ACCELERATOR-DRIVEN SYSTEMS IN ADVANCED FUEL CYCLES

M. Salvatores
ANL, USA and CEA Cadarache, France

Abstract

Approximately two decades ago, H. Takahashi revived the concept of accelerator-driven systems to propose it for the transmutation of radioactive nuclear wastes.

In parallel, partitioning and transmutation (P/T) strategies have also been revisited, so as to enlarge the options as concerns waste management. At present, after numerous studies and some experimental demonstrations, it is possible to characterise the different options and strategies, in order to put them into perspective and to offer some practical paths towards implementation.

The framework

The increasing urgency to provide robust and acceptable solutions regarding the problem of waste management and the recognised imperative, whatever is the strategy, to implement deep geological repositories, has provided the framework for most P/T studies. Utilities and industries have participated in these studies with some reluctance, as P/T has been perceived as a costly option, projected in an uncertain, far future.

R&D laboratories have provided most of the effort, and international organisations have been active in this field, since there is a widespread consensus that the attempt to find global solutions to the waste management problem, benefits from wide international collaborations.

A turning point

P/T is a multi-disciplinary endeavour. This is a well-recognised characteristic, reflected in the R&D programmes which have been established in the fields of the chemistry of actinide separation, metallurgy of fuels dedicated to transmutation, liquid metal technologies, nuclear physics at intermediate energies, high power proton accelerator technology, waste forms, etc.

The "building blocks" necessary for P/T implementation are:

- Standard spent fuel reprocessing capability with selected isotope or full non-separated TRU recovery.
- Dedicated fuel fabrication capability: MA-dominated U-free/inert-matrix-based fuels or homogeneous non-separated TRU-bearing fuels.
- Transmutation devices (critical or ADS).
- Dedicated fuel reprocessing capability.

The decision to implement P/T must be supported by demonstration experiments at a significant engineering level for each "building block" and by a global cost/benefit analysis.

In the past, P/T has been mostly conceived as a strategy with the objective to cope with the waste legacy from the past development of nuclear energy. In this perspective, the implementation of P/T and its associated costs are perceived in the framework of a "static" environment, dominated by existing technologies and relatively unfavourable to the development of new technologies to complement the inevitable implementation of a deep geological repository.

Recently, a new perspective has emerged, in which waste minimisation is one of the objectives of future nuclear system development, making P/T part of the assessment of the advanced fuel cycles in support of future reactors.

This is a real turning point which can influence specific developments and priorities in the field of P/T.

Transmutation scenarios and advanced fuel cycles

As far as transmutation and the transmutation device, simple physics considerations allow to make unambiguous comparisons among different systems, in terms of impact on the "transmuter" core characteristics, transmutation performance and impact on the fuel cycle. Detailed examples are given in Ref. [1], where the concepts of neutron balance and of neutron consumption/fission, coupled with a generalisation of the Bateman equations to include specific fuel cycle characteristics, are used to intercompare different LWR and FR systems and different multi-recycling strategies (e.g. selective MA recycling).

Moreover, the potential and possible role of accelerator-driven systems (ADS) has also been widely assessed (e.g. Ref. [2]).

In summary, most of the studies devoted to the assessment of the potential of transmutation in the framework of waste management have pointed out the interest of three major scenarios:

1) *Transmutation of not-separated TRU (e.g. as recovered from the reprocessing of spent fuel from LWRs) in fast reactors*. Whatever the coolant, the generic features of a fast neutron spectrum allow the multi-recycling of the TRU. Moreover, the neutron balance feature of a fast reactor allows flexibility in the design in order to achieve a conversion ratio which can be lower, equal or higher than one, according to the specific strategy objectives.

   This scenario meets the requirements of both sustainability and waste minimisation.

   In fact, the inventory of TRU can be stabilised or decreased, according to the choice of the appropriate conversion ratio, and the waste sent to a repository correspond to the losses at reprocessing. A maximum gain is obtained as far as reduction of the potential source of radiotoxicity, heat load in a repository, and even in terms of non-proliferation resistance.

2) *Selective partitioning of TRU, and transmutation of Am (and possibly Np) in MOX-loaded LWRs*. This scenario can be seen as a temporary option. In fact there are several drawbacks to its application: the inventory of Pu can eventually be stabilised, but not that of Am; the build-up of ^{238}Pu is very significant; there is the need to separate Cm and to envisage a strategy for its storage and the further use of the ^{240}Pu built-up in the process. The potential interest is the use of existing reactors and technologies.

3) *Use of accelerator-driven systems (ADS) to transmute TRU.* This can be done for two different objectives: a) to transmute MA in a "double-strata" perspective, and b) to burn all TRU, in a nuclear energy "phase-out" perspective.

Scenario 1 is the preferred one in the new perspective, as indicated earlier, as it is consistent with the sustainable development of nuclear energy and meets the requirement of waste minimisation without significant penalties as regards the fuel cycle, and even providing increased non-proliferation resistance, since it does not require selective TRU separations.

Scenarios 2 and 3 are to be seen as transition options, in order to temporarily stabilise Pu stocks, while reducing the MA impact on a repository.

In comparing these last two scenarios, one relevant factor is the perceived cost of the deployment of new technologies. In fact, as mentioned above, Scenario 2 does allow using present reactor technology, even if adapted to the specific mission of Am recycling, but requires the development of a sophisticated technology to separate Cm and the development of appropriate installations for Cm storage, decay and re-utilisation, mostly in the form of ^{240}Pu.

The burden of Scenario 3 is the industrial deployment cost of a new reactor concept, the ADS, beyond the proof of principles phase.

In this context, it is interesting to explore a strategy in which international collaboration is extended from the current phase of basic and supporting R&D, to the practical implementation of the scenario at an industrial level.

A "regional" scenario for ADS-based transmutation deployment

Up to now there has been no attempt to consider the deployment of P/T not only as a national endeavour but rather as a "regional" endeavour.

However, one can imagine regional scenarios [3], wherein countries with different policies and objectives could share regional facilities developed with shared resources, appropriately conceived in order to meet the objectives of the different participating countries. An example is given in Figure 1, where the shared deployment of Scenario 3 by two countries (A and B) is shown, Country A being committed to the use of nuclear energy and having developed reprocessing capability in order to use Pu in LWRs at first, and fast reactors in a more distant future. In order to reduce the burden on a waste repository, this country considers the possibility of deploying a "double-strata" approach. Country B has a legacy of spent fuel and wants to avoid a massive storage in a repository.

Regional facilities can be imagined as shown in Figure 1, with mutual benefits. As an example, the type of ADS to be developed in common, would benefit from the different objectives: in fact Country A if alone, would devote some Pu to make a viable fuel for the ADS in order to burn MA, and Country B, if alone, would face the difficulty of designing an ADS with a Pu-dominated fuel.

The values quoted in Figure 1 for this "blend and burn" scenario are indicative, and a detailed scenario study is underway to quantify mass flows and other fuel cycle characteristics. However, previous studies indicate that, if Country A decides upon the multi-recycling of Pu in existing LWRs, an equilibrium will be reached after 5 ， 7 recyclings, and the Pu stocks will stabilise. The build-up of separated MA from Country A spent fuel reprocessing and the existing stocks of Pu and MA of Country B will be used to fabricate the fuel for a rather aggressive introduction of medium-power (~300 MWe) ADS. The number of needed ADS, in terms of power, is defined by the need to absorb the MA production of the power fleet of Country A at equilibrium (~3 t/year) and to keep an optimised ratio of Pu to MA in the ADS fuel (Pu/MA $\simeq$1).

The overall need in terms of installed ADS power is sizable: 6 ， 8 GWe, of the order of ~10% of the total nuclear power produced in this scenario.

Which type of ADS?

In Figure 1, we have indicated a generic ADS modular system, each module having a power of ~2 ， 300 MWe.

In order to get an idea on the required performance of each module, the following simplified considerations can be made:

- *Hypothesis:*
  - Proton beam energy E_p = 600 MeV.
  - Heavy metal spallation target providing $z = \frac{neutrons}{proton} = 16$.
  - Γ (number of neutrons/fission in the subcritical core due to the external source, if all the energy produced in it is used to feed the accelerator) = 1.06.
  - Thermal power of the subcritical core W = 500 MWt.
  - MA/Pu ratio in the fuel ~1, to which corresponds a ΔK/cycle $\simeq$ 1%/$\Delta K/K$/year and $\beta_{eff} \simeq$ 0.15%/$\Delta K/K$.
  - φ^* (ratio of the importance of the source neutrons to the importance of fission neutrons) $\simeq$ 1.

- *Energy requirements:*

  The fraction f of energy produced in the subcritical core used for feeding the accelerator depends on the subcriticality level:

$$f \simeq \frac{\nu}{\Gamma} \frac{1-K}{K}$$

  If ν (average number of prompt fission neutrons per fission) = 2.8:

f = 2.6% if 1 – K = 0.01
f = 5.3% if 1 – K = 0.02
f = 13% if 1 – K = 0.05

- *Current (power) of the proton beam ip (Wp):*

  If E_f (energy released/fission) $\simeq$ 200 MeV:

$$i_p \simeq \frac{\Gamma}{z} W \frac{1}{E_f} \quad \begin{cases} 4.3\,mA \;\; if \;\; 1-K = 0.01 \\ 8.6\,mA \;\; if \;\; 1-K = 0.02 \\ 22\,mA \;\; if \;\; 1-K = 0.05 \end{cases}$$

  which correspond, respectively, to:

$$W_p = \begin{cases} 2.5\,MWt \\ 5\,MWt \\ 12.5\,MWt \end{cases}$$

A few comments on the outcome of these simplified evaluations:

- The subcriticality level choice is a crucial parameter. In fact, it is probably difficult to envisage a deep subcriticality level (e.g. $K = 0.95$), in view of the demanding characteristics of the required accelerator (~12.5 MWt in the beam) and the cost of the energy to feed it.

- The appropriate choice of the MA/Pu ratio, made possible by a regional scenario as the one illustrated in Figure 1, can help to optimise the reactivity swing during irradiation (down to £ 1%/DK/K), and reduce the accelerator current requirement.

- It is clear that the choice of the primary coolant will have an impact on the safety case and on the minimum margin of subcriticality which is allowable.

- A modular architecture, such as the one shown in Figure 2, can provide a significant degree of flexibility, both in terms of deployment and in terms of operation of the overall system (availability).

- The stringent requirements in terms of accelerator reliability have to be met whatever the type of ADS. However, a modular structure can help to optimise the requirements and their cost/benefit impact.

- If the subcritical level is chosen in the range $K = 0.97$, 0.98, it will be very relevant to demonstrate the safe operation of an ADS in the “transition” from a “source-dominated” to a “feedback-dominated” regime.

- The continuous and effective monitoring of the subcriticality level will be mandatory, and appropriate experimental techniques should be developed and demonstrated.

- The overall layout of a modular system, such as the one of Figure 2, will require a careful evaluation and optimisation of the shielding structures to optimise costs.

The European Integrated Project EUROTRANS

European R&D organisations, universities and industries have been co-operating over the past decade in order to assess the potential of ADS-based transmutation, to perform basic research in the different scientific and technological domains of relevance to ADS and to define a common platform for the development of that strategy.

The three major outcomes of these activities are:

- The document *A European Roadmap for Developing Accelerator-driven Systems (ADS) for Nuclear Waste Incineration*, issued by the European Technical Working Group, chaired by Professor Rubbia in 2001.

- Launching of experimental programmes to validate the major ADS components (MUSE for neutronics of the subcritical core, MEGAPIE for flowing Pb-Bi target and IPHI for high power proton accelerator injector, etc.).

- R&D programmes with EU funding in the domains of ADS design, fuel development, HLM technology, nuclear data.

For the Sixth Framework Programme of the EU, a new Integrated Project, IP-EUROTRANS, is being proposed for funding, with the objective to streamline all R&D efforts towards the assessment of the feasibility of a European Facility for Industrial Transmutation.

The proposed project (to be co-ordinated by J. Knebel of FZK-Germany) is structured in DOMAINS (DM, see Table 1), and should start in 2005.

The EFIT ADS could represent the first model of the modular system described in Figure 2.

Conclusions

The perceived role of P/T has evolved from an optional strategy aiming to reduce the burden on a deep geological storage, to an integral component of future nuclear systems. In this new perspective "transmutation" is achieved in an optimum manner in a fast neutron reactor, with the homogeneous recycling of not-separated TRU.

Specialised devices like ADS can play a role in a transition scenario between the present LWR-dominated to a future FR-dominated situation.

In any case, the ADS deployment can hardly be considered by a single country in isolation, and a "regional" approach, wherein countries with rather different policies in terms of nuclear power development can join efforts to develop shared facilities, is a practical solution.

In the case of a regional scenario for ADS-based transmutation, a modular concept seems to be the most promising. Each module could be an ADS of intermediate power (2-300 MWe or lower), fed by a proton accelerator with ~5 MWt of power in the beam.

The decision to go ahead with ADS-based transmutation can only be made if significant demonstrations of feasibility in all the domains (reprocessing and separation of TRU from commercial power plants, ADS design, dedicated fuel, reprocessing of irradiated dedicated fuel) are available to decision makers, accompanied by sound cost evaluations.

The IP-EUROTRANS, proposed for funding to the EU, is an essential initiative to meet that objective.

REFERENCES

[1] Salvatores, M., *et al.*, "The Physics of TRU Transmutation – A Systematic Approach to the Intercomparison of Systems", *Proc. Int. Conf. PHYSOR 2004*, Chicago, IL, 25-29 April 2004.

[2] "Accelerator-driven Systems (ADS) and Fast Reactors", *Advanced Fuel Cycles*, OECD Nuclear Energy Agency, Paris, France (2002).

[3] Salvatores, M., "Nuclear Fuel Cycle Strategies Including P/T", *Annual Meeting on Nuclear Technology 2004*, Düsseldorf, Germany, 25-27 May 2004.

Table 1. IP-EUROTRANS structure

DM1 DESIGN	Development of a reference design for a European Facility for Industrial Transmutation (EFIT) with a power of up to several 100 s MW(th). The coolant for the reference design of the core and the spallation target is a heavy liquid metal (Pb-Bi), but Pb and gas cooling are to be considered as back-up solutions for the core as well. An interconnected and consistent objective is to undergo a more detailed design activity leading to a short-term experimental demonstration of the technical feasibility of Transmutation in an Accelerator Driven sub-critical System (XT-ADS), i.e. demonstration starting at the least within the next 10 years. The latter facility is representing the first-of-a-kind of the EFIT system.
DM2 TRADE-PLUS	Design, realisation and operation of the experimental facility TRADE to demonstrate the coupling between proton accelerator, spallation target and subcritical blanket at sizeable power (several 100 kWs) in the presence of thermal reactor feedback effects. The expected outcomes of this domain – in terms of proof of stable operability, procedures for start-up and shutdown, reactivity monitoring, dynamic behaviour, response to accelerator beam trips and definition of licensing issues of an ADS – are crucial for and give input to the future realisation of the EFIT and XT-ADS (see DM1 DESIGN).
DM3 AFTRA	Design development and qualification in representative conditions of a U-free fuel concept for the EFIT, compatible with the reference design studied in DM1 DESIGN. Ranking of different fuel concepts according to their main out-of-pile properties, their in-pile behaviour and their predicted behaviour in normal, transient operating conditions, safety performance in accidental conditions at the end of the project. Recommendations about fuel design and fuel performance of the most promising fuel candidate(s).
DM4 DEMETRA	Improvement and assessment of the heavy liquid metal (HLM) technologies and thermal-hydraulics for application in ADS, and in particular to EFIT and XT-ADS, where the HLM could act both as spallation material and primary coolant; characterisation of the reference structural materials in representative conditions (with and without irradiation environment) in order to provide the data base needed for design purposes (fuel claddings, in-vessel components, primary vessel, instrumentation, target container, beam window, etc.).
DM5 NUDATRA	Improvement and assessment of the simulation tools and associated uncertainties for ADS transmuter core and shielding design. The activity is essentially focused on the evaluated nuclear data libraries and reaction models for materials in transmutation fuels, coolants, spallation targets, internal structures, and reactor and accelerator shielding, relevant for the design and optimisation of the EFIT and XT-ADS.

Figure 1. Regional “blend-and-burn” scenario (R2B)

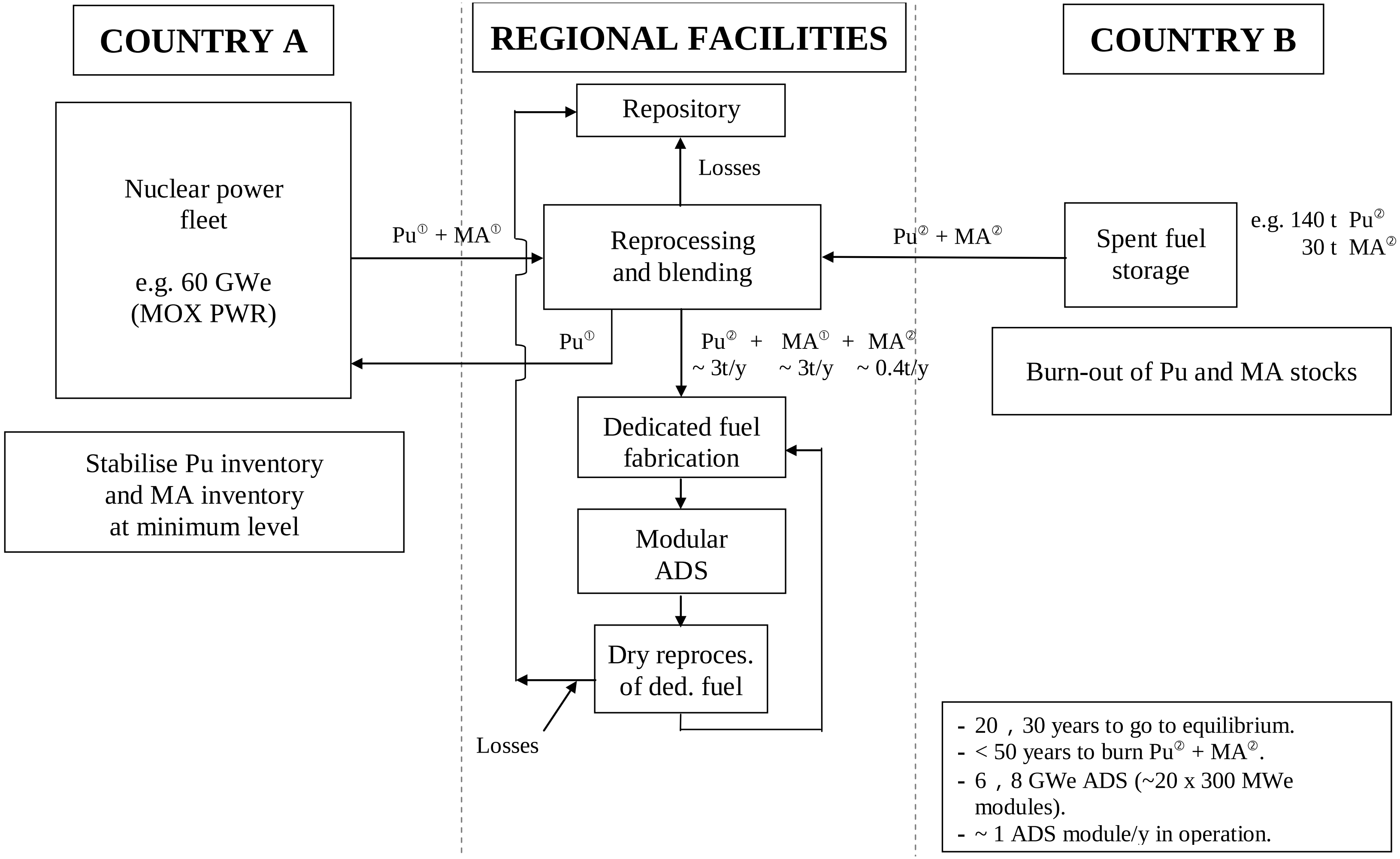
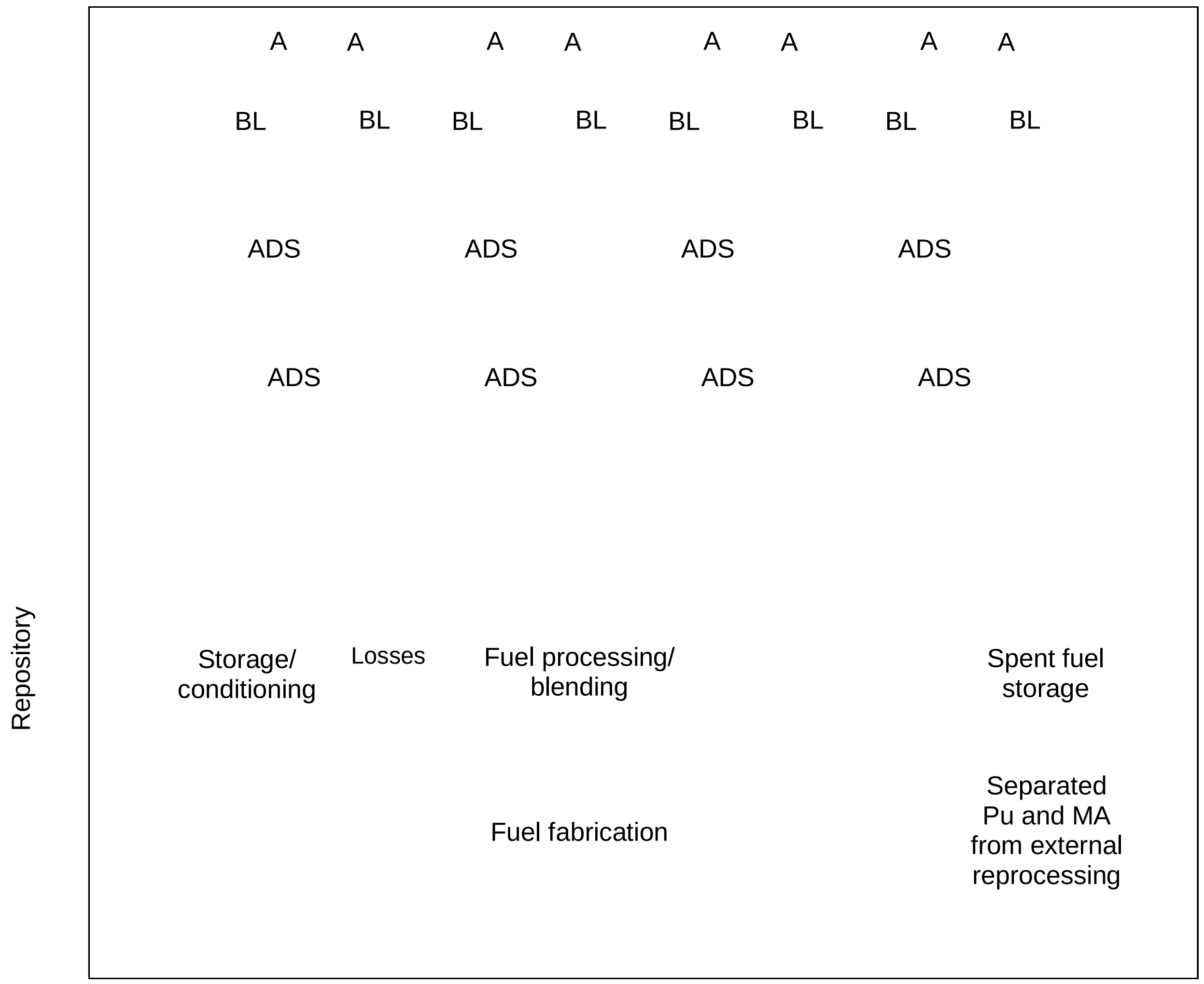


Figure 2. “Regional” concept for waste transmutation with modular ADS



A	:	Proton accelerator - Ep $\simeq$ 600 MeV $i_p \simeq 5$, 10 mA
BL	:	Beam transport line
ADS	:	~ 500 MWt K $\simeq$ 0.98 DK/cycle $\simeq$ 1 % DK/K f $\simeq$ 5 % (fraction of energy to feed A) Pu/MA ratio in the fuel $\simeq$ 1.

Total power: ~ 4 000 MWt

fi 2 , 3 of such installations for e.g. Europe?

① COUNTRY B: Spent fuel stock

② COUNTRY A: Nuclear power fleet with minimisation of wastes

TABLE OF CONTENTS

CHAIRS: B-H. CHOI, R. SHEFFIELD

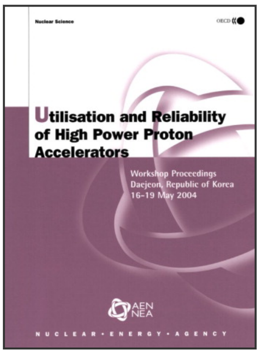
CHAIRS: A. MUELLER, P. PIERINI

CHAIRS: X. CHENG, T-Y. SONG

TECHNICAL SESSION IV: SAFETY AND CONTROL OF ADS

CHAIRS: R. SHEFFIELD, B-H. CHOI

CHAIRS: R. SHEFFIELD, B-H. CHOI



From:

Utilisation and Reliability of High Power Proton Accelerators

Workshop Proceedings, Daejeon, Republic of Korea, 16-19 May 2004

Access the complete publication at:
https://doi.org/10.1787/9789264013810-en

Please cite this chapter as:

Salvatores, M. (2006), “Accelerator-Driven Systems in Advanced Fuel Cycles”, in OECD/Nuclear Energy Agency, *Utilisation and Reliability of High Power Proton Accelerators: Workshop Proceedings, Daejeon, Republic of Korea, 16-19 May 2004*, OECD Publishing, Paris.

DOI: https://doi.org/10.1787/9789264013810-4-en