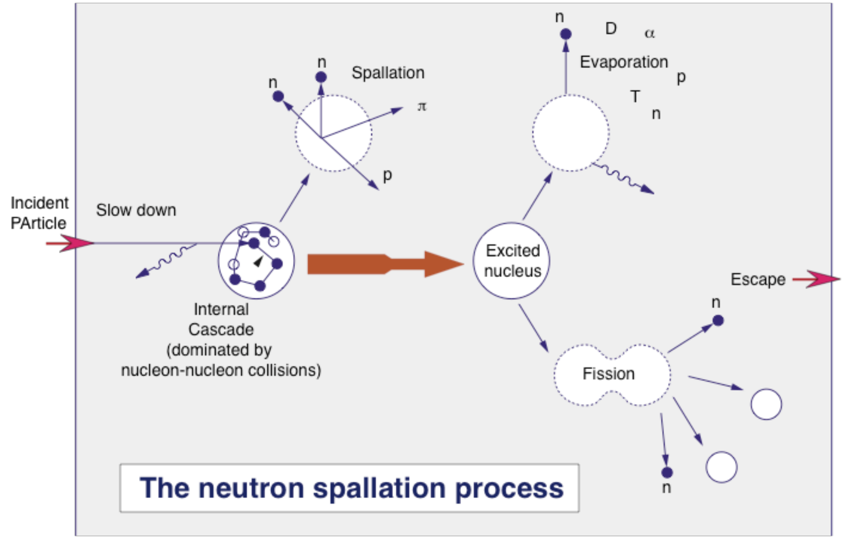
Results from TARC



^{99}Tc ($t_{1/2}$ = 2.1×10^5 ans) + n → ^{100}Tc ($t_{1/2}$ = 15.8 s) + γ prompts (1)

^{100}Ru* → ^{100}Ru (stable) + γ's (2)

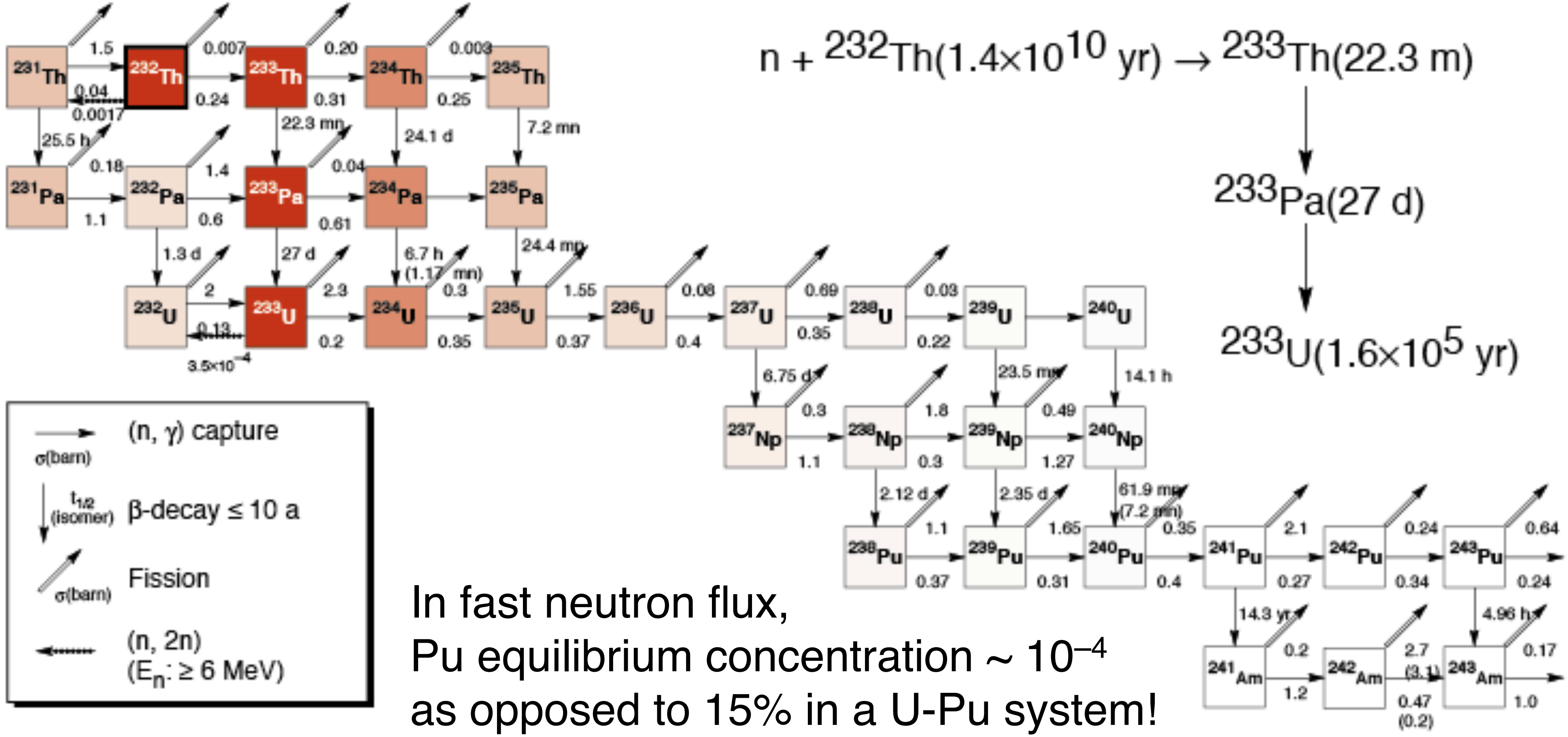




- Demonstrated **Adiabatic Resonance Crossing** for the elimination of long-lived fission fragments proposed by C. Rubbia.

Go to thorium fuel cycle:

- it takes 5 neutrons captures to go from ^{233}U to ^{238}U!
- ^{233}Pa decay 10 times slower than ^{239}Np.



$$n + {}^{232}Th(1.4\times10^{10}\ yr) \rightarrow {}^{233}Th(22.3\ m)$$

$$\downarrow$$

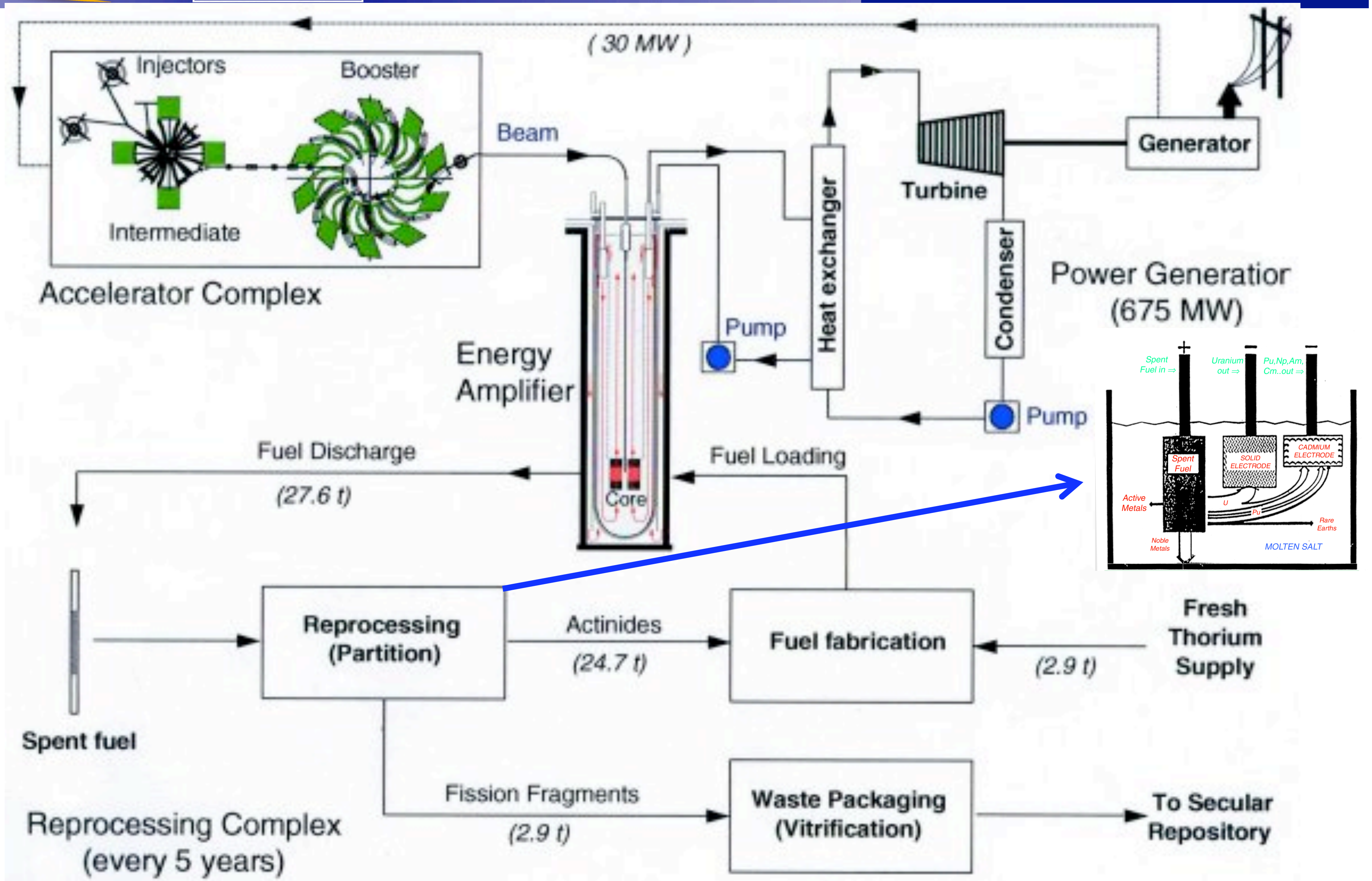
$$^{233}Pa(27\ d)$$

$$\downarrow$$

$$^{233}U(1.6\times10^{5}\ yr)$$

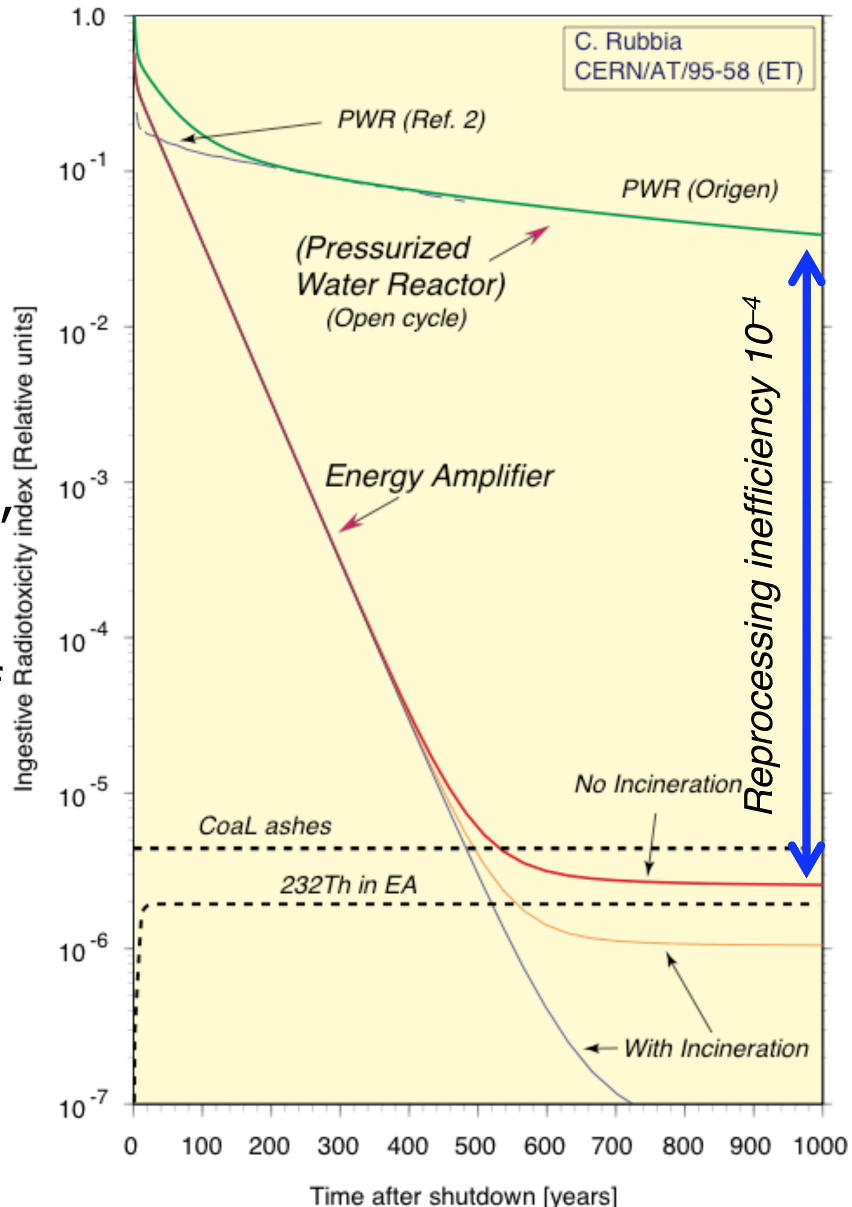
In fast neutron flux,
Pu equilibrium concentration ~ 10^{-4}
as opposed to 15% in a U-Pu system!

Fuel cycle strategy



- The simulation (validated by CERN experiments) shows that one could **destroy** 36 kg of TRU/TW_{th}.h (A PWR **produces** 14 kg of TRU/TW_{th}.h)

- Today the emphasis has clearly shifted towards energy production.
  - The two options are not incompatible, since in both cases one wants to minimize TRU production.
  - The difference might be in the size of the unit, depending on local needs, and the optimization of the energy efficiency (high temperature).

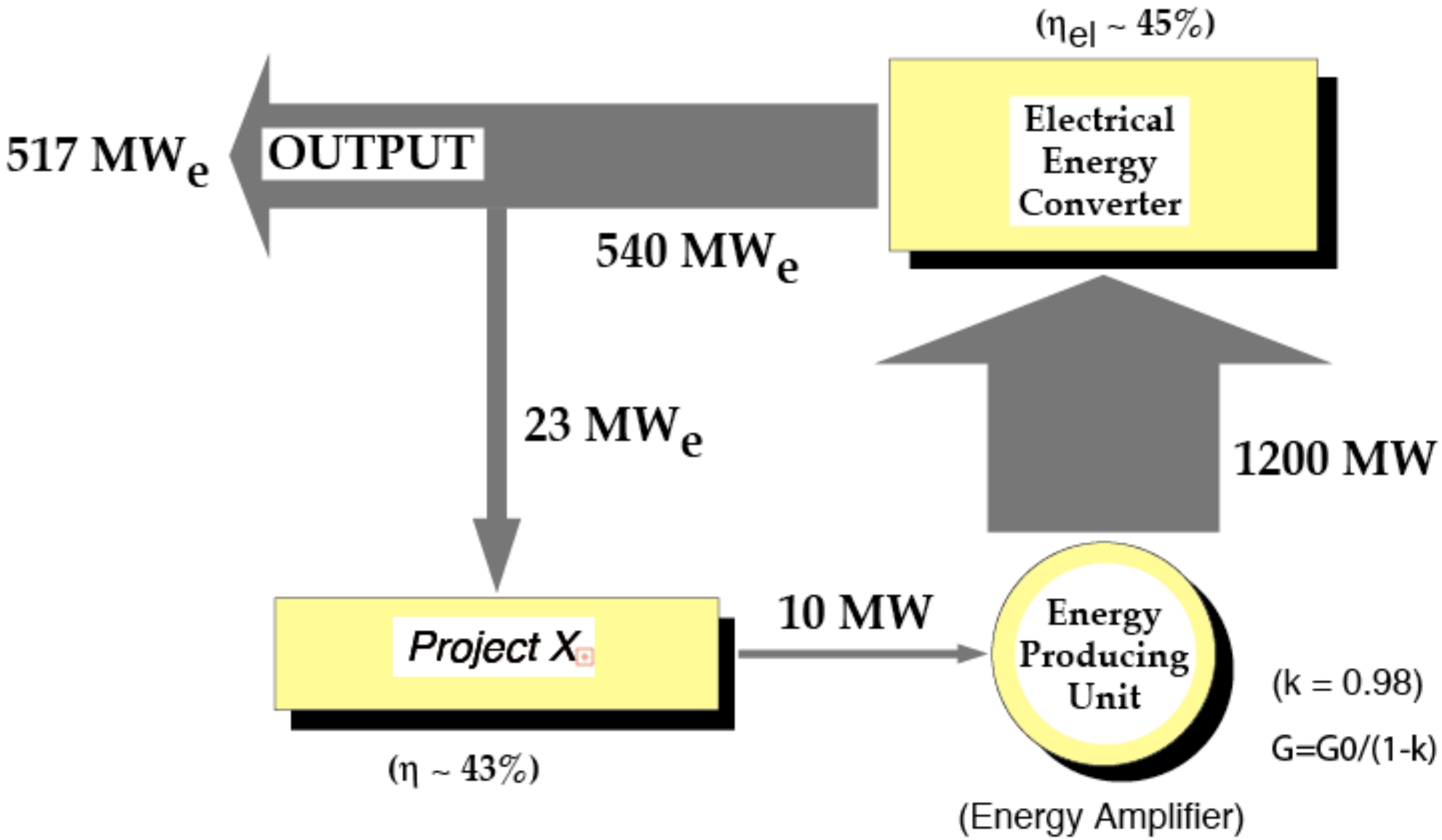


- From the point of view of ADS physics, it does not matter how ”external” neutrons are produced. It is technological constraints that will determine the properties of the beam:

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

- The highest beam power was produced with the PSI separate turns cyclotron (approaching 3mA and 1.8 MW, with 0.59 GeV protons) would allow P_{ADS} = 243MW with k=0.98, or P_{ADS} = 486MW with k=0.99

- Example of a 10 MW beam (Project X?); very close to the power of standard EA unit defined by C. Rubbia.



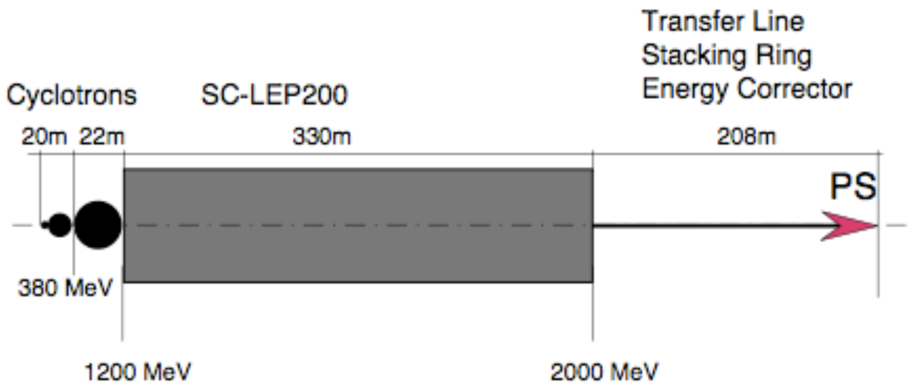
The accelerator parameters

- The choice for an industrial system will rely on specifications in terms of:
  - Power: 10 MW probably OK depending of k value, and desired unit power; $E \geq 900$ MeV
  - Reliability, ease of maintenance (have several injectors?)
  - Energy efficiency (maximize fraction of electric grid power into the beam)
  - Beam losses (irradiation of the accelerator and of environment)
  - Size, cost

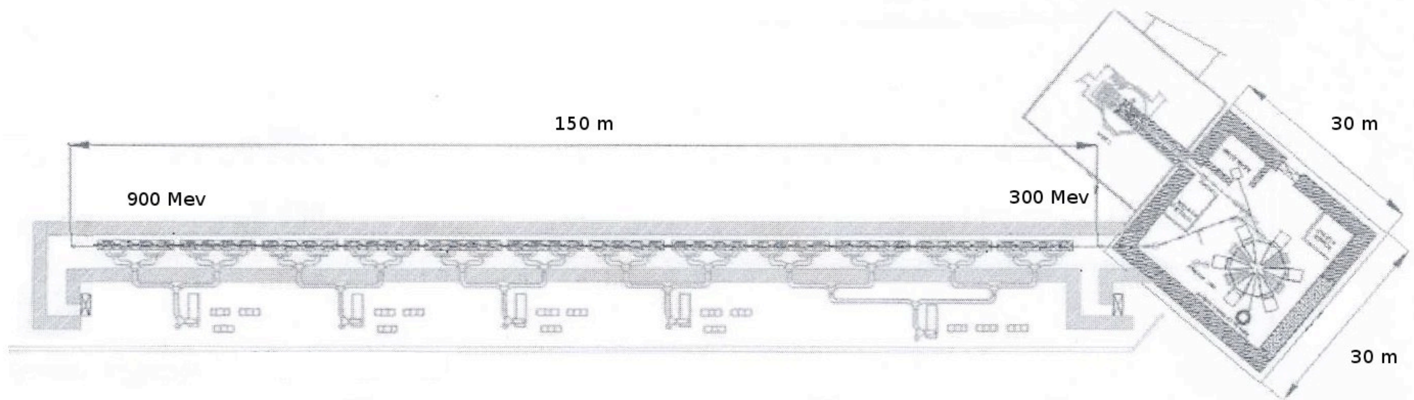
- In principle several possible technologies:
  - Linac, Cyclotron, FFAG? or Hybrid system (Cyclotron injection into a c.w. linac)

- Combining advantages of both technologies:

ALTERNATIVE SOLUTION: Cyclotrons 0 to 380 MeV and 380 MeV to 1.2 GeV, H^+
(gain of 528 m)



(EET group study (2000) using LEP SC cavities)



(Solution being studied by Pierre Mandrillion (AIMA))

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

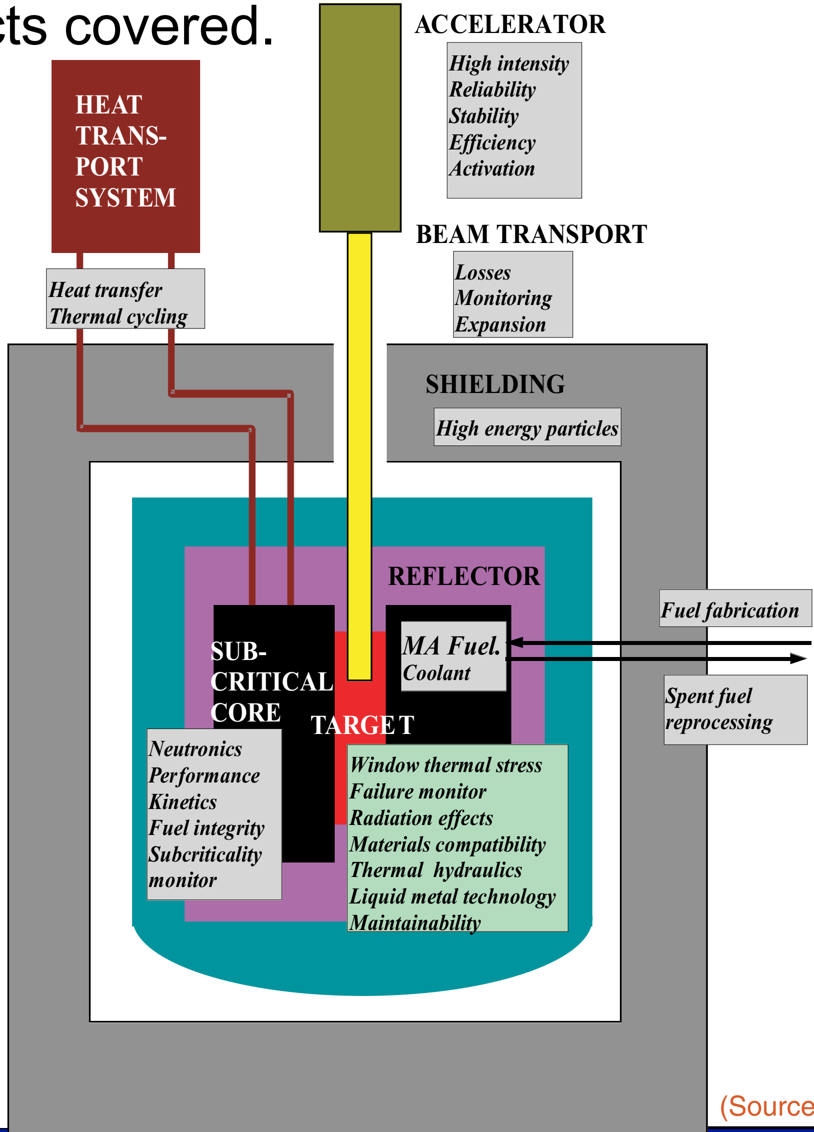
PARTITIONING
PYROREP
PARTNEW
CALIXPART

TRANSMUTATION
Fuels
CONFIRM
THORIUM CYCLE
FUTURE

TRANSMUTATION
Preliminary Design Studies for an Experimental ADS
PDS-XADS

TRANSMUTATION
Basic Studies
MUSE
HINDAS
N_TOF_ND_ADS

TRANSMUTATION
Technological Support
SPIRE
TECLA
MEGAPIE-TEST
ASCHLIM



(Source:PSI)

- Eurotrans using the many loop facilities existing Europe Thermodynamics and corrosion studies

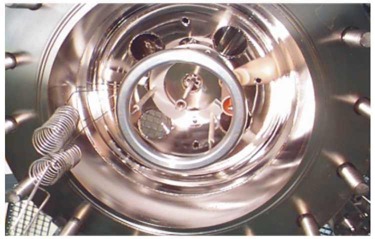
KALLA Loops
FZK

STELLA Loop
CEA

CIRCE Loop
ENEA

CorrWett Loop
PSI

VICE Loop
SCK-CEN



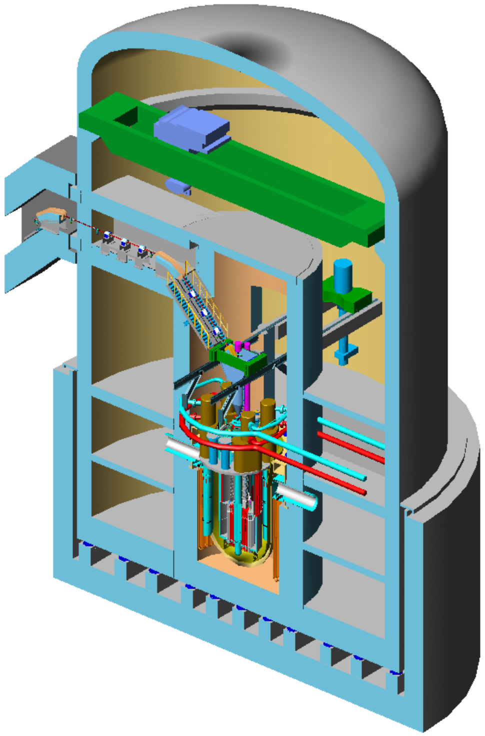
CHEOPE Loop
ENEA

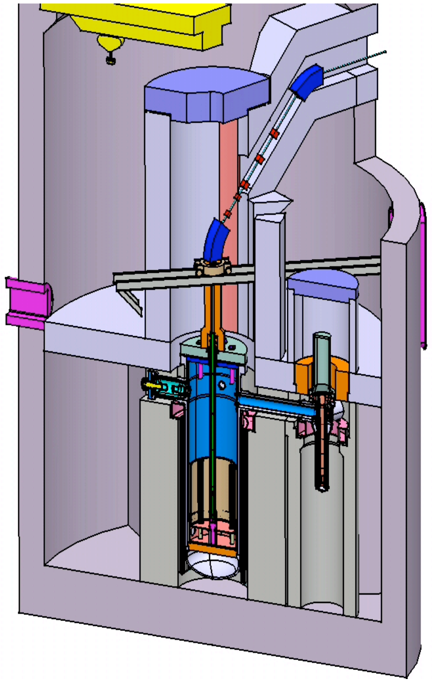
COSTA
FZK

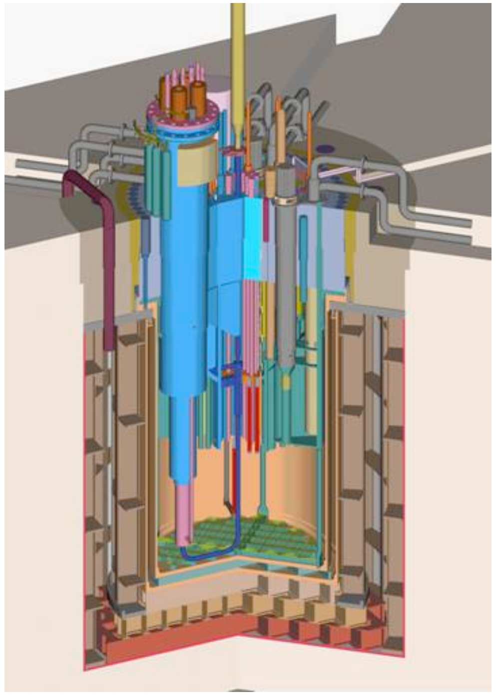
TALL Loop
KTH

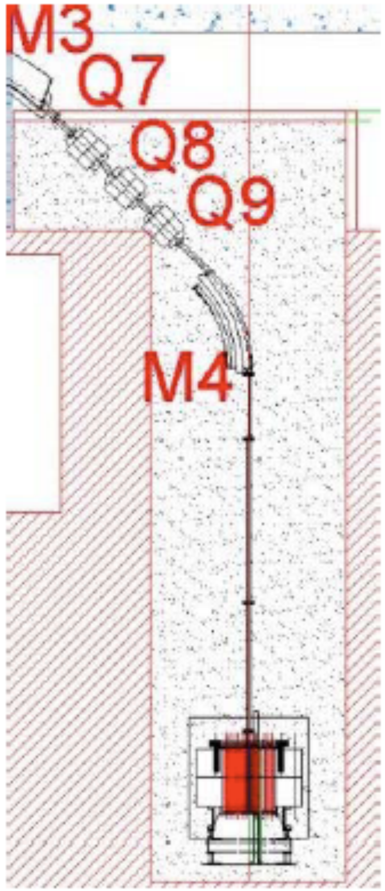
CIRCO Loop
CIEMAT

- Different systems proposed (funding?)









80 MW LBE-cooled XADS

80 MW Gas-cooled XADS

50-100 MW LBE-cooled XADS (*MYRRHA*)

Hamid Aït Abderrahim

TRADE (TRIGA Accelerator Driven Experiment)

Other developments concerning thorium

- **Example of India**: Very little uranium resources, but a lot of thorium:
  - Use PWR heavy water reactors (CANDU) and LWR to produce plutonium from their small uranium supply
  - Use sodium cooled U-Pu fast reactor with Th blanket to breed ^{233}U
  - Reprocess blanket and manufacture ^{233}U-Th fuel for advanced heavy water reactor

    (1) Wouldn't an accelerator simplify considerably the scheme?
    (2) Thermal neutron scheme not addressing waste issue!
- More recently two **Thorium studies in Norway**:
  - **Miljøkonsekvenser og regulering av potensiell thoriumrelatert industri i Norge** from the Norwegian Radiation Protection Authority
  - **THORIUM as an ENERGY SOURCE: Opportunities for Norway** by Thorium Report Committee (2008)
- Studies world-wide: China, Russia, UK, Korea, Japan, etc.
  - It is only a matter of time before an ADS prototype is built
  - **Who will take the lead? Use existing elements to go fast or go for a more ambitious industrial project from the start?**

Conclusion on ADS

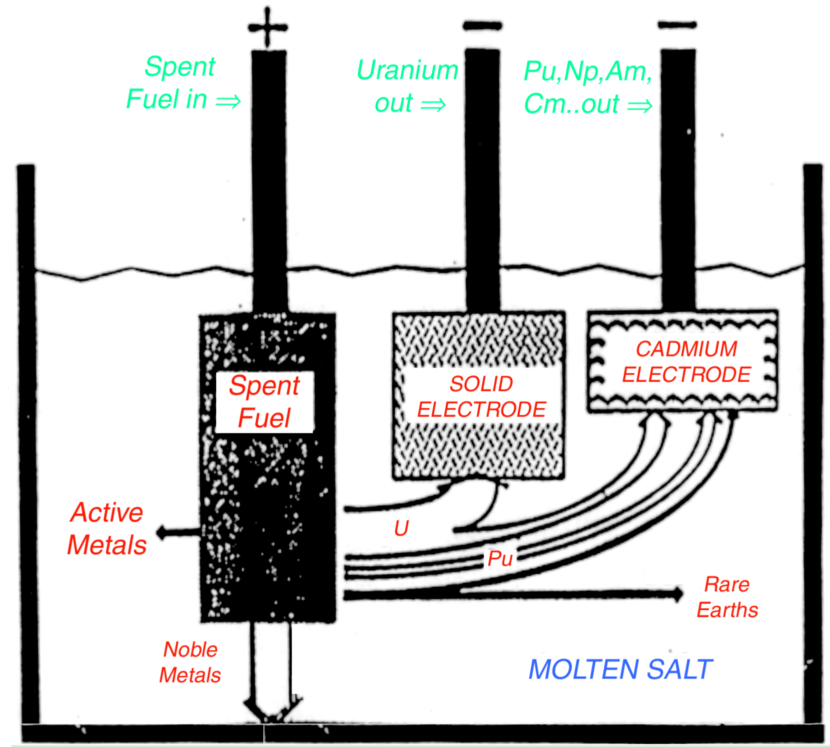
- Tremendous ADS R&D effort worldwide, in the past 15 years!
- Challenging idea but no show stopper. The next step should be a "demonstrator" of significant power, preferably with international collaboration (global problem).
- Nuclear fission energy is in my view the only way we have for a long time to produce sufficient clean energy to sustain harmonious growth on our planet:
  - ☛ ADS can change the image of nuclear energy, and make it "acceptable to society"; if nuclear energy is to be deployed on a large scale, then it must be ADS;
  - ☛ ADS would be complementary to renewable energies, allowing modulation of electric power production;
  - ☛ Proof of existence needed for the accelerator (Project X).
- It would be very good for particle physics to make an important contribution in the domain of the "energy problem"

Projects world-wide

Project	Neutron Source	Core	Purpose
FEAT (CERN)	Proton (0.6 to 2.75 GeV) (~10^{10}p/s)	Thermal (≈ 1 W)	Reactor physics of thermal subcritical system (k≈0.9) with spallation source - done
TARC (CERN)	Proton (0.6 to 2.75 GeV) (~10^{10}p/s)	Fast (≈ 1 W)	Lead slowing down spectrometry and transmutation of LLFP - done
MUSE (France)	DT (~10^{10}n/s)	Fast (< 1 kW)	Reactor physics of fast subcritical system - done
YALINA (Belorus)	DT (~10^{10}n/s)	Fast (< 1 kW)	Reactor physics of thermal & fast subcritical system - done
MEGAPIE (Switzerland)	Proton (600 Me) + Pb-Bi (1MW)	-----	Demonstration of 1MW target for short period - done
TRADE (Italy)	Proton (140 MeV) + Ta (40 kW)	Thermal (200 kW)	Demonstration of ADS with thermal feedback - cancelled
TEF-P (Japan)	Proton (600 MeV) + Pb-Bi (10W, ~10^{12}n/s)	Fast (< 1 kW)	Coupling of fast subcritical system with spallation source including MA fuelled configuration - postponed
SAD (Russia)	Proton (660 MeV) + Pb-Bi (1 kW)	Fast (20 kW)	Coupling of fast subcritical system with spallation source - planned
TEF-T (Japan)	Proton (600 MeV) + Pb-Bi (200 kW)	-----	Dedicated facility for demonstration and accumulation of material data base for long term - postponed
MYRRHA (Belgium)	Proton (350 MeV) + Pb-Bi (1.5 MW)	Fast (60 MW)	Experimental ADS - under study FP6 EUROTRANS
XT-ADS (Europe)	Proton (600 MeV) + Pb-Bi or He (4-5 MW)	Fast (50-100 MW)	Prototype ADS - under study FP6 EUROTRANS
EFIT (Europe)	Proton (≈ 1 GeV) + Pb-Bi or He (≈ 10 MW)	Fast (200-300 MW)	Transmutation of MA and LLFP - under study FP6 EUROTRANS

Fuel reprocessing strategy

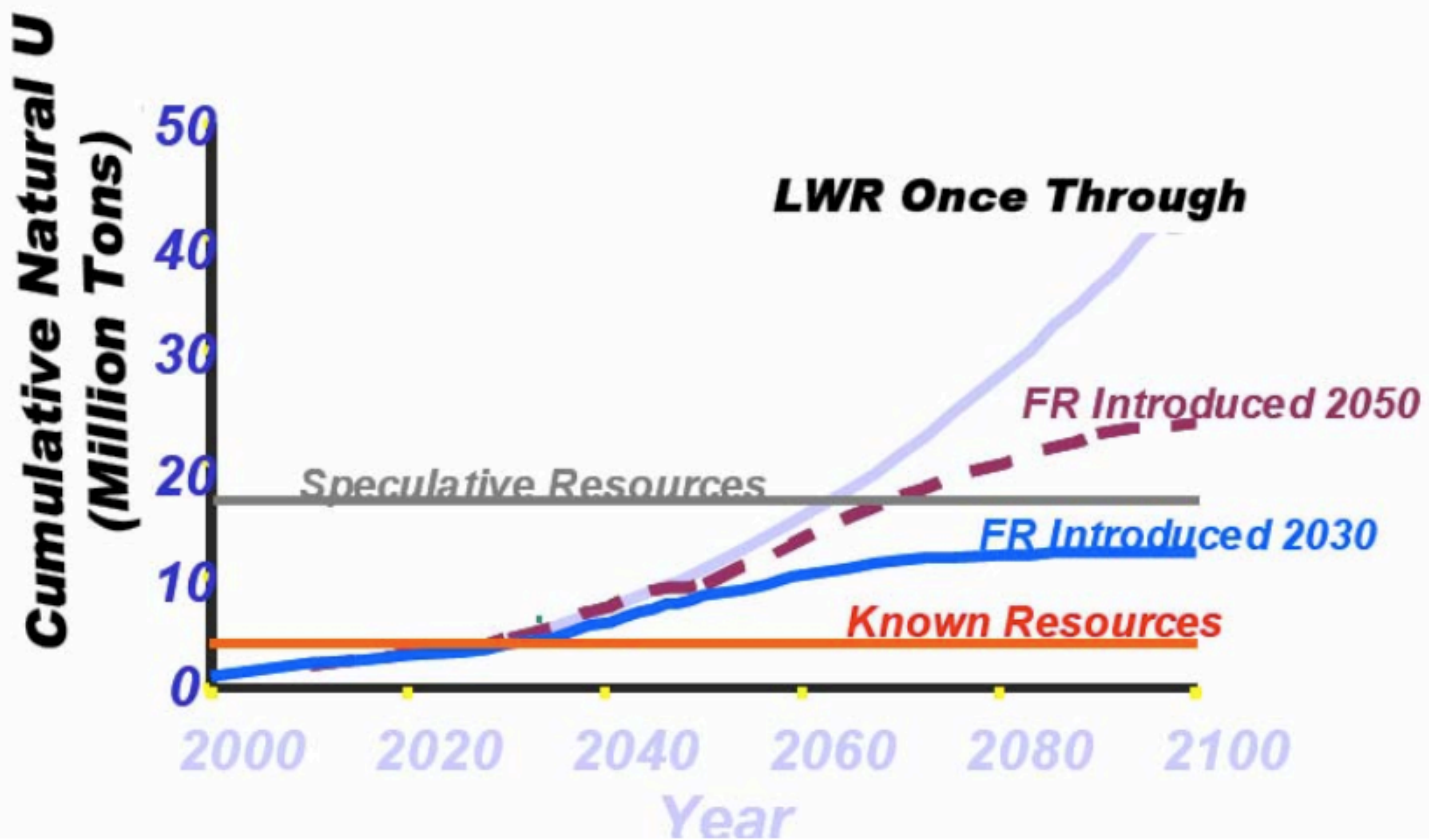
- As all TRUs fission in a fast neutron flux, there is no need to separate them from one another. Pyroelectric reprocessing developed at Argonne National Lab seems ideally suited. (PUREX, the Pu extraction method for MOX fuel is aqueous, so environmental impact is an issue).
- Actinides are collected under metallic form on a cathode with a small fraction of rare earths (inert can be recycled) coming from fissions fragments (electrolyte LiCl-KCl with actinide as chloride compound).
- Small size of system would allows operation at the power plant site.
- This process might have already been developed for the thorium cycle. Some studies in Europe, in 6th and 7th Framework Programmes.
  The leadership in this area is in the USA.



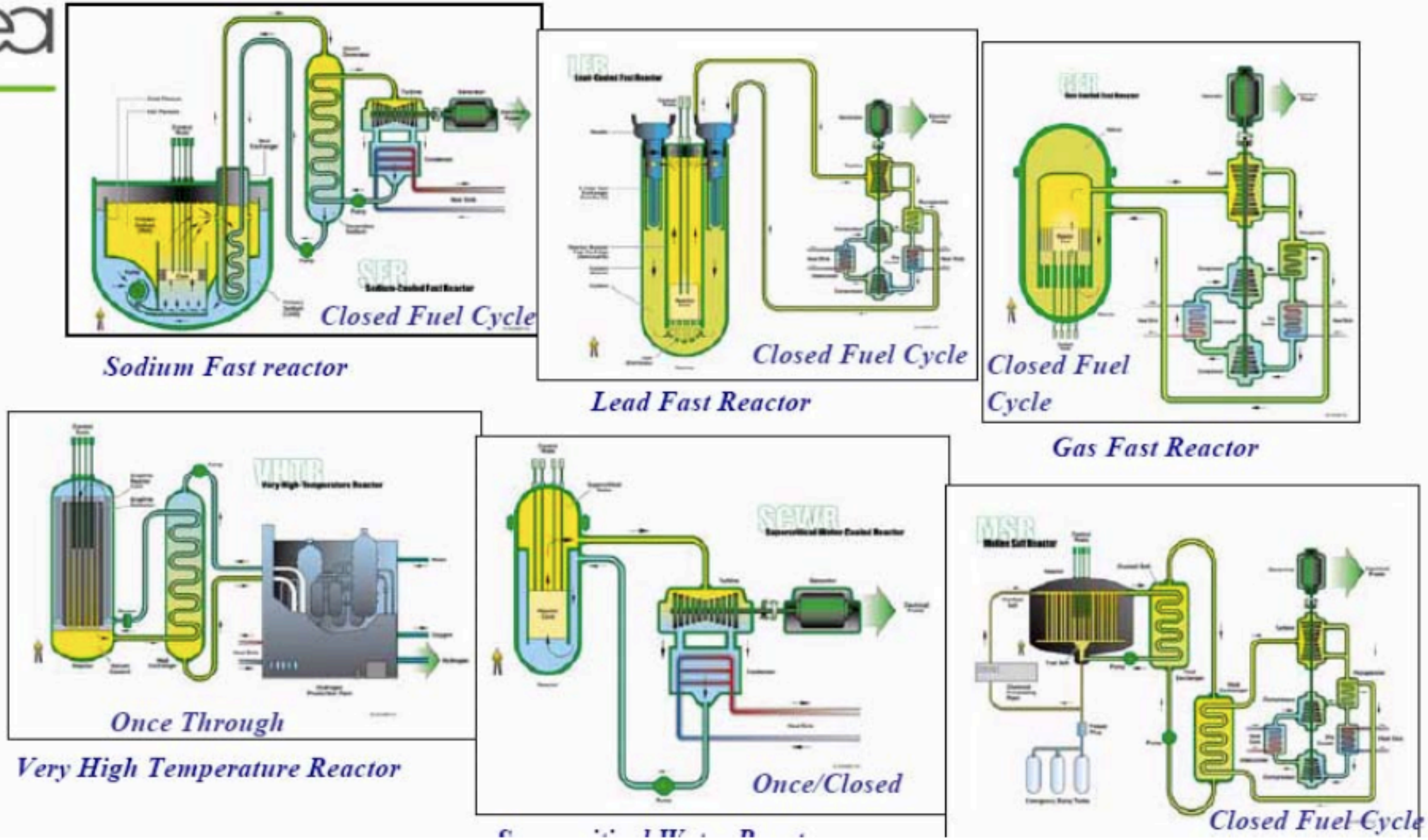
- Both the USA and Europe had projects to build linacs to produce tritium:
  - TRISPAL at CEA (France): 600 MeV, 40 mA, 24 MW
  - APT at LANL (USA): 1 GeV, 100 mA, 100 MW

- Minor Actinide production in thermal reactors (C. Renault, Oslo, Aug. 2007):
  - 3kg/TW_e.h in PWR with $^{235}U/U$ fuel
  - 12kg/Tw_e.h in PWR with MOX fuel

- Present nuclear energy is not sustainable



- 6 reactor concepts



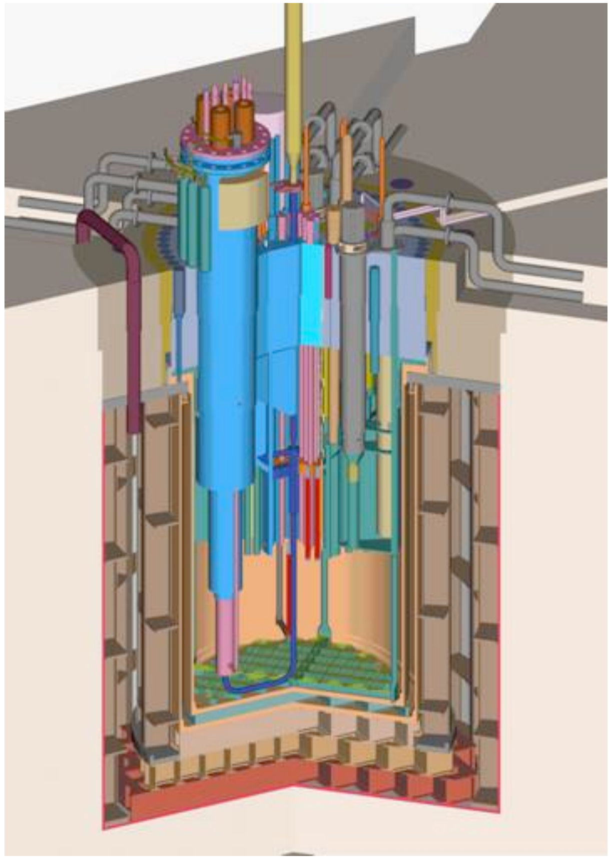
- The main strategic matter, ^{233}U, present in the fuel as an isotopic mixture of ^{232}U (1.4 kg), ^{233}U (2463 kg), ^{234}U (260 kg), ^{235}U (24 kg), ^{236}U(2.8 kg):
  - ☛ high γ activity, due in particular to ^{208}Tl (2.6 MeV); for a 30 kg mixture, the lethal does is obtained after 10 minutes (27 Sv/h).

- Total discharge of Np and Pu is 4 to 5 kg after 5 years of operation
  - ☛ to produce a sufficient quantity of plutonium and accumulate one critical mass (10.4 kg) requires several EA cycles.
  - ☛ Decay heat of Pu mixture 4.4 kW!

$\Rightarrow$ **unfortunately, there are much easier ways to do damage to society !**

- In view of the lack of EU funding for a prototype, Belgium proposed MYRRHA (international collaboration, part of Eurotrans) with the following two stage scenario:
  - ☛ 50 MWth subcritical system driven by a linac (IBA) to test ADS coupling (600 MeV, 4 mA, k ~ 0.97)
  - ☛ Turn the subcritical unit into a high flux critical unit for material testing; turn the accelerator into an ISOLDE type facility (Eurisol)

  OK for coupling tests, not sufficient to test thorium fuel (insufficient burnup), and transmutation. Funding?



50 MW LBE-cooled XADS (*MYRRHA*)