Reinventing Nuclear Power

July 13, 2023

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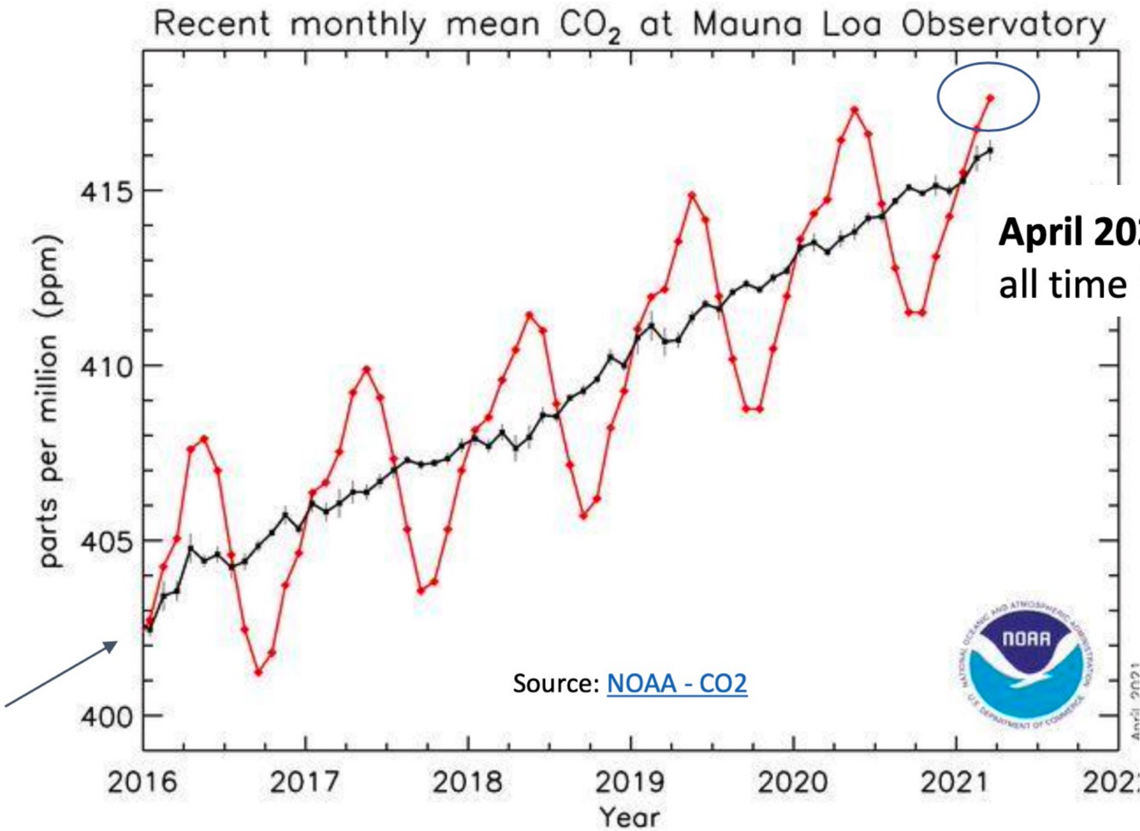
Co-founder and Technical Director, Transmutex SA

WHY BOTHER

Relentless CO_2 rise

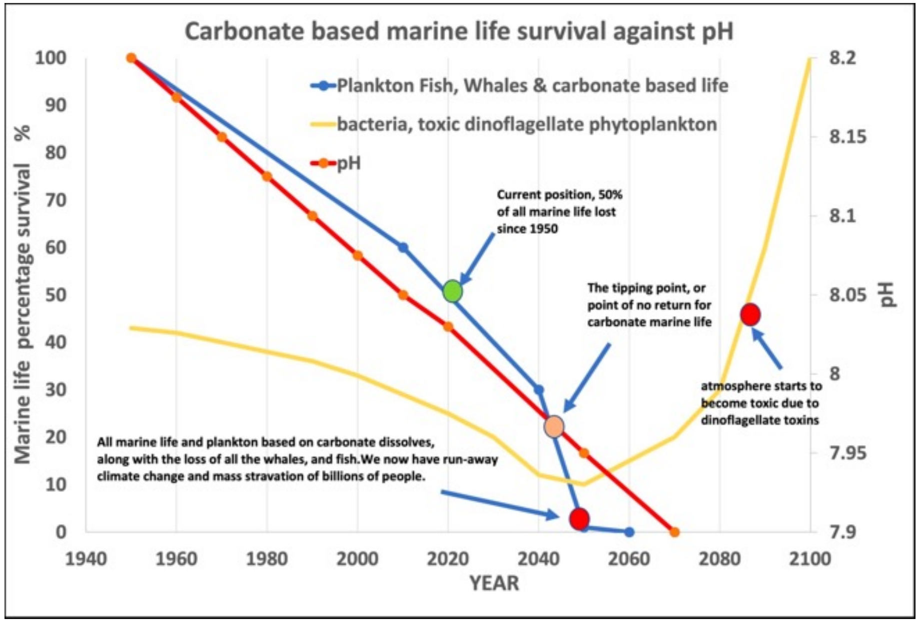
2015
Paris Agreement



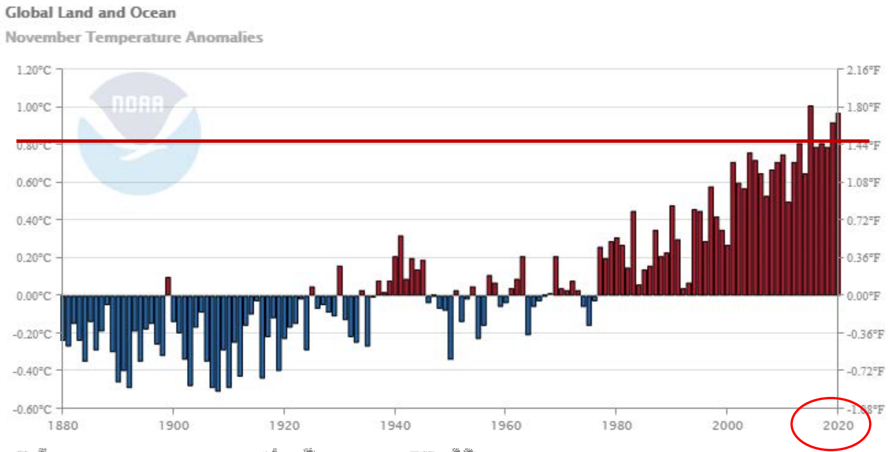
Source: NOAA - CO2

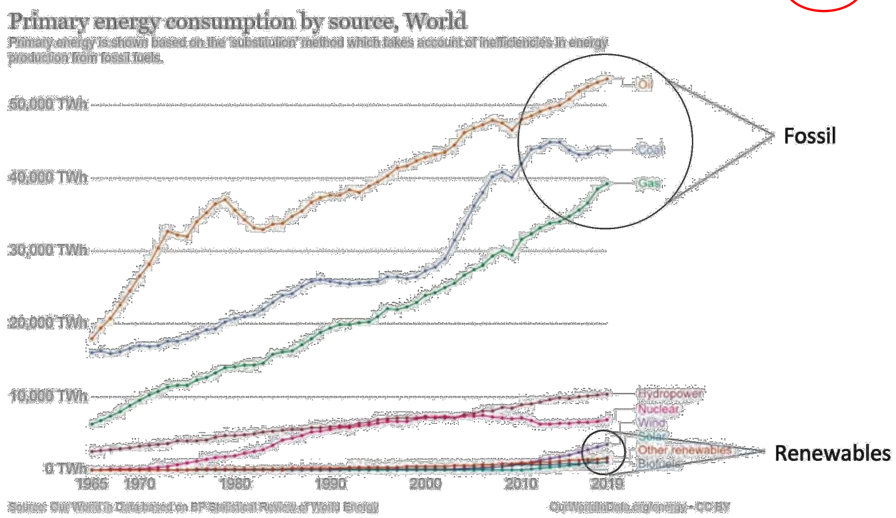
April 2021: 417 ppm
all time high record

1ºC Two decades before the prediction

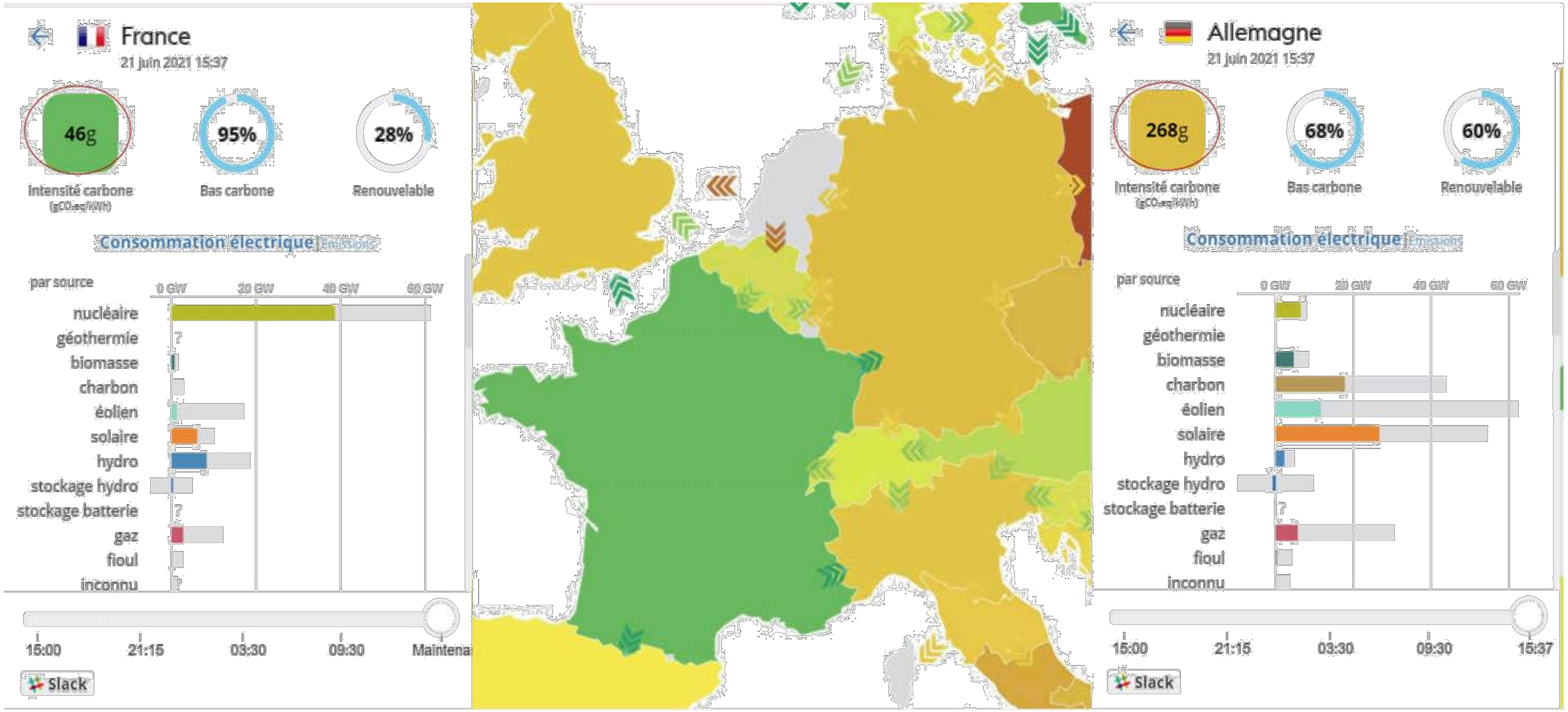


http://www.goesfoundation.com/





France vs Germany

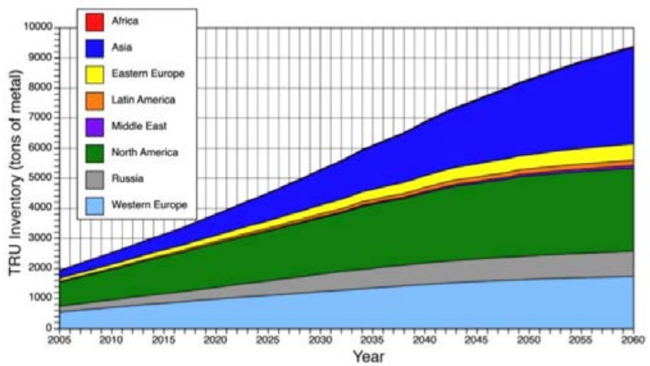


Only three solutions

A miracle in battery technology

A miracle in nuclear Fusion

Nuclear Fission

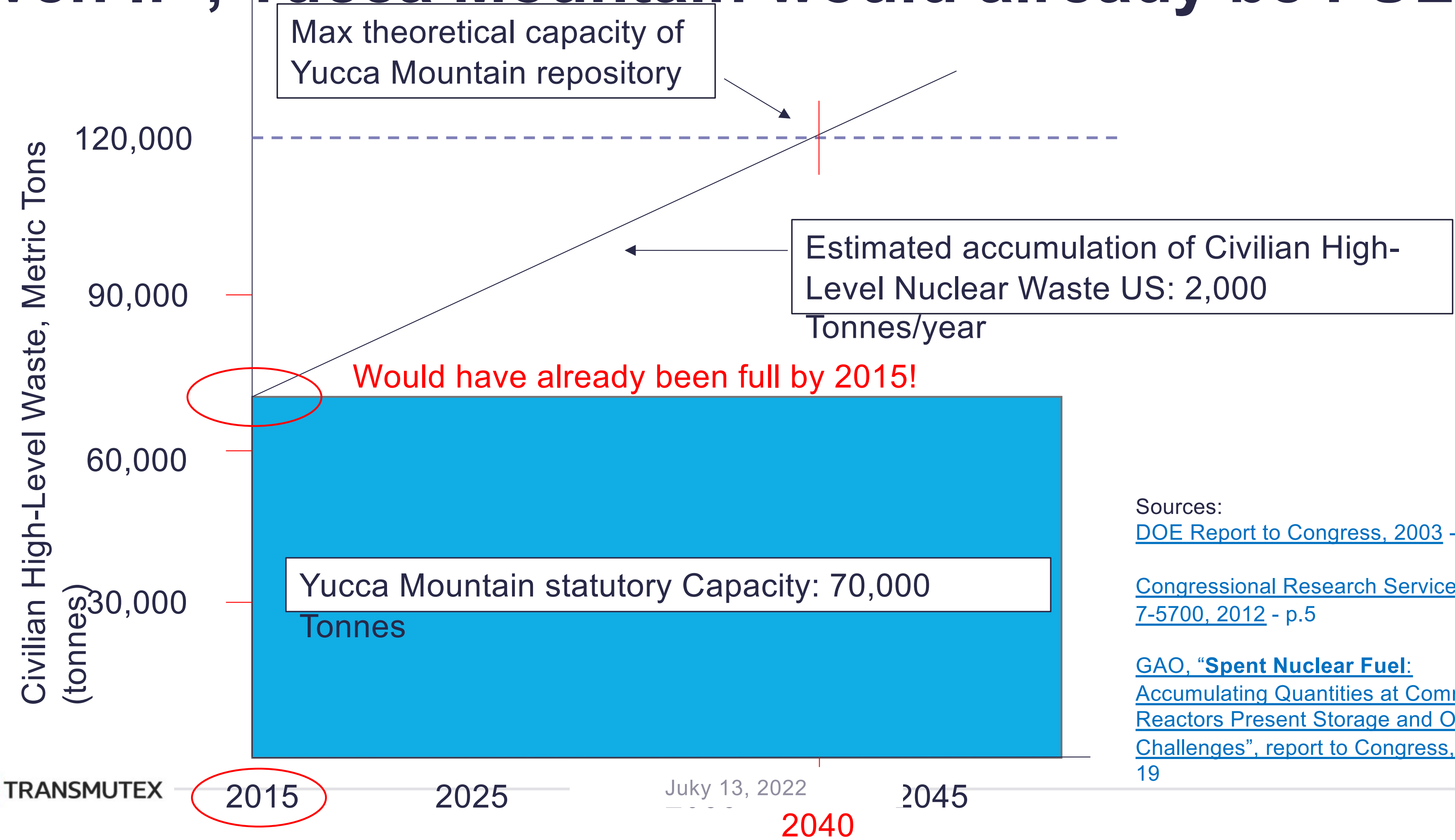


Assumes the present number (450) of NPP and those expected by 2035 (58).
Highly radioactive waste will exceed 9000 tons by 2060.

...BUT...

- Nuclear waste
- Accidents
- Proliferation

«Even If», Yucca Mountain would already be FULL



Sources:
DOE Report to Congress, 2003 - p.I-3

Congressional Research Services, Report 7-5700, 2012 - p.5

GAO, "**Spent Nuclear Fuel**: Accumulating Quantities at Commercial Reactors Present Storage and Other Challenges", report to Congress, 2012, p. 19

Nuclear waste

NATIONAL GEOGRAPHIC

Photos: Leaking Nuclear Waste Fills Former Salt Mine

https://www.nationalgeographic.com/history/article/100708-radioactive-nuclear-waste-science-salt-mine-dump-pictures-asse-ii-germany

One example, India

Wouldn't be nice…

Enhanced "Chernobyl" safety (no possibility of reactivity accidents).

Substantially increased "safeguards" against proliferation.

Possibility to burn waste while producing energy.

Incineration of offending intermediate-level waste (99Tc and 129I), further enhancing safety and reducing neutralization time for intermediate-level waste.

Negligible generation of new waste, which is in any case continuously recycled.

Reduction of costly intermediate and final high-level waste storage facilities.

"Local" reprocessing of fuel, only intermediate-level waste (Fission Fragments) leaves the plant to be buried. High-Level Waste (Uranium and beyond) is continuously recycled inside the plant.

Essentially no effluents from fuel reprocessing.

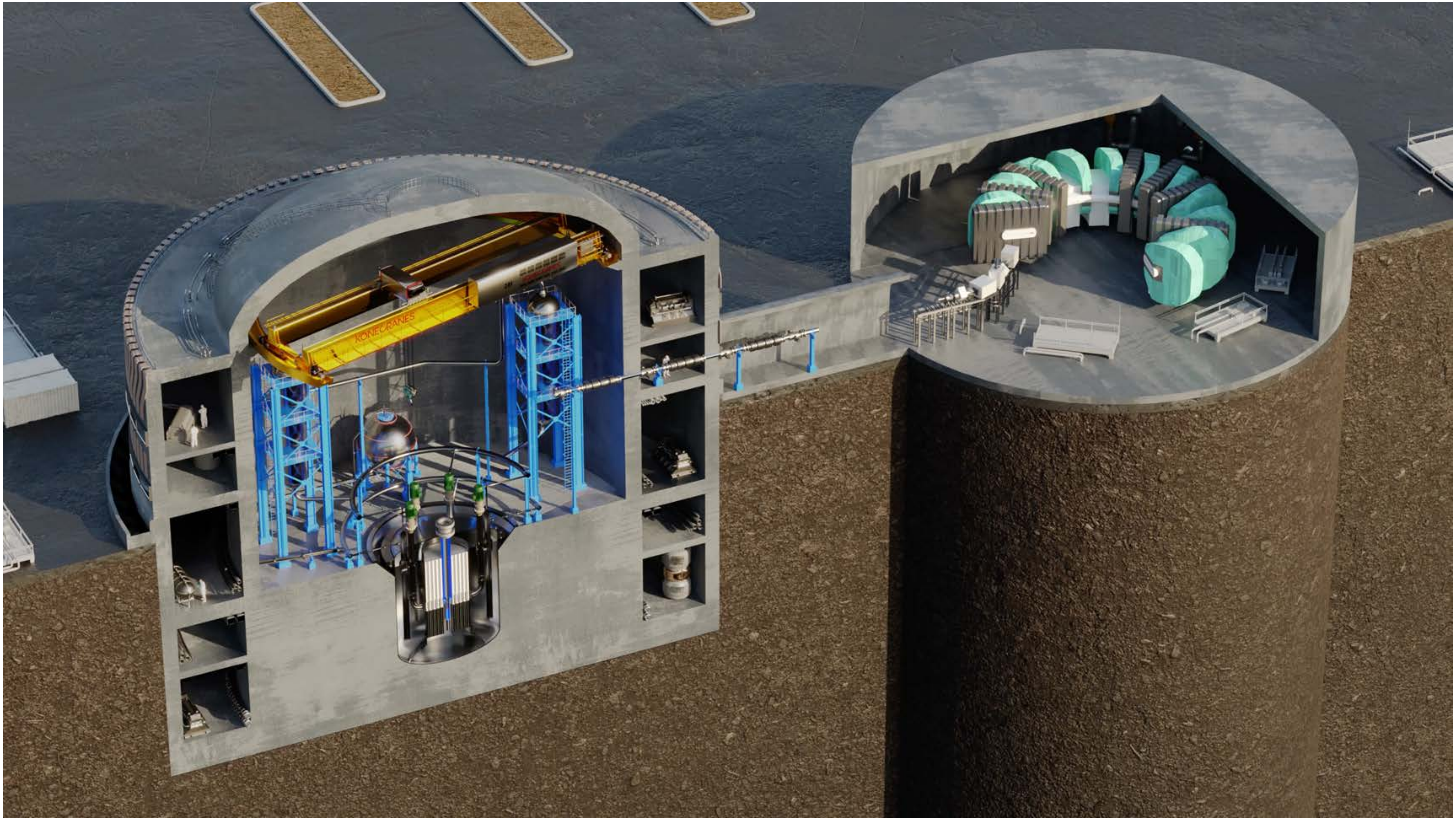
Fuel is constructed inside the plant; no fuel – spent or fresh – enters or leaves the plant

Elimination of the enrichment procedure, which is expensive and proliferating.

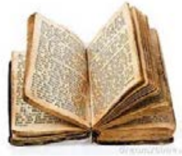
Less "demanding" fuel parameters, increasing effective fuel yield.

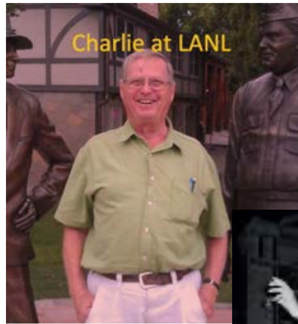
Possible integration with existing nuclear cycles.

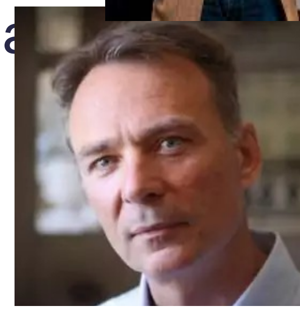
Possibility to use both U and Th fuel cycles, effectively doubling the available resources, reducing geopolitical tensions, and the price of fuel raw material due to larger supply.


KONECRANES

A new old idea







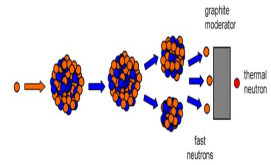
The concept of ADS (Accelerator Driven System) is developed in the 80s by Charles D. Bowman at Los Alamos

In the 90s it was taken up by the Nobel Prize winner Carlo Rubbia at CERN who developed it with the name of Energy Amplifier

It is then studied extensively by the CEA French

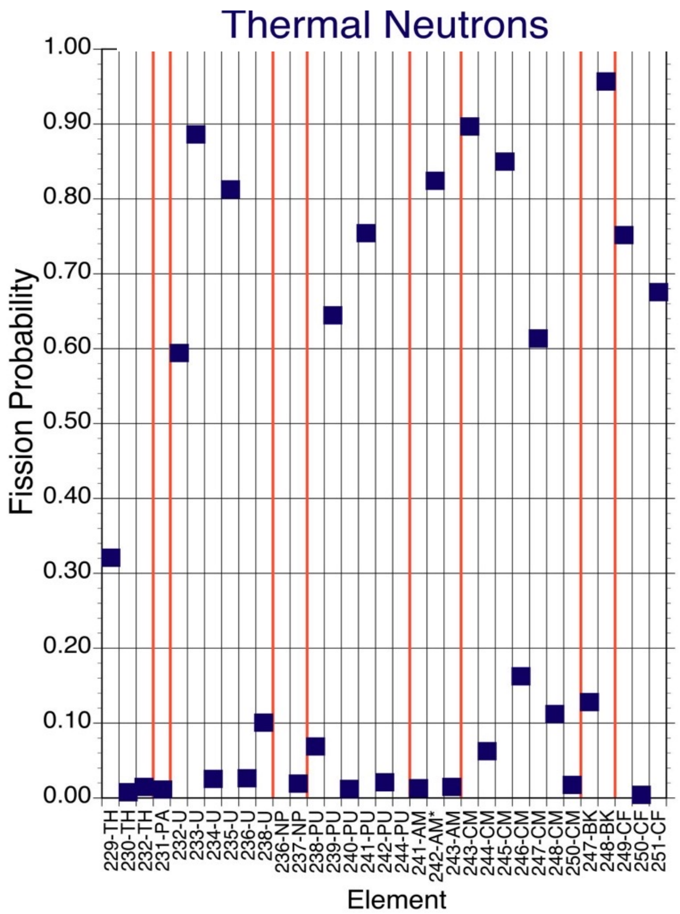
But never realized in practice

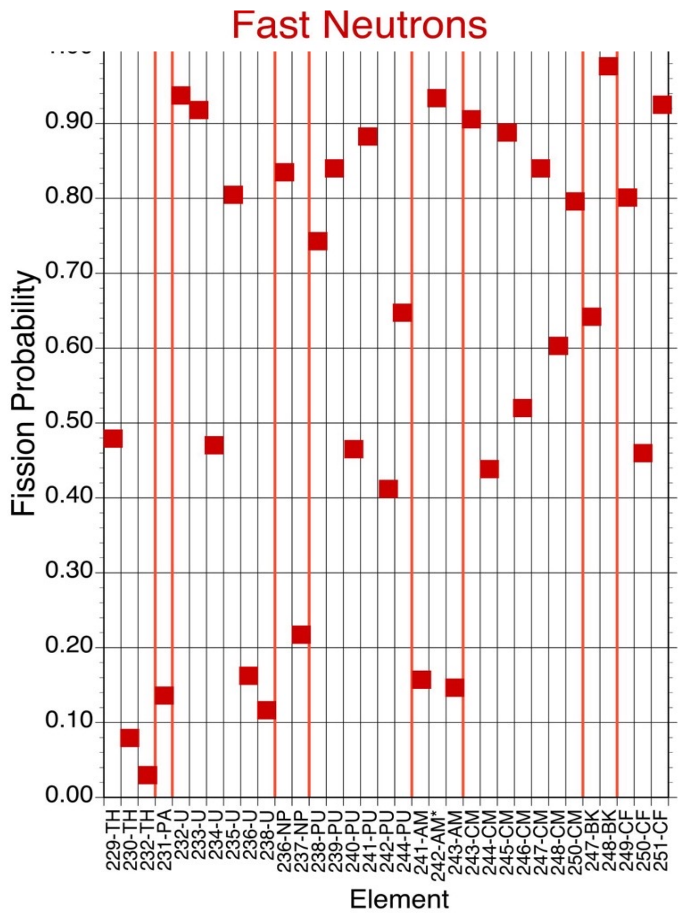
In 2019 Transmutex SA was founded in Geneva by Franklin Servan-Schreiber and colleagues with the aim of building a First Of A Kind (FOAK) ADS by 2032



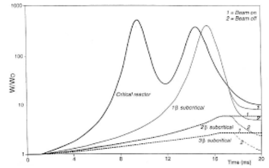
Fast Neutrons

In a fast neutron flux, transuranic elements can fission, and do not accumulate as much as in a thermal neutron flux

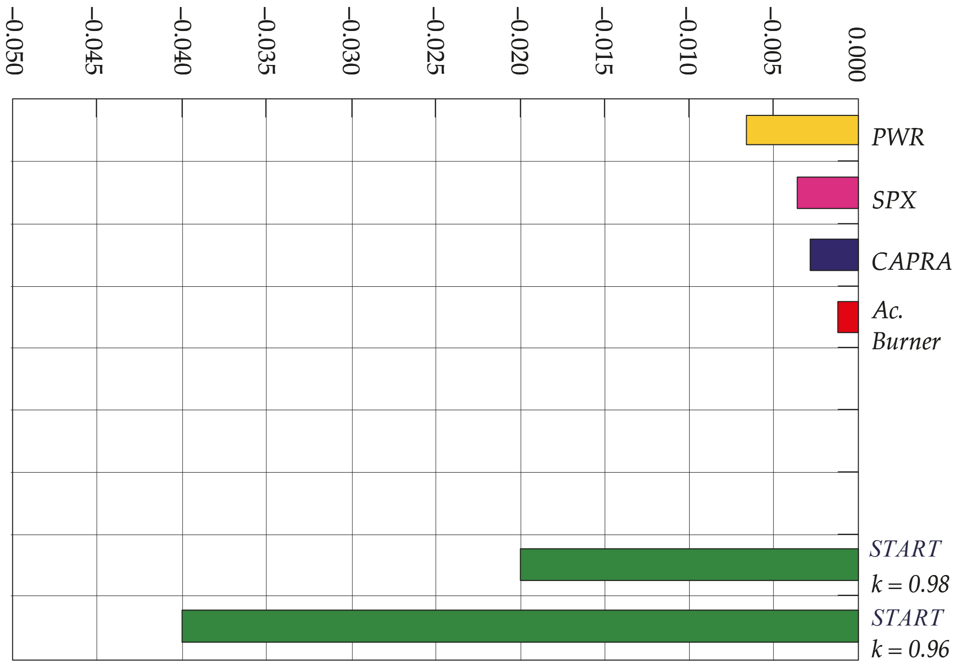




Critical vs Sub-Critical Systems

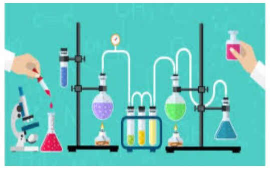


$$\rho = (1 - k)/k$$



Maximum distance from prompt criticallity

1. Non-self-sustained chain reaction
   - ⇨ minimizes criticality and power excursions
   - ⇨ stays sub-critical whether the accelerator is on or off
   - ⇨ Extra level of safety against criticality accidents
3. The accelerator is a control mechanism
   - ⇨ more convenient than control rods in a critical reactor
   - ⇨ safety concerns, neutron economy
4. Decouple the neutron (spallation) source from the fissile fuel (fission neutrons)
5. Accept fuels not acceptable in critical reactors
   - ⇨ Minor Actinides
   - ⇨ High Pu content
6. Can incinerate LLFP



Review of Sub-Critical Core Experiments

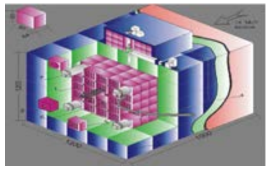
Highly specific experiments have been carried out to verify the fundamental physics principle of Accelerator-Driven Sub-Critical Systems:

1. The First Energy Amplifier Test (FEAT):
   S. Andriamonje *et al.* Physics Letters B 348 (1995) 697–709
   J. Calero *et al.* *NIM* A 376 (1996) 89–103

2. The TARC experiment:
   A. Abánades *et al.* *NIM A478(3)* (2002) 577-730

3. The MUSE Experiment (MUltiplication de Source Externe):
   M. Salvatores *et al.*, 2nd *ADTT Conf.*, Kalmar, Sweden, June 1996

4. The YELINA Experiment (ISTC-B-70):
   S. Chigrinov et al., Institute of Radiation Physics & Chemistry Problems, National Academy of Sciences, Minsk, Belarus



Reactivity Feedbacks

Major difference between a critical reactor and an START (reactivity in $\$ = \frac{\rho}{\beta}$ where $\rho = \frac{k-1}{k}$):

- Effect of a rapid reactivity insertion in the START for two values of subcriticality (0.98 and 0.96), compared with a Fast Critical Reactor
- 2.5\$ ($\Delta k/k \sim 6.5\times10^{-3}$) of reactivity change corresponds to the sudden extraction of all control rods from the reactor

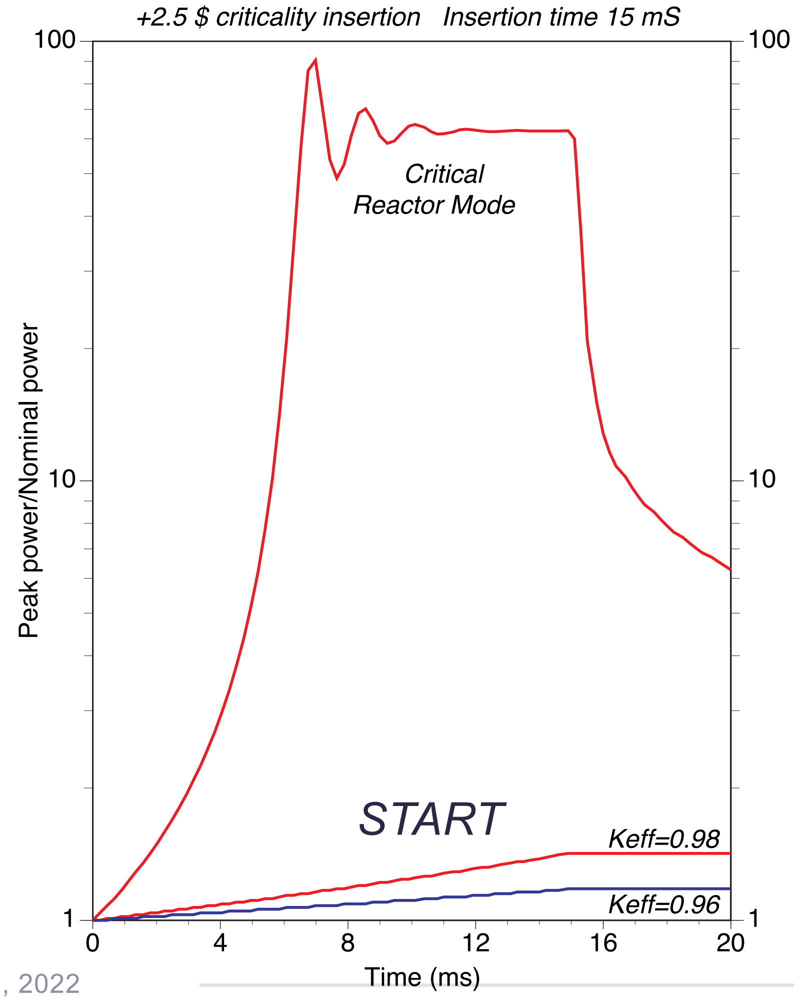


Figure 1.3

C. Rubbia et al., CERN/AT/95-53 9

Is the gain worth the pain?

Record gain with fusion JET Q=0,01

https://whyy.org/segments/fusion-energy/

Total energy produced by an START

$$P_{beam} + P_{beam}\frac{G_0 k}{1-k}$$

Total electricity produced

$$P_{beam}\eta_{el}\left(1+\frac{G_0 k}{1-k}\right)$$

Electricity used by the accelerator

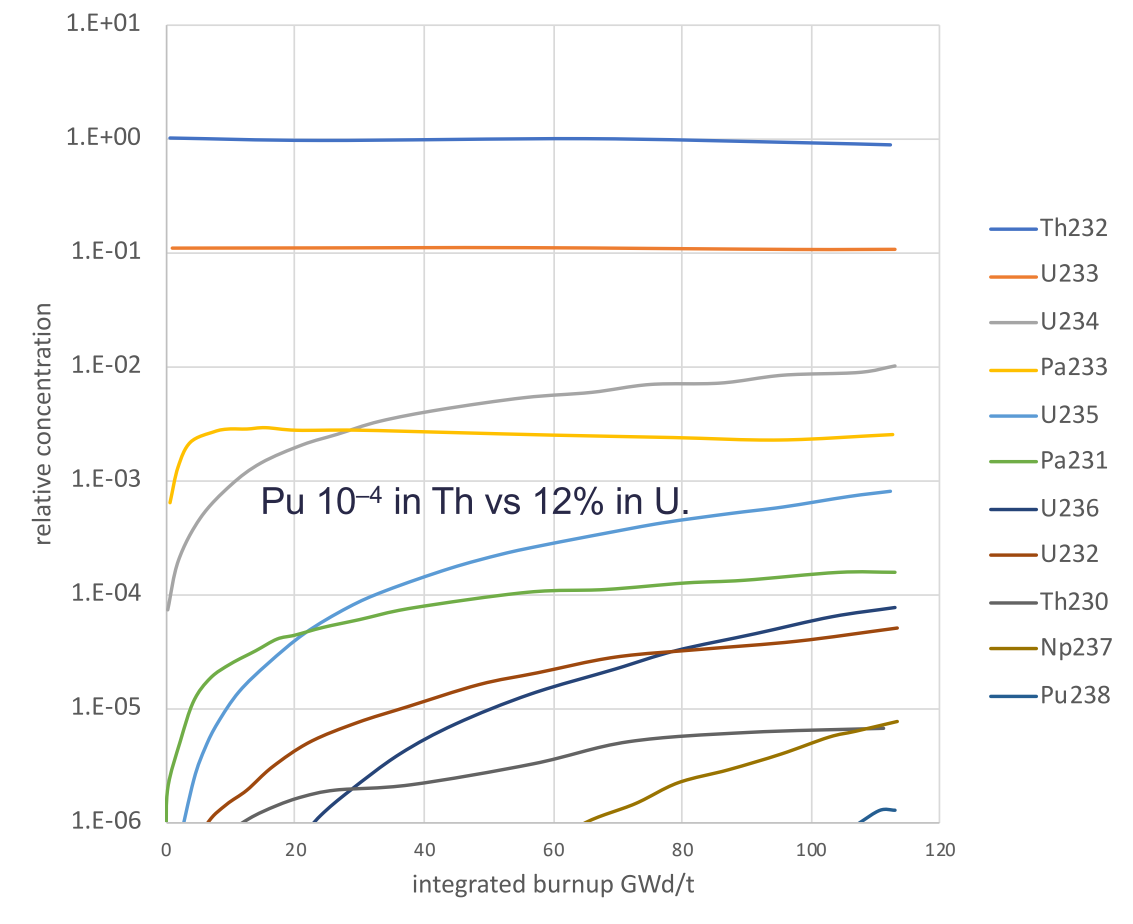
$$P_{beam}\frac{1}{\eta_{acc}}$$

Ratio of the electric energy in and electric energy out

$$Q = \eta_{acc}\eta_{el}\left(1+\frac{G_0 k}{1-k}\right)$$

Typical values $\eta_{el} = 0.4,\ \eta_{acc} = 0.2 \Longrightarrow Q = \mathbf{6.5}\ @\ k = 0.97$

Thorium fuel

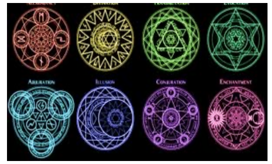


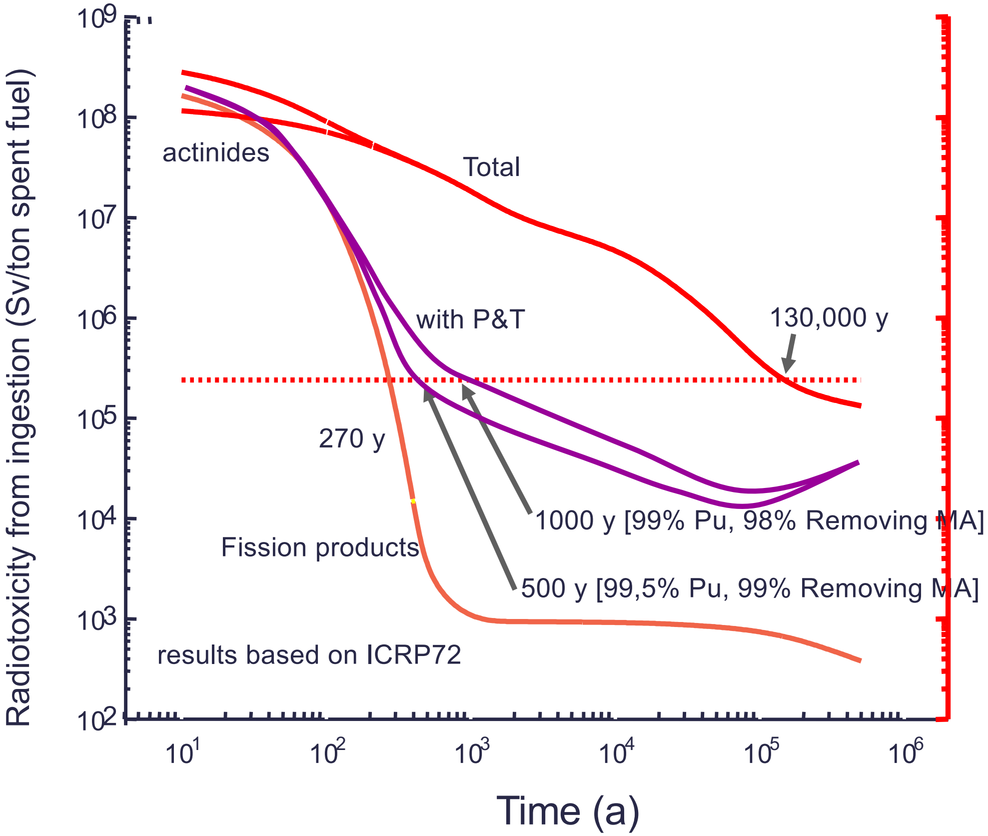
Transmutation in kg/TW$_{th}$h

Nuclide	START (ThPuO2)	PWR (UO2)
^{233}U	+ 31.0	
Pu	– 42.8	+ 11.0
Np	+ 0.03*	+ 0.57
Am	+ 0.24*	+ 0.54
Cm	+ 0.007*	+ 0.044
^{99}Tc prod	+ 0.99	+ 0.99
^{99}Tc tras	– 3.77	
^{129}I prod	+ 0.30	+ 0.17
^{129}I tras	– 3.01	

*equilibrium concentrations

Partitioning and transmutation

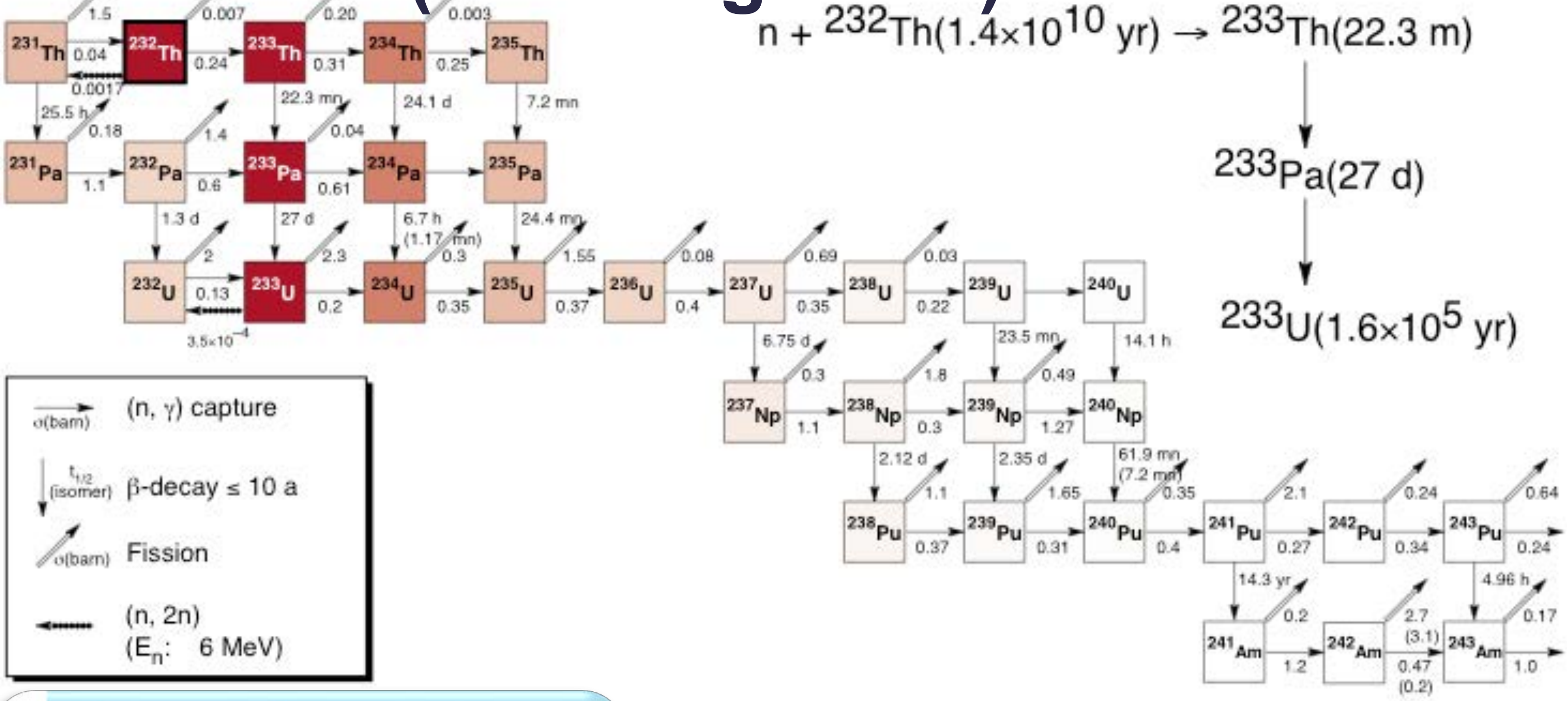




START P&T reduces long-term HLW activity by transforming long-lived radionuclides (MA, LLFP) into short-lived radionuclides

- MOX recovers energy but worsens the isotopic composition of waste
- A C-FNR cannot recycle more than 2% Pu and MA due to TRU-β
- The more complex the retreatment, the greater the loss

Thorium as fuel (breeding 233U)



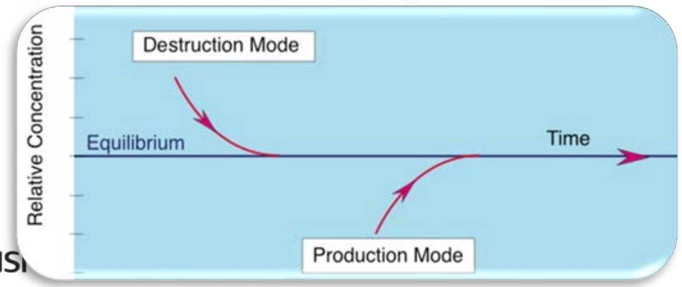
$$n + {}^{232}Th(1.4\times10^{10}\ yr) \rightarrow {}^{233}Th(22.3\ m)$$

$$\downarrow$$

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

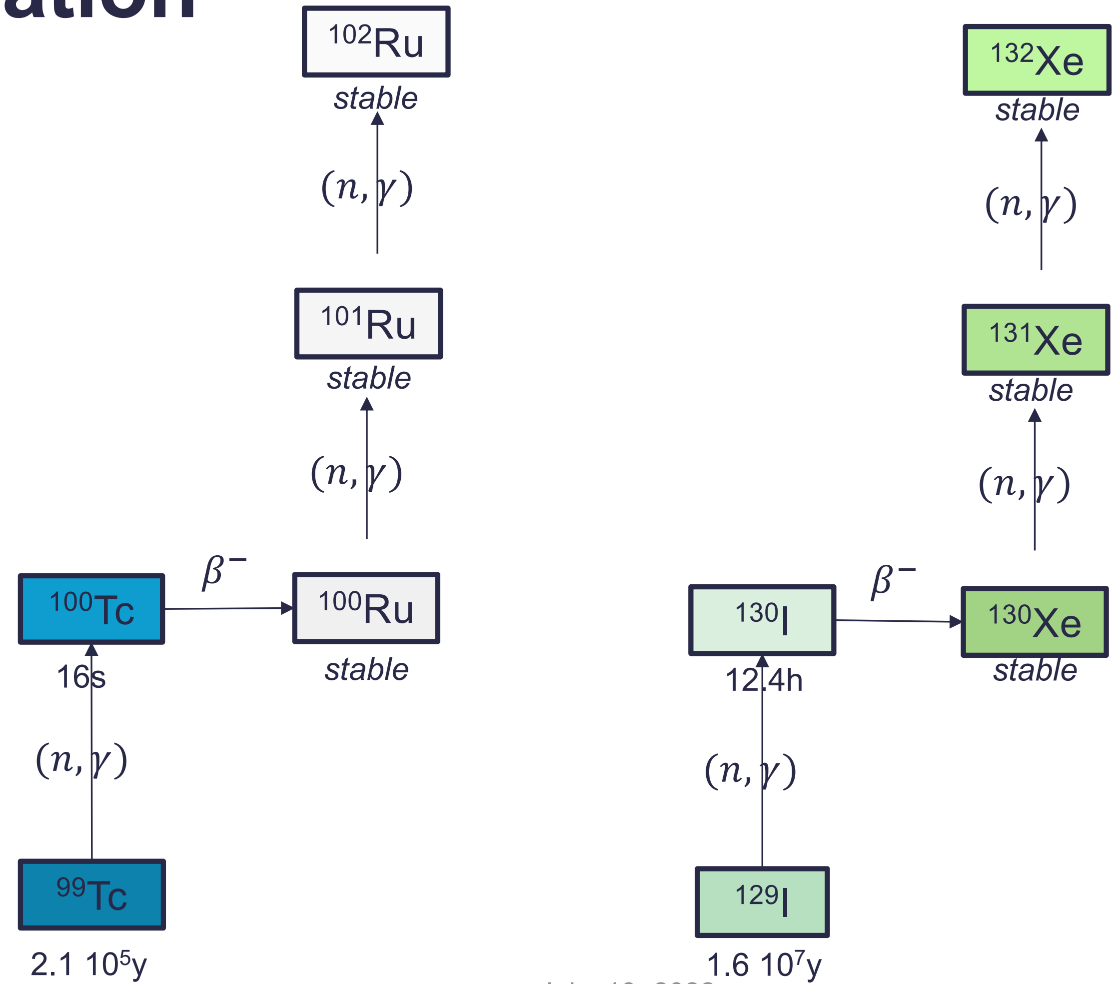
$$\downarrow$$

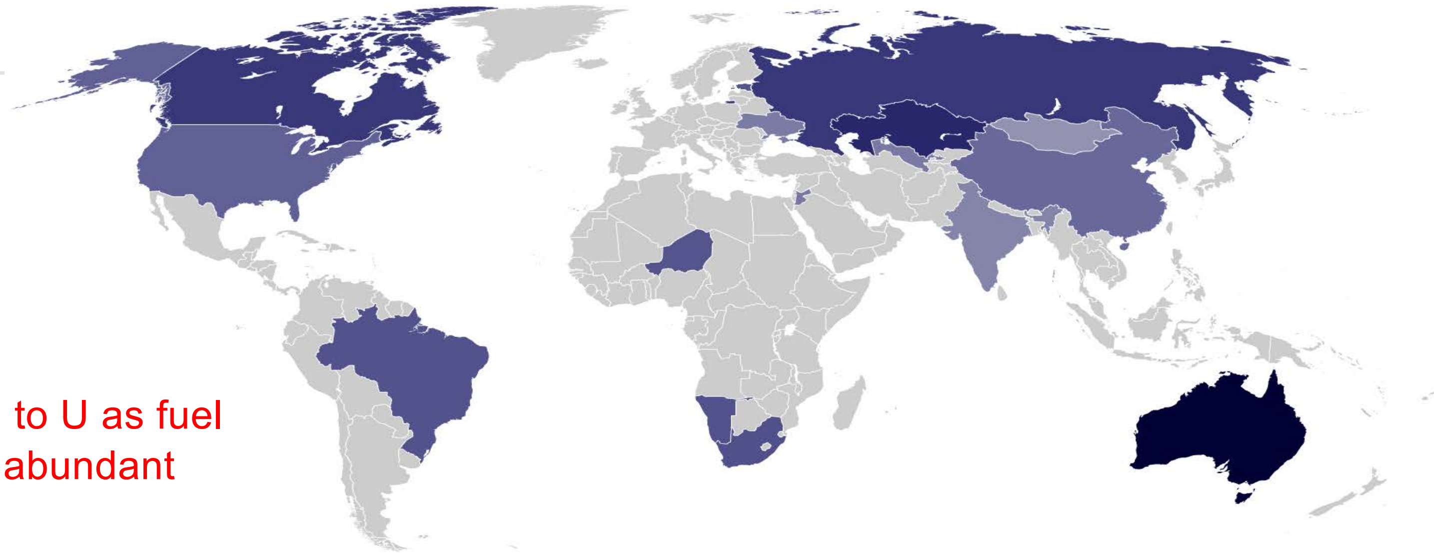
$${}^{233}U(1.6\times10^{5}\ yr)$$



It is the presence of the accelerator which makes it possible to choose the optimum fuel.
Low equilibrium concentration of TRU makes the system favourable for their elimination:
Pu 10^{-4} in Th vs 12% in U.

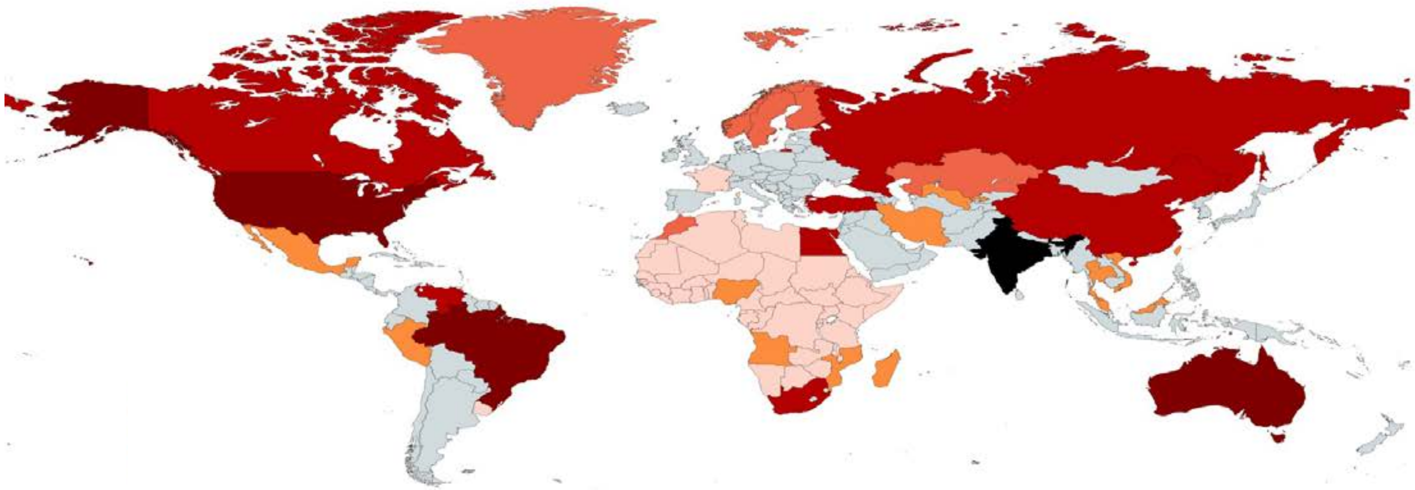
FF incineration





Uranium

Addition of Th to U as fuel
360x more abundant

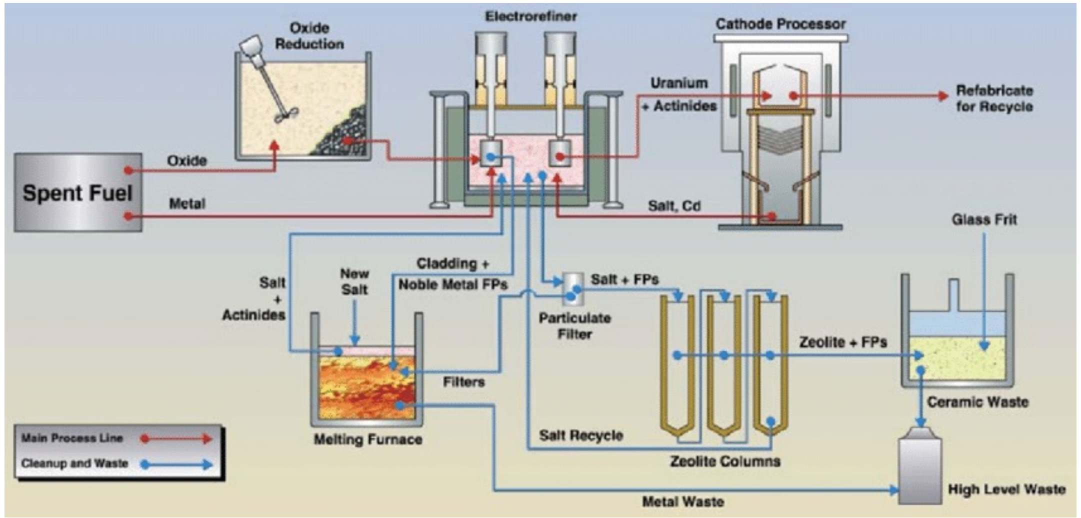


Thorium

Pyro-processing

Fully tested at the laboratory level
Very efficient (> 99.9%)

No effluents waste, all chemicals recycled: no discharges in the environment



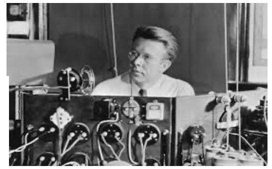
- Small size*: it may be located on the reactor site, minimizing fuel transport*
- Non proliferating: all TRU's always intimately mixed
- Small batches: no criticality risks.
- Short cooling time (no organic chemicals and remote handling)

Cyclotron

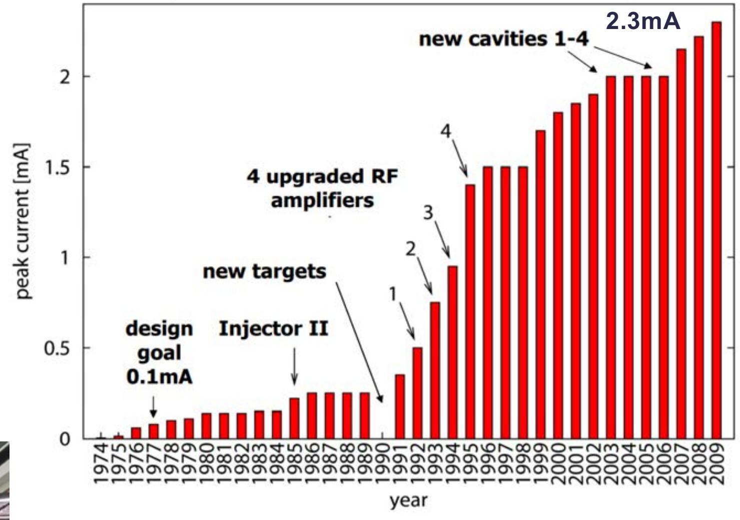
Framework agreement with PSI

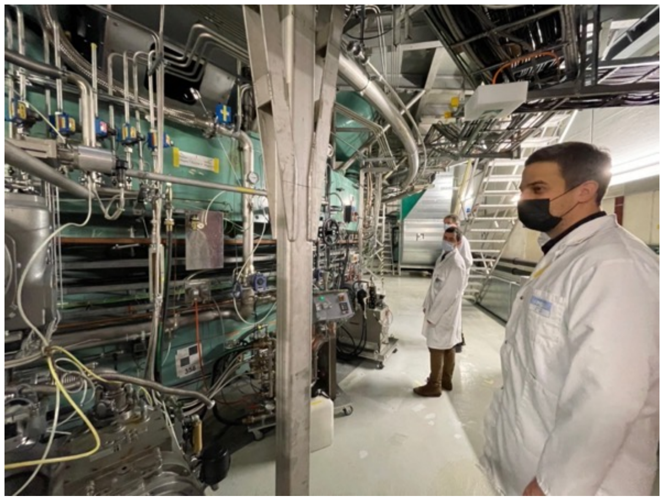
Collaboration to build the new flaptop

Development of the START cyclotron project



Evolution of peak current in the 590MeV cyclotron (HIPA)





WORKING WITH THE BEST

THE HIGH-POWER TARGET

Target

Collaboration with LANL, ENEA Brasimone and PSI

Target design group is composed of 14 members with world's best reactor and target experts

Studying both solid and LBE target

Projected target lifetime 18+ months

n/p ~ 16-18 according to the target geometry

Final design selection by fall

Experimental campaign to be planned with LANL and ENEA

PAUL SCHERRER INSTITUT PSI

Los Alamos NATIONAL LABORATORY EST. 1943

ENEA

CERN

LFR integration with ANSALDO Core design with ENEA

Lead-cooled fast reactor

SMR-size 125MWe / 300MWth

Primary refrigerant circuit with forced circulation

Primary system 400÷520°C

Fuel: MOX and Th

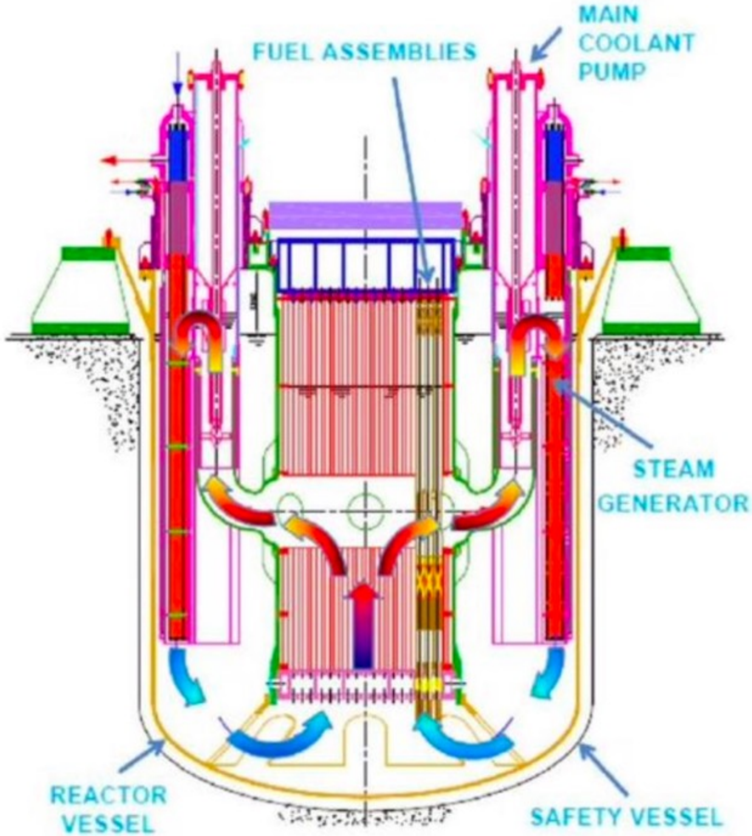
Fuel cycle/residence time: 12 months / 6 years

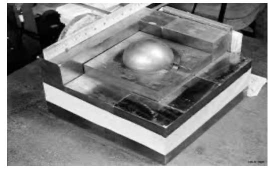
No need for safety injection systems

Passive removal of waste heat

Lifetime: 40 years

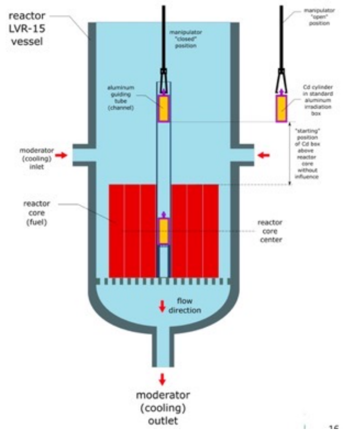
15 years of design studies & pre-licensing activities

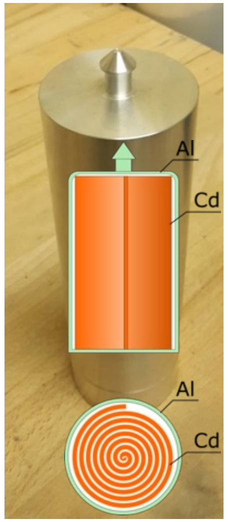


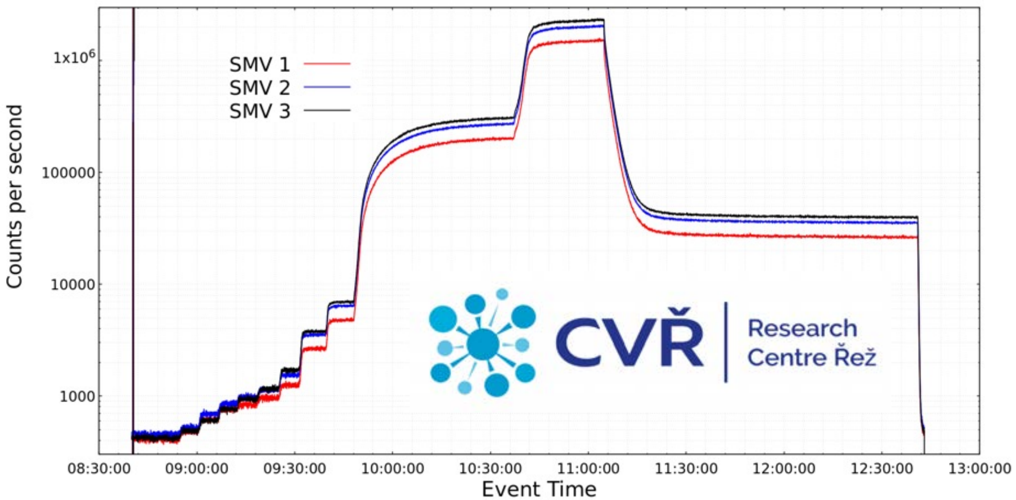


VALIDATION EXPERIMENTS

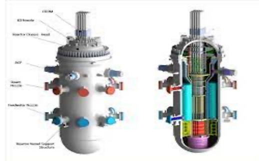
First sub-critical safety experiment at CVR-REZ



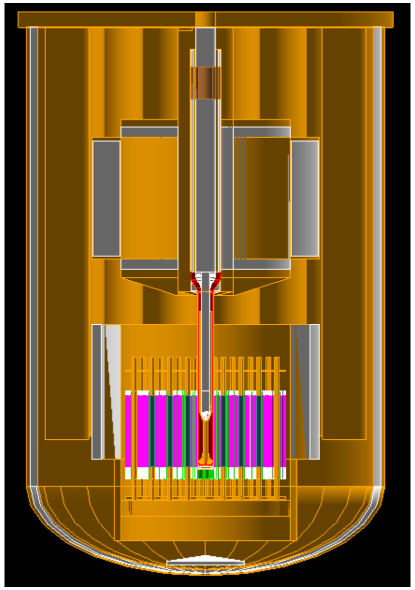


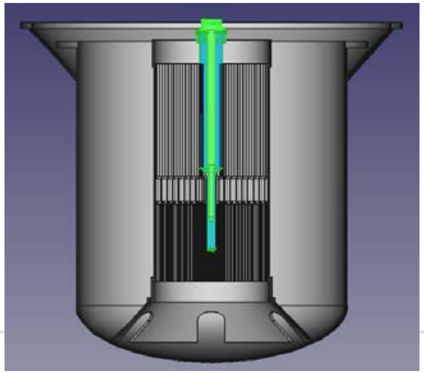


ADS Simulation

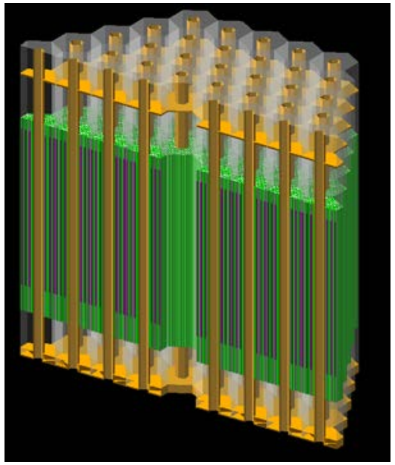


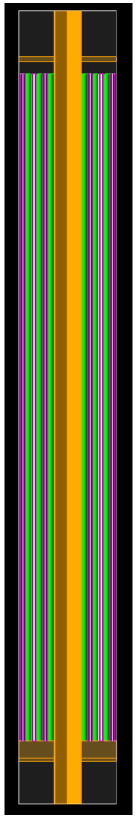
Reactor + Target

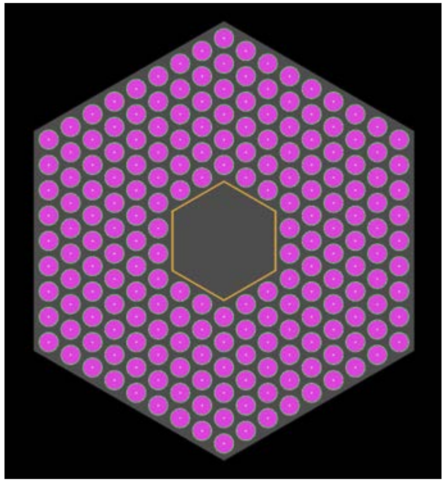




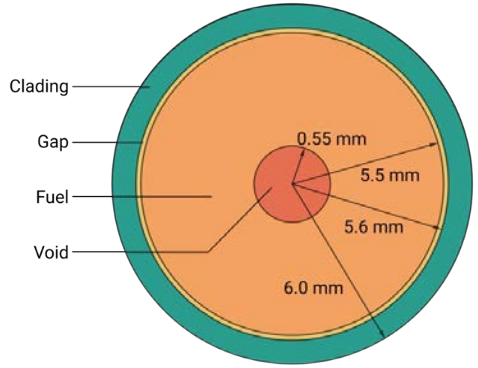
Fuel Assembly

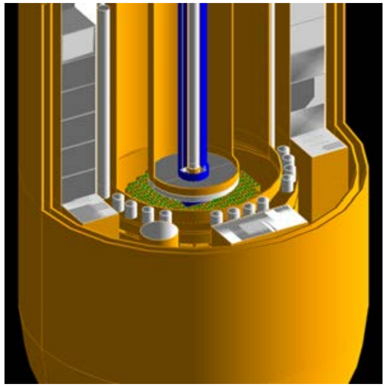




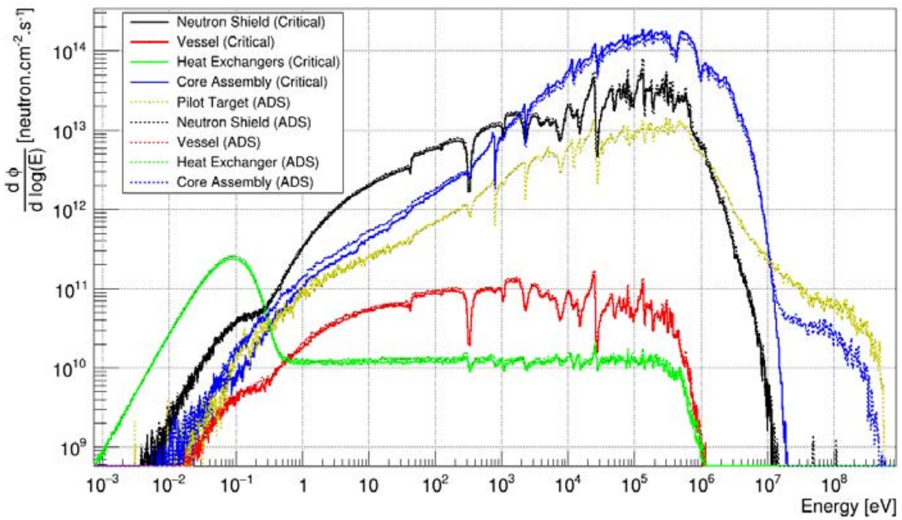


Fuel Pin

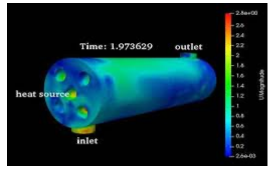




Core



Development of deterministic toolset



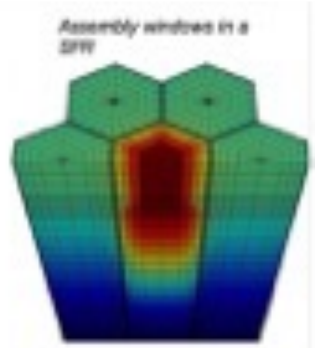
Collaboration with EPFL/PSI for the development of a multi-physics package for ADS

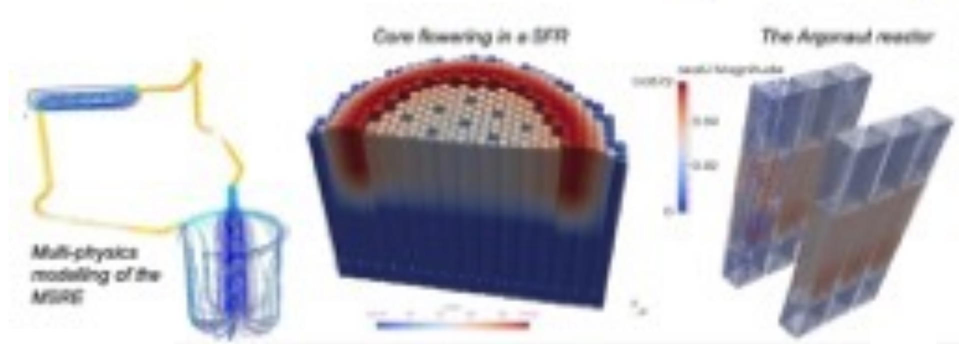
Multi-physics code (GenFOAM) based on the C++ OpenFOAM toolbox

- Coupled thermal-hydraulics, thermal-mechanical, and neutronics solvers
- SN, SP3, Point-Kinetics, diffusion, adjoint diffusion
- Thermal-mechanical solver with mesh deformation

Validated against FFTF experimental data, MC Serpent, PARCS, TRACE

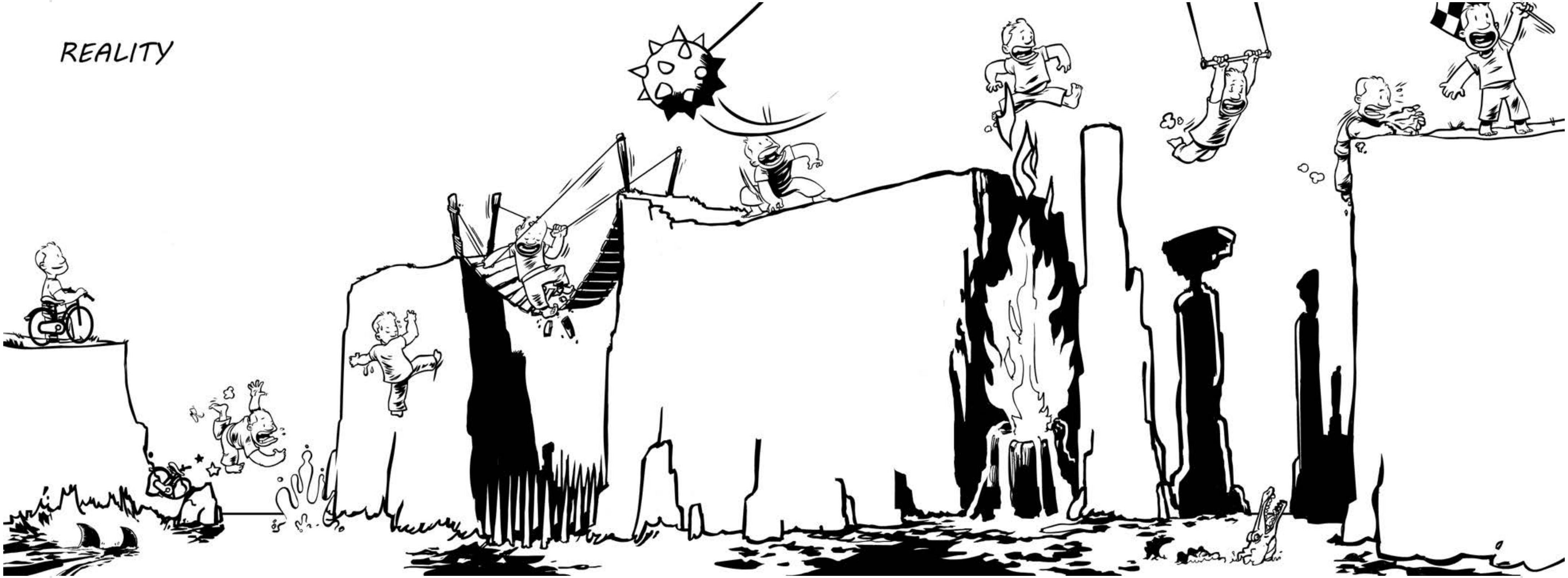
Code applied to CROCUS experimental light water reactor, ESFR, MSFR, ...

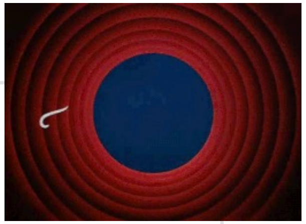




C.Fiorina, Basics of GeN-Foam
https://conferences.iaea.org/event/255/contributions/19575/attachments/10623/15404/Day04_02_Carlo.pdf

Using existing technologies


REALITY



Questions?