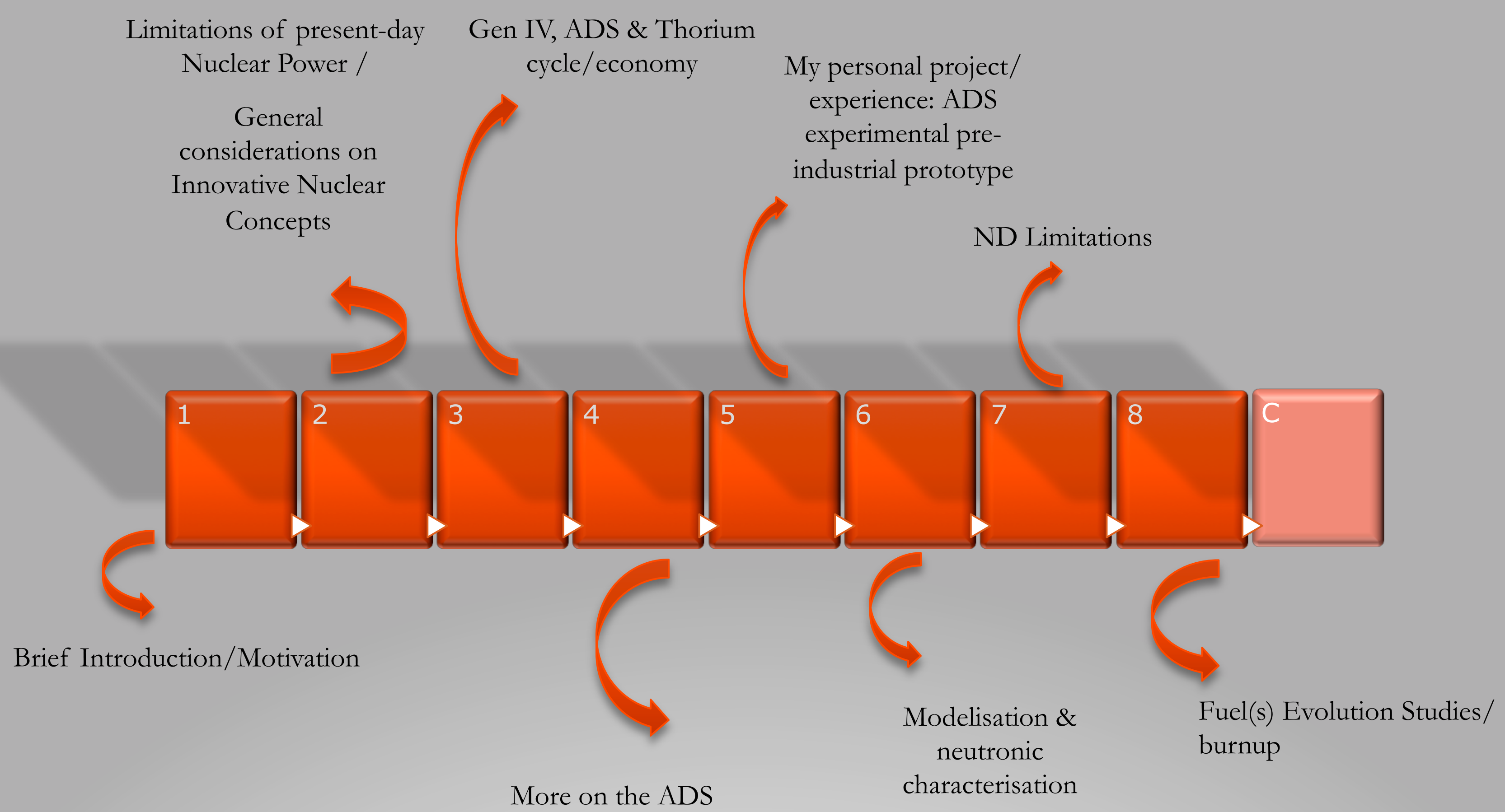
A few elements on innovative nuclear fission concepts – the particular case of a ground-laying ADS (Accelerator-Driven System) and the Thorium Cycle

Leonardo VILA NOVA GONCALVES

NCBJ – Świerk Research Centre, 7th May 2019

Presentation Overview

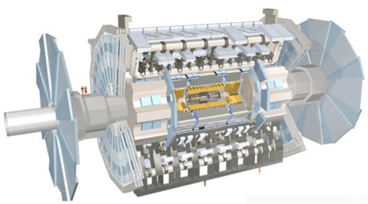


- **Instituto Superior Técnico (I.S.T.), Lisbon**

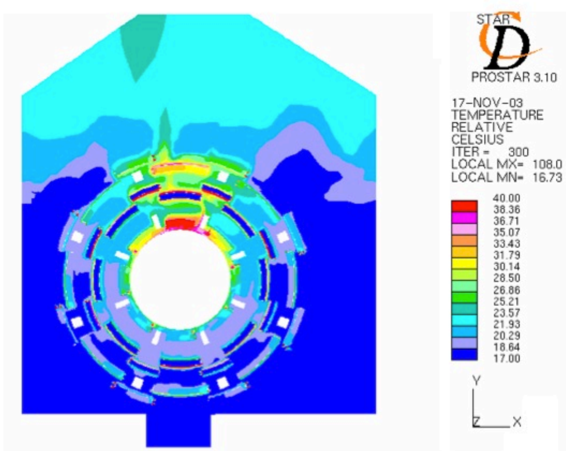
University Master Level Degree, 5 years . Final specialization field (last 2 years out of the 5): automation, control and robotics.

- **1999 to 2004: CERN (European Organization for Nuclear Research), Geneva CH**

ST - CV (Cooling and Ventilation) group under two consecutive (Research Associate and Research Fellow) contracts.

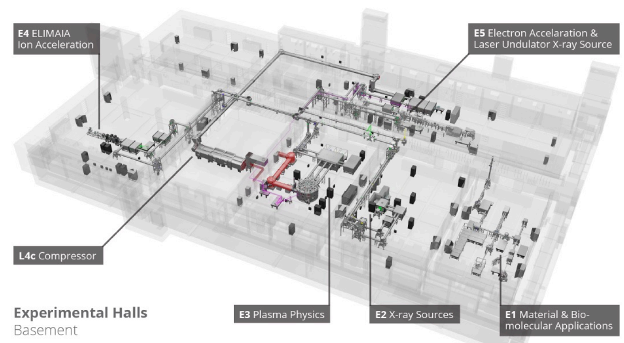


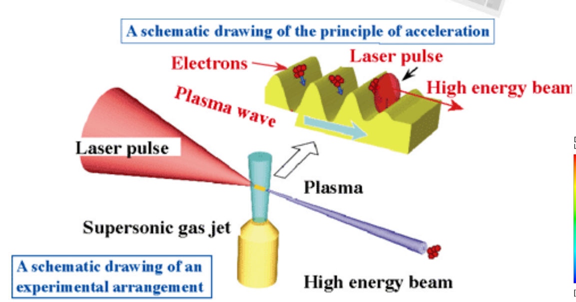
Source: (CERN-TS-Note-002 May 2004)

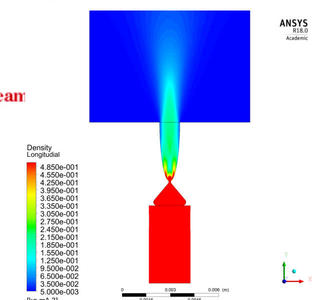


- **present: Fyzikálni ústav AV CR, v.v.i (Institute of Physics of the Czech Academy of Sciences) / ELI Beamlines, Prague, Czech Republic.**

Research activities on Laser Wake Field electron Acceleration (LWFA), a method aiming at the generation of ultra-relativistic electron beams in dense plasma by means of a very compact set-up when compared to conventional particle accelerators.







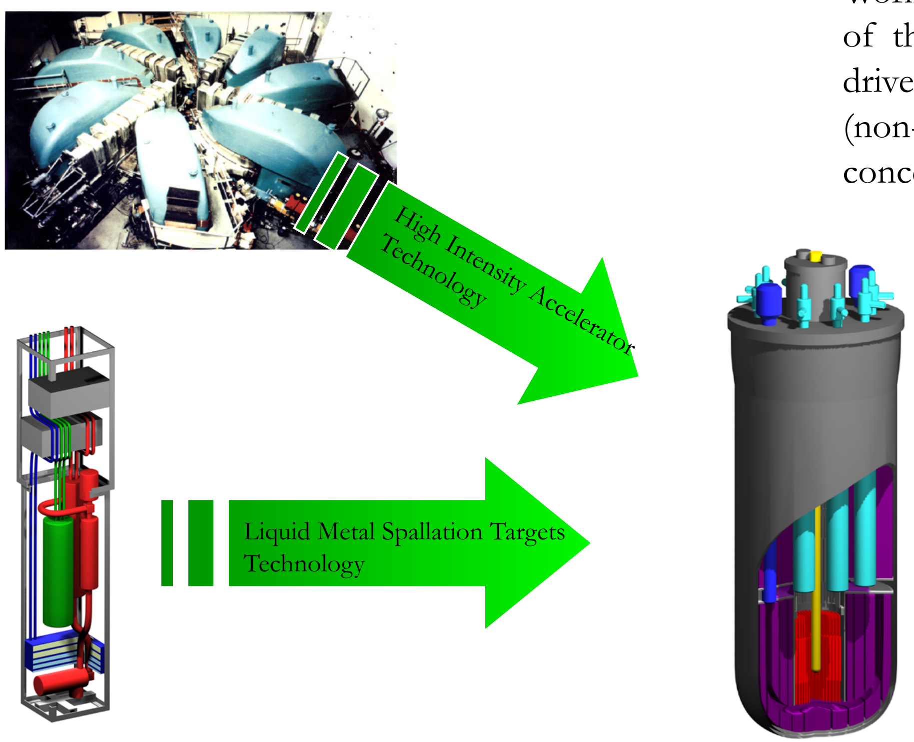
- **2009 – PhD, ENSM-SE 'Sciences et Génie des Matériaux' (in the fields of reactor physics and nuclear engineering).**

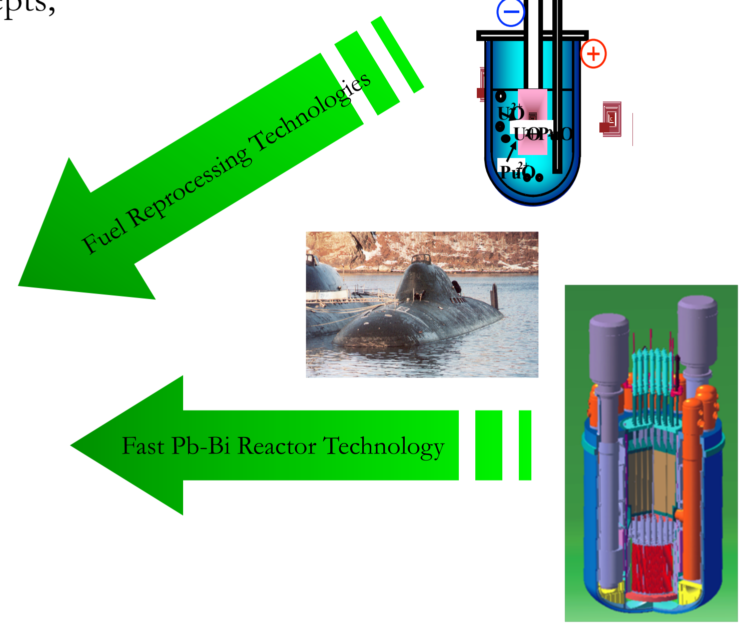
'study of a 6 MW industrial prototype of a lead-bismuth subcritical ADS (Accelerator Driven System)'

- **1/2009 to 5/ 2010: University of Cambridge, UK**

Postdoctoral Research Associate in the Department of Engineering

Work in the field of the ADS: Identification and simulation of the physics of a number of design options for ADSRs driven by one or multiple accelerators, including ns-FFAG (non-scaling Fixed Field Alternating Gradient) accelerator concepts;





BUT ALSO: Thorium Cycle, ND, Monte Carlo neutronic codes…

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• Energy in the world and the role of Nuclear

By 2050, the world's energy consumption (≈+ 2%/y) ★ *Two main Factors: Population growth & economic development development (*Inevitable closing of the gap in per capita consumption between developed and developing countries) ★ *should reach 34 TW, of which 20 TW should come from new energy sources;*

Major technological and political innovations are needed in order to replace the expected "decay" of the traditional energy sources (mainly fossil fuels (Greenhouse effects); this R&D efforts to be deployed should not exclude any direction a priori:

Renewables
Nuclear (fission and fusion - not yet proven to be practical.
Conceptual level not reached (magnetic or inertial confinement?).
ITER a step, hopefully in the right direction.
Use of hydrogen

Nuclear fission energy is technologically well understood (≥ 50 years) experience, however, present scheme has its own problems:

Military proliferation (production and extraction of plutonium);

Possibility of accidents (Chernobyl [1986]; Three Mile island [1979]…. **Fukushima!** *[2011]);*

Waste management

Extended life-cycle of existing units

Nucleus	Half-life (y)	Dose Factor (Sv/Bq)	Activity (Bq/kg)	Radiotoxicity (Sv/kg)
^{237}Np	2.14×10^{6}	0.11×10^{-6}	2.6×10^{10}	0.3×10^{4}
^{135}Cs	2.30×10^{6}	0.20×10^{-8}	4.2×10^{10}	0.8×10^{2}
^{239}Pu	2.41×10^{4}	0.25×10^{-6}	2.3×10^{12}	0.6×10^{6}
^{129}I	1.57×10^{7}	0.11×10^{-6}	6.5×10^{9}	0.7×10^{3}
^{99}Tc	2.11×10^{5}	0.78×10^{-9}	6.3×10^{11}	4.9×10^{2}

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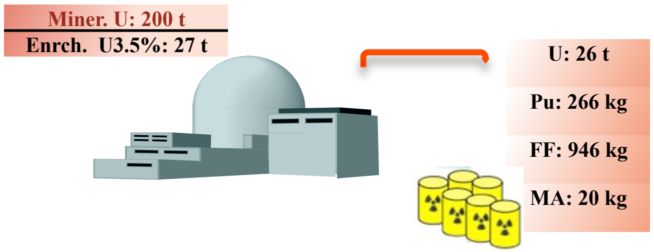
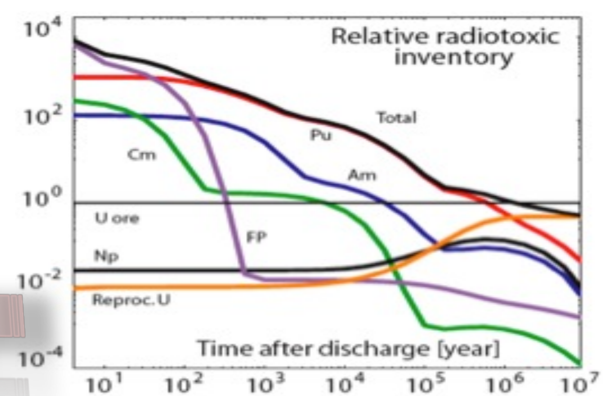
Example: Annual Production of a PWR 1 GWe



- *For the total 442 commercial reactors in the world and the 369.6 GWe (2005 data), an average 8077 t of waste are produced out of which 7675 t come from Uranium and the remaining 402 t are divided into 296 t of Fission Products (48 t LLFP), 94 t of Plutonium and 12 t of MA.*



Radiotoxic inventory of a used UOX fuel coming from a PWR 4 years after discharge (3.7% enriched ^{235}U) with a combustion rate of 41.2 GWd/tHM

Radiotoxological data for a few of the most important LLFP &Actinides

• Can Nuclear Energy play a major role?

Nuclear energy (specially if we consider the joining efforts to move to a new type of economy – Thorium) has the potential to satisfy the demand for a long time (at least 15 centuries for fission, essentially infinite for fusion if it ever works), and is obviously appealing from the point of view of atmospheric emissions.

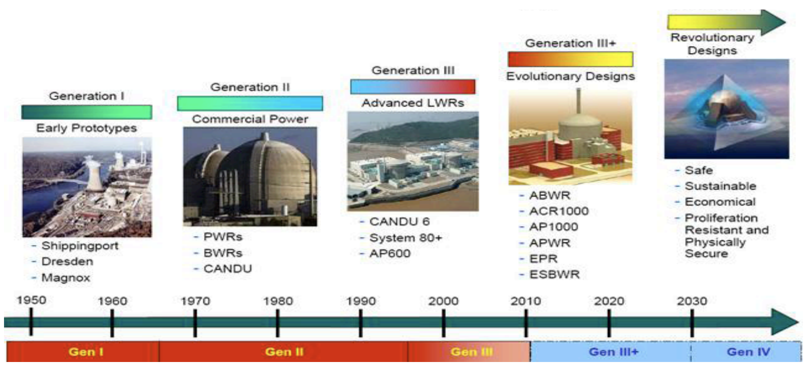
Energy source	Consumption 2000 (10.2 GTep)	Consumption 2050 (22.5 GTep) *
Fossil Fuels (Oil, Natural Gas, Coal)	7.6	7.6
Hydro + Traditional	1.9	2.3 (+20% ?)
Nuclear	0.6	X
Renewable Sources such as SOLAR, WIND, Geothermal, Biomass, etc	0.2	Y

- IF X=Y (**renewables *30**) ⇒ X=6 Gtep, i.e,. *Nuclear should increase by *10* thus representing 27% of Total produced energy in 2050;
- IF Y=2 (**renewables *10**) ⇒ X=10 Gtep, soit i.e,. *Nuclear should increase by *16* thus representing 44% of Total produced energy in 2050;
- **Conclusion, Nuclear energy will be indispensable, even for an overly optimistic clean scenario!**

BUT: Which type of nuclear energy? However, it is not given by Nature, that the way we use nuclear fission energy today is the only and best way to do it. One should rather ask the question: *Could nuclear fission be exploited in a way that is acceptable to Society?*

• Nuclear Energy for the future

Present research in the field of fission is focused on improving safety, proliferation resistance, reducing waste radiotoxicity and providing independence from energy markets. Two types of facilities exist: (a) the evolutionary (GenIII), based on the development of previous designs and, (b) the **innovative concepts (GenIV),** where, beyond the complex technological challenges, new manufacturing strategies and fuel management are required.

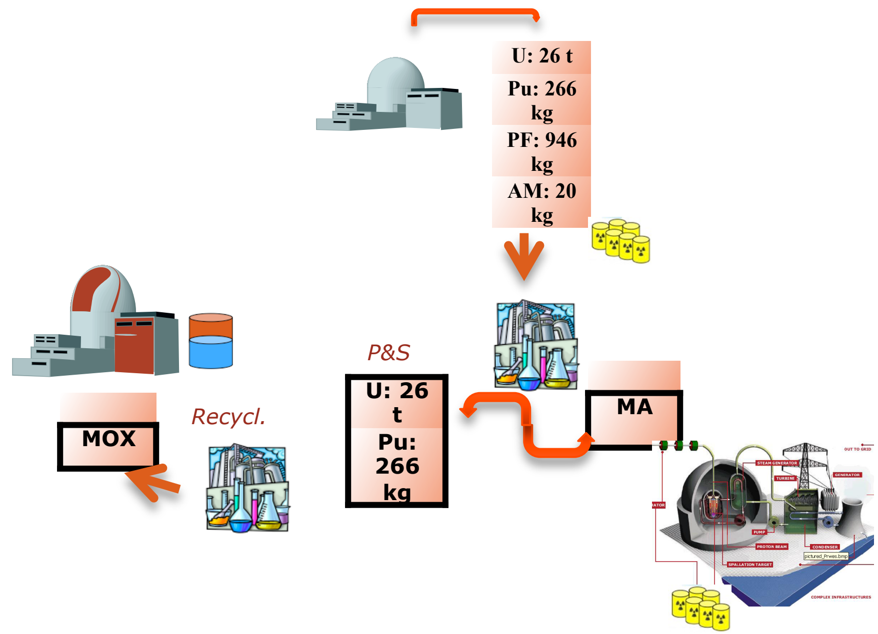


high-temperature gas-cooled reactors.

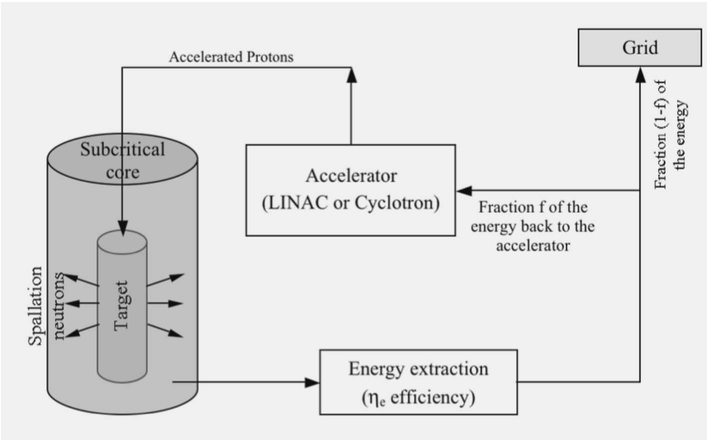
Deep underground disposal:

Risk of leaks (direct or indirect) to the biosphere – ex: ^{129}I;
Risk of proliferation;
Heat Production by decay (degradation of containers and over-dimensioning of the site);
Technological difficulties;
Costs;
Contexts of future acceptability;

- *The concepts of subcritical reactors driven by accelerator (ADS) will open new avenues for waste management and non-proliferating nuclear fuel, including the thorium cycle.*



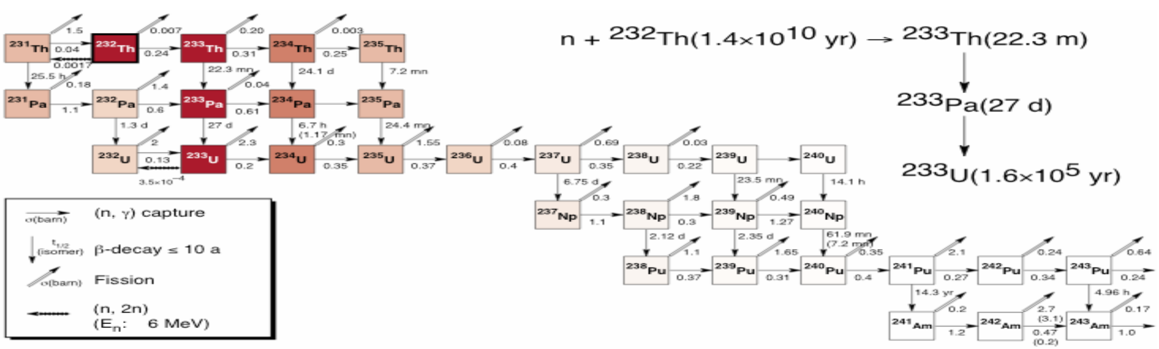
• The ADS concept



- ❑ *The accelerator provides the High-Energy protons;*
- ❑ *Spallation produces a very intense neutron source;*
- ❑ *Neutrons are multiplied in the subcritical core.*

Subcritical system driven by a proton accelerator:

- ○*Subcriticality of the core leading to active safety;*
- ○*Fast neutrons (to fission all transuranic elements) due to the neutron economy;*
- ○*Accepts less conventional fuels such as Thorium, MA and FF, for which the delayed neutron fraction is very small;*
  - ✸ *^{232}Th is more abundant than Uranium & weakly radioactive (minimisation of nuclear waste);*
  - ✸ *Can be transmuted into fissile ^{233}U, by neutron capture+2 β - (neutrons come from fission of ^{235}U or ^{239}Pu or spallation reactions);*
  - ✸ *Smaller production of long-lived actinides;*
  - ✸ *Less attractive for weapon construction;*
  - ✸ *Considerable reactor and reprocessing experience;*
- ○*Lead (Lead-Bismuth) as target to produce neutrons through spallation, as neutron moderator and as heat carrier;*
- ○*Higher boiling point of coolants is traduced by safer and simpler operation;*
- ○*Deterministic safety with passive safety elements (protection against core melt down and beam window failure).*



$n + {}^{232}Th(1.4\times10^{10}\ yr) \rightarrow {}^{233}Th(22.3\ m) \downarrow {}^{233}Pa(27\ d) \downarrow {}^{233}U(1.6\times10^{5}\ yr)$

Drawbacks

- ❑ *Lack of operating experience;*
- ❑ *Construction of more powerful accelerators than existing ones;*
- ❑ *Window is a very critical issue;*

- ❑ *Innovative materials technologies;*
- ❑ *Development of new chemical P&S methods;*
- ❑ *Poorly known ND*
- ❑ *Thorium – New economy!!*

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• Technological issues (some common problems with GEN IV) #1

"For Christ's sake, Soddy, don't call it transmutation. They'll have our heads off as alchemists".
[Ernest Rutherford, to Frederick Soddy on the discovery of thorium transmutation, 1901].

- ❑ Type of neutron spectra: Fast / Thermal
- ❑ Type of accelerator system: LINAC / Cyclotrons / NS-FFAG
- ❑ Type of spallation target: Solid / Liquid
- ❑ Type of coolant: Gas / Metal / Molten Metal / Molten Salts
- ❑ Type of fuel: Solid / Liquid

+

❑ ND, numerical codes, fuel development, material research, licensing, integration, etc

Type of neutron spectra

- ○ Thermal spectrum leads to larger fission products poisoning and requires molten salt reactors;
- ○ Fast neutron spectra allow easier incineration due to their larger fission cross-sections;
- ○ The protactinium effect, which limits the achievable values of *k*, is less severe for fast spectra;
- ○ In general reactor control is easier with fast spectra, especially for thorium based cycles;
- ○ The inventory of ^{233}U is much larger in fast reactors (about 7times)

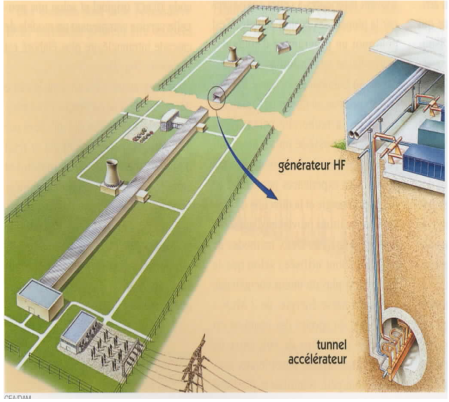
Choice of Fuels

- ○ Solid fuels and reprocessing techniques (especially oxides) are very well known and documented; Metallic fuels are promising when associated to pyrochemistry reprocessing;
- ○ Due to progressive poisoning by FF, neutronics of solid fuels are not optimized;
- ○ Liquid fuels like molten salts allow a continuous monitoring and optimization of the neutronics…however:
- ○ Reliability and safety of the on-line processing of the salt for large reactors has to be demonstrated;
- ○ Good properties of hastalloy against corrosion by the salt but…
- ○…to be verified for the very high irradiation doses expected with ADSR
- ○ Fluorides are less corrosive than chlorides

• Technological issues (some common problems with GEN IV) #2

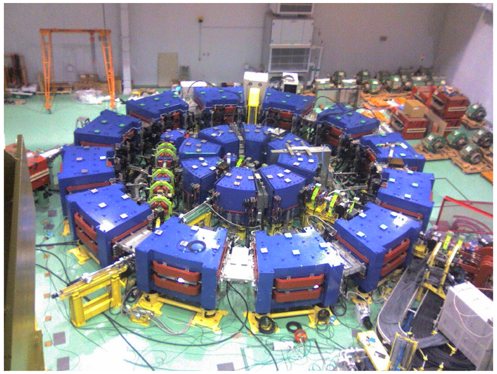
Accelerator Options

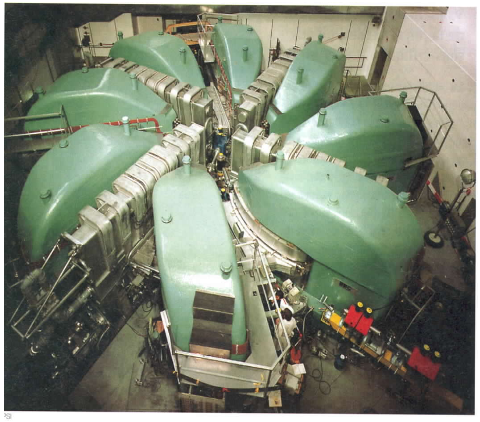
Provide 10 mA, 1 GeV



LINAC (LEP 200 - CH)

- ❑ No limitation of space
- ❑ Beam intensities in the 100 mA range are considered feasible
- ❑ Expensive





Cyclotron (PSI - CH)

- ❑ More compact and economical
- ❑ Potential Industrial-scale production
- ❑ Difficulty in providing beam intensities larger than 5-10 mA

NS-FFAG (Non-Scaling Fixed Field Alternating Gradient)

(combines the simplicity of the cyclotron (the fixed field) with the flexibility of the synchrotron (variable energy),

- ❑Cost advantages
- ❑ Small beam losses
- ❑ More compact than Cyclotron
- ❑ Higher intensity beams
- ❑Future technology

Full multistage Cyclotron? Hybrid Cyclotron-Linac? Trefoil of NS-FFAG?

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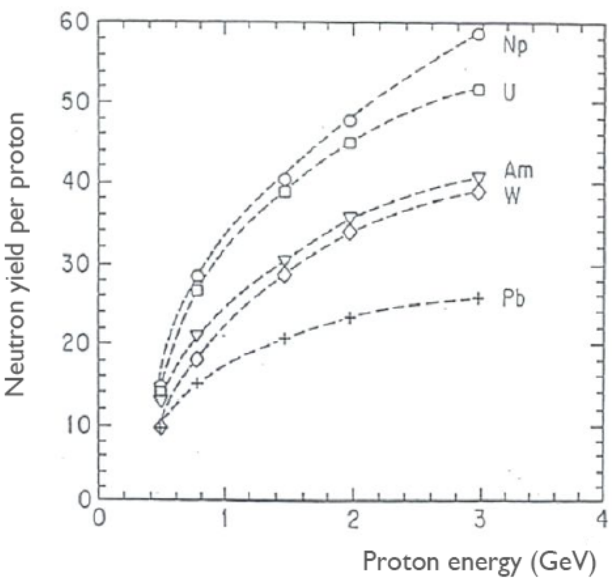
• Technological issues (some common problems with GEN IV) #3

Spallation target

The spallation target has to provide the highest possible neutron yield, be transparent to neutrons, and at the same time sustain a large beam power of 10 to 20 MW.



Solid (Uranium, Tungsten, Lead)

- Heat produced within the target has to be conducted to the surface producing large axial gradients and radial stress;
- Water cooling is generally used – the cooling system can be contaminated;
- If significantly higher beam powers are required water cooling may not be adequate
- Shorter lives (*follow ESS progress)

Liquid (Hg, Lead*, LBE)

- Higher heat removal capability;
- Higher spallation material density in the volume due to absence of cooling channels;
- No or minimum amount of water;
- No life time limit caused by radiation damage;
- Significantly lower specific radioactivity;
- The inside pressure can be significantly lower than in water cooled system;
- Complex technology, and safety issues - window is a critical part of the system

*Lead has a rather high fusion temperature, it might be difficult and costly to keep it in a fused state at all times.

• Technological issues (some common problems with GEN IV) #4

Coolant Options

Coolants should have the following properties:

- ❑ Low melting temperature and high boiling temperature
- ❑ Low neutron absorption cross-section
- ❑ Radiation stability
- ❑ Low viscosity and density
- ❑ High heat capacity and thermal conductivity
- ❑ High thermal expansion coefficient
- ❑ Low chemical activity

Molten Salts

- Coolant and fuel simultaneously;
- Possibility of quasi online treatment and purification;
- Transparent to visible light, and thus allowing visual inspections;
- Even with solid fuels molten salts might be considered as an interesting option
- ❑ Great complexity of the system
- ❑ Corrosion problems

Gas (Helium, CO_2)

- Can be heated to high temperatures (> η);
- Minimizes neutron slowing-down;
- Easier inspection of the fuel during operation;
- No radiological concern
- ❑ High internal pressure operation
- ❑ Incompatibility with fuels containing carbon
- ❑ Complicated heat extraction in natural circulation for a LOCA

Sodium

- Considerable operational experience;
- Good thermal-hydraulic properties;
- ❑ Low boiling point (1156 K) which arises safety concerns concerning coolant heatup.
- ❑ High chemical activity with water, water vapor and air

Lead or LBE

- Both coolant and spallation target material;
- Neutron slowing down smaller than that of sodium;
- Chemical inertness;
- Low working pressure of the coolant

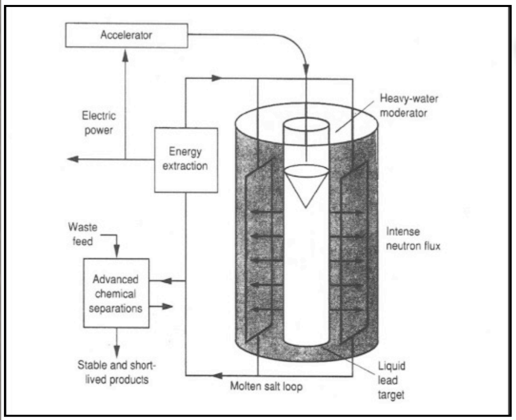
LBE versus Lead

- ❑ ^{210}Po evaporation – 3 orders of magnitude less for Lead only
- ❑ Cost & reserves of bismuth – Lead is cheap & production is well organised
- ❑ Corrosion at high temperatures – common problem

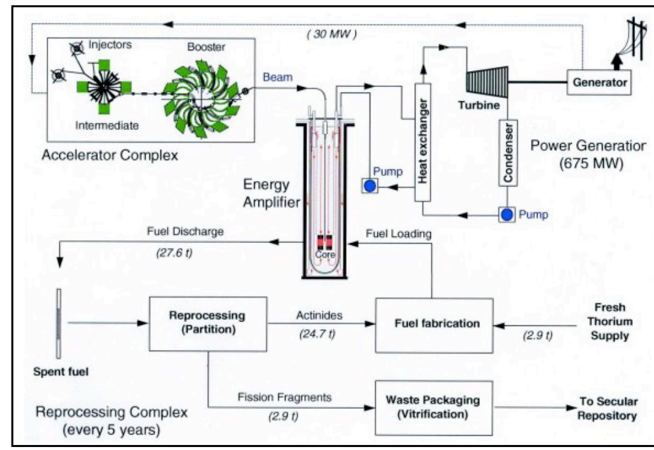
• Historical Proposals (Bowman [1991] and Rubbia [1993])

Bowman's Thermal Reactor at Los Alamos ATW (Accelerator Transmutation of Waste: The proton beam interacts with a molten lead target surrounded by a heavy water pool. The molten salt fuel circulates within tubes inside the pool. Extraction of fission products and of ^{233}U takes place outside the pool.

Concept	Accelerator parameters				K_{eff}	Blanket power	Spectrum	Coolant	Target	Fuels
	Energy	Proton Energy	Current	Type						
ADEP	100MW	1 GeV	100 mA	Linac	0.95	≈2300 MW	Thermal	Heavy Water	Lead	MS fluorides Th-U

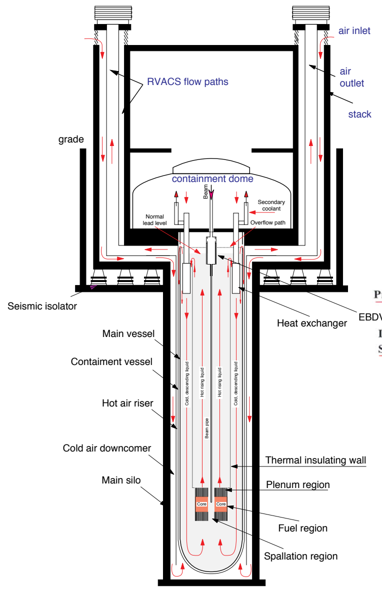


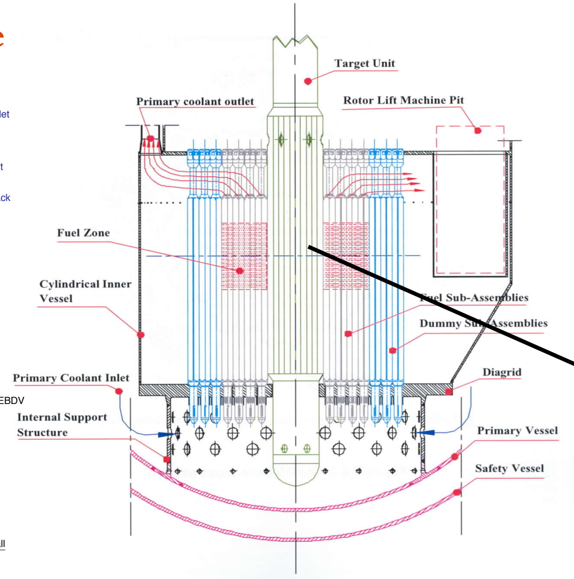
Rubbia's CERN Fast EA (Energy Amplifier): The molten lead pool is 30 meters high and 6 meters in diameter. It contains 10000 tons of molten lead.

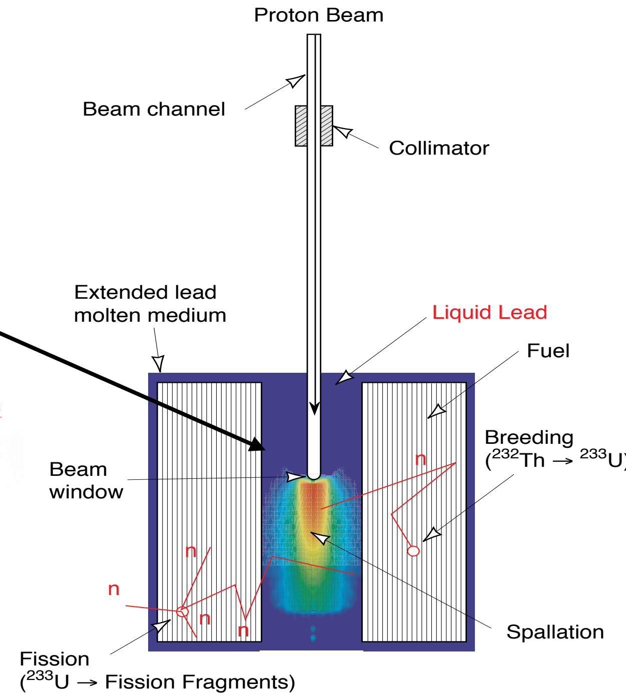


Concept	Accelerator parameters				K_{eff}	Blanket power	Spectrum	Coolant	Target	Fuels
	Energy	Proton Energy	Current	Type						
EA (CERN)	10 MW	1 GeV	10 mA	Cyclotron	0.98	1500 MW	Fast	Lead	Lead	ThU

• EA Breakdown Structure





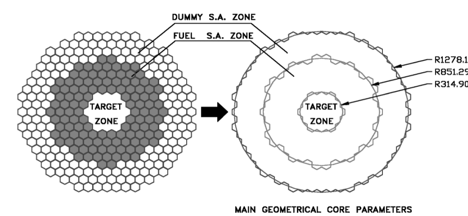


High specified experiments at 0 power have been carried out to verify the fundamental physics principle of the EA systems:

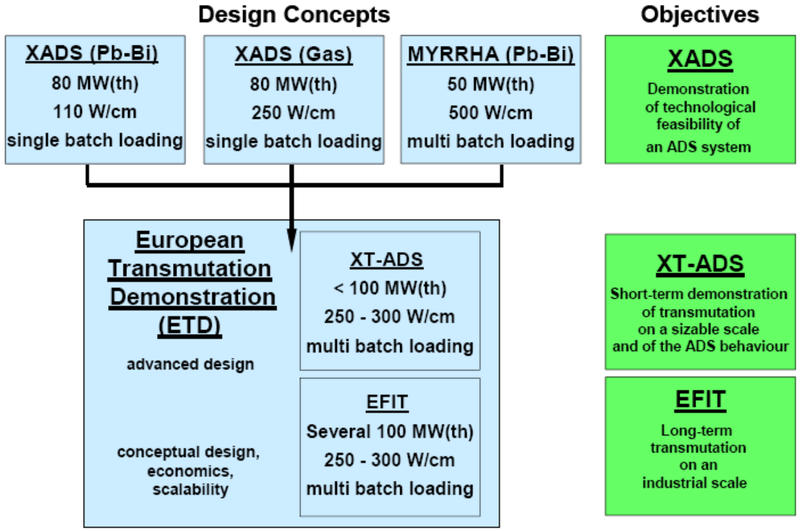
- The First Energy Amplifier Test (FEAT) Experiment: Subcriticallity levels, Amplification, Gain, etc…)

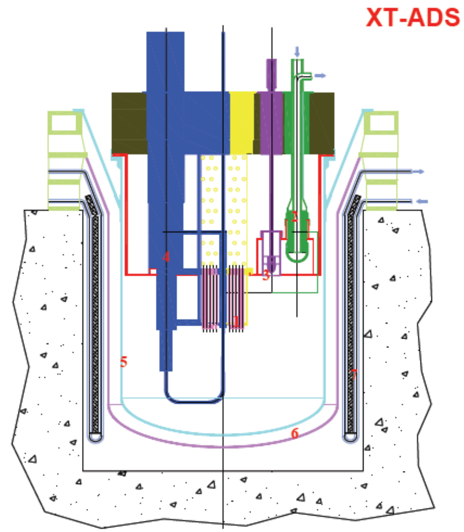
- The Transmutation by Adiabatic Resonance Crossing *(TARC Experiment): Verification of LLFF incineration principle* (^{129}I, ^{99}Tc, etc…), Understanding of the spallation phenomenology in lead (neutron fluxes measurements by electronic detectors and by activation measurements); Development and validation of appropriate simulation and computing tools;

- The neutron Time-of- Flight facility *(nTOF) project:* Systematic measure of neutron cross section.



• Historical Developments





Concept XADS	Accelerator parameters				K_{eff}	Blanket power	Spectrum	Coolant	Target	Fuels
	Energy	Proton Energy	Current	Type						
A ANSALDO	3.6 MW	600 MeV	3-6 mA	Linac	0.95-0.97	80	Fast	LBE	LBE	MOX
B FRAMATOME	3.6 MW	600 MeV	3-6 mA	Linac	0.95-0.97	80	Fast	Gas	LBE	MOX
C MYRRHA	1.75 MW	350 MeV	5 mA	Cyclotron	0.95	50	Fast	LBE	LBE	MOX

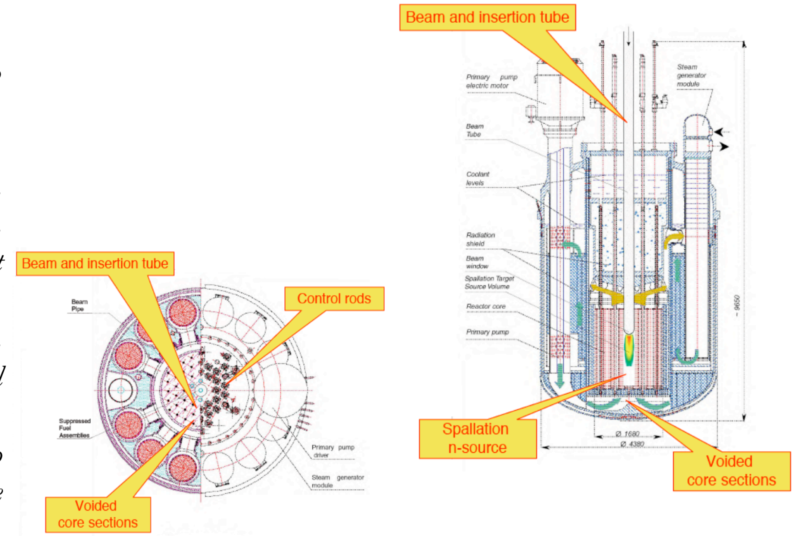
• The Project: a lead-bismuth cooled ADS Burner

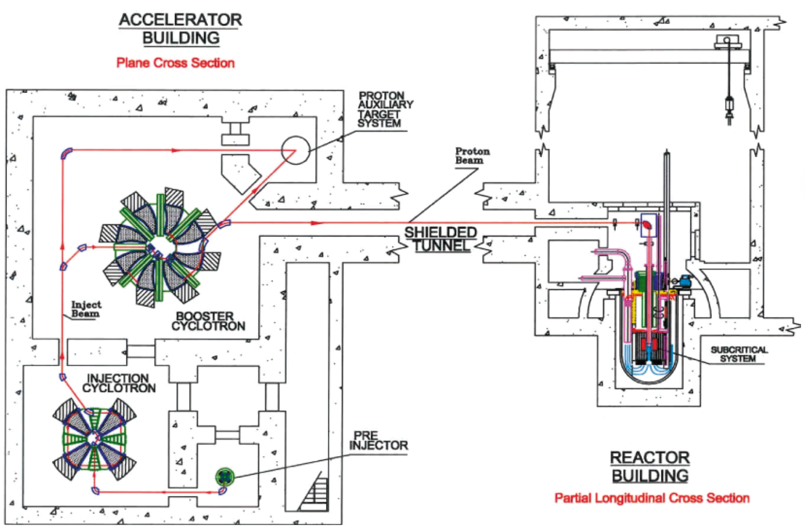
Overview of the prjoct: Three different levels of validation of an ADS can be specified:

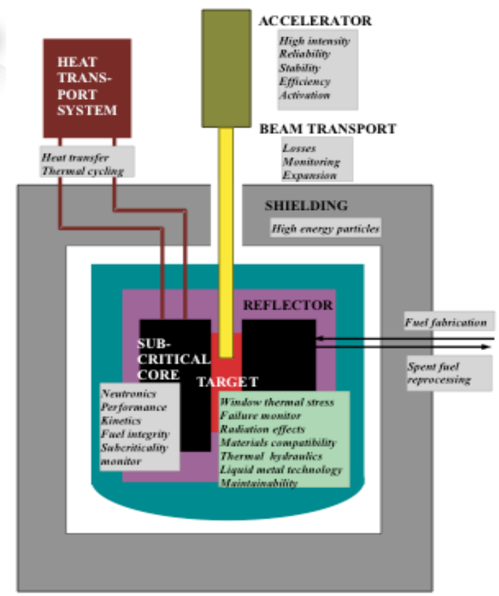
1 - *Validation of the different component concepts, taken separately (accelerator, target, subcritical core, dedicated fuels and fuel processing methods). In Europe: The FEAT, TARC, MUSE & YALINA experimental programs and the MEGAPIE project are significant examples.* ➽ *IP-EUROTRANS…*

2 - *Validation of the coupling of the different components in a significant environment, e.g. in terms of power of the global installation, using as far as possible existing critical reactors, to be adapted to the objectives.*

3 - *Validation in an installation explicitly designed for demonstration. This third step should evolve to a demonstration of transmutation fuels, after a first phase in which the subcritical core could be loaded with "standard" fuel.*



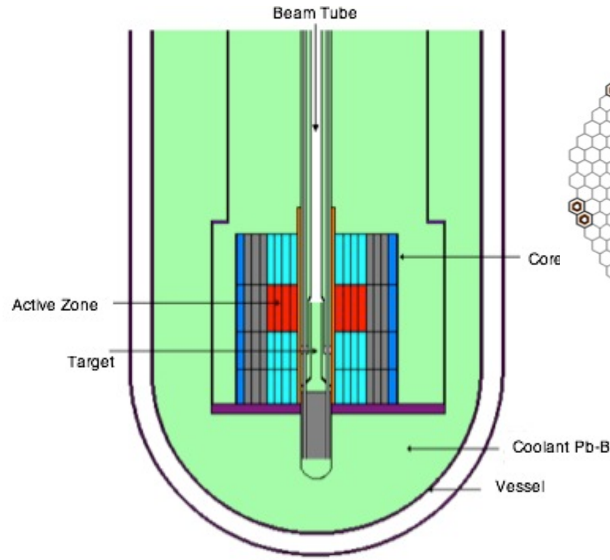


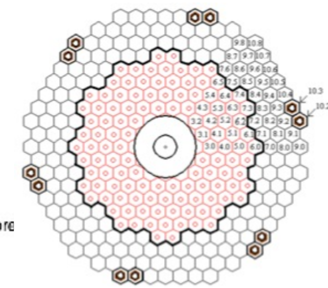


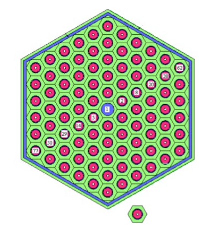
• Studies on the reference configuration

Some of the main tasks concerning the simulations of the physics of the prototype :

- *Benchmark testing of the code;*
- *Dimensioning of the spallation target;*
- *Construction of the Model for the 'Fluka - Monte Carlo' Simulations;*
- *Study of the dynamic behaviour of the fission and the spallation neutrons;*
- *Reference configuration description and characterisation;*
- *Study of the ND sensibility;*
- *Determination of the neutron flux distributions;*
- *Determination of the radiation damage (dpa) on the structural materials (spallation target, beam tubes, vessels, fuel clad, etc);*
- *Calculation of the reactivity safety margins;*
- *Extensive studies of fuel burnup for different fuel mixtures being tested the prototype.*







Combustibles				
LEU	UPu	Th^{233}U	Th^{235}U	ThPu
Compositions (%)				
^{235}U 13.60 ^{238}U 74.53 ^{16}O 11.84 ^{17}O 0.4792x10^{-2} ^{18}O 0.2671x10^{-1}	^{238}U 78.19 ^{16}O 11.81 ^{17}O 0.4781 x10^{-2} ^{18}O 0.2665 x10^{-1} ^{238}Pu 0.2775 x10^{-1} ^{239}Pu 7.051 ^{240}Pu 2.492 ^{241}Pu 0.2661 ^{242}Pu 0.1311	^{16}O 12.08 ^{17}O 0.4891 x10^{-2} ^{18}O 0.2726 x10^{-1} ^{232}Th 80.28 ^{233}U 7.606	^{235}U 12.32 ^{16}O 12.07 ^{17}O 0.4885 x10^{-2} ^{18}O 0.2722 x10^{-1} ^{232}Th 75.58	^{16}O 12.04 ^{17}O 0.4875 x10^{-2} ^{18}O 0.2717 x10^{-1} ^{232}Th 75.70 ^{238}Pu 0.3404 x10^{-1} ^{239}Pu 8.649 ^{240}Pu 3.056 ^{241}Pu 0.3264 ^{242}Pu 0.1609

- **A few lines on the methods**

Monte Carlo particle transport code are design to accurately simulate interaction of radiation with matter. The most well know codes are eventually MCNP(X) or GEANT 4, they are designed to track many particle types over broad ranges of energies. Their history goes back to the end of WWII. Their principle is repeatedly random sample to obtain numerical results of different outcomes.

Applications

Design of accelerator spallation targets
Investigations for accelerator isotope production and destruction programs, including the transmutation of nuclear waste
Research into accelerator-driven energy
Design of shielding in accelerator facilities
High-energy dosimetry and neutron detection
Medical physics, especially proton and neutron therapy
Charged-particle propulsion concepts for spaceflight
Investigation of fully coupled neutron and charged-particle transport for lower- energy applications
Transmutation, activation, and burnup in reactor and other systems
Nuclear criticality safety
Design of neutrino experiments

But: This codes are obviously highly dependent on available ND libraries. Nuclear Data ADS related issues and the discrepancies and certain deficiencies may be found between different databases (JEFF, JENDL,ENDF, etc) concerning in particular different isotopes and reaction channels of colossal importance for the studies of advanced nuclear systems (this importance can be greatly attested by the scientific efforts involved for example in the n_TOF experiment),

$^{238, 234}$Pu, thorium, americium, curium, structural materials such iron or bismuth or even the very conventional $^{233, 235, 238}$U, or $^{239, 241}$Pu outside the thermal regime.

• A few examples of the neutronic analysis/characterisation of the model #1

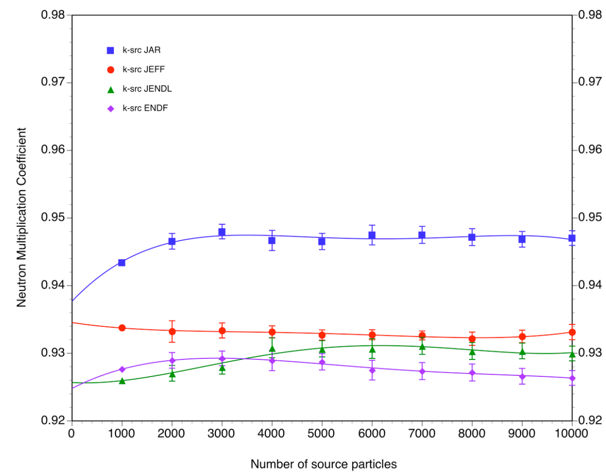
Sensitivity to ND

Paramètres Globales	Symbole	SVBR-ADS 600 MeV $k_s = 0.95$ **JAR**	SVBR-ADS 600 MeV $k_s = 0.95$ **JEFF**	SVBR-ADS 600 MeV $k_s = 0.95$ **JENDL**	SVBR-ADS 600 MeV $k_s = 0.95$ **ENDF**	Unités
Mélange initial combustible	ThPu					
Masse initiale combustible	m_{cb}	17521	17521	17521	17521	Kg
Concentration initiale ^{232}Th	$m^{232}Th/m_{cb}$	86.00	86.00	86.00	86.00	wt.%
Concentration initiale Pu	mPu/m_{cb}	14.00	14.00	14.00	14.00	wt.%
Puissance thermique délivrée	P_{th}	15.53	15.68	15.71	15.76	MW
Énergie du faisceau d/protons	Ep	600	600	600	600	MeV
Rendement des neutrons de spallation (yield)	N	14.81 +/- 0.11	14.81 +/- 0.11	14.81 +/- 0.13	14.81 +/- 0.11	n/p
Multiplic. neutronique nette	M	18.88 +/- 0.40	14.96 +/- 0.26	14.28 +/- 0.27	13.58 +/- 0.15	
Coefficient de multiplication	K=(M-1)/M	0.94704+/- 0.00109	0.93314 +/- 0.00113	0.92997 +/- 0.00129	0.92635 +/- 0.00083	
Gain d'énergie	G	29.30 +/- 0.63	23.06 +/- 0.41	22.09 +/- 0.42	20.84 +/- 0.26	
Coefficient de Gain	G_0	1.55	1.54	1.55	1.53	
Courant de l'accélérateur	Ip	0.88 +/- 0.019	1.13 +/- 0.020	1.19 +/- 0.023	1.26 +/- 0.016	mA

Table I: *BoC parameters of the system in function of ND Databases*

Combustibles	JAR (CERN)	JEFF-3.0 (EUR)	JENDL-3.3 (JAP)	ENDF/B-VI.8 (US)
LEU	0.9462	0.94071	0.92881	0.9449
(erreur)	±0.00061	±0.00106	±0.00063	±0.00042
Δk/k en pcm	-	-580	**-1838**	-137
UPu	0.94975	0.92406	0.92421	0.94259
(erreur)	±0.00114	±0.00136	±0.00104	±0.00112
Δk/k en pcm	-	**-2705**	**-2689**	-754
$Th^{233}U$	0.94629	0.94596	0.94292	0.94252
(erreur)	±0.00103	±0.00062	±0.0009	±0.00065
Δk/k en pcm	-	-35	-356	-398
$Th^{235}U$	0.95445	0.95561	0.93894	0.94603
(erreur)	±0.00081	±0.00094	±0.00078	±0.0008
Δk/k en pcm	-	+121	**-1625**	-882
ThPu	0.94704	0.93314	0.92997	0.92635
(erreur)	±0.00109	±0.00113	±0.00129	±0.00083
Δk/k en pcm	-	**-1468**	**-1802**	**-2185**

Table II: *Effects of ND on Ks*



- Figure 1*: the variation of the multiplication coefficient (ks) in function of the different ND, over the number of simulated protons (ThPu Case).*

We can see systematic differences (0.02 - 2.000 pcm) between JAR and JENDL and also important deviations but lesser significant between JAR and JEFF or JAR and ENDF (values < 1000 pcm) with the exception of fuels containing plutonium.

For ThU fuels the divergences are smaller.

In conclusion, apart from good punctual convergences, the exactitude in the calculation of k is far from the desired precision. We can see also the surprising results for well known fuels LEU but then again, well known in the thermal spectra.

- A few examples of the neutronic analysis/characterisation of the model #2

$Th^{233}U$	JAR	JEFF	Δ_{JEFF}	JENDL	Δ_{JENDL}	ENDF	Δ_{ENDF}
Combustible							
Captures	55.25 %	55.34 %	+ 0.16 %	55.70 %	+ 0.81 %	55.85 %	+ 1.09 %
Fissions	43.67 %	43.52 %	- 0.34 %	43.26 %	- 0.94 %	42.66 %	- 2.31 %
n,xn	0.79 %	0.77 %		0.76 %		0.93 %	
Others	0.29 %	0.37 %		0.28 %		0.56 %	
Caloporteur							
Captures	69.44 %	67.49 %	- 2.81 %	65.71 %	- 5.37 %	64.72 %	- 6.80 %
n,xn	30.30 %	32.37 %	+ 6.83 %	34.16 %	+ 12.74 %	34.95 %	+ 15.35 %
Others	0.26 %	0.14 %		0.13 %		0.33 %	
Gaines de comb.							
Captures	84.94 %	83.62 %	- 1.56 %	86.12 %	+ 1.39 %	81.94 %	- 3.53 %
n,xn	4.40 %	3.70 %	- 15.91 %	3.91 %	- 11.36 %	6.09 %	+ 38.41 %
Others	10.66 %	12.68 %	+ 18.95 %	9.97 %	- 6.47 %	11.97 %	+ 12.28 %
Reflecteur							
Captures	98.99 %	98.87 %	- 0.12 %	99.13 %	+ 0.14 %	98.71 %	- 0.28 %
n,xn	0.28 %	0.26 %		0.26 %		0.42 %	
Others	0.73 %	0.87 %		0.61 %		0.87 %	
Structures							
Captures	100 %	100 %	0 %	100 %	0 %	100 %	0 %
Cible							
Captures	82.24 %	81.42 %	- 1.00 %	80.99 %	- 1.52 %	80.55 %	- 2.05 %
n,xn	16.56 %	16.99 %	+ 2.60 %	17.89 %	+ 8.03 %	18.06 %	+ 9.05 %
Others	1.20%	1.60 %		1.12 %		1.39 %	

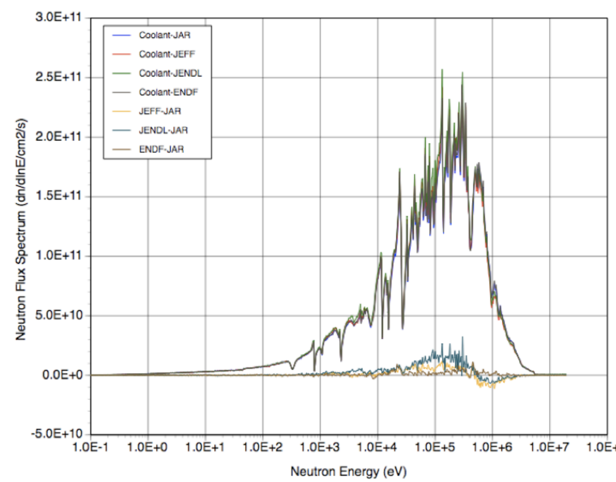
- *Figure 1: Neutronic balance for the reactor core, reflector, target and reactor structures ($Th^{233}U$).*

$Th^{233}U$	JAR	JEFF	Δ_{JEFF}	JENDL	Δ_{JENDL}	ENDF	Δ_{ENDF}
^{204}Pb							
Captures	97.41 %	97.60 %	+ 0.20 %	97.94 %	+ 0.54 %	96.49 %	- 0.94 %
n,xn	2.59 %	2.40 %	- 7.34 %	2.06 %	- 20.46 %	3.47 %	+ 33.98 %
Autres	0.00 %	0.00 %		0.00 %		0.05 %	
^{206}Pb							
Captures	79.84 %	73.71 %	- 7.68 %	74.20 %	- 7.06 %	75.62 %	- 5.29 %
n,xn	19.79 %	26.18 %	+ 32.29 %	25.72 %	+ 29.96 %	23.89 %	+ 20.72 %
Autres	0.37 %	0.11 %		0.07 %		0.49 %	
^{207}Pb							
Captures	86.57 %	83.43 %	- 3.63 %	83.98 %	- 3.00 %	83.75 %	- 3.26 %
n,xn	13.20 %	16.51 %	+ 25.08 %	16.00 %	+ 21.21 %	15.86 %	- 20.15 %
Autres	0.23 %	0.06 %		0.02 %		0.39 %	
^{208}Pb							
Captures	17.93 %	13.62 %	- 24.04 %	13.15 %	- 26.66 %	14.44 %	- 19.46 %
n,xn	81.37 %	85.92 %	+ 5.60 %	86.24 %	+ 5.99 %	85.22 %	+ 4.73 %
Autres	0.69 %	0.46 %		0.61 %		0.34 %	
^{209}Bi							
Captures	62.47 %	63.55 %	+ 1.73 %	58.54 %	- 6.29 %	57.96 %	- 7.22 %
n,xn	37.28 %	36.28 %	- 2.68 %	41.33 %	+ 10.86 %	41.76 %	+ 12.02 %
Autres	0.25 %	0.17 %		0.13 %		0.28 %	

- *Figure 2: Neutronic balance for the isotopes of the coolant ($Th^{233}U$).*

ThPu	JAR	JEFF	Δ_{JEFF}	JENDL	Δ_{JENDL}	ENDF	Δ_{ENDF}
^{56}Fe							
Captures	84.81 %	84.12 %	- 0.81 %	87.21 %	+ 2.84 %	84.22 %	- 0.69 %
n,xn	8.93 %	10.37 %	+ 16.13 %	6.99 %	- 21.74 %	9.62 %	+ 7.72 %
Autres	6.26 %	5.51 %	- 12.04 %	5.80 %	- 7.42 %	6.16 %	- 1.67 %
^{52}Cr							
Captures	82.90 %	65.82 %	- 20.60 %	87.34 %	+ 5.36 %	82.15 %	- 0.90 %
n,xn	10.47 %	0.00 %		7.37 %	- 29.56 %	11.45 %	+ 9.42 %
Autres	6.63 %	34.18 %	+ 415.19 %	5.29 %	- 20.33 %	6.40 %	- 3.57 %
^{58}Ni							
Captures	67.55 %	69.95 %	+ 3.56 %	70.28 %	+ 4.04 %	69.95 %	+ 3.56 %
n,xn	0.33 %	0.23 %		0.17 %		0.34 %	
Autres	32.12 %	29.82 %	- 7.15 %	29.56 %	- 7.97 %	29.71 %	- 7.49 %

- *Figure 3: Neutronic balance for the isotopes of the fuel cladds (ThPu).*



- *Figure 4: Neutron Spectra divergences with ND for the coolant in LEU.*

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- **A few examples of the neutronic analysis/characterisation of the model #3**

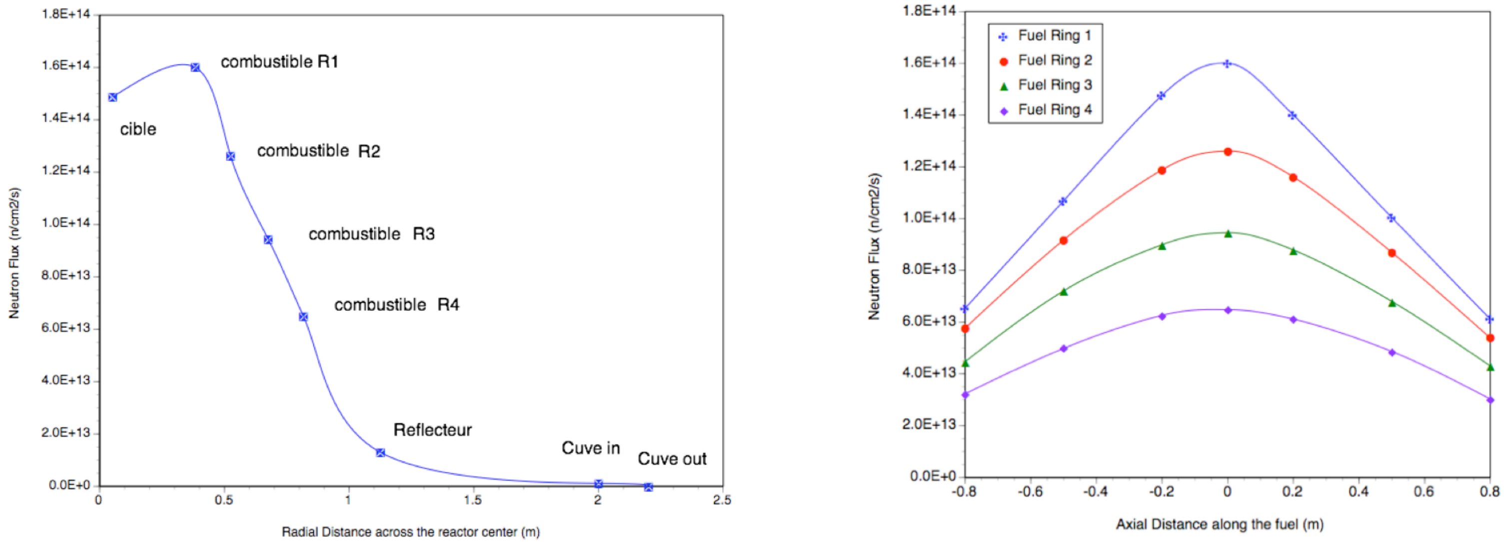

Figure 1: Typical case of neutron flux distribution (a) radial, and (b) axial for the SVBR reactor and a ThPu fuel at E0600MeV/k=0.95

The low values in the reactor vessel illustrate both the good confinement inside the core and the efficiency of the coolant. The axial neutron flux presents the typical parabolic behaviour peaking at ~1.37 (particularly important for fuel elements close to the spallation target). A moderate ratio between medium and max values of flux due to the domination of fission neutrons above the entire neutron population, results into a better homogeneous utilisation of fuel.

8

Fuel evolution calculation – Burnup studies

MOX as the initial fuel mixture

- Global Parameters of the system

Table I: *Evolution of the main neutronic parameters for the SVBR75/100 reactor system, loaded with a MOX type fuel for a 900 day operation cycle at 80 MW_{th}.*

Paramètres Globaux	Symbole	SVBR75/100 BOC	SVBR75/100 EOC	Unités
Mélange initial du combustible	MOX	$(U-Pu)O_2$	$(U-Pu)O_2$	
Masse du combustible	m_{comb}	3793	3723	Kg
Concentration du plutonium	m_{Pu}/m_{comb}	17.9	17.4	Wt.%
Enrichissement fissile	M_{fiss}/m_{comb}	15.1	14.6	Wt.%
Combustion (burnup)		-	20	GWj/t
Longueur du cycle		-	900	jours
Puissance thermique délivrée	P_{th}	80	80	MW
Énergie du faisceau de protons	Ep	600	600	MeV
Rendement des neutrons de spallation (yield)	N	14.51 +/- 0.10	14.51 +/- 0.10	n/p
Multiplication neutronique Nette	M	27.80 +/- 0.56	14.77 +/- 0.65	
Coefficient de multiplication	K=(M-1)/M	0.9640 +/- 0.0007	0.9323 +/- 0.0011	
Gain énergétique	G	42.73 +/- 0.88	21.27 +/- 1.01	
Coefficient de Gain	G_0	1.54	1.44	
Courant de l'accélérateur	Ip	3.20 +/- 0.07	6.00 +/- 0.11	mA
Distributions de puissance dans le cœur				
Densité moyenne de puissance du combustible	P_{th}/V_{comb}	255	255	W/cm^3

✓During this period of operation the reactivity of the system drops by 2.94%, which is compensated by a factor two increase in the accelerator current to 6.0 mA in order to maintain a constant power output.

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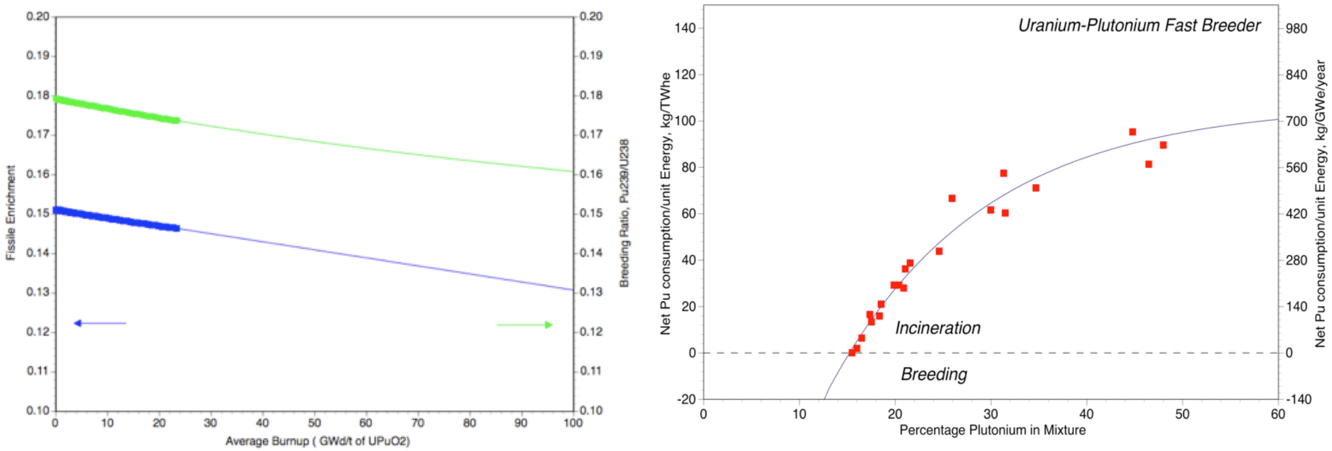


Figure 1: (a) Evolution of fissile enrichment level and the breeding ratio of the system over a 900-day burnup cycle

- Fuel consumption ~ 19 kg/t;

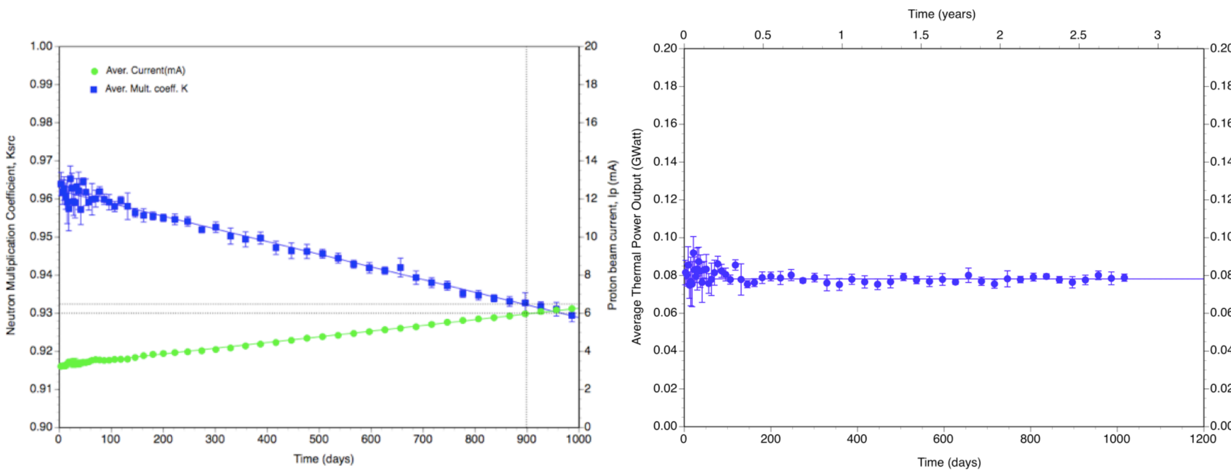
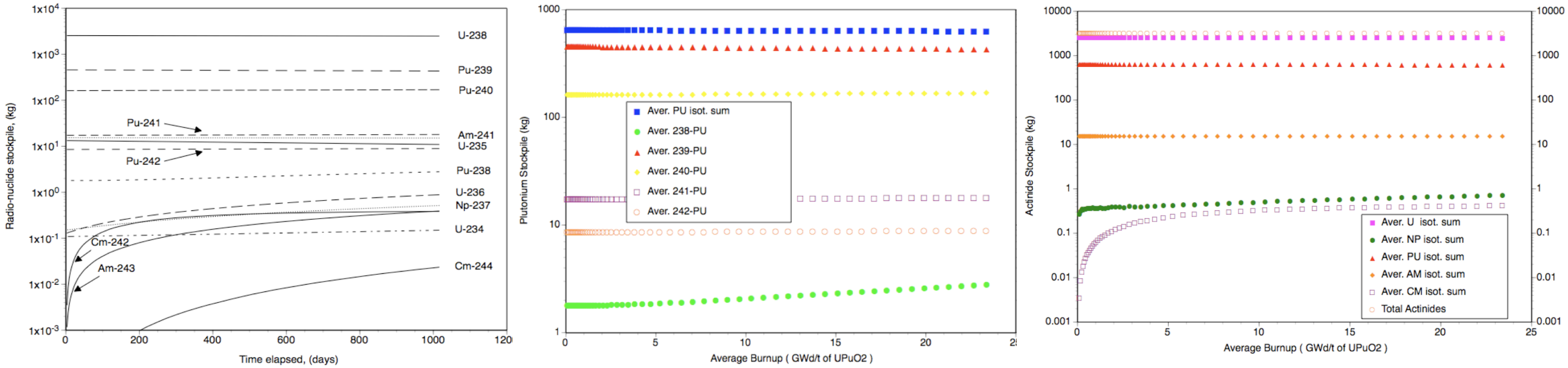
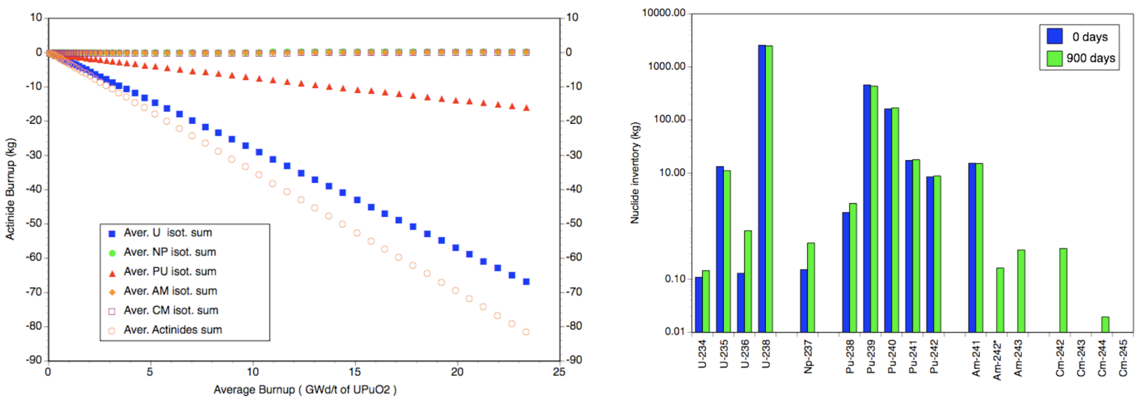


Figure 2: (a) Linear time evolution of the multiplication coeff. and the intensity of the proton beam current of the system over a 900-day burnup cycle; (b) Thermal power of the system. (Initial fluctuations are mainly due to the first days short-lived FF isotopes)

- The fissile enrichment drops during the cycle implies a Δ ks of ~3288 pcm (15.1% à 14.6%;) Pu (17.9% to 17.4%). The decline in the neutron multiplication brings about an increase of the accelerator current up tp 6 mA (~ 87.5% initial value) in order to keep the 80 MWth power level



Figures 1, 2, 3, 4 and 5: Isotopic evolution of the actinides of the system over a 900-day burnup cycle



- Concentration of the main isotopes of the fuel, $^{235, 238}U$, $^{239, 240, 241, 242}Pu$ and ^{241}Am remains ~ constant over the cycle;
- Concentration of ^{238}Pu increases by ~ 50%;
- Augmentation (<1 kg) of the inventory of heavy actinides (^{243}Am, ^{242}Cm, ^{237}Np);
- weak formation of ^{244}Cm (~18 g).

- EoC actinides balance: total actinides ≈ - 71 kg (≈ - 57 kg transmuted uranium);
- Plutonium – 14 kg
- Neptunium + 415 g
- Américium + 281 g
- Curium + 402 g

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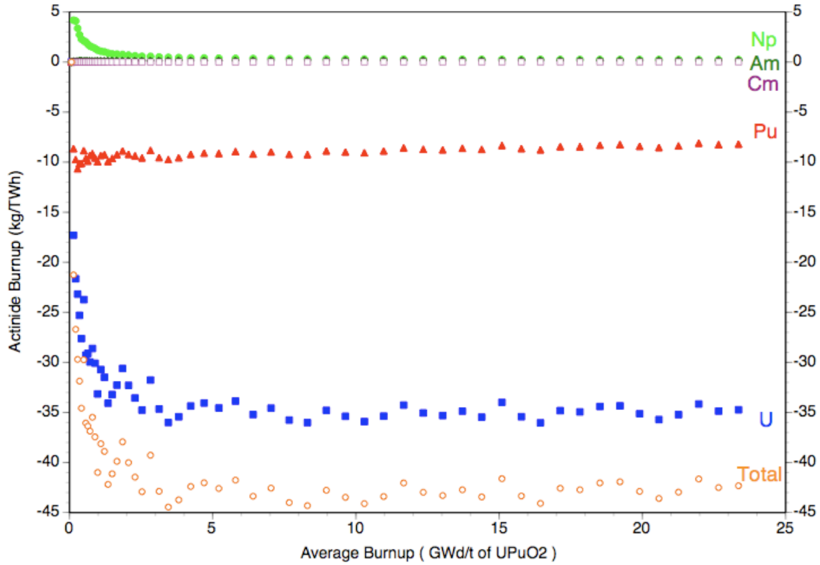

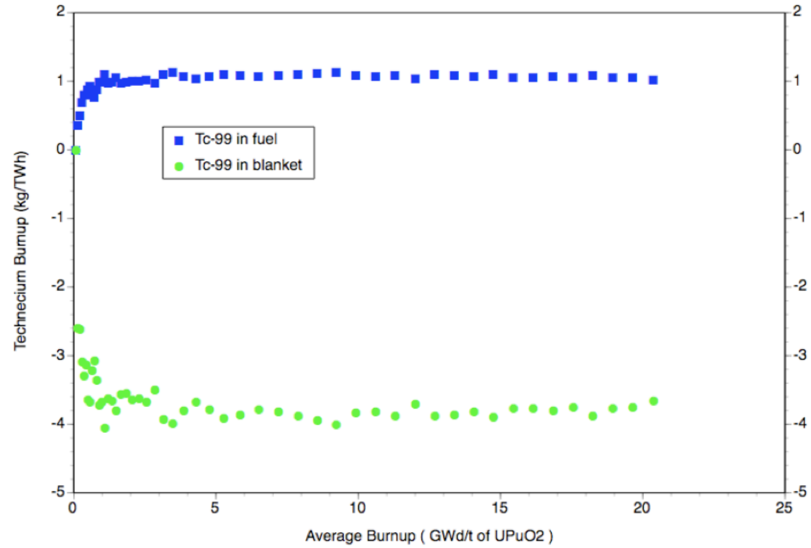

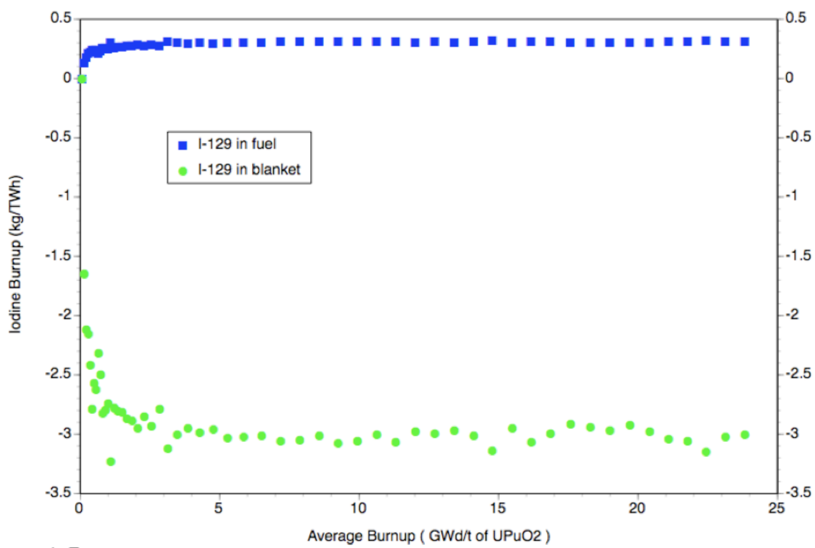

Balance actinides (kg/ TW.h of fuel)	SVBR ($UPuO_2$) 20 GWj/t	REP (UOX)
Plutonium	- 8.4	+ 11.0
Neptunium	+ 0.24	+ 0.57
Americium	+ 0.17	+ 0.54
Curium	+ 0.017	+ 0.044
Technétium-99	- 2.7	+ 0.99
I-129	- 2.7	+ 0.17

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Transmutation strategies

• Utilisation of a thorium-based fuel introducing Plutonium as seed to start the fission process, eliminating a significant amount of TRUs while producing energy based on the thorium fuel (Rubbia/CERN);

• Utilisation of an important number of heavily loaded of ADS with MA different fuel matrices, in a multi-strata configuration (JAERI)

$ThPuO_2$ as the initial fuel mixture

- Global Parameters of the system

Table II: *Evolution of the main neutronic parameters for the SVBR75/100 reactor system, loaded with a $ThPuO_2$ type fuel for a 900 day operation cycle at 80 MW_{th}.*

Paramètres Globaux	Symbole	SVBR-ADS BOC	SVBR-ADS EOC	Unités
Mélange initial du combustible		$(Th–Pu)O_2$	$(Th–Pu)O_2$	
Masse du combustible	m_{comb}	3666	3586	Kg
Concentration du plutonium	m_{Pu}/m_{comb}	20.2	18.8	Wt.%
Enrichissement fissile	M_{fiss}/m_{comb}	16.9	16.3	Wt.%
Combustion (burnup)		0	20	GWj/t
Longueur du cycle		0	900	jours
Puissance thermique délivrée	P_{th}	80	80	MW
Énergie du faisceau de protons	Ep	600	600	MeV
Rendement des neutrons de spallation (yield)	N	14.51 +/- 0.10	14.51 +/- 0.10	n/p
Multiplication neutronique Nette	M	27.47 +/- 0.75	17.67 +/- 0.65	
Coefficient de multiplication	K=(M-1)/M	0.9636 +/- 0.0028	0.9434 +/- 0.0011	
Gain énergétique	G	41.37 +/- 3.99	27.26 +/- 1.00	
Coefficient de Gain	G_0	1.51	1.54	
Courant de l'accélérateur	Ip	3.23 +/- 0.07	4.88 +/- 0.04	mA
Distributions de puissance dans le cœur				
Densité moyenne de puissance du combustible	P_{th}/V_{comb}	258	258	W/cm^3

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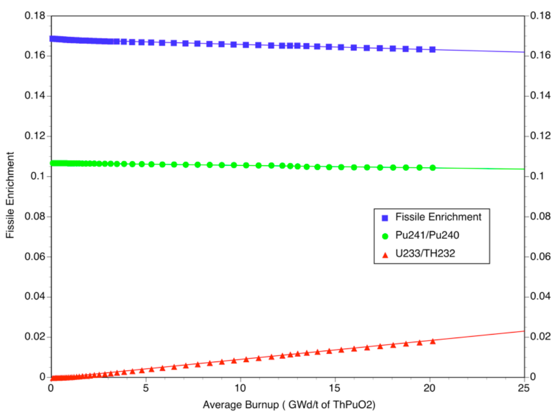
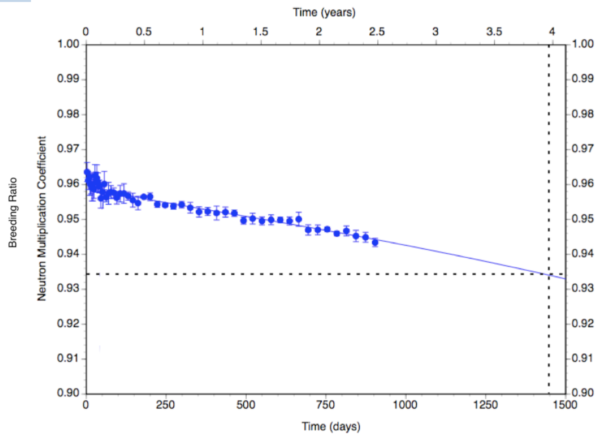
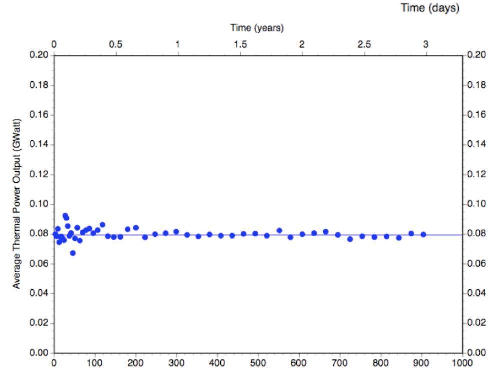
Paramètres Globaux	Symbole	SVBR75/100 BOC	SVBR75/100 EOC	SVBR75/100 BOC	SVBR75/100 EOC	Unités
Mélange du combustible		(U –Pu)O_2	(U –Pu)O_2	(Th –Pu)O_2	(Th –Pu)O_2	
Masse du combustible	m_{comb}	3793	3723	3666	3586	Kg
Concentration Pu	m_{Pu} /m_{comb}	17.7	16.3	20.2	18.8	Wt.%
Enrichissement fissile	m_{fiss} /m_{comb}	14.7	14.3	16.9	16.3	Wt.%
Multip. neutronique Nette	M	27.80 +/- 0.56	14.77 +/- 0.65	27.47 +/- 0.75	17.67 +/- 0.65	
Coef. multiplication	K=(M-1)/M	0.9640 +/- 0.0007	0.9323 +/- 0.0011	0.9636 +/- 0.0028	0.9434 +/- 0.0011	
Gain énergétique	G	42.73 +/- 0.88	21.27 +/- 1.01	41.37 +/- 3.99	27.26 +/- 1.00	
Coefficient de Gain	G_0	1.54	1.44	1.51	1.54	
Courant de l'accélérateur	Ip	3.20 +/- 0.07	6.00 +/- 0.11	3.23 +/- 0.07	4.88 +/- 0.04	mA

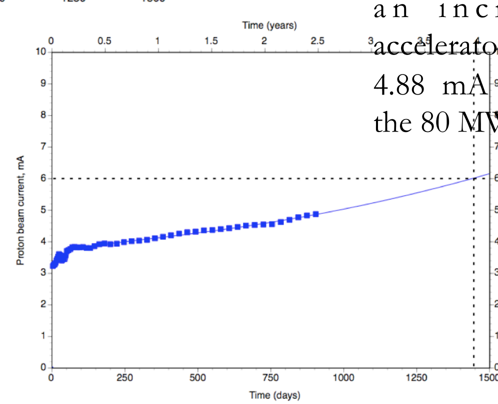
- Fuel consumption: ~ 22 kg/t;
- The fissile enrichment drops during the cycle from 16.9% to 16.3%; Pu also decreases from20.2% to 18.8%





- The system is more stable than the preceding: the fissile enrichment drops during the cycle implies a Δ ks of ~2096 pcm.
- The decline in the neutron multiplication brings about an increase of the accelerator current up tp 4.88 mA in order to keep the 80 MWth power level





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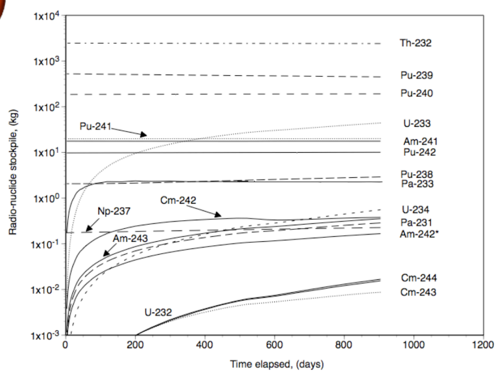
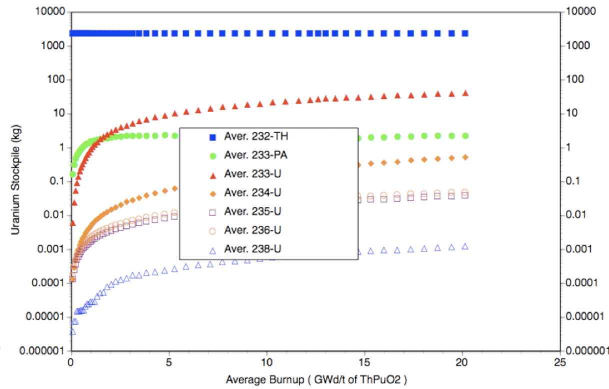
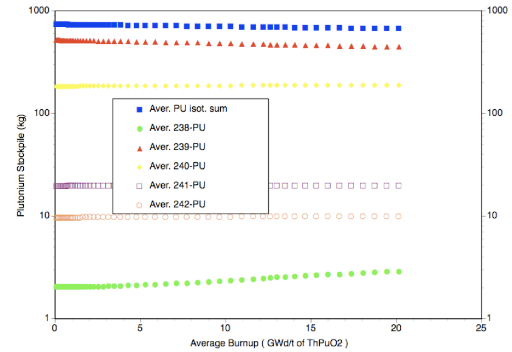
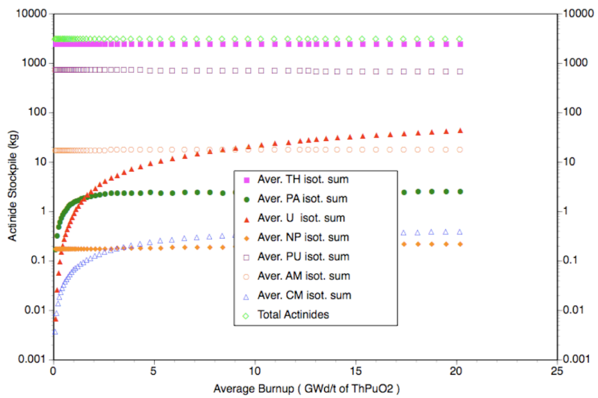
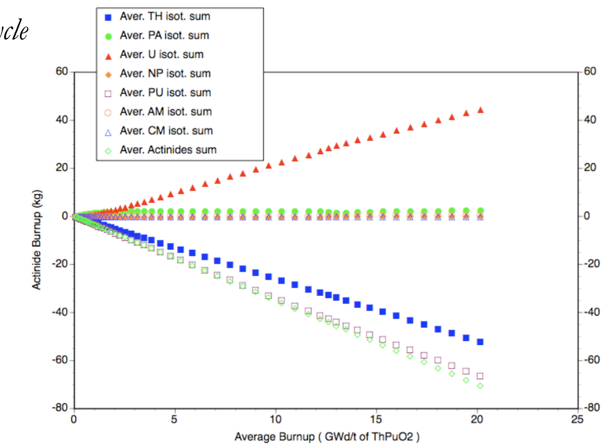






Figures 1, 2, 3, 4 and 5: Isotopic evolution of the actinides of the system over a 900-day burnup cycle





- Concentration of the main of the fuel, ^{232}Th, $^{239, 240, 241, 242}$Pu et ^{241}Am remains ~ constant over the whole duration of the cycle;
- Important production of ^{233}U (44.17 kg);
- Concentration of ^{238}Pu increases by ~ 41% but…plutonium is reduced by ~ 66.3 kg;
- Augmentation (<1 kg) of the inventory of heavy actinides (^{243}Am: + 352 g; ^{242}Cm: + 372 g; Np: - 51 g).

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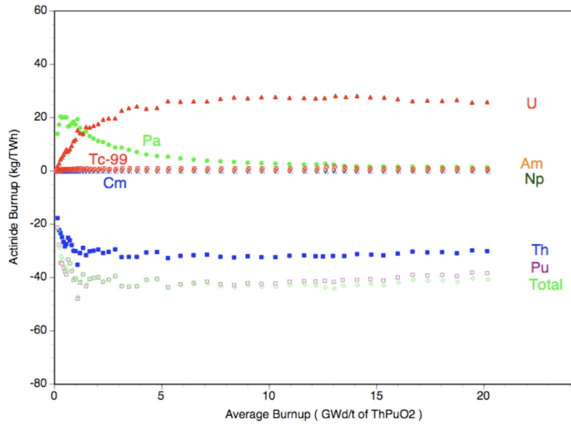

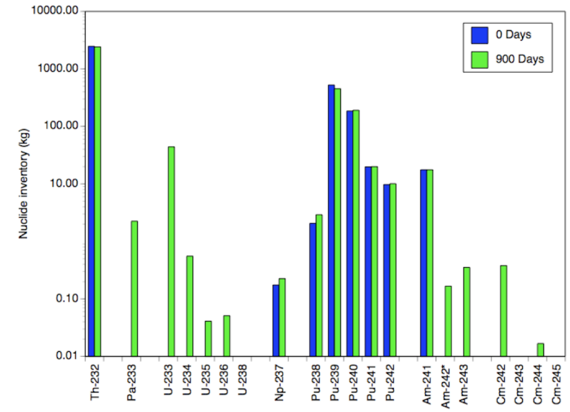

Balance of actinides (kg/ TW.h in fuel)	SVBR ($ThPuO_2$) 20 GWj/t	SVBR ($UPuO_2$) 20 GWj/t	REP (UOX)
^{233}U	+ 25.56		
Plutonium	- 38.31	- 8.4	+ 11.0
Neptunium	+ 0.03	+ 0.24	+ 0.57
Americium	+ 0.29	+ 0.17	+ 0.54
Curium	+ 0.014	+ 0.017	+ 0.044
Technétium-99	- 2.78	- 2.70	+ 0.99
Iode-129	- 2.71	- 2.70	+ 0.17

- EoC of cycle:

- Plutonium – 66.3 kg
- Neptunium + 51 g
- Americium + 505 g
- Curium + 405 g
- ^{233}U + 44.17 kg

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Minor Actinides as the initial fuel mixture

- Choice of the Fuel mixture

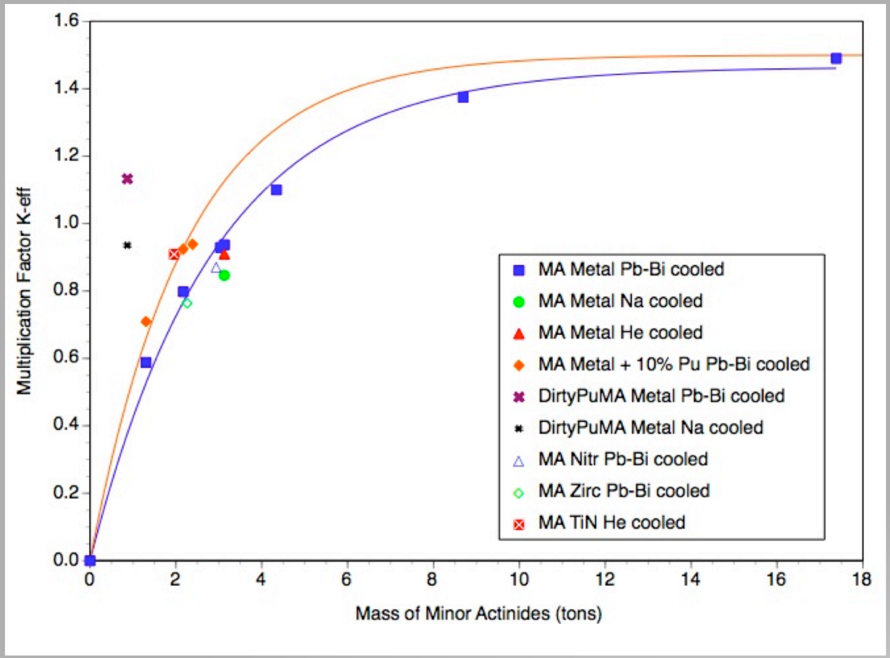

Figure 1: *Multiplication coefficient for different fuel mixtures*

- Independently of the coolant, it is difficult to reach criticality with a pure AM fuel;
- The addition of a 10% Pu to the metallic MA matrices can indeed contribute to a significant reduction of the critical mass of the system (from 3.2t to 2.5t);

Minor Actinides as the initial fuel mixture

- Global Parameters of the system

Table III: *Evolution of the main neutronic parameters for the SVBR75/100 reactor system, loaded with a Minor Actinide type fuel for a 5000 day operation cycle at 250 MW_{th}.*

Paramètres Globaux	Symbole	SVBR-ADS BOC	SVBR-ADS EOC	Unités
Mélange initial du combustible		AM	AM	
Masse du combustible	m_{comb}	2164	802.4	Kg
Combustion (burnup)		0	600	GWj/t
Longueur du cycle		0	5000	jours
Puissance thermique délivrée	P_{th}	250	250	MW
Énergie du faisceau de protons	Ep	600	600	MeV
Rendement des neutrons de spallation (yield)	N	14.51 +/- 0.10	14.51 +/- 0.10	n/p
Multiplication neutronique Nette	M	27.47 +/- 0.75	17.67 +/- 0.65	
Coefficient de multiplication	K=(M-1)/M	0.7863 +/- 0.0206	0.7577 +/- 0.0139	
Gain énergétique	G	4.29 +/- 0.66	4.96 +/- 0.43	
Coefficient de Gain	G_0	0.92	1.20	
Courant de l'accélérateur	Ip	64.56 +/- 2.99	83.87 +/- 2.82	mA
Distributions de puissance dans le cœur				
Densité moyenne de puissance du combustible	P_{th}/V_{comb}	526	797	W/cm^3

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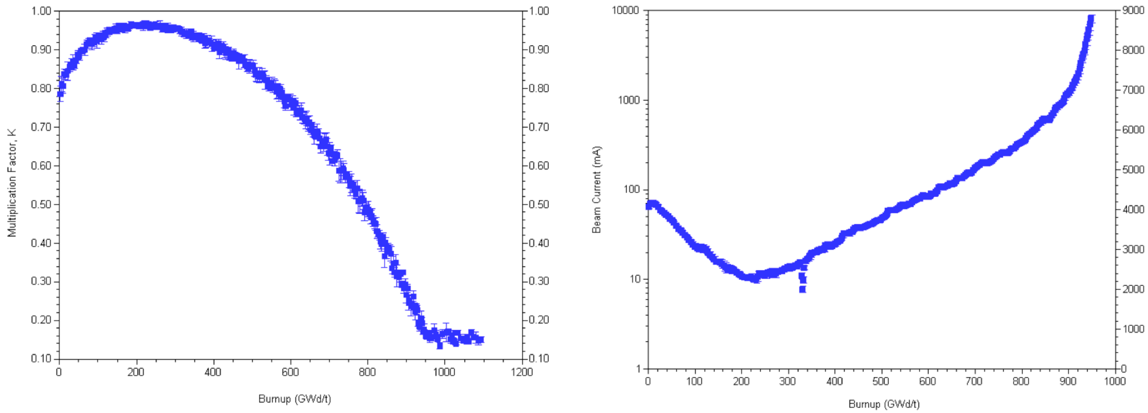
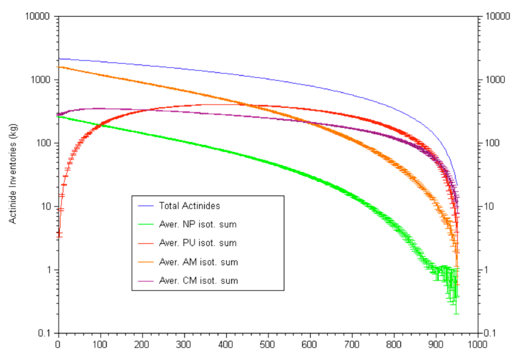
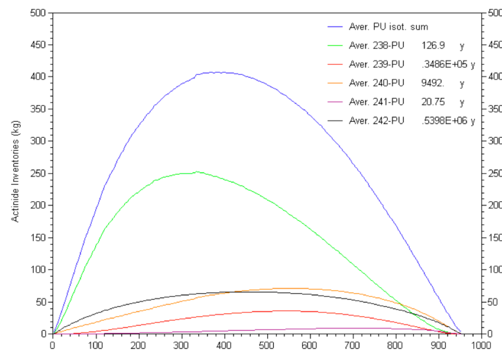
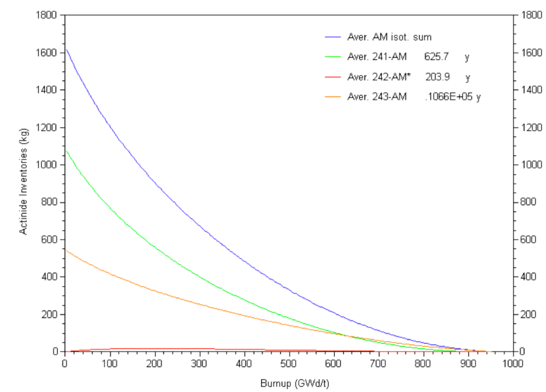


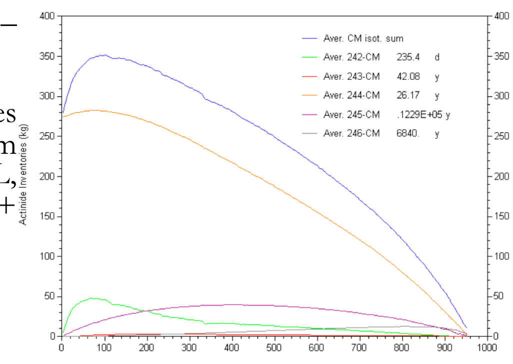
Figure 1: *(a) time evolution of k , and (b) accelerator current*



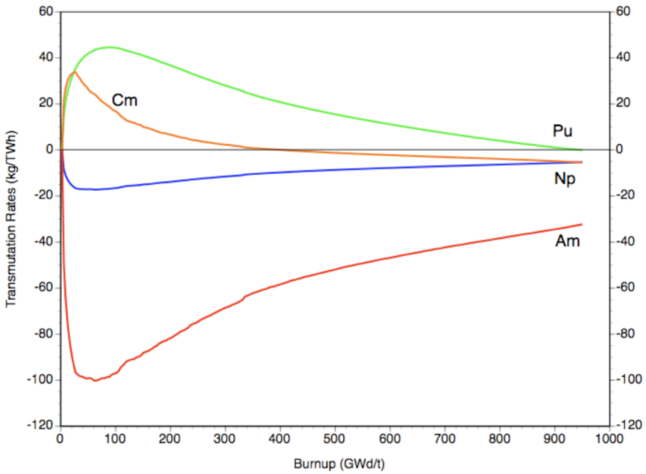




- Mass balance of actinides at EoC: ~ – 1362 kg (~ 63% of initial mass;
- Concentrations of plutonium isotopes increases (due to captures in americium isotopes) up to ~ + 407 kg at 395 GWj/tML, dropping steadily from then to reach ~ + 339 kg at 600 GWj/tML;



- Americium isotopes and de ^{237}Np fall dramatically;
- Curium: weak concentration increase (~ + 26%) until ~ 105 GWj/tML due to captures in americium isotopes; from this level of burnup, the mass of curium decreases to reach ~ 212.5 kg at EoC (~ 24% of curium is therefore eliminated)



Actinides (kg/TW.h) balance in the fuel	SVBR (AM) 600 GWj/t	SVBR ($ThPuO_2$) 20 GWj/t	SVBR ($UPuO_2$) 20 GWj/t	REP (UOX)
^{233}U		+25.56		
Plutonium	+ 11.12	- 38.31	- 8.4	+ 11.0
Neptunium	- 7.79	+ 0.03	+ 0.24	+ 0.57
Américium	- 46.77	+ 0.29	+ 0.17	+ 0.54
Curium	- 2.23	+ 0.014	+ 0.017	+ 0.044

- SUMMARY: (including burnup (+ 10% Pu)):

Bilan d'actinides (kg/TW.h de combustible)	SVBR (AM+Pu) 460 GWj/t	SVBR (AM) 600 GWj/t	SVBR ($ThPuO_2$) 20 GWj/t	SVBR ($UPuO_2$) 20 GWj/t	REP (UOX)
^{233}U			+25.56		
Plutonium	- 39.15	+ 11.12	- 38.31	- 8.4	+ 11.0
Neptunium	- 2.99	- 7.79	+ 0.03	+ 0.24	+ 0.57
Américium	- 2.98	- 46.77	+ 0.29	+ 0.17	+ 0.54
Curium	+ 0.62	- 2.23	+ 0.014	+ 0.017	+ 0.044

A few preliminary conclusions concerning the ADS burner?

- Nuclear power represents a very well established technology of paramount importance for our common energetic future, all forms considered. ADS has been accepted by members of the nuclear community as a valuable concept for waste transmutation while producing electricity;

- A collaborative approach and effort is by far the most efficient way of developing sustainable nuclear technology and creating a new energy sector; it is therefore of the uppermost importance to make the maximum profit from worldwide available results of research, development and design work performed earlier;

- ADS and GenIV concepts development involves rather innovative technologies and fuel cycles and the validation phases ranging from different components separately to their coupling and the effective construction of an industrial installation are necessary;

- The prototype in question: *The system is an important incinerator of Plutonium and waste, using a metallic matrix of MA fuel and plutonium; The system is an important incinerator of Plutonium using thorium oxide fuel, but a weak incinerator of plutonium for a MOX fuel.* Note: A major advantage of this system is the speed of its implementation (existing foundational components), encouraging the active search for the necessary funds.

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APPENDIX – Outline of work in ADS performed in Cambridge

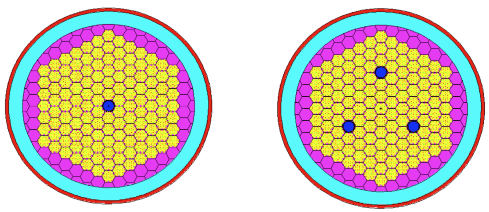
- *Extensive comparative analysis of the key technological features and challenges related to the existing ADS concepts.*
- *Participation on several financial analysis and road mapping, related to the perspective of building and operating a commercial ADS for the UK electricity market.*
- *But also….*

Table 1: Core design parameters.

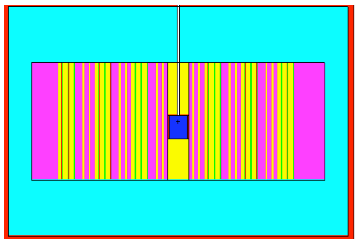
Parameter	Value/Choice
Container vessel outer radius	3 m
Container vessel inner radius	2.9 m
Container height	4 m
Core active radius	2.5 m
Fuel pin height	2 m
Fuel pin outer diameter	1.2 cm
Cladding thickness	0.3 cm
Pitch	1.25 cm
Fuel material	85% ThO_2-15% PuO_2
Coolant material	^{208}Pb
Cladding	316 stainless steel

Table 2: Spallation system design parameters.

Parameter	Value
Beam energy	1 GeV protons
Beam spatial profile	Parabolic
Spot diameter	8 cm
Target material	^{208}Pb
Target diameter	32 cm
Target length	40 cm
Target containment vessel	316 stainless steel



Cross-section of the core models for the two configurations: (a) one-target configuration and (b) three-target configuration



The core consists of a hexagonal lattice immersed in lead and it is composed of 126 fuel assemblies, each loaded with 27 fuel pins. The fuel in the active core region is composed of 85% ThO_2 and 15% $^{239}PuO_2$. (The addition of plutonium was necessary to achieve an operational multiplication factor of ~ 0.98 at the beginning of cycle). The ENDF/B-VI nuclear data library was used)

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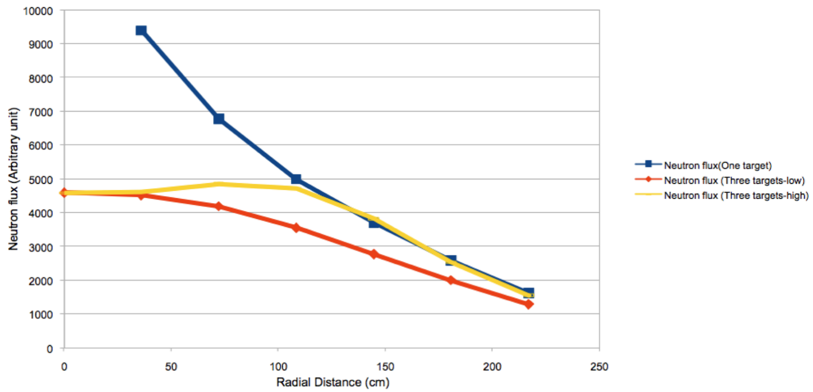
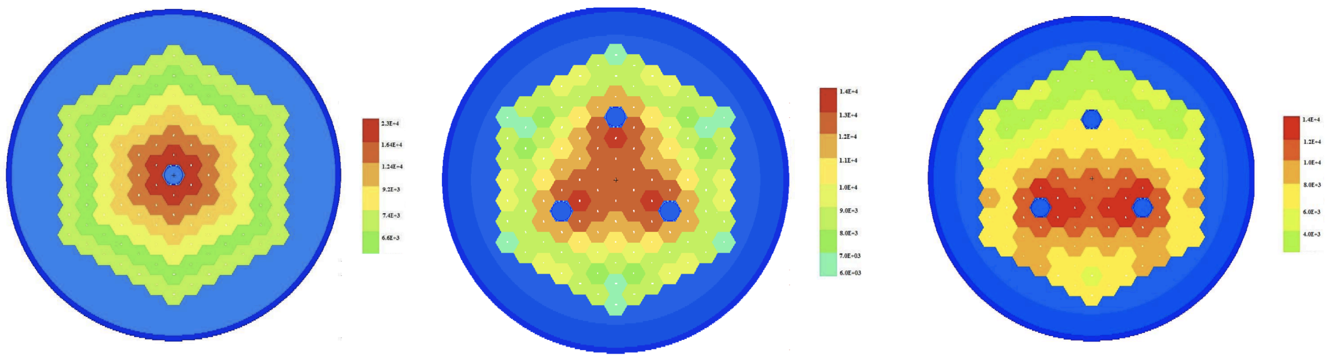


- ThorEA Workshop, Trinity College, Oxford - 13th April 2010 and
- *AEN/NEA – 'Technology and Components of Accelerator Driven Systems', 15th-17th March 2010, Karlsruhe, Germany*



Cross-section of the core models for the two configurations:
(a) one-target configuration and (b) three-target configuration

Although the symmetry of the power distribution has been broken, there are still a significant number of fissions in the assemblies around the target that has lost its beam. An overall reduction of 10% in the power generated is observed when compared to normal three-beam operation.

Thank you all for both your time and your attention !

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