

Nuclear Waste Transmutation

Enrique M. Gonzalez
CIEMAT

- Transmutation Basics
- Advance fuel cycles
- Dedicated transmuters – ADS
- R&D needs and programs

Transmutation Basic Concepts 1

The nuclear waste Transmutation is a possible component of the nuclear fuel cycle, that aims to transform a large fraction of the long term source of radioactivity, radiotoxicity and heat:

Plutonium (Pu)

Minor Actinides, MA (Np, Am, Cm)

Long lived fission fragments, LLFF (^{99}Tc , ^{129}I , ^{135}Cs , ^{126}Sn , ...)

Into stable or short lived (<30 years) materials.

With the final objective of:

- Reducing the radiotoxicity inventory and the volume of the High Level Wastes, HLW, of future reactors and fuel cycles, to improve their sustainability
- Increasing the capacity of the Geological Repository for the waste already produced, and to be produced, by the present reactors
- Facilitating the technical requirements and public acceptance of the Geological Repository

Transmutation Basic Concepts 2

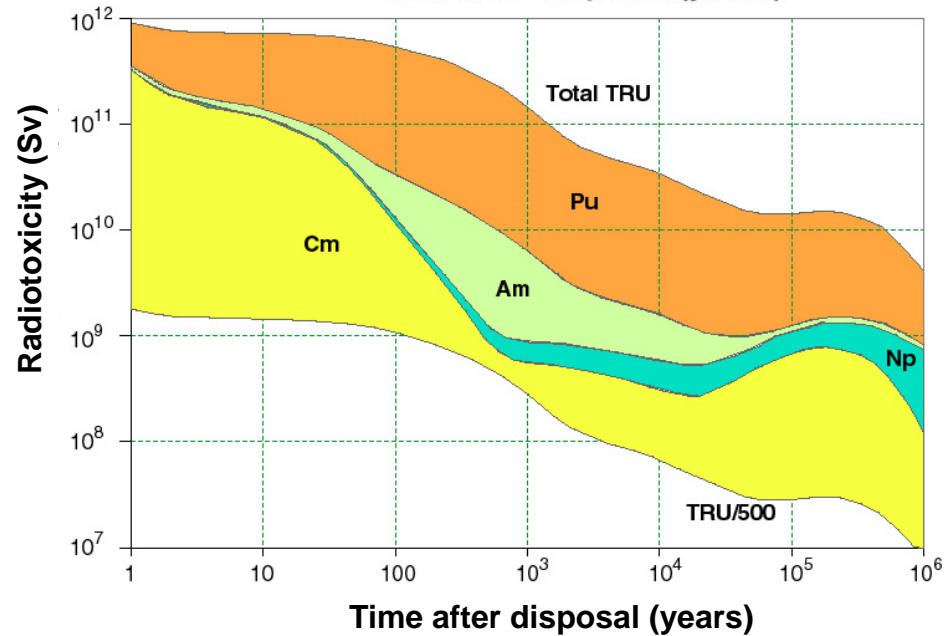
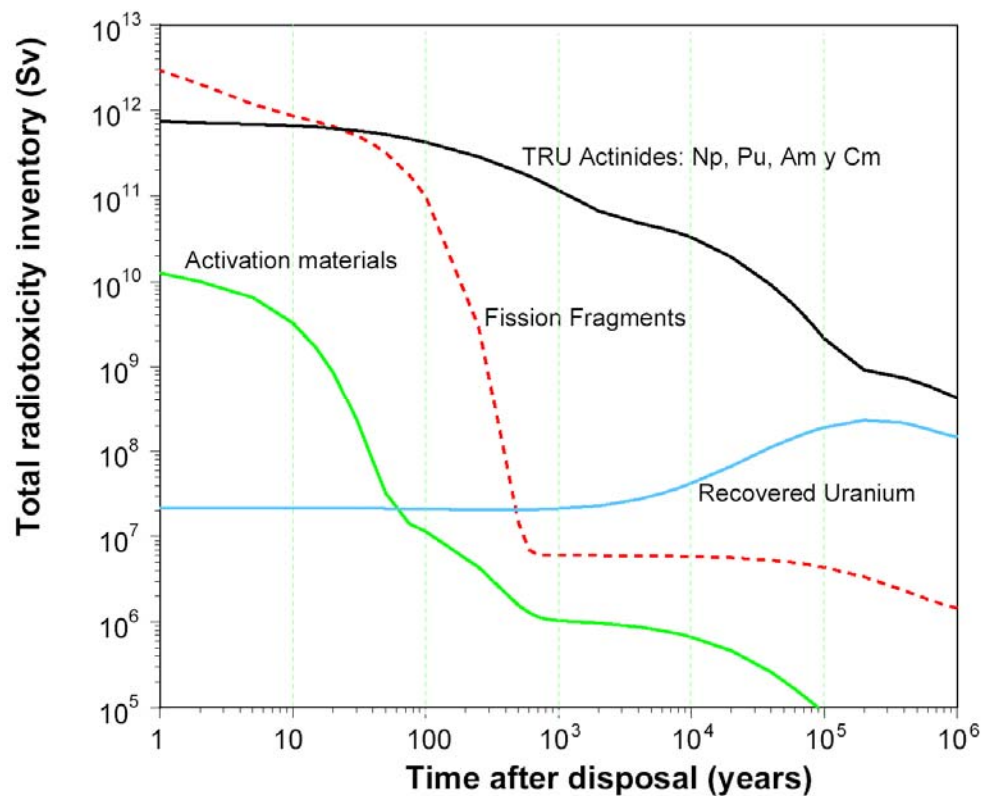
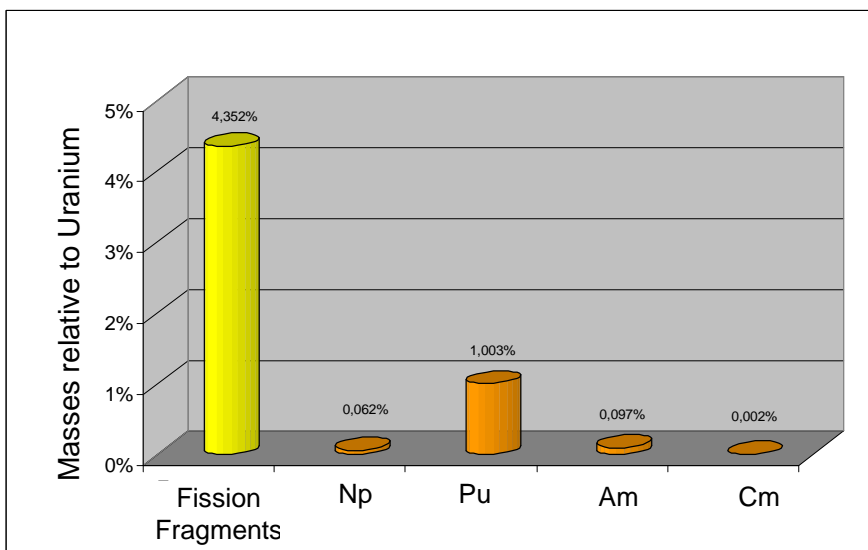
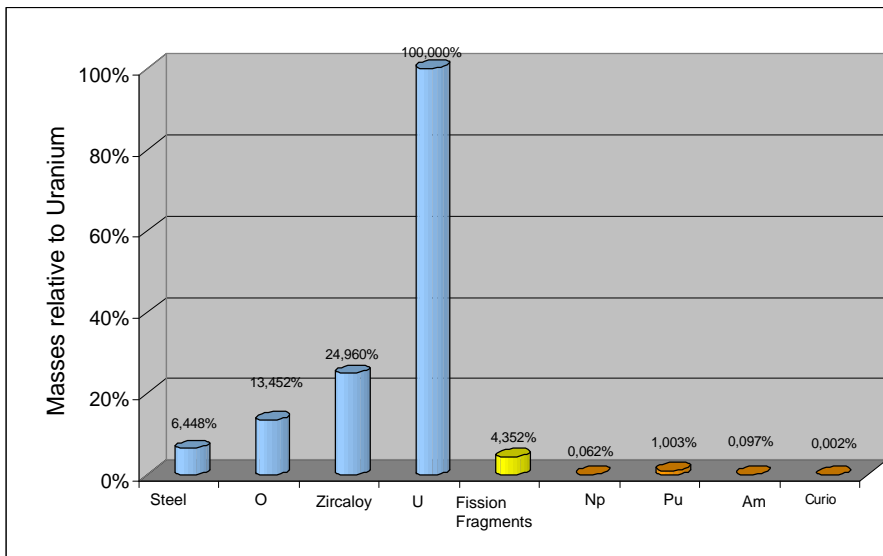
Reduction of the potential risk

The measurement of the potential risk contained in the HLW is the Radiotoxicity.

The main source of HLW is the nuclear reactors spent fuel.

At long term the main component of the radiotoxicity in the spent fuel are the Transuranic elements, TRU: Pu and MA.

So the main subject for transmutation are the TRU. At the same time the reduction of TRU will reduce the long term heat source allowing for a more compact arrangement of waste on the Geological Repository



Transmutation Basic Concepts 3

Transmutation by Fission

Transmutation is induced by the irradiation of TRU by high neutron fluxes.

TRUs will fission producing FF (mainly stable of short lived) + Energy ⇒

Several captures and decays may happen to one particular nucleus before fission.

(Note: The transmutation chains of the different isotopes irradiated during the waste transmutation is a very interesting physics problem very similar to stellar nucleosynthesis ⇒)

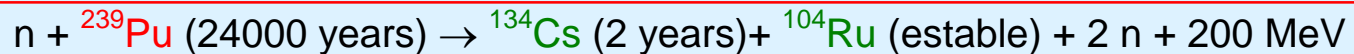
- TRU ⇒ FF reduces by large factors the long term risk for the general public **but** increases slightly the short term risk for the fuel cycle operators.
- The reduction of TRUs minimizes the proliferation attractive of the nuclear wastes, although it might increase the risk of the fuel cycle.
- The energy produced in transmutation can be used to produce electricity (about 30% of the total electricity produced in the present reactors). This electricity has a high economical value. The early utilization of the Pu of the nuclear waste will consume a valuable fissile material that could be needed for the startup of future advance reactors.

Specific R&D and a careful planning of the future nuclear energy utilization and of the transmutation implementation is required to obtain the long term advantages without new short term problems.

What is the Nuclear Waste Transmutation

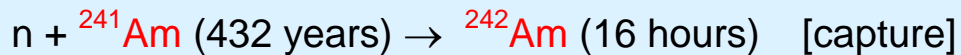
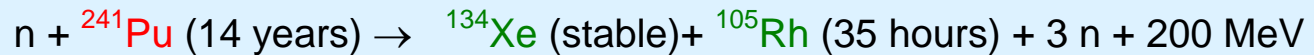
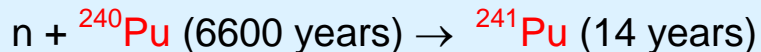
To Transmute means to convert one element to another and by extension one isotope to another.

The main physical process to perform useful transmutation is nuclear fission. One example of transmutation by fission can be:



Strong reduction on the time to become stable (small overall initial activity increase)

Some times one or several captures and decays must take place before fission can perform the useful transmutation:



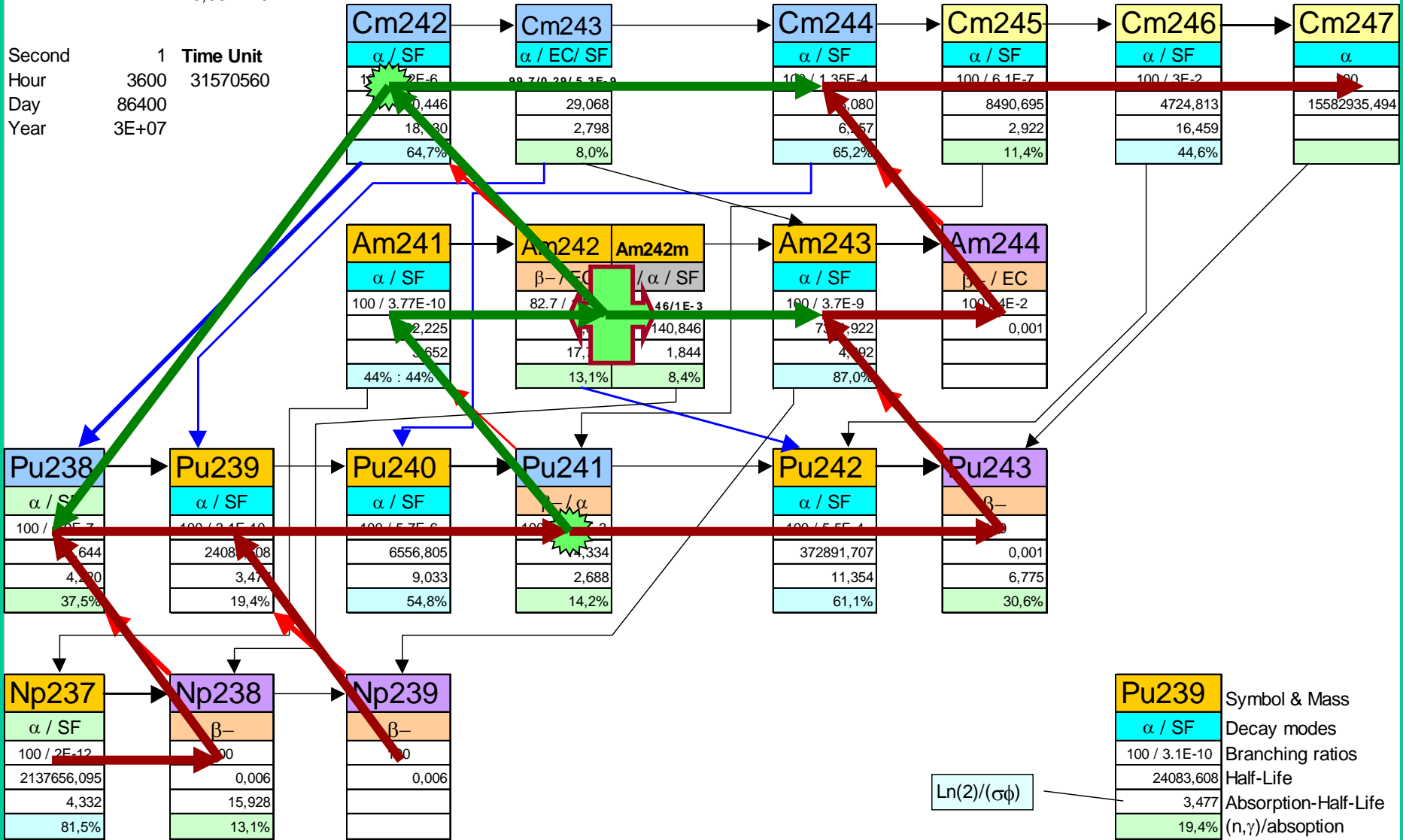
- Present in nuclear wastes
- Medium Half-Life (<100 años)
- Short Half-Life (< 30 dias)
- High A actinides
- Thermal and Fast Fission
- Fast Fission
- Low Fission Cross Section

TRU Transmutation Scheme

Fast Spectrum

Av. Flux Intensity (n/cm2/s)
3,00E+15

Second 1 Time Unit
Hour 3600 31570560
Day 86400
Year 3E+07



Transmutation Basic Concepts 4

Transmutation in Reactors / ADS

Industrial scale Transmutation requires intense neutron source and produce large amount of energy -> It must be done in some kind of nuclear reactor.

- The TRU may be placed in the reactor fuel or in separated targets
- The different TRU elements may be handled homogeneously or in different targets

The total amount of transmutation in one reactor is proportional to the power produced by the TRU fission. With the typically proposed transmuters and installed power the transmutation of already existing wastes will take a few decades.

This is independent of the type of transmuter.

However,

the viability of the transmutation and the mass and isotopic composition of the final wastes after transmutation depend on the neutron energy spectrum of the reactor.

Thermal reactor induces higher masses in the waste isotopes than Fast Reactor and has a worse neutron economy.

Transmutation Basic Concepts 5

Transmutation in Reactors / ADS

The maximum efficiency of transmutation for a fix reactor power is achieved when the only actinides in the fuel are the TRU to be transmuted. For this reason Dedicated Transmuters are usually proposed with fuels with no or low U/Th content (\Rightarrow),

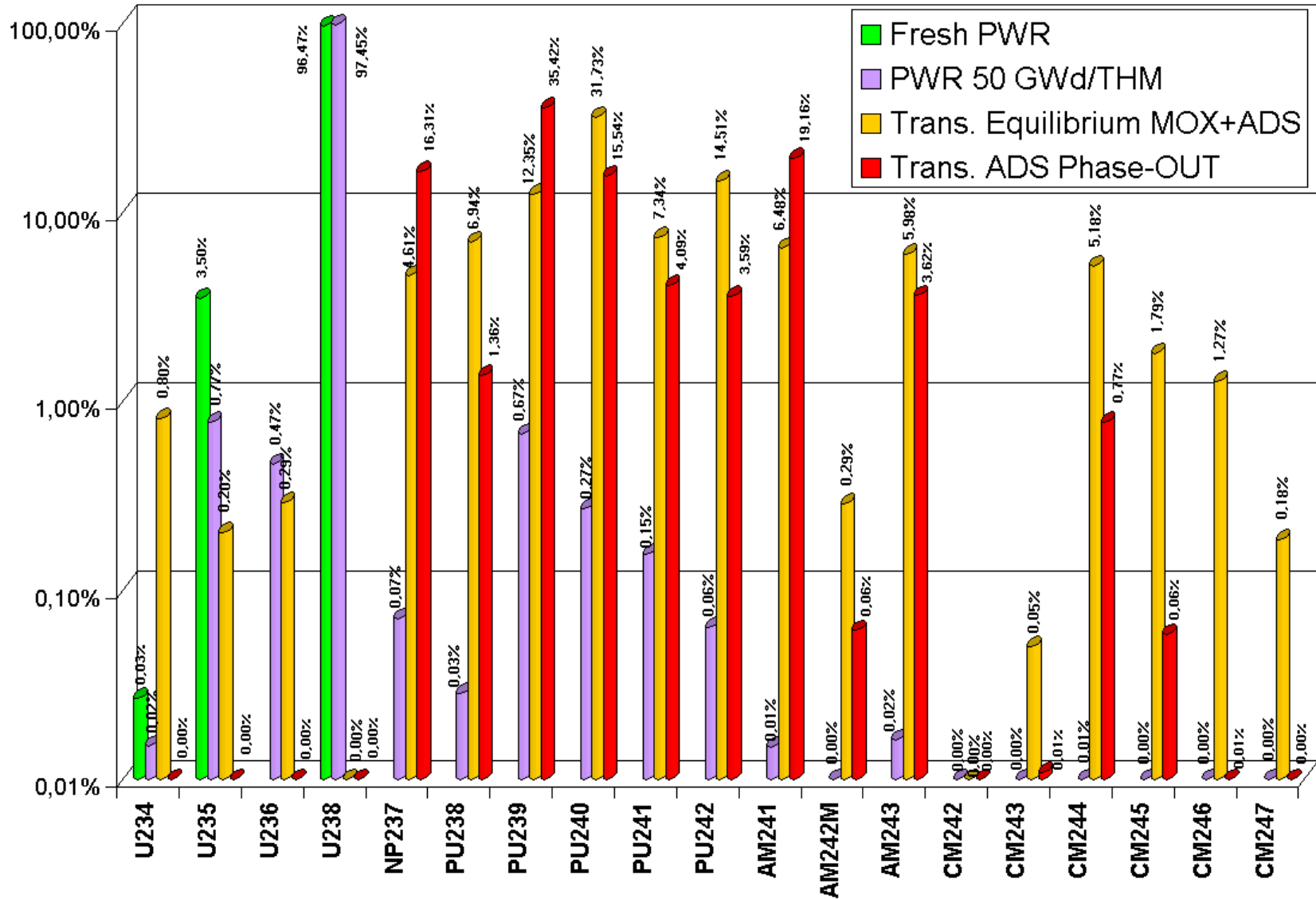
But, with these fuels:

- The intrinsic safety is largely degraded (Low delayed neutron fraction, low Doppler feedback, Bad void coefficient, ...)
- The reactivity of the reactor drops very rapidly (limit to the fuel burn-up)

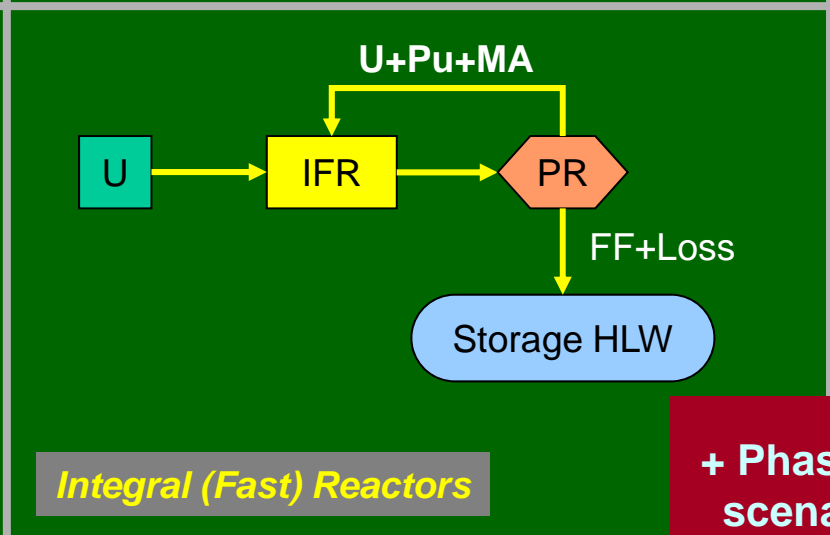
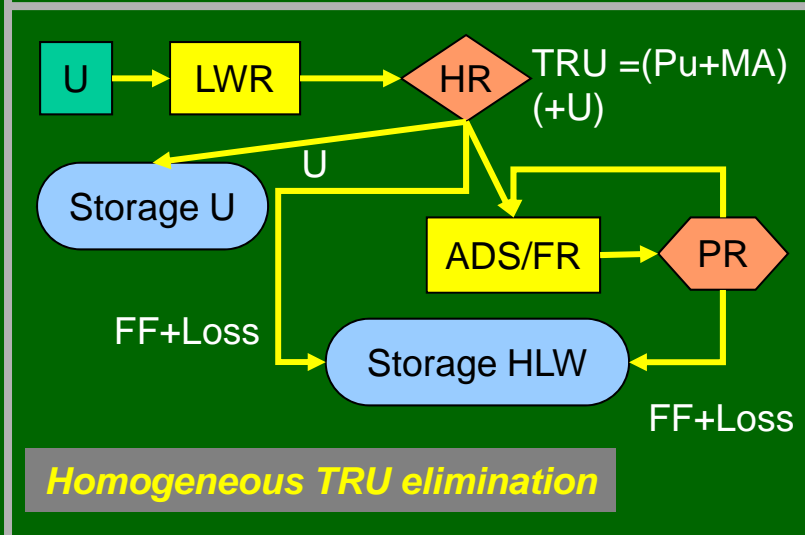
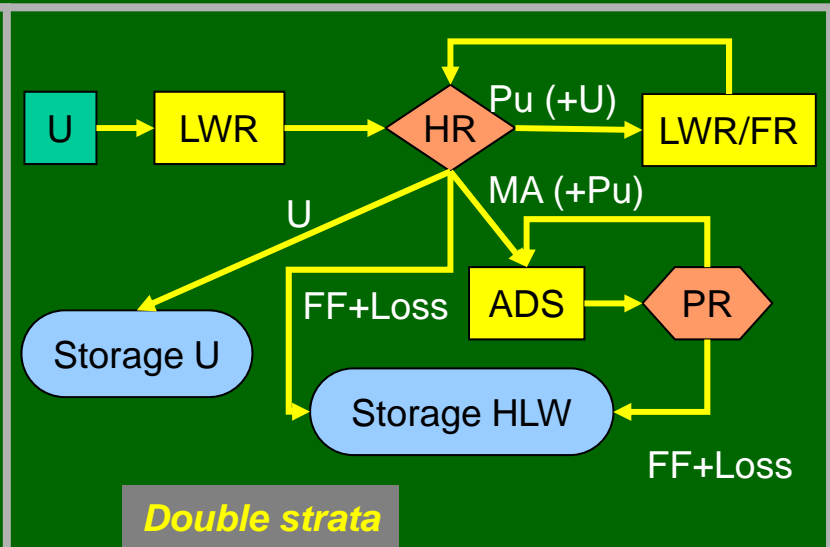
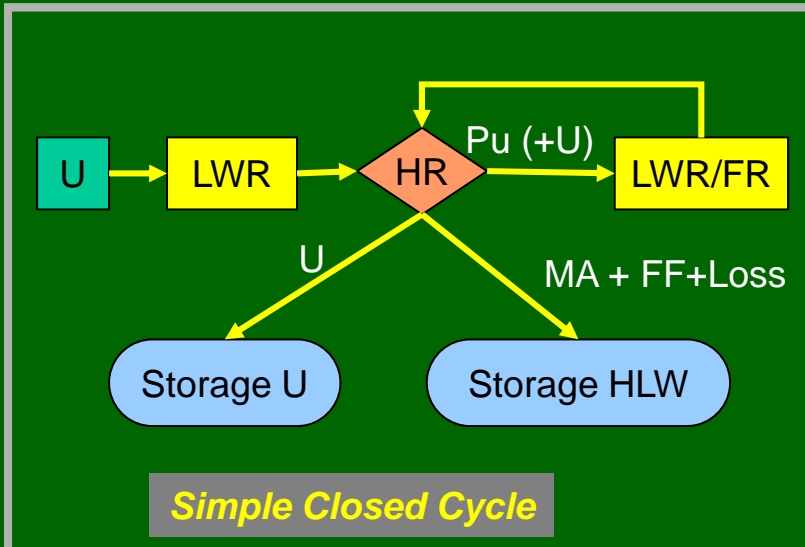
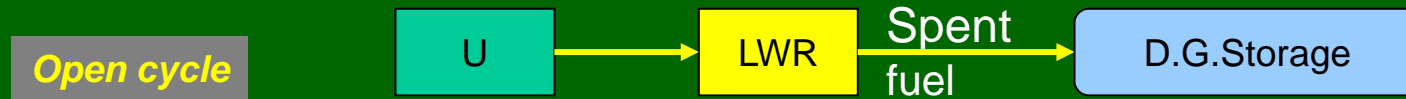
The large flexibility and external safety required to design and operate a reactor with these characteristics has motivated the proposal of ADS for dedicated Transmuters.

ADS are subcritical nuclear systems with the power maintained by a powerful and flexible external neutron source. Normally this source is produced from the spallation induced in heavy materials by high energy (1 GeV) protons.

New isotopic composition of transmutation fuels



Transmutation is one piece of the (advance) nuclear fuel cycle



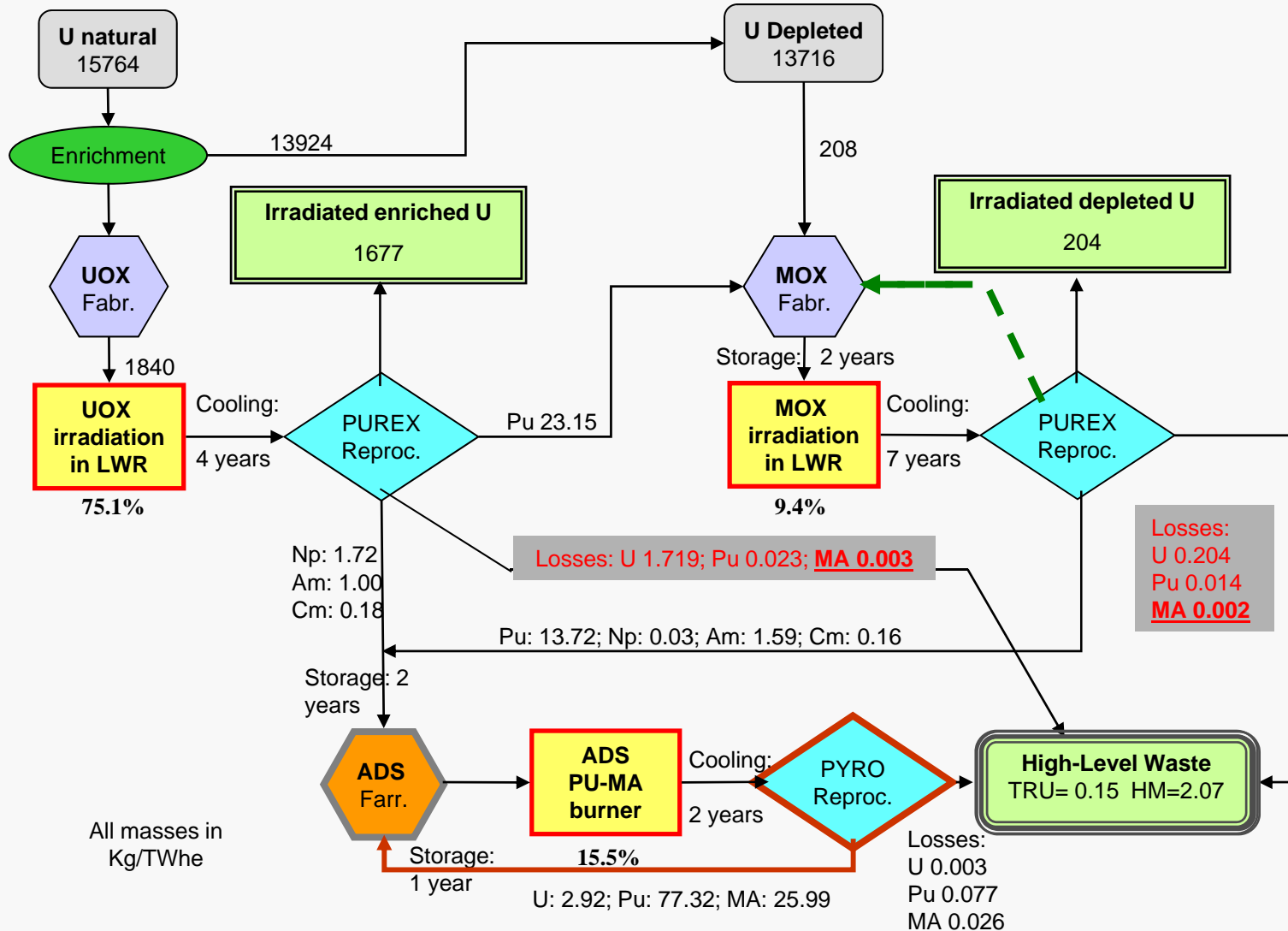
+ Phase-out scenarios

Example of double strata.

In open cycles the HLW is mainly the spent fuel

In closed cycles the HLW are mainly the reprocessing losses

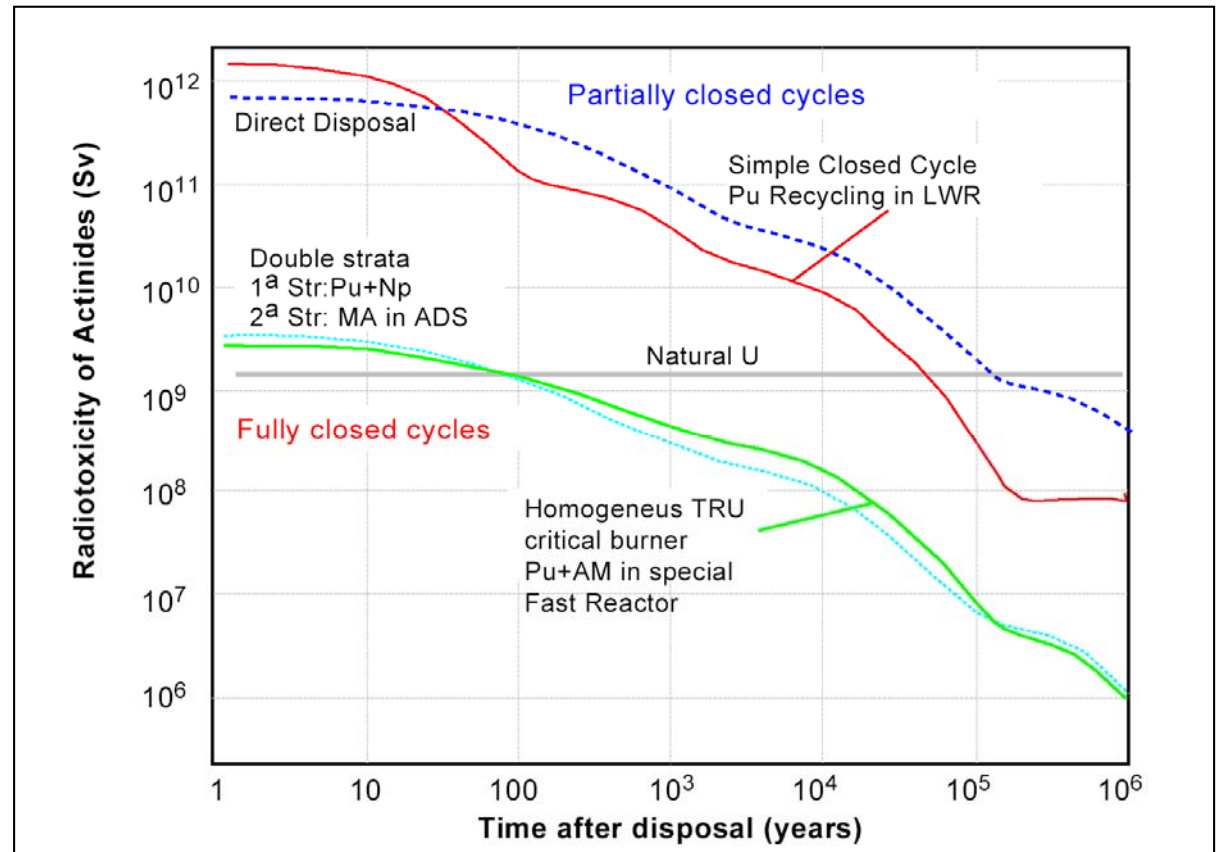
Double strata cycle: maximum use of technologies in exploitation



Expected Transmutation performance

European ADS Roadmap:

Assuming a reprocessing recovery fraction of 99.9% for all actinides in the different partitioning operations.



Consequences for the repository (of fully closed cycles)

Strong reduction of the radiotoxicity inventory

Increase of the repository capacity by factors $\approx 5-10$ (Yucca Mountain)

Reduction of a factor ≈ 1000 on the time required to reach any reference level of risk

Separation of the short term heat source: Sr (90) and Cs (137):

will allow further reduction of the repository capacity reaching factors $\approx 10-100$.

General Conclusions from Accelerator-Driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles. A comparative Study”, Nuclear Development, NEA/OCDE (2002).

- *While P&T will not replace the need for appropriate geological disposal of high-level waste, the study has confirmed that different transmutation strategies may significantly reduce, i.e. a hundred-fold, the long-term radiotoxicity of the waste and thus improve the environmental friendliness of the nuclear energy option. In that respect, P&T could contribute to a sustainable nuclear energy system.*
- *Very effective fuel cycle strategies, including both fast spectrum transmutation systems (FR and/or ADS) and multiple recycling with very low losses, would be required to achieve this objective.*
- *Multiple recycle technologies that manage Pu and MA either together or separately could achieve equivalent reduction factors in the radiotoxicity of wastes to be disposed. The study shows that pyrochemical reprocessing techniques are essential for those cycles employing ADS and FRs where very high MA-content fuels are used.*
- *In strategies where Pu and MA are managed separately, ADS can provide additional flexibility by enabling Pu-consumption in conventional reactors and minimising the fraction of dedicated fast reactors in the nuclear system.*
- *In strategies where Pu and MAs are managed together, the waste radiotoxicity reduction potential by use of FRs and ADS is similar and the system selection would need to be made based on economic, safety and other considerations.*
- *Further R&D on fuels, recycle, reactor and accelerator technologies would be needed to deploy P&T. The incorporation of transmutation systems would probably occur incrementally and differently according to national situations and policies.*
- *Fully closed fuel cycles may be achieved with relatively limited increase in the electricity cost of about 10-20%, compared with the LWR once-through fuel cycle.*
- *The deployment of these transmutation schemes need long lead-times for the development of the necessary technology as well as making these technologies more cost-effective.*

R&D Needs from Accelerator-Driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles. A comparative Study”, Nuclear Development, NEA/OCDE.

- **Basic R&D** is needed for the new FR and ADS in the fields of nuclear data and neutronic calculations, fuel technologies, structural materials, liquid metals, reprocessing technologies, target materials and high power accelerators (the last two only for ADS).
- **Experimentation on fuels is a priority.** No concept can be considered seriously, if the appropriate fuels are not defined and proven, i.e. characterised, fabricated, irradiated and reprocessed.
 - Since fuels play a central role in all scenarios of waste minimisation and nuclear power development, an international share of efforts around nitrides, oxides and metals should be organised in order to ensure an optimum use of resources in the few existing laboratories which can handle very active fuels.
 - In this context, *the availability of irradiation facilities, in particular fast neutron facilities which can produce high damage rates in the specimens, is a key issue and major concern.* Again, an international initiative could be envisaged to harmonise programmes and to allow the best use of existing resources to be made. Identification of the experimental irradiation needs in such a shared international fast-spectrum facility would be a worthwhile undertaking.
- **Demonstration at appropriate scale of the performance of pyrochemical processes** (level of losses, secondary waste, etc.) is needed in order to assess in more detail the technico-economic viability of certain fuel cycle options.
- In the field of basic R&D supporting FRs as well as ADS, the discussion around the **coolants for fast-spectrum systems** would benefit from a better international agreement on pro and cons of the different options.
- **Improved modelling tools to simulate the materials behaviour under (mixed) irradiation conditions** (and possibly high temperatures) may prove to be a very valuable approach and a sharing of expertise and benchmarking within an international context may be advocated.
- **Safety analysis of ADS** should identify the possible paths to exclude hypothetical core disruptive accidents (HCDA) in ADS. If such a HCDA has to be taken into account in the safety analysis of an ADS, a prompt negative feedback mechanism for quenching such an accident has to be developed.
- In addition to this R&D, countries embarking on an ADS-based fuel strategy should envisage a **demonstration experiment** which allows the ADS concept to be validated from operation and safety viewpoints.
- And last but not least, **Performance assessment studies for a geological disposal site using a P&T source term** are necessary in order to seek clarification of the cost/benefit analysis of such advanced fuel cycles, including geological disposal.

The optimal advanced fuel cycle with transmutation

There is no universal optimal cycle to implement transmutation:

Different solutions can be better suited to different countries depending on the already existing fuel infrastructure:

reprocessing,
MOX fabrication,
Fast reactors, ...

and on the future nuclear energy policy:

sustainable,
increase of installed power,
phase-out.

The sustainable nuclear energy case

Any future nuclear reactor will be evaluated as part of a complete fuel cycle, and at present, one of the main requirements to the future cycles will be waste minimization.

So **Transmutation will be present in future sustainable fuel cycles, one way or another.**

If the cycle include a large fraction of energy generation in **fast reactors,FR**, (GEN IV):

The Pu will be part of the fuel and the MA can also be transmuted in the reactor.

(IFR concept)

In this case the concentration of M.A. And probaly also of Pu in the (fertile-U) fuel will be limited, allowing to operate in critical reactors. In addition the reprocessing and fuel fabrication will be less extreme. However it has not been demonstrated that present technologies can fabricate and reprocess such fuels, and even if it is possible the cost increase will penalize a large fraction of the energy production.

Another option, is **double strata**, optional for cycles with FR and nearly mandatory for thermal reactor cycles (with the possible exception of thermal molten salt reactors):

In this case the energy producing part of the cycle (a very large part of the total) will use cheap “conventional” known fuels and reprocessing techniques, that can handle some Pu. All the minor actinides and the rest of the Pu are transmuted in dedicated reactors, most probably ADS.

For these dedicated transmuters, fuel fabrication and reprocessing will be extreme, and consequently expensive, but only a small part (10-20%) of the cycle will be affected.

In either case, the **increase in the electricity price is expected to be between 10-20%** higher than without transmutation. Part of this increase can be compensated by the simplification of the Geological Repositories. The final choice will be political or economical when price estimations become more realistic and precise.

The case of the phase out of nuclear energy

In the phase out scenario, it will be very difficult to justify the deployment of very large facilities, like the ones required for the reprocessing of the present reactors spent fuel, that will be used for short period of time.

However it will still be desirable to profit from the transmutation to simplify and reduce the size of the repository, and to help on the public acceptance of the final repository.

A possible solution at regional level is being analyzed in several forums. The idea assume that close to the country A going to phase out, there is country B sustaining the use of nuclear energy. There are 2 options:

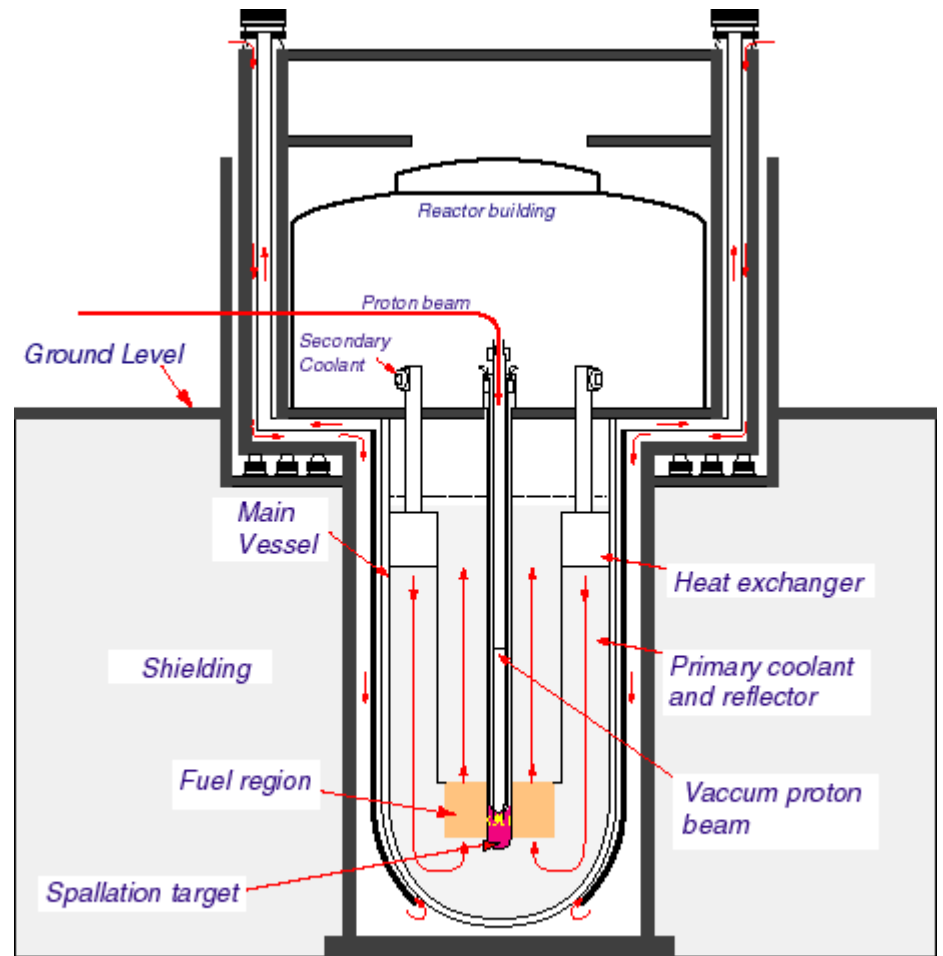
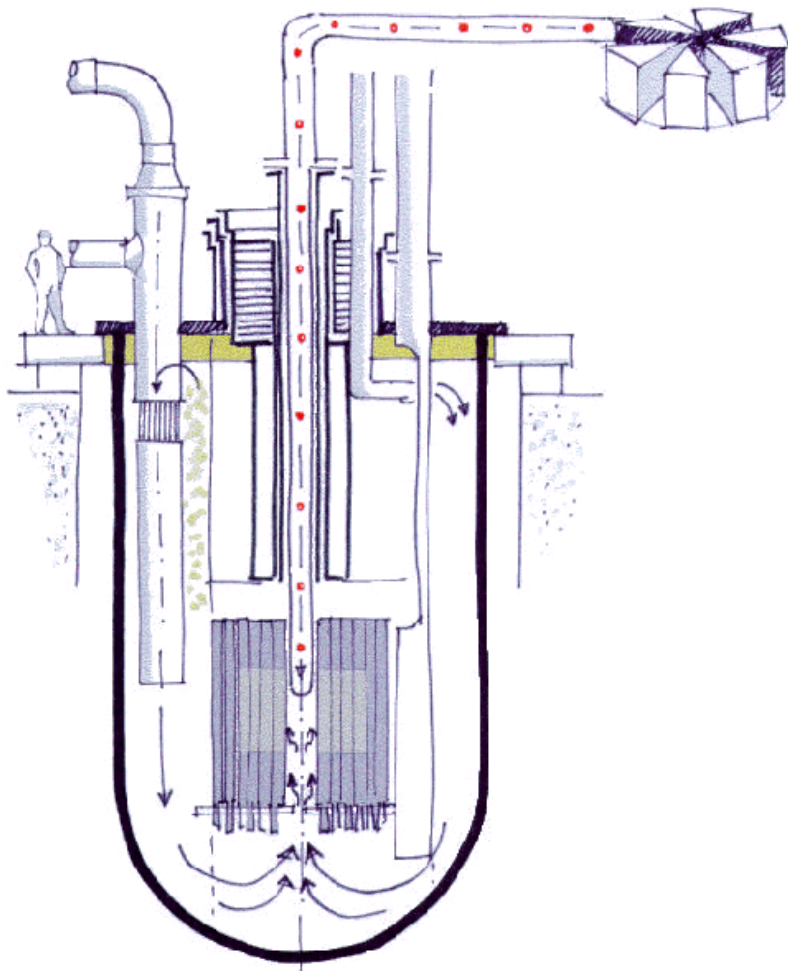
- 1) Country B does P&T for the country A spent fuel and return the final wastes to A.
- 2) Country A uses the large facilities of country B and then deploys small or medium size facilities to perform P&T. For example:

Country B makes the reprocessing of the spent fuel of the present reactor and produces special transmutation fuel that is sent back to country A

Country A installes a small park of ADS transmuters, Pyroreprocesing and Fabrication facilities to perform localy the P&T

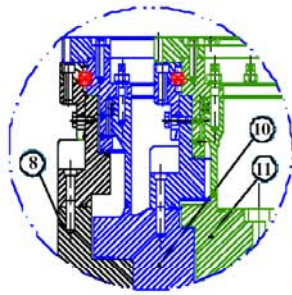
The technology for these ADS, pyroreprocesing and fabrication plants is jointly developped by countries A, B and others, with variants specifically suited for each country situation.

ADS Subcritical Systems as Dedicated transmuters

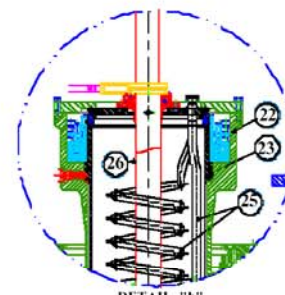


0.0 2.5 5.0 7.5 10 (m)

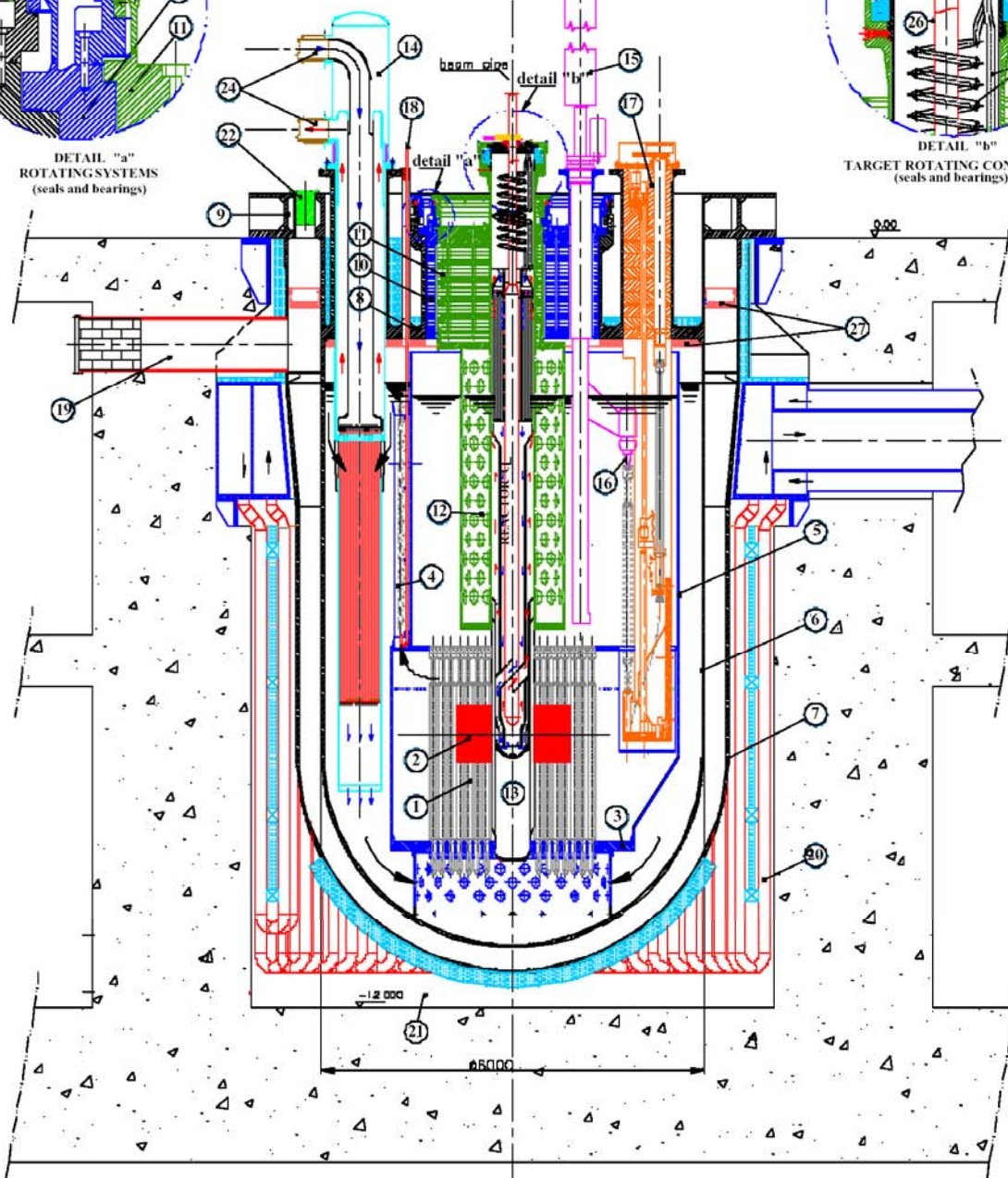
General layout: Central spallation source, surrounded by a region containing the fuel (in bundles of pins) with coolant (Pb, Pb/Bi and Na, Gas) and internal (steel) structures. The fuel is surrounded by a neutron reflector (coolant buffer) and the vessel surrounded by technical and biological shielding (concrete and steel).



DETAIL "a"
ROTATING SYSTEMS
(seals and bearings)



DETAIL "b"
TARGET ROTATING CONNECTION
(seals and bearings)



- | | |
|---|--|
| 1 REACTOR CORE :
- fuel elements: # 120
- dummy elements: # 174 | 7 SAFETY VESSEL |
| 2 FUEL ZONE | 8 REACTOR ROOF |
| 3 DIAGRIDD | 9 REACTOR VESSELS
SUPPORT |
| 4 RISER: #24, 202 mm I.D. pipes | 10 ROTATING PLUG |
| 5 CYL. INNER VESSEL | 11 ACS (Above Core Structure):
upper part |
| 6 REACTOR VESSEL | 12 ACS : lower part |
| 15 TARGET UNIT | 19 ACCESS FOR ISI |
| 14 IHX (Intermediate Heat Exchanger):
4 units | 20 RVACS (Air Cooler) |
| 15 TRANSFER MACHINE | 21 REACTOR PIT |
| 16 TRANSFER MACHINE GRIPPER | 22 TARGET UNIT: Outer Support |
| 17 ROTOR LIFT MACHINE | 23 TARGET UNIT: Inner Support |
| 18 GAS INJECTION PIPE | 24 IHX DIATHERMIC FLUID:
Inlet-Outlet |
| 25 TARGET UNIT DIATHERMIC FLUID:
Inlet-Outlet | |
| 26 BEAM PIPE | |
| 27 METALLIC THERMAL INSULATION | |

XADS Reference Configuration

Ansaldo Nucleare
Divisione di ANSALDO ENERGIA S.p.A.

XADS - MYRRHA concept

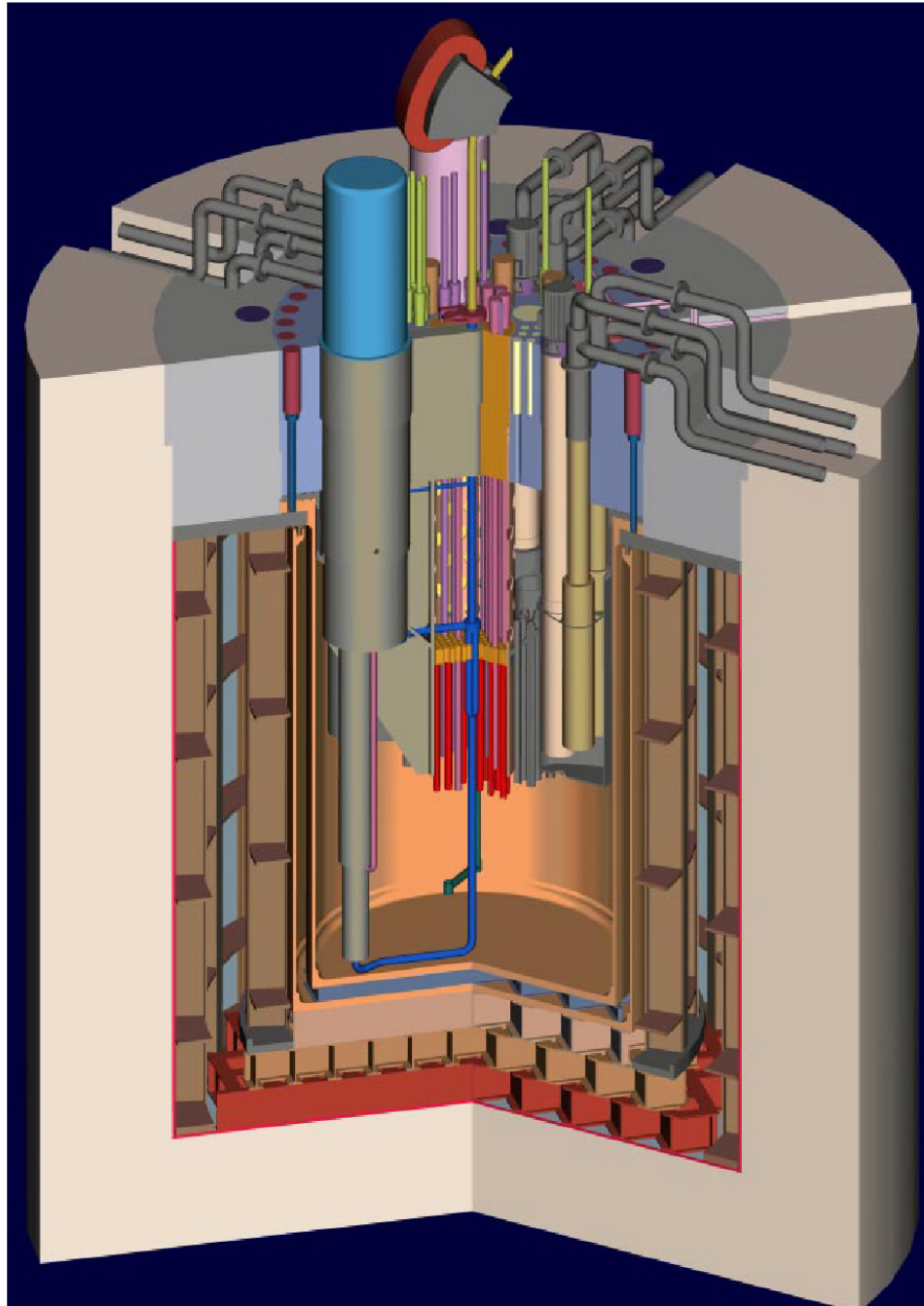
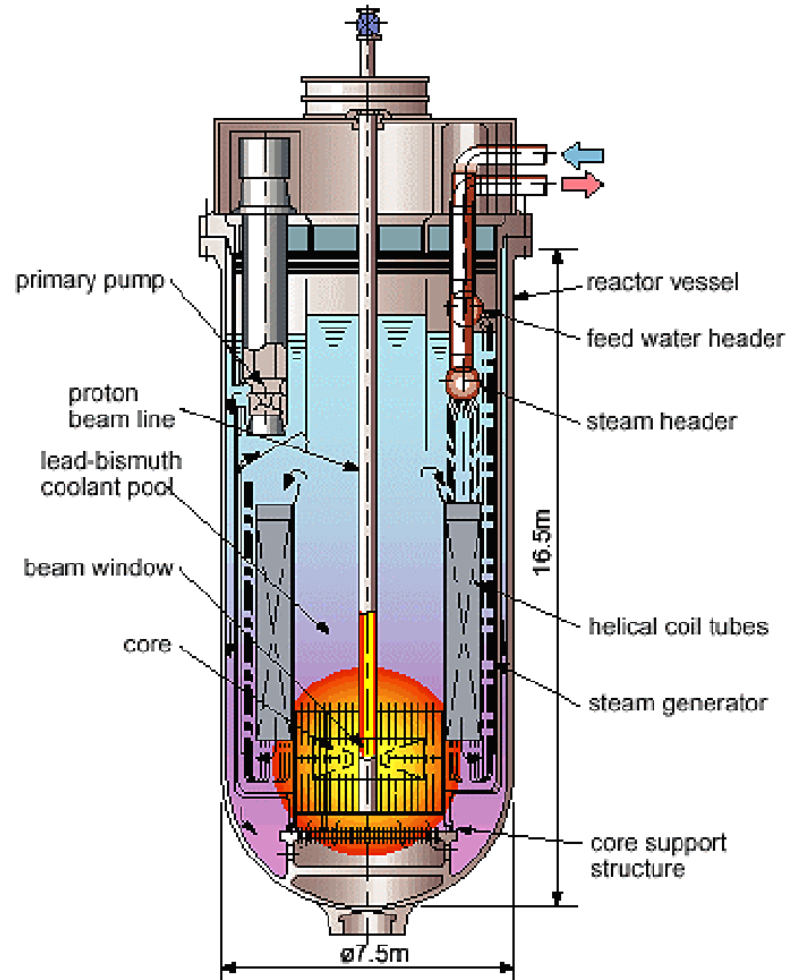
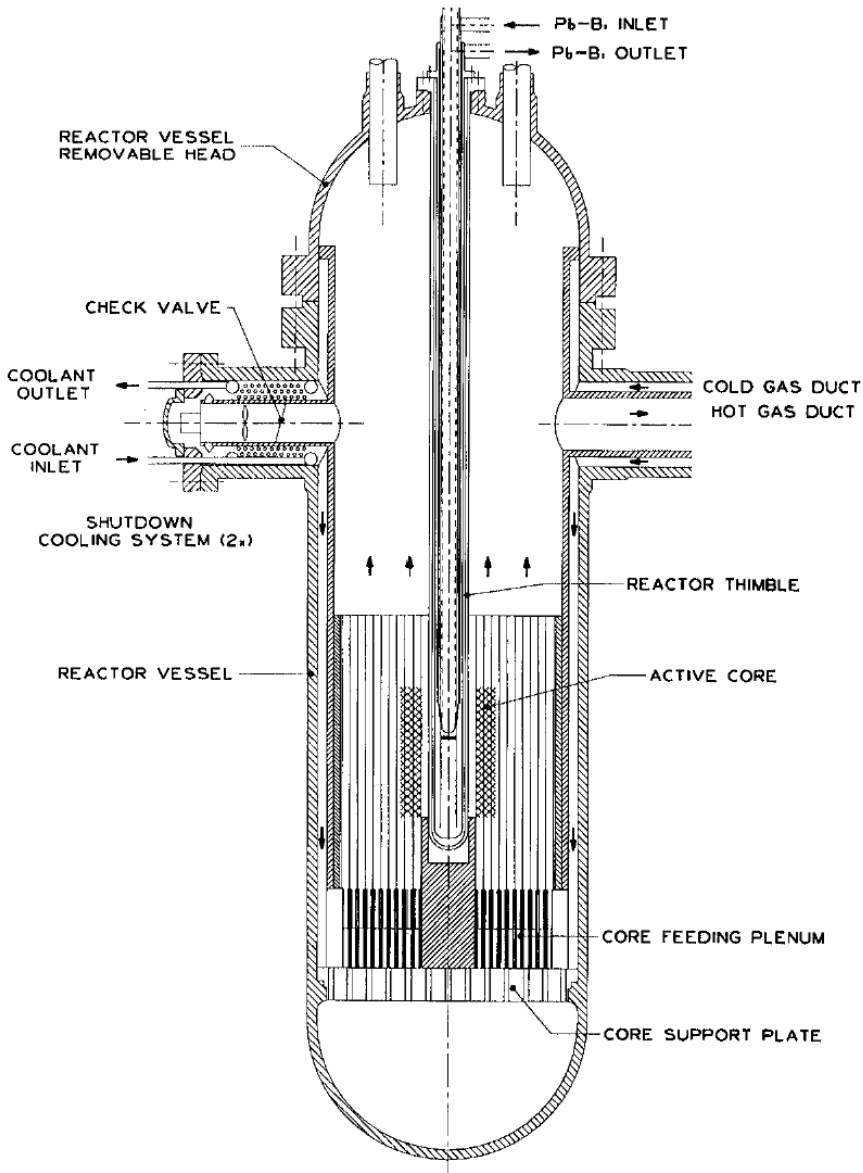


Figure F.2. Gas-cooled XADS concept



ADS vs Critical Reactors

The main differences are a larger flexibility of the ADS towards the fuel properties and its operation cycle, and the need for an external source.

Favorable to ADS: Flexibility and Safety

- Ability to use fuels and coolants with low intrinsic safety (e.g. High MA content)
- The accelerator allows to replace or simplify some safety components
- Allow to have larger ranges for the compensation of loss of reactivity during burn-up
- ADS might be the only solution for a dedicated MA (+Pu) transmuter

Negative to ADS: Novelty and Expected price

- Introduce new elements (accelerator and spallation source) that will have to conform with the reliability and safety nuclear plant standards
- Kinetics and Dynamics are different between the ADS (source driven) and the critical reactor (reactivity and feedback driven). This will require the development and licensing of new monitoring and control systems
- There is no demonstration plant built so far
- Although not fully verified the ADS is considered more complex than the reactor
- Besides the large uncertainties, the common wisdom is that the ADS will be substantially more expensive than a critical reactor of the same power. However this is not the relevant parameter, and it may happen that the fuel cycle with ADS become finally cheaper than with critical reactors, if they have to handle the TRU

Status of ADS: NO show stopper found !

ADS prototypes of zero power are in operation:

FEAT (Thermal/spallation), MUSE (Fast/DT), Yalina (Thermal/DT), ...

Test of the ADS physics, validation of ADS computer simulation , Development of diagnostic techniques

More realistic ADS prototypes of zero power available in less than 3 years

Yalina-Booster (Fast/thermal/DT), SAD(Fast/Spallation 600MeV p)

First mock-ups with some power (0.1-1 MWt) and feedbacks in about 4-5 years

TRADE (thermal/Spallation 150 MeV)

In addition, there are a few detailed pre-engineering designs of 100 MWt ADS

XADS Pb/Bi 80MWt, XADS Gas 80MWt, ...

And a specific design with a proposed site (Mol at Belgium)

Myrrha (Pb/Bi 50MWt)

Present ADS R&D Focus

- Dedicated transmutation fuels (oxides and nitrides) fabrication and reprocessing, matrixes and behavior under irradiation.
- Accelerator reliability
- Materials compatibility (Pb and PB/Bi corrosion) and resistance to p/n irradiation
- Conception of a full scale ADS for transmutation
- ADS Safety analysis, reactivity monitoring and control
- Nuclear and Material Data and simulation of ADS behavior

5th Framework program of R+D UE-Euratom on P&T

Nuclear Data and Basic physics:

nTOF-ND-ADS
HINDAS
MUSE

Materials:

TECLA
SPIRE
MEGAPIE
ASHLIM

Preliminary Design:

PDS-XADS

Fuel:

Thorium Cycle
CONFIRM
FUTURE

Reprocessing:

PYROREP
PARTNEW
CALIXPART

Network: ADOPT

R&D for P&T in the 6FP of Euratom

IP-EUROPART (Started)

Partitioning of advanced fuels: Hydrometallurgic and Pyrometallurgic technologies

IP-EUROTRANS (expected Start end 2004)

Design of a full scale ADS for transmutation, Including:

DESIGN: Design of the ETD, reliability test of key accelerator (p linac) elements

TRADE-PLUS: Experiments on an ADS prototype TRADE (Thermal/Spallation 150MeV with thermal feedbacks

AFTRA: Fuels for transmutation Oxide (CERCER and CEMET), irradiation

DEMETRA: Compatibility of steels with Pb/Bi and combined p/n irradiation

NUDATRA: Nuclear data for ADS and Transmutation (En from thermal to GeV)

STREP RedImpact (Started)

Strategies study of the influence of P&T on the Nuclear Waste management and on the final waste repository

STREP on transmutation by critical reactors (expected Start middle 2005)

Several types of reactor being considered, including HTR and Fast critical Gas reactor.

P&T activities outside the EU

International organizations:

- NEA/OCDE:** Several Expert groups, Benchmarks and 2 large reports
WPPT
- IAEA:** Several CRP, Topical Meetings, Several publications
An experimental facilities DataBase

Individual countries:

- USA:** Projects ATW, AAA and AFCI. Objective avoid the need of a second Yucca Mountain.
Several Roadmaps and The UREX process. Large investment to reconstruct the reprocessing infrastructures at large scale
- Japan:** Concept of Double Strata, Continuation of the OMEGA project activities. A large experimental facility including an ADS testing facility in construction.
- South Korea:** Projects HYPER and Komac. DUPIC fuel cycle.
- Russian federation:** Large number of projects in all areas related to ADS and transmutation, with substantial financing of ISTC.
Large experience in fuels, reprocessing, steel-PB compatibility,...
Some activities in collaboration with Belarus, Poland,...
Several large experimental facilities. SAD ADS prototype in construction.
- India & China:** Both countries are exploring the possibilities of ADS for nuclear energy production. India includes studies of the thorium cycle.

Concluding Remarks

More than 10 years have pass from the start of the visionary adventure by a few groups in the USA, Japan and notably in Europe on ADS and their application for a revisiting of transmutation.

This adventure was inspired by, and recognized by the public as an effort of “**pure science**” trying to help solving one of the main challenges of our global society: to **design a sustainable and sufficiently intense source of energy that allows to keep and improve our quality of live, but with complete respect to the population and the environment.**

The R&D bring together again, after long time, Nuclear Physicists and Nuclear Engineers. This collaboration, as always, has produced very interesting cross fertilizing results.

Those visionary efforts, initially strongly critizaized, have resulted today on **P&T** becoming **a major R&D program** on most countries with electricity from nuclear energy, and even in several countries with no nuclear energy but interested on the science and technology behind P&T

Concluding Remarks 2

During the more than 10 years of R&D, many questions and difficulties had been found, but for every one either a solution has been found or it is being investigated and engineered. As today, no show stopper has been found for the construction of ADS or the implementation of Transmutation.

Large difficulties still remains and require intense R&D, mainly on the areas of

- Dedicated transmutation fuels
- Accelerator reliability
- Integral material compatibility, and
- General plant safety

Indeed, Although with some delays coming from the reduce economical support from EU, the European Roadmap towards an ADS proceeds on its road, and if the sufficient financial support is provided, there is no doubt that a demonstration plant of an ADS for transmutation can be built in less than 15 years.

Concluding Remarks 3

The results of the R&D on ADS, together with the progress on critical reactors are preparing the path for transmutation as a possible reality of future fuel cycles. Its implementation will offer our generation the possibility of leaving to future generations a **just legacy in terms of resource availability, wastes burden and risk.**

My final remark, is to acknowledge, that the R&D on ADS and Transmutation has been **specially attractive for young physicists and engineers**, and in this way is contributing to the strength of both disciplines and to prepare the basis to **maintain their Know-how** for the future.