ACCELERATOR DRIVEN SUB-CRITICAL SYSTEMS FOR WASTE TRANSMUTATION: CO-OPERATION AND CO-ORDINATION IN EUROPE AND THE ROLE OF THE TECHNICAL WORKING GROUP

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1. Background

In 1998 the Research Ministers of France, Italy and Spain, recognising the potential of accelerator driven systems (ADS) for the transmutation of long lived nuclear waste, decided to set up a Group of Advisors (Ministers' Advisors Group – MAG) to define a common R&D European platform on ADS. In its meeting on May 1998, the MAG recommended an European demonstration programme over a 10-year time scale.

A Technical Working Group (TWG) under the chairmanship of Carlo Rubbia was also established with the task of identifying the critical technical issues in which R&D, in such a demonstration programme, is needed. In October 1998 the TWG issued an Interim Report which, in particular, highlighted a) the need for a demonstration programme, b) the basic components and the different options for the proposed demonstration facility, and c) the R&D directly relevant to the realisation of such a facility.

This report was endorsed by the MAG at its meeting of March 1, 1999. In the same meeting, it was proposed to extend participation beyond the three countries France, Spain, Italy; to consider the role of ADS R&D within the 5th European Framework Programme (FWP); and to recognise an eXperimental ADS (XADS) as an European goal.

As a consequence, a MAG "ad hoc" meeting open to all interested EU member states was held in Rome on April 21, 1999. Representatives of eleven countries (Austria, Belgium, Denmark, Finland, France, Germany, Italy, Portugal, UK, Spain and Sweden) participated in that meeting which concluded:

It was agreed that neutron induced transmutation represents an attractive approach to radioactive waste management, being complementary to geological disposal.

All participants appreciated the proposal to extend the participation in the initiative to other European countries besides France, Italy and Spain, particularly considering that similar approaches were being undertaken in the USA and Japan.

The interim report of the TWG issued in 1998 was accepted as a good basis for future work to be carried out by an Enlarged Technical Working Group (ETWG), under the chairmanship of Carlo Rubbia.

In September 1999, the ETWG – composed of representatives of Austria, Belgium, Finland, France, Germany, Italy and Spain – issued a second technical report aimed at providing an overview of the different ongoing activities on ADS in various European countries, along with an examination of the proposals to be submitted to the 5th FWP. The report, presented to and endorsed by MAG on its meeting of September 17, 1999, also identified a number of open points and gave recommendations for the future development of the activities. In particular, the ETWG strongly recommended an increased support – in particular by European Commission – and co-ordination of ADS-related activities at multinational level.

At the beginning of 2000 the ETWG (further enlarged to representatives of the JRC, Portugal and Sweden), recognising that the R&D programme on ADS has reached a turning point with regard to programme co-ordination and resource deployment in Europe and taking also into account the substantial recent progress on the subject in the United States and in Japan, issued a so-called "four-page document" on a strategy for the implementation of an ADS programme in Europe. In particular, the document called for the urgent definition of a consensual European "Roadmap" towards demonstration of feasibility of a European waste transmutation facility and recognised its potentially-relevant implications on the 6th European Framework Programme.

The "four-page document" was endorsed by the MAG on its meeting of February 25, 2000 and, consequently, the ETWG started an intensive work aimed at defining the above mentioned European Roadmap. In particular, in order to specifically address some relevant key issues such as accelerator, fuel and fuel processing development, two dedicated sub-groups have been created inside the ETWG and co-ordination with the European ADS system design group has been established.

The roadmap document is expected to be issued at the very beginning of 2001.

In the report, the ETWG will identify the steps necessary to start the construction of an XADS towards the end of the decade. The construction and operation of an XADS at that point in time is considered as an essential prerequisite to assess the safe and efficient behaviour of ADS for a possible large scale deployment of ADS for transmutation purposes in the first half of the century.

The first goal of the roadmap is to propose a technological route to reduce the risks associated with nuclear waste, based on the transmutation of nuclear waste in ADS and to assess the impact of this approach in the reduction of the radiotoxicity of nuclear waste. The report will review historical developments and will identify and review the status of current activities and facilities related to ADS research in the EU and worldwide. A decision to go ahead with the project will require a detailed planning of the technical aspects, a substantially increased budget, together with close synchronisation with the 6th and 7th Framework Programmes. The second and main goal of the roadmap is, therefore, to prepare a detailed technical programme, with cost estimates, which will lead to the demonstration of an experimental ADS (XADS) in 10 years, within the 6th and 7th Framework Programmes. The programme as described in the roadmap will lead to the development of innovative fuels and reprocessing technology, a rationalisation of human resources and experimental facilities, a training ground for young researchers, spin-offs in the fields of accelerators, spallation sources, liquid metal technology, radioisotope production and actinide physics and chemistry. Hence, a final goal of the roadmap is to identify possible synergies and rationalisations that this programme could have within the nuclear community, indicate potential spin-offs, show how competence can be maintained in a currently stagnating field.

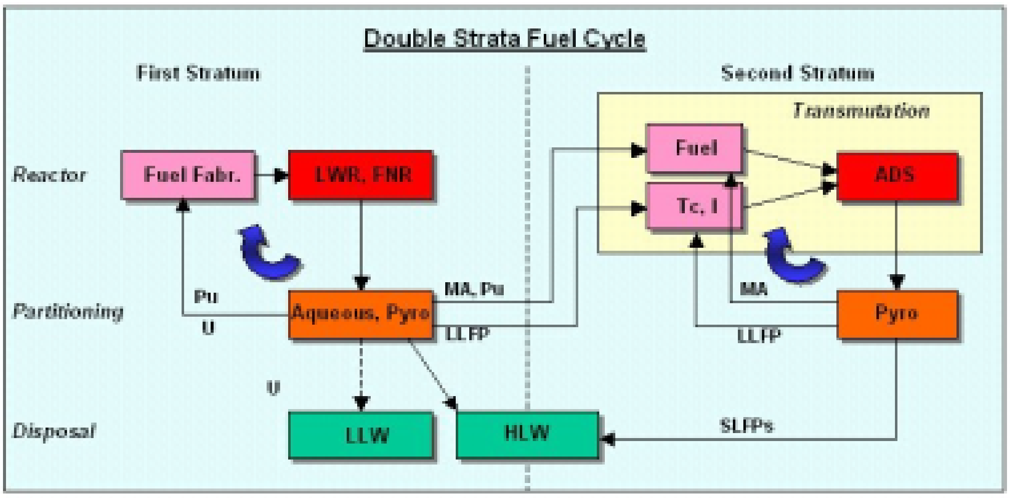
The roadmap will be a result of a mandate given to the ETWG on ADS by the MAG. In the first instance, therefore, the report will be directed at the MAG. The document will be of interest, however, to policy makers throughout Europe, in particular to research ministries in the Member States of the European Union, to members of the European Parliament, and to the relevant Directorates General of the European Union. In addition, the report will be of interest to parties involved with ADS research and development within the EU and worldwide.

2. Motivations for ADS

In contrast to standard critical nuclear reactors in which there are enough neutrons to sustain a chain reaction, sub-critical systems used in ADS need an external source of neutrons to sustain the chain reaction. These "extra" neutrons are provided by the accelerator. More exactly the accelerator produces high-energy protons, which then interact with a spallation source to produce neutrons.

But why go to all this trouble to build an ADS when critical reactors already work? The answer to this lies in the fact that one has more control and flexibility in the design of the sub-critical reactor. This is required when the reactor is being used to transmute large amounts of nuclear waste in the form of minor actinides (MAs). Today it appears that ADS has great potential for waste transmutation and that such systems may go a long way in reducing the amounts of waste and thereby reducing the burden to underground repositories. A schematic description of how an ADS can be used in conjunction with conventional reactors in a "Double Strata" approach is shown in Figure 1.

Figure 1. **Schematic description of the transmutation of nuclear waste by ADS within a Double Strata Fuel Cycle (LLFP: long-lived fission products, SLFP: short-lived fission products, LLW: low level waste, HLW: high level waste)**



The first stratum is based on a conventional fuel cycle and consists of standard light water reactors (LWR) and fast neutron reactors (FNR), fuel fabrication and reprocessing plants. The recovered plutonium is recycled as mixed oxide fuel in the thermal and fast reactors. The remaining plutonium, MAs and long-lived fission products are partitioned from the waste and enter the second stratum where they are transmuted in a dedicated ADS. In the second stratum, devoted primarily to waste reduction, the Pu, MAs, and long-lived fission products are fabricated into fuels and targets for transmutation in dedicated ADS. The use of dry reprocessing in this stratum allows for multiple reprocessing of the fuel. A key advantage of this is that higher levels of radiation can be tolerated in the molten salts, used in this process, and therefore allows reprocessing of spent fuel which has been cooled for periods as short as one month.

Accelerator driven systems therefore open the possibility of "burning" waste material from LWRs in dedicated actinide burners. These actinide burners can burn large quantities of minor actinides per unit (in contrast to critical reactors) safely, and generate heat and electricity in doing so. In addition, schemes have been proposed, in which the long-lived fission products are also destroyed. An advantage of ADS is that, since there is no criticality condition to fulfil, almost any fuel composition can be used in the system.

3. Overall roadmap towards ADT industrial implementation through an ADS demonstration

From now on, taking for granted the potential role of Accelerator Driven Technology (ADT) for radio-toxicity reduction of the ultimate nuclear waste, the main issue is to define a path towards industrial implementation of this very innovative system.

An extended “skeleton” for ADS technology development is given in Figure 2. It consists of three main phases:

- Phase 1: Development/realisation/operation of an XADS/XADT (eXperimental Accelerator Driven System/Transmuter).
- Phase 2: Development/realisation/operation of a PROTO-ADT.
- Phase 3: Industrial application.

In particular, the preparation of the construction of the XADS must be performed in parallel to the development and qualifications of the main components and the basic R&D programme. It starts with a system analysis of different concepts to be performed in 2001 to 2003. Further milestones are:

- A decision on the basic features of the XADS in 2005.
- Start of detailed design work in 2005.
- Final decision and start of construction in 2009.
- Operation of XADS in 2013-2014.

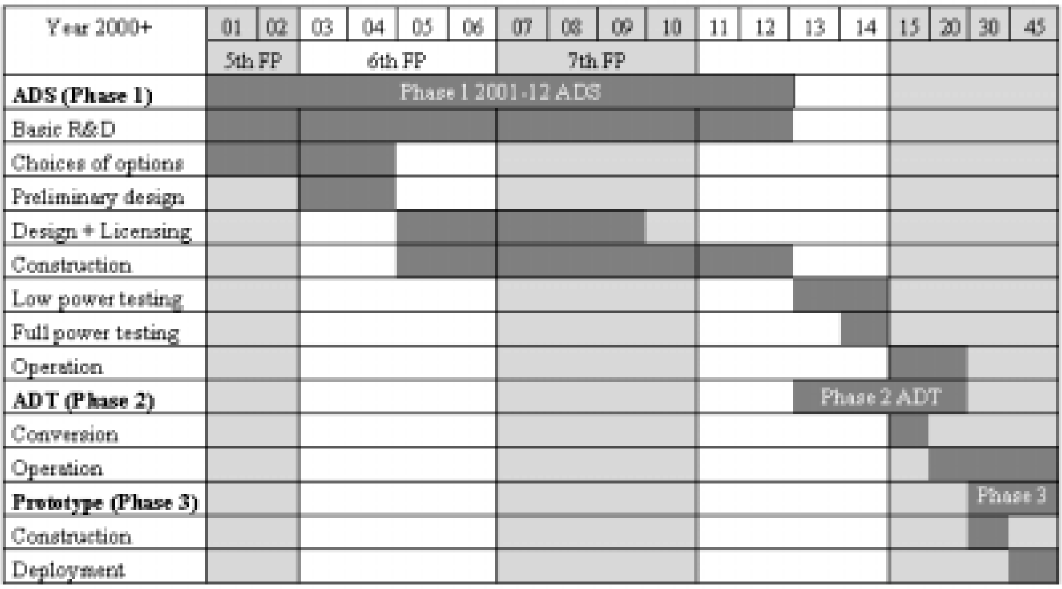
In parallel to the construction of the XADS, which can be considered as the “spallation-fission facility” oriented demonstration, pilot plants have to be built and operated in order to:

- Feed the XADS/XADT – prototype with fuel and targets.
- Get an “As Soon As Possible (ASAP)” operation feedback for further development of industrial scale facilities.

The ADS demonstration phase is characterised, in an ASAP perspective, by the use of available fuel technology, at least in the first sub-phase of the XADS. The two sub-phases currently considered are:

- Sub-Phase 1: which uses available fuel technology and is devoted to the demonstration of the ADS concept and possibly to irradiation purposes (XADS).
- Sub-Phase 2: which is devoted to the transmutation demonstration with a large number of MA-based fuel assemblies. During this phase the XADS will be used more and more as demonstration of a transmuter. In about 2017-2018 a decision has to be made, whether the facility can be modified to a full transmuter (XADT) or whether a new facility would be needed, which possibly should be available in 2025. From 2025 on in any case a full demonstration of accelerator driven transmutation should occur. This requires successful development of the fuel and the fuel cycle facilities till about 2020!

Figure 2. **Time schedule and milestones for the development of an experimental accelerator driven system (ADS) and accelerator driven transmutation (ADT) technology in Europe**



4. TWG sub-group on fuels and fuel processing

As above mentioned, a specific subgroup on "Fuels and Fuel Processing", under the chairmanship of Rudy Konings (ITU-Karlsruhe), has been set up within the TWG. Two status reports have been issued by this sub-group:

- Part I: The Fuel of the ASAP DEMO.
- Part II: Advanced Fuel Cycles.

As far as fuel for XADS, Mixed OXide (MOX) is considered the only "ASAP" fuel option in Europe; indeed, for this fuel:

- Extensive knowledge exists.
- Existing fuel elements or fuel pins (SNR-300 or SPx) are available.
- The required infrastructure for fabrication of new fuel elements is existing.
- Core design has to be adapted (partially) to elements.
- Austenitic cladding of the SNR and SPx elements are compatible with He cooling and can also be used for Pb/Bi coolant, but the oxygen content of the liquid metal should be low.

As far as advanced fuels for transmutation, following the mandate of the TWG, the following boundary conditions were assumed:

- Solid fuel forms.
- High TRU content (up to 50% with MA/(Pu+MA) ratio between 1/5 and 5).

- Fertile support (uranium) is not considered.
- Gas or liquid metal coolant.
- Fast neutron system.

Pros and cons of metal, oxide, nitride, carbide fuel form have been examined. Composite fuels (including coated particle fuels), such as CERCER and CERMET, have been also analysed, as well as fission product targets.

The subgroup also addressed the key issue of fuel reprocessing, concluding that some drawbacks are expected for advanced fuels treated by hydro-chemical reprocessing. On the contrary, pyro-chemical reprocessing is considered a promising technology, given the fact that good fuel solubility can be achieved even for refractory materials. Furthermore, compact facilities and small cooling times are required. Drawbacks of this technology are: aggressive process media, secondary wastes and sophisticated technology which is under development.

The main conclusions of the "fuels and fuel processing subgroup" were the following:

- The European fuel research should be focussed on innovative oxide-based fuels, either as a solid solution or as a composite (CERMET or CERCER), with emphasis on the helium issue.
- Thorium-based fuel should be considered as back-up solution, e.g. (Th, TRU)O_2.
- The pyro-chemical reprocessing of these fuel types should be studied.
- In the short term (4-5 years) an out-of-pile testing programme should be performed to establish the properties of MA-based oxide fuels (solid solution, composite).
- In the longer term (8-10 years) a dedicated irradiation programme for these fuels should be performed.
- In parallel a collaboration with Japan and the Russian Federation on nitride fuel must be pursued (U-based nitrides, with limited MA content).

5. TWG Subgroup on accelerators for ADS

A second subgroup devoted to HPPA development for ADS, under the chairmanship of Alex Mueller (CNRS-IN2P3), has been set up within the ETWG. This subgroup has issued a status report on "Accelerators for ADS". The main outcomes of this status report can be summarised as follows.

The orders of magnitude of the characteristics of the accelerator for XADS were defined assuming a 100 MW thermal power for the sub-critical core.

A proton beam of 1 GeV, 10 mA may be obtained both by linac- or cyclotron- type accelerators, although at the very limits of potential performance gains for the latter case.

Concerning the beam structure, the preliminary analysis has not identified principle technical difficulties comparing pulsed or continuous beam operation. However, it seems that the latter option is overall preferred because of a closer similarity to the classical critical reactor.

The accelerator of the XADS has not to be defined only by the needs of the XADS itself, but it should also anticipate the requirements and the technical issues of a future industrial ADS burner. This concerns in particular the reliability, the economical, and the nuclear safety aspects.

A superconducting linac is adapted to a high power industrial ADS burner. Its different components are currently being investigated in several European laboratories. The studies show that a 100 mA proton beam can now be handled.

For comparative cost estimates an energy of 600 MeV has been used: it is the minimum energy (and therefore cost) for a complete ADS demonstration; for this energy band convincing accelerator studies exist for both types of accelerators. The extrapolation to 1 GeV, the energy of best neutron economy, is straightforward for the linac, however delicate for the cyclotron.

The investment cost of a 20 mA, 600 MeV linac, adapted to the XADS needs, including all industrial aspects, is preliminary evaluated to around 200 M €. Its development (R&D and construction) requires around eight years. An extension to 1 GeV would require an additional investment cost of about 100 M €.

A single cyclotron (600 MeV, 5 mA) is adapted to low power applications which is enough for the XADS if coupling of accelerator and reactor are the basic objective. A rough cost evaluation, on a similar base than for the linac, is around 70 M €. Approximately six years are requested for development and construction. If the industrial burner demonstration is a must, the coupling of at least 3 such machines must be demonstrated, of which the global cost is estimated to 240 M €.

6. Harmonisation of industry and R&D proposals for a preliminary design study of an XADS

Nine countries are participating to a 3-years proposal to be submitted to the second call of P&T within the 5th European Framework Programme.

The purpose is to develop conceptual plant configurations to enable definition of the supporting R and D, to perform objective comparisons and to propose reference solutions to be engineered in detail.

- Preliminary design concentrate mainly on three concepts:
  - A small XADS (20-40 MWt) cooled by Pb/Bi (MYRRHA-Belgium).
  - A large Pb/Bi cooled XADS (~80 MWt), developed in Italy.
  - A similar size gas-cooled ADS, developed in France.

Some work will be devoted to a pebble-bed concept developed in Spain.

The work will be carried out in three different phases:

- Phase 1: definition of the main technical specifications of XADS (6 months).
- Phase 2: preliminary engineering design studies (including safety approach, accelerator, core and target, system integration), to consolidate feasibility and cost estimation and to provide essential elements of comparison (2 years).
- Phase 3: comparisons and recommendations to implement the road-mapping towards XADS (6 months).

7. Conclusions

The TWG under the chairmanship of Carlo Rubbia, enlarged from the three initial partners (France, Italy, Spain) to ten partners (Austria, Belgium, Finland, France, Germany, Italy, JRC, Portugal, Spain, Sweden), has worked to identify critical technical issues, R&D needs and a strategy in view of an ADS demonstration programme.

A roadmap document is being prepared, and state of the art reports have been issued in Accelerator and Fuel and Fuel Processing Technologies.

The TWG allows also a monitoring and harmonisation of other European projects, like:

- The MEGAPIE project for the construction and operation of a 1 MWt Pb/Bi target in the SINQ installation in PSI-Switzerland.
- The proposal for a preliminary design study of an XADS.
- Which will be both submitted to the second call of P&T within the 5th European Framework Programme.