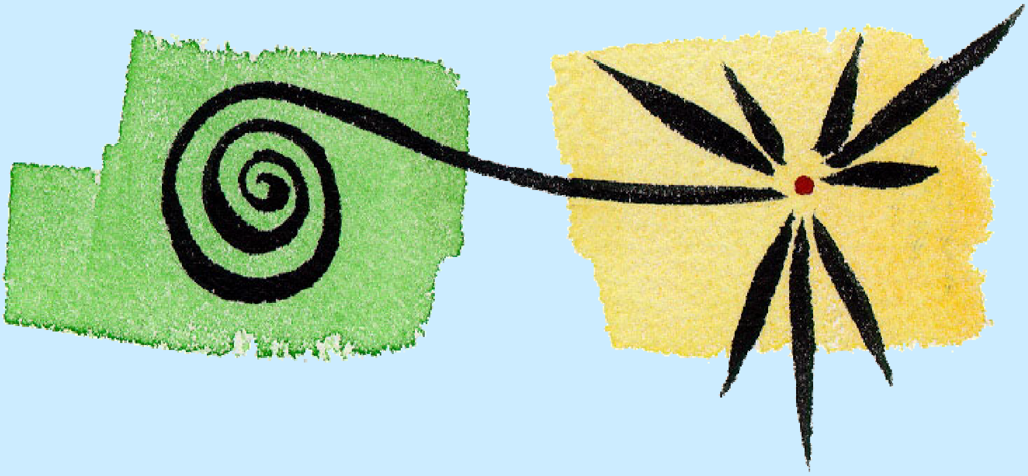

A European Roadmap for Developing Accelerator Driven Systems (ADS) for Nuclear Waste Incineration

April 2001

The European Technical Working Group on ADS

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ADS LOGO in the cover page by Bettina Björnberg

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A European Roadmap for the Development of Accelerator Driven System Technology for Nuclear Waste Transmutation

EXECUTIVE SUMMARY

Background

In 1998 the Research Ministers of France, Italy and Spain, set up a Ministers' Advisors Group on the use of accelerator driven systems (ADS) for nuclear waste transmutation. This led to the establishing of a technical working group under the chairmanship of Prof. Carlo Rubbia to identify the critical technical issues and to prepare a "Roadmap" for a demonstration programme to be performed within 12 years.

In the following Roadmap, the technical working group (consisting of representatives from Austria, Belgium, Finland, France, Germany, Italy, Portugal, Spain, Sweden and the JRC) has identified the steps necessary to start the construction of an experimental accelerator driven system towards the end of the decade. This is considered as an essential prerequisite to assess the safe and efficient behaviour of such systems for a large- scale deployment for transmutation purposes in the first half of this century.

Audience, Goals and Scope of the Roadmap

Since this Roadmap is a result of a mandate given to the technical working group, the report is directed, in the first instance, to the Ministers' Advisors Group.

The document is 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. It is also of general interest to the public since it concerns the disposal of nuclear waste - an issue which strongly dominates public opinion.

The *first goal* of this Roadmap is to propose a technological route to reduce the risks associated with nuclear waste, based on the transmutation of nuclear waste in accelerator driven systems (ADS); and to assess the impact of this approach in the reduction of the radiotoxicity of nuclear waste. The report reviews historical developments and identifies and assesses 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 of the EU.

The *second and main goal* of the Roadmap is to prepare a detailed technical programme, with cost estimates, which will lead to the realisation of an experimental ADS within 12 years, covering 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 co-ordination 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.

A *final goal* of the present Roadmap is to identify possible synergies that this programme could have within the scientific community, indicate potential spin-offs, show how competence can be maintained in the currently stagnating field of nuclear energy research. This is also consistent with the European Research Area policy for synergism among research programmes and activities in the EU.

Nuclear Energy in the EU and Spent Fuel Disposal

The recent European Commission's GREEN PAPER: *Towards a European strategy for the security of energy supply* clearly points out the importance of nuclear energy in Europe. With 145 operating reactors with a total power of 125 GW_e, the resulting energy generation of about 850 TWh per year provides 35% of the total electricity consumption of the European Union. The GREEN PAPER also points out that the nuclear industry has mastery of the entire nuclear fuel cycle, with the exception of waste management. For this reason, research "*focusing on waste management has to be continued*".

The spent fuel discharged from nuclear power plants constitutes the main contribution to nuclear waste. Most of the hazard from the spent fuel stems from only a few chemical elements - plutonium, neptunium, americium, curium, and some long-lived fission products such as iodine and technetium at concentration levels of grams per ton. At present approximately 2500 tons of spent fuel are produced annually in the EU, containing about 25 tons of plutonium and 3.5 tons of the "minor actinides" neptunium, americium, and curium and 3 tons of long-lived fission products.

These radioactive by-products, although present at relatively low concentrations in the spent fuel, are a hazard to life forms when released into the environment. As such, their disposal requires isolation from the biosphere in stable deep geological formations for long periods of time.

A measure of the hazard of these elements is provided by the *toxicity* and in particular the *radiotoxicity* arising from their radioactive nature rather than their chemical form. Some general features of the radiotoxicity of spent fuel are shown in fig.1. A reference point is the radiotoxicity associated with the raw material used to fabricate 1 ton of enriched uranium, including not only the uranium isotopes but also all their radioactive progenies. The radiotoxicity of the fission products dominates the total radiotoxicity during the first 100 years. Thereafter, their radiotoxicity decreases and reaches the reference level after about 300 years. The long-term radiotoxicity is solely dominated by the actinides, mainly by the plutonium and americium isotopes. The reference radiotoxicity level is reached by spent nuclear fuel only after periods of more than 100,000 years.

This is the basis of the motivation for partitioning and transmutation programmes worldwide, and for the development of dedicated burner reactors such as ADS.

Partitioning and Transmutation

Different concepts have been proposed and reflect national policies on nuclear energy.

For example, both countries such as France and Japan consider plutonium as a valuable resource for energy production. Therefore, the uranium fuel irradiated in light water reactors is reprocessed, to separate plutonium. This recovered plutonium is used together with uranium to fabricate mixed oxide fuel for thermal reactors. The remaining waste containing minor actinides and fission products will be disposed of in a repository or transmuted.

In other countries, for example in Sweden, plutonium for various reasons is not separated. The spent fuel is considered as waste, which either has to be disposed of in geological repositories or will be transmuted.

In the transmutation scenario there are two options. The waste can either be recycled and transmuted in available conventional critical reactors (homogenous fuel recycle option, with no separation of plutonium and minor actinides), or in dedicated burner reactors. In the double strata fuel cycle option, plutonium is kept separated from the minor actinides and 5 to 20% of dedicated burner reactors in the reactor "park" would be required. If plutonium and the minor actinides are kept together, the fraction of dedicated burner reactors would be approximately 20%.

Accelerator Driven Systems

In contrast to conventional nuclear reactors in which there are enough neutrons to sustain a chain reaction, sub-critical systems used in accelerator driven systems need an external source of neutrons to sustain the chain reaction.

These "extra" neutrons are provided by the accelerator.

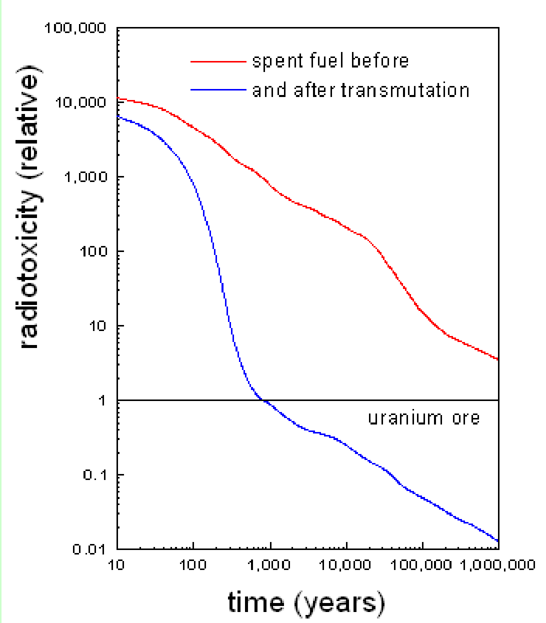


Fig.1. Ingestion radio-toxicity of 1 ton of spent nuclear fuel. With a separation efficiency of 99.9% of the long-lived by-products from the waste, followed by transmutation, reference radiotoxicity levels can be reached within 700 years.

More exactly, the accelerator produces high-energy protons which produce neutrons via a spallation source.

But why build such a sub-critical system when critical reactors already work? The answer to this lies in the fact that one has more control and flexibility in the design and operation 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. Fig.1 shows how the radiotoxicity of spent nuclear fuel can be reduced through partitioning and transmutation.

With a separation efficiency of 99.9% of the long-lived by-products from the waste, followed by their complete transmutation in a dedicated burner reactor, the radiotoxicity reaches the reference levels of the original ore, used to feed the power park, in about 500 - 700 years.

Accelerator driven systems therefore open the possibility of “burning” or incinerating waste material from existing light water reactors in dedicated actinide burners.

These actinide burners can burn safely large quantities of minor actinides per unit (in contrast to critical reactors), 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 accelerator driven systems is that, since there is no criticality condition to fulfil, almost any fuel composition can be used in the system.

It must be emphasised, however, that there are safety issues, which are common to both critical and sub-critical reactors, e. g. appropriate cooling during normal operation or decay heat removal.

Development and Deployment of Accelerator Driven Systems in Europe

The development and deployment of accelerator driven systems requires three steps:

- A comprehensive mid- and long term R&D program, to develop the single elements and components of the system. This includes development of new fuels and fuel cycle systems.
- Planning, design, construction and operation of an Experimental Accelerator Driven System for the demonstration of the concept.
- Planning, design, construction and operation of a large size prototype accelerator driven systems with subsequent large-scale deployment.

Following a first phase of R&D focused on the understanding of the basic principles of ADS (already partly underway), the programmes should be streamlined and focused on a practical demonstration of the key issues.

These demonstrations should cover high intensity proton accelerators (beam currents in the range 1-20 mA), spallation targets of high power (of power in excess of 1 megawatt), and their effective coupling with a sub-critical core.

In the field of fuels[1] and materials, the realisation of representative MA-based fuels and targets, the assessment of their physico-chemical properties and behaviour under irradiation, together with the assessment of the related processing methods, becomes a priority for a credible waste transmutation programme. The time schedule and milestones for the development of ADS technology in Europe are shown in table 1.

In the next few years (2-3 years), a broad system analysis will be performed on the two concepts under consideration: the Pb-Bi cooled system and the He cooled concept. After a decision on the most suitable concept, to be made prior to 2004 a detailed design of the ADS could be started. For the first five to seven years, the R&D shall concentrate on a) the development of high intensity accelerators and megawatt spallation sources, and their integration in a fissile facility and b) the development of advanced fuel fabrication and reprocessing technology.

[1] This Roadmap covers only solid fuel systems. An alternative approach to transmutation is through the use of molten salts in which solid fuels are not required. Such an approach, which merits detailed consideration, is not within the scope of the present study.

Table 1. Time schedule and milestones for the development of an experimental accelerator driven system (ADS) and accelerator driven transmutation (ADT) technology in Europe

Year 2000+	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	20	30	45
	5th FWP		6th FWP				7th FWP											
ADS (Phase 1)																		
Basic & Supporting R&D																		
Choices of Options																		
Design & Licensing																		
Construction																		
Low power testing																		
Full power testing																		
Operation																		
ADT (Phase 2)																		
Conversion																		
Operation																		
Prototype																		
Industrial Deployment																		

Start of construction of an ADS could be 2008 and start of operation 2013.

The fuel to be used in the first phase of operation will be conventional mixed oxide fuel. Use of existing fuel stemming from SNR-300 or Superphenix can be envisaged. Innovative and dedicated minor actinide fuel will be tested in the accelerator driven system and will replace the mixed oxide fuel in a second phase of operation (XADT). This mode of operation is envisaged for 2025.

Around 2030 construction of a prototype could be started. This prototype has to have all features of the ADS to be deployed at a later stage (power, coolant, fuel etc.). After successful operation of the prototype, it could be deployed on a large and industrial scale starting around 2040.

Cost Estimates

At present (March 2001), the total manpower commitment in different member states in the EU is estimated to be approximately 300-400 my/y (man-years per year). Most of this effort is concentrated on basic R&D support for partitioning and transmutation.

The projects launched (or to be launched) within the 5th European Framework Programme, will allow a better visibility of activities directly related to accelerator driven systems. The total budget for related projects is 50 M€ over 3 years, of which 50% will be financed by the EU.

A considerable part, however, of the national efforts, e.g. the R&D on high-power accelerators, are not funded by the EU.

Table 2. Estimated costs (M€) for the development of a 100 MW_{th} accelerator driven system

Year 2000+	1	2	3	4	5	6	7	8	9	10	11	12	**Total**
	5th FWP		6th FWP				7th FWP						
Basic & Support R&D	30		90				70				10		200
Engineering Design	5		75				60				10		150
Construction	0		80				300				70		450
Fuel	0		10				120				50		180
Total	**35**		**255**				**550**				**140**		**980**
R&D for Dedicated Fuel	***5***		***70***				***70***				***35***		***180****

* Estimated cost to 2012 for development of dedicated fuel & fuel processing

Following the first call for proposals for the 5th Framework Programme, seven ADS related projects were selected for funding. The projects have been grouped into three clusters: partitioning (chemical separation), transmutation-technological support and acquisition of basic data.

Recently three new projects have been proposed to the EU (still within the 5th Framework Programme): the system analysis of two possible ADS configurations, the megawatt pilot experiment for spallation studies and the project for development of appropriate dedicated fuels.

The estimated costs for the development of an experimental accelerator driven system (as opposed to partitioning and transmutation in general) are given in table 2. The total costs covering R&D, engineering design, construction, and fuel is estimated at 980 M€ over a twelve year period until 2012. The estimated costs are grouped within the respective Framework Programmes covering the 5th, 6th, 7th Framework Programmes and beyond.

Basic & Support R&D: at present, approximately 30 M€ are devoted to basic R&D until 2002. This effort (of 15 M€/y) should be increased during the 4 years period of the 6th Framework Programme for which a total of 90 M€ is required.

In the 7th Framework programme, some of the R&D will be terminated (e.g. for the accelerator and prototype target - by this time construction should have started). The costs during this period should decrease to 70 M€, followed by 10 M€ for the period 2011-2012.

Engineering Design Studies: for the detailed design phase a total of at least 1000 man years for engineering design is expected, with total costs amounting to 150 M€. These studies will start in 2003 at the beginning of the 6th Framework Programme and extend through the 7th Framework Programme. In the first phase up to 2006, priority will be given to the accelerator and the prototypical target; thereafter, the main emphasis will be on the reactor and system integration.

Construction: a detailed assessment of the construction costs must await the results of the engineering design studies. As a first indication 450 M€ can be assumed, contingencies and fuel excluded. The site and infrastructure preparation, estimated at the level of 80 M€, would start within the 6th Framework Programme, the next phase contains the essential construction effort, with the accelerator and the prototypical target terminated during this phase, while the complete system is ready by 2012.

Fuel: From the numbers known from SPX or SNR300 fuels it is expected that the preparation/fabrication cost of an ADS fuel by conversion of such existing fuels is in the order of 180 M€. The effort for this task is essentially concentrated within the 7th Framework Programme.

Dedicated Fuel for Transmutation: Though not absolutely necessary for the first phase of operation of the accelerator driven system, the long-term development of dedicated fuel and related fabrication and reprocessing facilities must be started. For this a constant effort during the next 12 years with a total of about 180 M€ is anticipated. This effort needs to be maintained beyond 2012.

ADS Activities in Japan and US

In Japan, the Government has approved a new project for a high intensity proton accelerator for construction. The first phase of the project has been approved with a budget of 133.5 billion yen (1335 M€) for a six-year period. This will lead to the development of a 400 MeV linear accelerator, a 3 GeV proton synchrotron with a power rating of 1 MW, a 50 GeV proton synchrotron with a power rating of 0.75 MW, and a 1 MW spallation neutron source facility. Thereafter, a second phase with a budget of 65.5 billion yen is foreseen in which an accelerator driven system will be constructed.

In the USA, the Advanced Accelerator Applications program is underway to develop a technology base for transmutation, to demonstrate this as an approach to long-term nuclear materials management, to build an accelerator driven test facility, and to strengthen the domestic nuclear infrastructure. An accelerator driven transmutation facility with a power rating in excess of 20 MW_{th}, driven by a high power proton linear accelerator with a beam power of approximately 8 MW, is planned to start operation in 2010. The level of funding for the year 2001 is $68M. The foreseen cost of the 10-year programme leading to the construction of the facility will be 1.5 billion dollars.

1. BACKGROUND AND INTRODUCTION

1.1. Nuclear Waste facts

The European Commission's GREEN PAPER: *Towards a European strategy for the security of energy supply*[2] clearly points out the importance of nuclear energy in Europe. With 145 operating reactors with a total power of 125 GW_e, the resulting electrical energy generation of about 850 TWh per year represents 35% of the total electricity consumption of the European Union.

The GREEN PAPER also points out that the European Nuclear Industry has a mastery of the entire nuclear fuel cycle, with the exception of waste management. The GREEN PAPER adds that the future of nuclear energy is uncertain, particularly in Europe, because it depends on several factors, including a solution to the problems of managing and stocking nuclear waste.

In particular, the PAPER devotes a specific paragraph to nuclear waste, where it is said:

> *"Current research, such as partition-transmutation, sets out to reduce the presence of long-lived elements. Research focusing on waste management has to be continued, ..."*

In the section on "Nuclear Energy: a source of energy in doubt", it adds:

> *"The European Union must retain its leading position in the field of civil nuclear technology in order to retain the necessary expertise and develop more efficient fission reactors and enable fusion to become a reality."*

It is therefore very important to clearly identify the problem of long-lived nuclear waste, in order to define the starting point of the research to find a solution for this problem.

Table 1.1. Transuranics in LWR spent fuel (40 GWd/ton U) after 15 years decay.

Nuclide	Amount (g/ton)
Np236	5.3E-04
Np237	6.5E+02
Pu238	2.3E+02
Pu239	5.9E+03
Pu240	2.6E+03
Pu241	6.8E+02
Pu242	6.0E+02
Pu244	4.2E-02
Am241	7.7E+02
Am242m	2.5E+00
Am243	1.4E+02
Cm242	5.9E-03
Cm243	4.3E-01
Cm244	3.1E+01
Cm245	2.3E+00
Cm246	3.2E-01
Cm247	3.7E-03
Cm248	2.4E-04

Spent fuel discharged from nuclear power plants is the main contributor to nuclear waste. The exact amount and composition of spent fuel depends essentially on the total energy generated, i.e. the discharge burn-up, and to a lesser extent on the history of burn-up undergone by a batch of fuel.

A useful *rule-of-thumb* here is that if X % of the heavy nuclei have been fissioned, an energy of 10 X GWd/ton has been generated along the burn-up history.

In a standard 1000 MW_e light water reactor (LWR), about 23 tons of fuel (heavy nuclei) are discharged per year, assuming a burn-up of 40 GWd per ton U. During the expected lifetime of a reactor of this type (~ 40 years) a total amount of 900 tons of spent fuel would be unloaded. At present, the total park of nuclear power plants in the European Union (~ 125 GW_e of nominal power) produces about 2500 tons of spent fuel annually (oxygen of the oxide not being accounted for in this figure), containing about 25 tons of Pu and 3.5 tons of the minor actinides (MA) Np, Am, and Cm. In addition the spent fuel contains about 100 t of fission products (3.1 tons of long-lived fission products). The figure of 2500 tons of spent fuel corresponds to an

[2] http://europa.eu.int/comm/energy_transport/en/lpi_lv_en.html

average burn-up of approximately 50 GWd/t which is more typical at present. A third family of radioactive nuclei, after the transuranics (TRUs) and the fission products (FPs), generated in a reactor is formed by activation products, which are mainly generated in structural materials. Table 1.1 lists the amount of TRUs in the spent fuel.

This spent fuel is highly radiotoxic. Some of the nuclides have extremely long half-lives. A way of measuring the potential risk associated to nuclear waste is through the concept of radiotoxicity (see inset). The radiotoxicity is a measure of the equivalent dose imparted to human beings following the intake of a given amount of waste. It is a rather simplistic measurement, because most of the nuclides do not have good migration properties along food chains, and it is therefore very unlikely for such an intake to happen. Nevertheless, it helps compare the risks of different types of nuclear waste and the level of risk associated to natural background radioactivity.

The radiotoxicity of nuclear waste evolves with time as shown in fig. 1 of the Executive Summary. A reference amount of 1 ton of initial uranium loaded in the reactor is used. The radiotoxicity does in fact, depend on the initial uranium enrichment and on the value of the discharge burn-up, but the general shape and order of magnitudes are similar for all LWR fuels, except those containing recycled plutonium.

A fundamental reference point is the radio-toxicity associated with the raw material used to fabricate 1 ton of enriched uranium, including not only the uranium isotopes but also all their radioactive progenies (this value is about 10^5 Sv/ton and can be taken as the level of natural reference). In fig. 1 the radio-toxicity of fission products dominate in the first few hundred years after discharge, and decrease to the natural reference level in about 300 y.

On the contrary, in the longer term, radiotoxicity is mainly dominated by transuranics (TRUs), particularly plutonium isotopes and decay products of Pu-241. In the time span between 100 and 1,000 years after fuel discharge, radiotoxicity is dominated by Am-241, the radioactive daughter of Pu-241, with a level of about $3x10^7$ Sv/ton U, i.e., about 300 times as large as the natural reference.

The *radiotoxicity* of a nuclide is determined by the product of the *activity* and the *effective dose coefficient e* for a given isotope

$$\text{Radiotoxicity} = \text{activity} \cdot e$$

The activity is just the number of disintegrations per second and is measured in units of Becquerel, Bq (1 Bq = 1 disintegration per second). The *effective dose coefficient e* is a measure of the damage done by ionising radiation associated with the radioactivity of an isotope. It accounts for radiation and tissue weighting factors, metabolic and bio-kinetic information. It is measured in units of Sievert per Becquerel (Sv/Bq) where the Sievert is a measure of the dose arising from the ionisation energy absorbed.
The Annual Limit of Intake (ALI) of an isotope is defined as the activity required to give a particular annual dose. This annual dose is usually taken as 0.02 Sv i.e.

$$\text{ALI} = (0.02\text{Sv})/e$$

The **Sievert**, **Sv**, is the unit describing the biological effect of radiation deposited in an organism. The biological effect of radiation is not just directly proportional to the energy absorbed in the organism but also by a factor describing the *quality* of the radiation. An energy deposition of 6 J per kg of gamma radiation (quality = 1) i.e. 6 Sv is lethal. This same energy deposited in the form of heat (quality = 0) will only increase the body temperature by 1mK and is therefore completely harmless. The difference between the two types of radiation is due to the fact that biological damage arises from ionisation.

Between 1,000 and 10,000 years, radio-toxicity is dominated by Pu-240, with a value of about $4x10^6$ Sv/ton U. Thereafter, Pu-239 is the main contributor to radiotoxicity with a value of $2x10^6$ Sv/ton U. Beyond 100,000 years, the total radiotoxicity decays to the level of 10^5 Sv/ton U. After that point, the main sources of radio-toxicity come from descendants of Am-241.

A detailed analysis of FP radiotoxicity reveals that there are a few long-lived radio-nuclides (e.g. I-129, Tc-99, etc.) which do contribute to very long-term radiotoxicity. However, their absolute magnitude remains below the TRU radiotoxicity, and even below the radiotoxicity of the natural ore materials removed to fabricate enriched uranium. The total radiotoxicity of fission products is about 1.4×10^7 Sv/ton U (enriched) 100 years after discharge, but decreases to 875 Sv/ton U (enriched) after 1,000 years. Thereafter, it is stabilised at that level for a long time (~100,000 years) i.e. at a level much lower than our reference level for natural ore.

As a tool for nuclear waste management, Partitioning and Transmutation (P&T) techniques are aimed at eliminating a huge fraction of the most offending nuclei. In the case of FPs, this can be done by neutron-induced stabilisation (for instance, Tc-99 captures a neutron and goes into Tc-100, which decays in few seconds to Ru-100, which is stable).

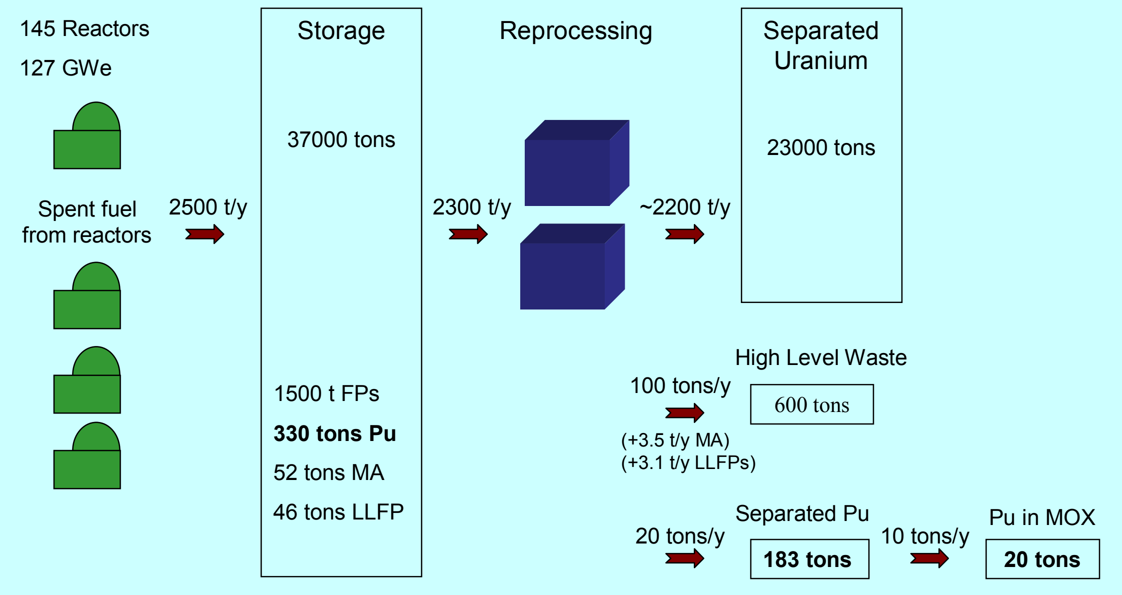


Fig. 1.1 Spent and processed fuel in the EU: cumulative and change per annum from 145 reactors (127GWe) currently (2001) in operation.

For TRUs, the only efficient way to eliminate them is by fission. This produces a small surplus of radiotoxicity in the short term (less than 300 years) but it can significantly reduce the radiotoxicity burden in the longer term. In addition, by fissioning these elements, a significant amount of energy is produced, which can be converted to electricity and thereby contribute to the financing of the P&T.

Of course, in the rationale to support P&T, it is taken into account that 300 years is a sort of technological period along which permanent monitoring and control of radioactivity confinement can be established. However, when talking about 10,000 years and beyond, it seems that such monitoring and control for a so long period becomes much less predictable.

Waste transmutation will require a suitable deployment of techniques for spent fuel reprocessing. The European Union has outstanding expertise in this field, because of the Sellafield and La Hague plants, plus a set of laboratories with the capability to study irradiated fuels and to test different types of chemical separation. At present, reprocessing is done by aqueous methods which are very efficient for Pu separation (up to 99,9%). Figure 1.1 summarises the amounts of spent and processed fuel in the EU.

For transmutation applications, new partitioning processes must be developed for minor actinides separation from the high level waste. Although these processes are still very much at the research stage, industrial scale-up will result in the deployment of new, more specific separation techniques for transmutation applications.

1.2. Nuclear Waste Transmutation using Accelerator Driven Systems

The disposal of radioactive wastes resulting from industrial nuclear energy has still to find a fully satisfactory solution, especially in terms of environmental and social acceptability. As a consequence of this situation, most countries with significant nuclear power generating capacity are currently investigating various options for the disposal of their nuclear wastes.

Within the nuclear scientific community, it is widely accepted that a deep geological repository would be a suitable solution for spent fuel disposal, including fission fragments and actinides not recycled in operating reactors. Ways and techniques used for final disposal could include technological barriers to increase the level of confidence for the radioactive products to remain confined for very long times. However, an alternative to that solution is gaining grounds on the basis of waste retrievability to enable future waste treatment.

Partitioning and Transmutation (P&T) techniques could contribute to reduce the radioactive inventory and its associated radiotoxicity. Scientists are looking for ways to drastically reduce (by a factor of 100 or more) both the mass and the radiotoxicity of the nuclear waste to be stored in a deep geological repository, and to reduce the time needed to reach the radioactivity level of the raw material originally used to produce energy.

Although there is a wide international consensus on the need for some kind of geological storage, there has been a revival of interest in P&T technologies in order to eliminate a significant fraction of the most offending nuclei (see § 1.1) and, consequently, reduce the burden to the underground repository. These technologies would allow the separation (partitioning) of the most hazardous materials, i.e. the plutonium (Pu), the minor actinides (MA: neptunium, americium, curium) and some long-lived fission products (LLFP), from the waste and convert (transmute) them into short lived or stable products.

Innovative critical fission reactors could be envisaged for this purpose. However, following studies performed in several countries, there has recently been an increasing interest in a two-step strategy where the conventional fuel cycle is supplemented by a P&T cycle to treat the waste.

Different concepts have been proposed and reflect national policies on nuclear energy.

For example, both French and Japan consider plutonium as a valuable resource, which should be used to the largest possible extent. The uranium (U) fuel irradiated in LWRs is reprocessed, the Pu is separated from the fission products and the MAs. The recovered Pu will be recycled in LWRs or in fast neutron reactors (FNRs) as Mixed-Oxide (MOX) fuel. Only the MAs and the FPs are considered as waste, which either will be disposed of or will be transmuted, possibly in the second stratum of the fuel cycle or homogeneously in a large part of the nuclear power park.

In other countries, e. g. in the US and Sweden, the plutonium for various reasons is not separated from the MA. Both, the Pu and the MAs are kept together and considered as waste, which either have to be disposed of together with the FPs in geological repositories or will be transmuted. Corresponding P&T schemes are considered both in Europe and USA.

Using the Double Strata concept, 5 to 20% of reactors in the European reactor park could fission (burn) all the plutonium and all minor actinides depending on the different envisaged national strategies.

Both critical reactors and sub-critical Accelerator Driven Systems (ADS) are potential candidates as dedicated transmutation systems. Critical reactors, however, loaded with fuel containing large amounts of MA pose safety problems caused by unfavourable reactivity coefficients and small delayed neutron fraction. With regard to this latter problem, the main characteristic of ADS (i.e. sub-criticality) is particularly favourable and allows a maximum transmutation rate while operating in a safe manner. An advantage of accelerator driven systems is that, since there is no criticality condition to fulfil, almost any fuel composition can be used in the system.

These, basically, are the main advantages of the ADS as compared to critical systems.

For these reasons, waste transmutation using ADS has become a relevant R&D topic in Europe. The resources presently allocated cover a large number of activities ranging from accelerator, spallation target, and reactor design to fuel and reprocessing technology. The total effort during the last three years, and foreseen for the year 2001, is approximately 300-400 man-year/year. The organisations involved include national R&D bodies, universities, several major nuclear industries. In some countries, co-ordinated national programs have been set up and some experimental facilities are under construction.

Important ADS activities are also going on or planned in Japan, Korea, and USA. In Japan, the Government has approved a new project carried out jointly by JAERI and KEK for a high intensity proton accelerator for construction. The first phase of the project has been approved with a budget of 133.5 billion yen (1335 M€) for a six-year period. This will lead to the development of a 400 MeV linear accelerator, a 3 GeV proton synchrotron with a power rating of 1 MW, a 50 GeV proton synchrotron with a power rating of 0.75 MW, and a 1 MW spallation neutron source facility. Thereafter, a second phase with a budget of 65.5 billion yen is foreseen in which an accelerator driven system will be constructed.

Recently, a *US "Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology"* lead to creation of a large Advanced Accelerator Applications (AAA) project which has been submitted to Congress for funding.

The programme, which has already started, is aimed at developing a technology base for transmutation, to demonstrate this as an approach to long-term nuclear materials management, to build an accelerator driven test facility, and to strengthen the domestic nuclear infrastructure. An accelerator driven transmutation facility with a power rating in excess of 20 MW_{th}, driven by a high power proton linear accelerator with a beam power of approximately 8 MW, is planned to start operation in 2010. The level of funding for the year 2001 is $68M. The foreseen cost of the 10-year programme leading to the construction of the facility will be 1.5 billion dollars.

The groups in Europe working on the development of ADS are already co-operating closely. A well co-ordinated and coherent European programme on waste transmutation using ADS in addition would ensure a more strategic impact and lead to:

- a full assessment of the impact of ADS in the reduction of the radiotoxicity of nuclear waste;
- the development of innovative fuels and reprocessing technology;
- the rationalisation of human resources and experimental facilities;
- motivation and training of young researchers, in a multidisciplinary field;
- spin-offs in the field of accelerators, spallation sources, liquid metal technology, gas system technology, radioisotope production, and actinide chemistry.

Following a first phase of R&D focused on the understanding of the basic principles of ADS (already partly underway), the programmes should be streamlined and focused on a practical demonstration of the key issues. These demonstrations should cover high intensity proton accelerators (beam currents in the range 1-20 mA), spallation targets of high power (of power in excess of 1 megawatt), and their effective coupling with a sub-critical core. In the field of fuels and materials, the realisation of representative MA-based fuels and targets, the assessment of their physical-chemical properties and behaviour under irradiation, together with the assessment of the related processing methods, becomes a priority for a credible waste transmutation programme.

For the coming five to seven years the R&D shall concentrate on a) the development of high intensity accelerators and megawatt spallation sources, and their integration in a fissile facility, b) the development of advanced fuel reprocessing technology and c) the acquisition of the physical and technological data needed for the operation of a fast neutron ADS. The main facilities and projects of relevance to ADS in Europe are shown in table 1.2.

Table 1.2. Main facilities and projects of relevance to ADS in Europe

Facilities/Projects	Location and purpose
GELINA, N_TOF, HINDAS	The neutron data activity at JRC-IRMM, Geel, (Geel Linac) and (Neutron Time of Flight) experiment at CERN, Geneva, for nuclear cross-section measurements, and the high- and intermediate energy nuclear data measurements for ADS (see sections 4.2.1 & 4.2.2).
IPHI, TRASCO	High Intensity Proton Injector and the Trasmutazione Scorie in Italy, on the path to a powerful and reliable accelerator (see section 4.3.2).
MEGAPIE	Megawatt pilot experiment - a robust and efficient liquid metal spallation target, integrated in the SINQ facility at the Paul Scherrer Institute in Switzerland. The SINQ facility, a spallation neutron source fed by a cyclotron, is of interest to the development of ADS (see section 4.4.1).
MUSE-4	at the MASURCA installation in Cadarache using the GENEPI Accelerator - a first image of a sub-critical fast core fed by external neutrons provided by an accelerator (see section 4.5.1).
MYRRHA	a multi-purpose neutron source for R&D applications at SCK-CEN Belgium (see section 4.5.2).
Minor Actinide & Fuel Processing Laboratories	Fuel fabrication and advanced aqueous and pyro-processing Laboratories at JRC-ITU in Karlsruhe; and at CEA-Cadarache and Marcoule (ATALANTE) laboratories (see section 4.7).
KALLA, LECOR, CHEOPE, CIRCE	Karlsruhe lead laboratory and Circuito Eutettico facilities for Pb-Bi technology development (see sections 4.6.3, 4.6.4, & 4.6.5).

Moreover a first experiment of ADS component coupling could be envisaged using the TRIGA reactor at Casaccia (Italy). This experiment can be run at several hundred kW_{th} power in the reactor and few tens kW_{th} in the target, thus providing e.g. a demonstration of the dynamic behaviour of an ADS in presence of reactor feedback effects.

Eight R&D projects listed in table 1.3, of direct relevance to ADS/ADT development, have been already approved and funded by the European Commission for the years 2000-2003 within the Partitioning and Transmutation sub-programme of the 5th European Framework Programme (Key Action 2: Nuclear Fission – Safety of the fuel cycle).

Table 1.3 Projects approved and pending by the EU for the years 2000-2003 within the Partitioning and Transmutation sub-programme of the 5th European Framework Programme.

Projects	Details
	Projects funded in the first call of the P&T sub-programme of the 5th European Framework Programme.
N-TOF-ND-ADS	ADS nuclear data project aimed at a consistent and cost effective production, formal evaluation and dissemination of neutron cross sections (see section 4.2.1)
HINDAS	high- and intermediate energy nuclear data measurements for ADS (see section 4.2.2)
MUSE	The Muse experiments for sub-critical neutronics validation (see section 4.5.1)
TECLA	Technologies, materials and thermal-hydraulics for lead alloys (see section 4.6.2)
SPIRE	Irradiation effects in Martensitic steels under neutron and proton mixed spectrum (see section 4.6.6)
CONFIRM	Collaboration on oxide and nitride fuel irradiation and modelling, i.e. a comprehensive safety evaluation of uranium free fuels for accelerator driven systems (section 4.7.4)
THORIUM CYCLE	Development steps for PWR and ADS Application - to supply key data for application of the Th-cycle in PWRs, FRs and ADS, related to Pu and TRU burning and reduction of the lifetime of nuclear waste (see section 4.7.6)
PYROREP	Pyro-metallurgical processing research programme (see section 4.7.7)
PARTNEW	Partitioning; new solvent extraction processes for minor actinides
CALIXPART	Selective extraction of minor actinides from high activity liquid waste by organized matrices
	Projects funded in the second call of the P&T sub-programme of the 5th European Framework Programme
ADOPT	ADOPT: Advanced options for partitioning and transmutation thematic network, which is intended to guarantee management and co-ordination of P&T and ADS activities within the 5th Framework Programme, as well as a link to national programmes
FUTURE	FUTURE: Fuel for transmutation of trans-uranium elements, i.e. new fuel and fuel cycle development for transmutation (see section 4.7.5)
MEGAPIE	Megawatt pilot experiment (see section 4.4.1)
PDS-XADS	Preliminary design study of a European XADS for assessing its feasibility, safety and licensing issues, R&D support needs and costs (two most promising technical options: XADS Pb-Bi and XADS gas, plus MYRRHA) (see section 4.8)

These projects involve more than 50 organisations with a total budget of 50 M€ over the years 2000-2003, of which 50% will be financed by the EU. A considerable part, however, of the national efforts, for example the R&D on high power accelerators, is not funded by the EU.

In addition the European Union supports, through the International Science and Technology Centre in Moscow, a number of interesting experimental projects of direct relevance to ADS. These include, for example, the construction of a 1 MW liquid Pb/Bi spallation target at the Institute for Physics and Power Engineering (IPPE) in Obninsk; a sub-critical assembly driven by external neutrons - the Yalina experiment in Minsk; SAD experiments, a sub-critical assembly in combination with a proton accelerator at Dubna, etc. These activities are, for the time being, well co-ordinated and/or integrated with other European projects.

As outlined in the two TWG reports issued previously (annexes 1 and 2), these activities provide an excellent platform on which to launch a European programme on nuclear waste transmutation. In the next few years (2-3 years) a broad system analysis will be performed on the two concepts under consideration: the Pb-Bi cooled system and the He cooled concept. After a decision on the most suitable concept, to be made prior to 2004, a detailed design of the eXperimental ADS (XADS) could be started. Start of construction could be 2005 for the accelerator and spallation module, 2008 for the sub-critical system and full XADS start of operationin 2013.

On this time scale the development of a new fuel concept and new fuel cycle components (based on Pu and MA) is impossible. Therefore the fuel to be used in the first phase of operation will be conventional MOX fuel. Even the use of existing fuel stemming from SNR 300 or Superphénix (SPX) can be envisaged. Innovative and dedicated MA fuel will be tested in the XADS and will replace the MOX fuel in a second phase of operation. This mode of operation is envisaged for 2025.

At about 2030 construction of a prototype could be started. This prototype has to have all features of the ADS to be deployed at a later stage (power, coolant, fuel etc.). After successful operation of the prototype ADS can be deployed on a large and industrial scale from 2040 on.

The present document outlines the route and the steps for the XADS facility, taking into account the overall ADS development strategy, as well as the scalability to industrial levels.

The decision to go ahead with the XADS project should be prepared in time to be synchronised already with the ongoing projects of the 5th FWP and with the 6th and 7th Framework Programmes (FWPs). In particular, a substantially increased budget will be required during the 6th FWP, to carry out the basic R&D (including more on accelerator development and fuel development and qualification) and the first detailed design.

In a few years, Europe may well have to consider the opportunity of building an ADS experimental facility, possibly in close co-operation with the United States, Japan and Russia. Europe must be ready, around 2005, for such collaboration, with a detailed design to be proposed. Only with such a common European approach can the complex and innovative technology be transferred from the scientific arena to mature industrial technology.

1.3. Historical background of ADS

Early history of ADS (1940-1993)

In the 1940s, it was known from work with research accelerators, that bombardment of a uranium target by high-energy protons or deuterons would produce a large yield of neutrons. These neutrons could in turn be used to produce fissionable material through nuclear reactions. In 1941, Glenn Seaborg produced the first man-made plutonium using an accelerator.

During the period 1950-54, the MTA (Materials Testing Accelerator) program at Lawrence Livermore (at that time the Livermore Research Laboratory) investigated in detail the use of accelerators to produce fissionable material. Almost concurrently in Canada, Lewis realised the value of accelerator breeding in the power programme and initiated spallation neutron yield measurements with the McGill cyclotron. The project ended in 1954 and the documents were declassified in 1957.

A materials production accelerator - the Electronuclear Reactor - was patented in 1960 by Lawrence et al. to provide adequate quantities of material which can only be produced artificially. The targets considered were natural uranium and thorium and the artificially produced materials were ^{239}Pu and ^{233}U respectively.

At Chalk River in Canada, the Intense Neutron Generator (ING) concept was proposed to provide a radical new approach to nuclear power.

Later studies (1975-88) on the Fertile-to-Fissile Conversion (FERFICON) Program - a collaborative effort with various laboratories - investigated the energy dependence, up to 800 MeV, of the fertile-to-fissile conversion efficiency using standardised target materials and geometries.

A relatively realistic concept of an "Accelerator Driven System" (ADS) in the present meaning, where safety issues and transmutation of waste play an important role, was developed in the late eighties by a research group at Brookhaven National Laboratory lead by H. Takahashi and G. Van Tuyle

The first detailed design of a transmutation facility using thermal neutrons was published by C. Bowman's Los Alamos group in 1991 introducing a common name The Accelerator Transmutation of Waste (ATW)

Recent Developments in Europe (1993-2000)

In 1993 a group of CERN's scientists led by Carlo Rubbia presented the basic concepts of a so-called "Energy Amplifier", a sub-critical nuclear system based on U-Th cycle, fed by a high intensity proton accelerator having the purpose to produce energy with very small amount of MA and LLFP production.

Later on the scientific feasibility and the verification of the principle of energy amplification by a high energy cascade were proven in experiments such as FEAT (autumn 1994) and TARC (1997-1998).

FEAT, an experiment carried out at CERN under the leadership of Carlo Rubbia, with the participation of research groups from France, Greece, Italy, Spain and Switzerland, stands for First Energy Amplifier Test, and was an experiment based on a sub-critical core of 3.5 tons a metallic natural uranium driven by an intense neutron source activated by a powerful beam of protons coming from the PS accelerator at CERN. Both natural uranium and lead targets were used in the experiments, were power, flux and temperature distributions and time evolution were recorded.

TARC represented a second series of experiments which was carried out at CERN by the same team in order to study the adiabatic resonance crossing of neutrons in a matrix of lead with some samples of specific material, particularly Tc-99. The TARC experiment (from Transmutation by Adiabatic Resonance Crossing) was conclusive to demonstrate that an appropriate neutron spectrum is shaped in a large lead matrix in order to enhance neutron capture in any significant resonance. This was the case for Tc-99, which was transmuted into Tc-100, rapidly decaying into Ru-100 (stable). The experiments showed that TARC is a powerful neutron technique for burning any type of nuclei showing resonances (which is the case for all offending nuclei in nuclear waste management).

In 1996 in the 4th Framework Programme, European Union funded a project “Impact of Accelerator Based Technologies on Nuclear Fission Safety – IABAT”, FI4I-CT96-0012. The overall objective of the IABAT project was a preliminary assessment of the potential of Accelerator Driven Systems for transmutation of nuclear waste and, additionally, for nuclear energy production with minimum waste generation. Moreover, more specific topics related to nuclear data and code development for ADS have been studied in more detail. 14 institutes and universities from Europe were participating or collaborating in the frame of the IABAT project.

The IABAT project stimulated very visibly the development of accelerator-driven transmutation research in many institutes in European Union and contributed to the creation of new projects and project proposals for the 5th Framework Programme. Almost every research group participating in the IABAT project has developed further activities in this field.

At institutional level, in 1996 the “Scientific and Technical Committee (STC) on a nuclear energy amplifier” set up by the Nuclear Science and Technology European Commission and chaired by Dr. D. Pooley, recognising that:

“several features of the energy amplifier do merit further work with the aim of developing potential additions …. which might make significant improvements particularly in the waste management and fissile material management fields”,

concluded that:

“the Commission should encourage further work on sub-critical, fast-neutron multipliers such as suggested by Professor Rubbia, primarily aimed at actinide burners”.

The STC also recommended “a step-wise approach with the best of the ideas in the energy amplifier proposals”.

In 1998 the Research Ministers of France, Italy and Spain, recognising the potentialities of Accelerator Driven System 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 a 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 (Annexe 1) which, in particular, highlighted a) the need for a demonstration programme, b) the basic components and the different options for the proposed 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 a European goal.

As a consequence, a MAG “ad hoc” meeting open to all the 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:

- that neutron induced transmutation represents an attractive approach to radioactive waste management, being complementary to geological disposal;

- 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;

- that the interim report of the TWG issued in 1998 be accepted as a good basis for future work to be carried out by an Enlarged (actually European) 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 new technical report (Annexe 2) 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” (Annex 3) 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 recognises its potentially-relevant implications on the 6th European Framework Programme.

The four-page document was submitted to the MAG at its last meeting on February 25, 2000 and received positive comments: consequently, the TWG was committed and encouraged by MAG to proceed in the forthcoming months in defining the above-mentioned roadmap.

In particular, in order to specifically address some important key issues such as accelerator and fuel & 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.

This report contains a synthesis of the work carried out by the ETWG and the various sub-groups.

1.4. Goals of the Present Roadmap

In this seventh decade of nuclear power, the issue of waste disposal strongly dominates public opinion. The basis of this is the perception of some kind of risk associated with the decision to store nuclear waste in underground repositories for very long periods of time. Such decisions clearly involve risks. However, abstaining from such a decision also involves risks. How can the power needs of a country be covered if nuclear plants are shut down? This matter requires a reasoned analysis, taking into account not only the "pros" and the "cons" of the decision in balance, but also on the consequences of alternate lines of conduct.

It has become fashionable to advocate the "Precautionary Principle"[3] when dealing with sensitive technological issues. In most cases, the underlying argument is negative*: "In dubio, abstine"*. In contrast, however, the Precautionary Principle does not imply making no decision or postponing a decision - application of the precautionary principle implies active investigation of "alternate lines of conduct".

- On this basis, the *first goal* of this Roadmap is to propose one such alternate line of conduct to reduce the risks associated with nuclear waste, based on the transmutation of nuclear waste in accelerator driven systems (ADS), and to assess the impact of this approach in the reduction of the radio-toxicity of the nuclear waste.

In this task, the report reviews historical developments and identifies and assesses the status of current activities and facilities related to ADS research in the EU and worldwide.

- The *second and main goal* of the Roadmap is to prepare a detailed technical programme, with preliminary cost estimates, which will lead to the realisation of an experimental ADS within 12 years, covering 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 co-ordination 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 present Roadmap is to identify possible synergies that this programme could have within the scientific community, indicate potential spin-offs, show how competence can be maintained in the currently stagnating field of nuclear energy research. This is also consistent with the European Research Area policy for synergism among research programmes and activities in the EU.

This Roadmap is a result of a mandate given to the technical working group (TWG) on ADS by the Research Ministers' Advisors Group (MAG). In the first instance, therefore, this report is directed to the MAG. The document is 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. The report is also of general interest to the public since it concerns the disposal of nuclear waste - an issue which strongly dominates public opinion.

[3] J. Couture, The Precautionary Principle: A Guide for Action, Proceedings of the INTERNATIONAL CONFERENCE ON "GLOBAL WARMING AND ENERGY POLICY Fort Lauderdale, Florida, November 26-28, 2000, to be published.

2. MOTIVATIONS FOR DEVELOPING ADS TECHNOLOGY IN THE FIELD OF P&T

2.1. Partitioning and Transmutation (P&T)

Partitioning and Transmutation (P&T) is considered as a way of reducing the burden on a geological disposal. Plutonium and the minor actinides are mainly responsible for the long-term radiotoxicity. If these nuclides are removed from the waste (partitioning) and fissioned (transmutation), the remaining waste loses most of its long-term radiotoxicity. This is important both in the case of a nuclear phase-out, as well as in the case of the continuous use of nuclear energy as contributor to a sustainable development. In the latter case, the main requirements are related to competitivity, reduction of long-lived, highly active nuclear waste, saving of natural resources, improved safety characteristics etc..

In order to assess the potential of transmutation, the following criteria usually are applied:

- the mass balance of transuranics (TRUs) including residual Pu and MAs;
- the radiotoxicity on diverse timescales.

In order to reach the goals of P&T the most effective way is to "burn" i.e. fission the actinides (Pu, Np, Am and Cm). The resulting fission products have, in general, much shorter halflives and, after a few hundred years, are no longer hazardous. A few long-lived fission products (LLFP), such as ^{99}Tc, are sometimes taken into account, even if their contribution to the global radiotoxicity is rather limited - most of their contribution being to the so-called "residual risk". Numerous studies on transmutation have been performed worldwide using different types of reactors and different fuel cycle strategies. General conclusions can be drawn from the results of these studies:

- it can be seen from fig. 2.1 that the radio-toxicity inventory can be reduced up to a factor of 10 if all the Pu is recycled and fissioned. Reduction factors higher than 100 can be obtained if, in addition, the minor actinides (MAs) are burned. A prerequisite for these reduction figures is a nearly complete fissioning of the actinides, for which multi-recycling is a requirement. Losses during reprocessing and re-fabrication must be well below 1% and probably in the range of 0.1%.

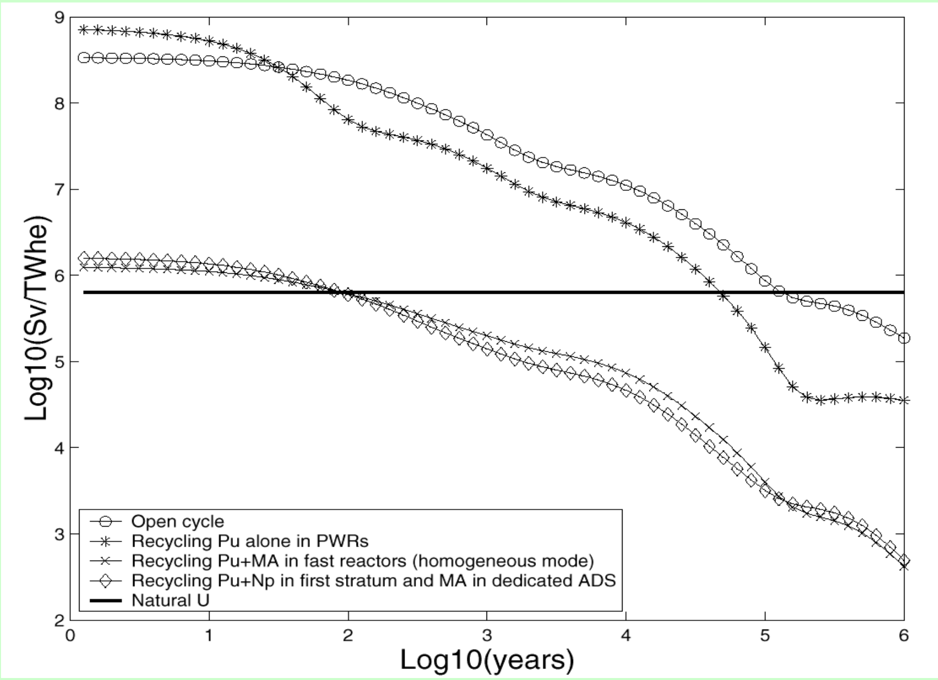


Figure 2.1 Radiotoxicity evolution with time for different scenarios

- In principle all types of reactors can be used to fission the actinides (thermal systems, fast systems, critical and sub-critical systems). Fast neutron systems however have significant advantages because of basic physical properties - all TRUs are neutron *sources* in a fast spectrum whereas most TRUs in a thermal spectrum act as neutron *poisons*. Unacceptable economic consequences resulting from this prohibit effective transmutation in thermal systems. In addition a thermal neutron energy spectrum increases the content of high-mass isotopes in the composition of the final waste discharged from the ADS (see results in table 2.1).

Table 2.1. Typical values of the neutron consumption per fission (D) for fast and thermal systems. D ≥ 0 implies a source of neutrons is required, whereas D < 0 implies excess neutron self-production

D, per fission

Isotope (or fuel type)	Fast Spectrum	Standard PWR*
^{238}U	-0.62	0.07
^{238}Pu	-1.36	0.17
^{239}Pu	-1.46	-0.67
^{240}Pu	-0.96	0.44
^{241}Pu	-1.24	-0.56
^{242}Pu	-0.44	1.76
^{237}Np	-0.59	1.12
^{241}Am	-0.62	1.12
^{243}Am	-0.60	0.82
^{244}Cm	-1.39	-0.15
^{245}Cm	-2.51	-1.48
D_{TRU}*	-1.17	-0.05
D_{Pu}*	-1.10	-0.20

* Value for fuel as unloaded from UOX PWR

- The addition of MAs to the fuel has adverse effects on safety parameters. This is true for both, thermal and fast neutron systems. The fraction of delayed neutrons and the Doppler coefficient are reduced. In liquid metal cooled reactors (LMRs) the positive void reactivity is increased. Because of the adverse effects on safety, the content of MAs in the fuel of critical reactors needs to be limited to a few percent. This has the consequence that large parts of the whole fuel cycle of a reactor park will be ”contaminated” by MAs. Depending on the particular strategy, up to 50% of all reprocessing and refabrication have to deal with fuel containing MAs.

- Fuel containing MAs needs special handling precautions during fabrication and reprocessing. Significant economic penalties are to be expected. Even the feasibility of the PUREX process as it is applied today must be questioned (Pu-238 content, radiolysis, neutrons, etc.)

- In order to overcome the adverse effects of MAs in the fuel, the so called ”Double Strata” strategy has been proposed. In the first (main) stratum, energy is produced using conventional reactors. Pu may or may not be recycled in this stratum depending on national policies. MAs are not recycled in the first stratum. MAs and some Pu, which no longer can be used in the first stratum, are transferred to the second stratum and will be burned there. Dedicated fuels, innovative reactor systems and new fuel cycle technologies will be applied in this stratum. As these probably are more expensive than the today's commercial systems, the fraction of the second stratum to the whole reactor fleet must be kept small.

A schematic view of the two strategies (i. e. MAs in small concentration in the fuel of many critical reactors with homogeneous recycling and the Double Strata concept) is illustrated in fig. 2.2.

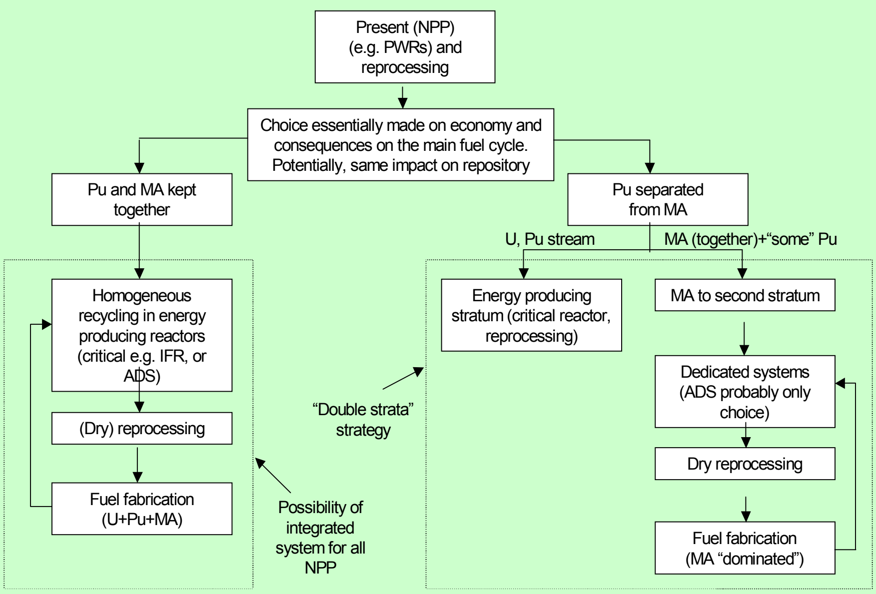


Figure 2.2 Comparison of the homogeneous (i.e. MA are distributed homogeneously throughout the fuel cycle) and the double strata (i.e. MA are restricted to only the second strata) fuel cycles

2.2. The Accelerator Driven System (ADS) Concept

In contrast to conventional 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 as shown schematically in fig. 2.3.

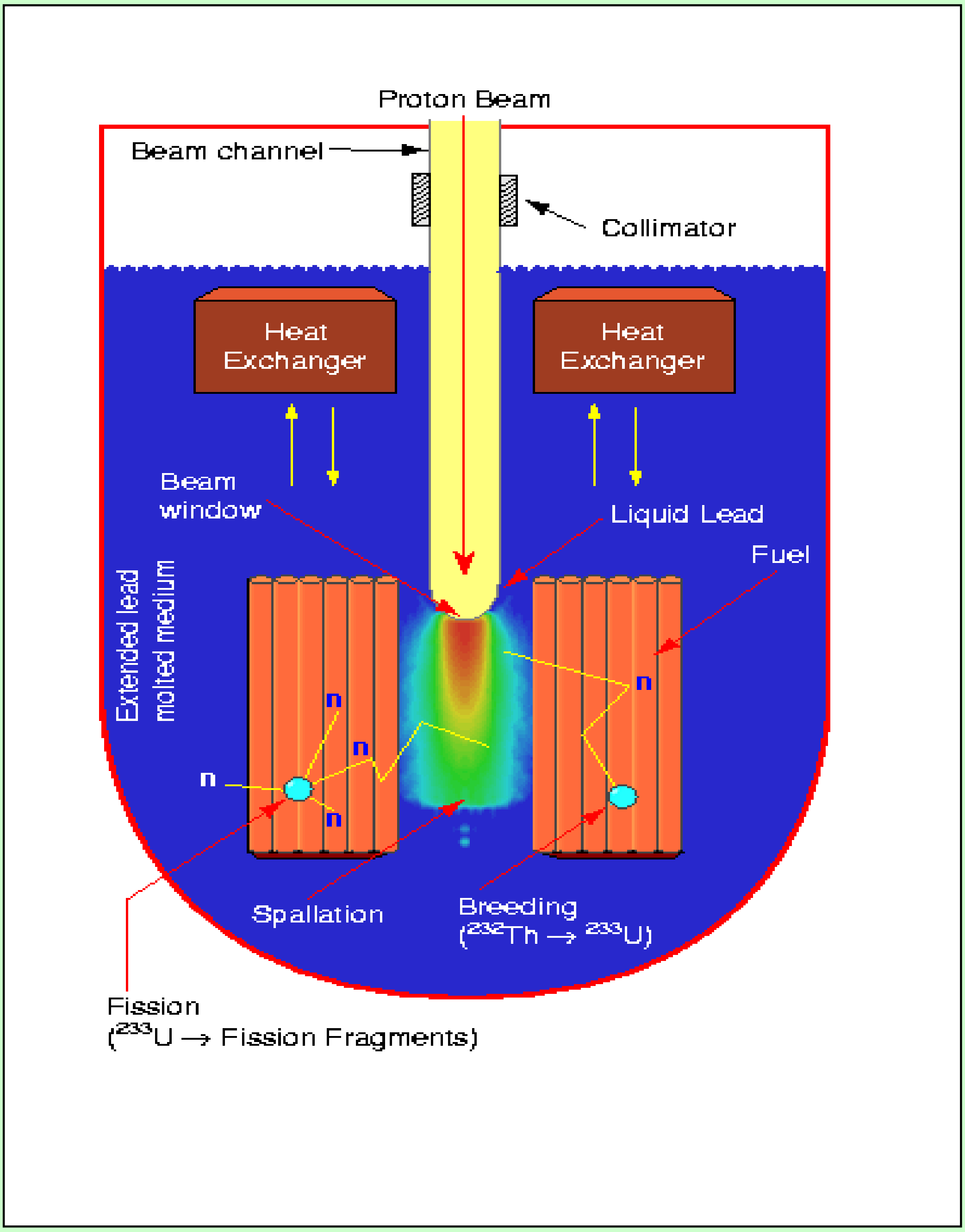


Figure 2.3 Schematic diagram of an ADS

But why build an ADS sub-critical system when critical reactors already work? The answer to this lies in the fact that one has more control and flexibility in the design and operation 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 fig. 2.4.

As indicated in section 2.1, 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.

ADS therefore open the possibility of "burning" or incinerating 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.

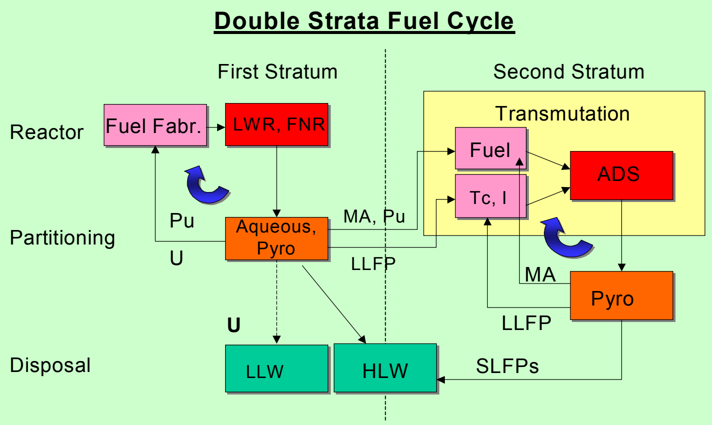


Figure 2.4 Schematic description of the transmutation of nuclear waste by ADS within a double strata fuel cycle (LLFP: long-lived fission products; SLFP: short-lived fission products, LLW: low level waste; HLW: high level waste).

It however must be emphasised, that there are safety issues, which are common to critical and sub-critical reactors, e. g. appropriate cooling during normal operation or decay heat removal. In addition it cannot be denied, that additional safety concerns might be created by the fact, that two highly sophisticated systems (the accelerator and the sub-critical core) are connected. Very high standards of safety are required for future nuclear facilities, e. g. in the case of future LWRs the consequences of a hypothetical core melt down accident must be controlled. Similar safety requirements have to be fulfilled by a future ADS.

2.3. ADS Strategies

ADS combines a high power proton accelerator (HPPA) and a fission reactor operated in a sub-critical mode. The fission reactor uses the external neutrons, which are produced by spallation processes, in order to sustain stable power generation. The dynamic behaviour of such a system during normal operation is not controlled by the reactivity coefficients of the reactor but rather it is determined by the proton beam. This is the key to the motivation for the use of ADS: in fact an ADS core can adopt a fuel which, because of its poor safety characteristics, cannot be used in a critical reactor.

Transuranics (TRUs) and primarily minor actinides (MAs) have such adverse characteristic that they drastically reduce the intrinsic features capable of moderating and stabilising the chain reaction i.e. the delayed neutron fraction (β_{eff}) and Doppler reactivity feedback coefficient. Great incentives exists therefore, to burn such fuels in dedicated innovative systems with "built-in" safety features such as in a sub-critical reactor.

There exist different strategies with respect to nuclear power in the member states of the EU. Whereas there are countries that consider nuclear power as a contribution to a sustained energy provision, there are others countries which have today a position aiming to phase out of nuclear energy. Furthermore in some countries plutonium will be recycled either in thermal or in fast reactors whereas in other countries plutonium is considered as a waste. Independent of the particular strategy, however, P&T using ADS can play an important role. The following are necessary prerequisites for the development of ADS for the task foreseen:

- a *maximum* beam power in the range of 12-40 MW (typically a current of 12-40 mA of protons at 1GeV) and a spallation target accommodating up to 40 MW of thermal power is required for an industrial prototype to be built and operated around 2030. This will allow deployment of ADS with a power of 500-1500 MW_{th} starting around 2040.

- A dedicated fertile free fuel and related fuel cycle will be developed by 2025. ADS equipped with such fuel will have the capability to burn about 120 kg TRUs /TWh_e which is equivalent to 1000 kg TRUs per GW_e a (365 full power days).

Strategy 1: ADS and continuous use of nuclear energy

- Pu recycling in the 1st stratum

In the double strata fuel cycle, the fraction of ADS in the park is minimum, if the Pu could be recycled more than once or as it is the case in the original double strata concept, indefinitely in the first stratum. This is not feasible, if only thermal reactors are used in this stratum.

It would however become feasible if fast reactors would be introduced in the first stratum. In this case only the MAs would be sent to the ADS. In this case 5% of ADS would be sufficient to burn the remaining minor actinides.

As a particular case, the plutonium produced in LWRs could be recycled once in MOX-LWRs and then sent to the ADS together with all the MAs. The assumed production and burning Pu are indicated in table 2.2.

Table 2.2 TRU production and burning (One recycling in LWR)

Category	Amount (kg/TWh_e)
Pu Production in UOX - LWR	28.5
Np Production in UOX - LWR	1.7
Am Production in UOX - LWR	1.6
Cm Production in UOX - LWR	0.3
Fabrication of MOX Elements	193.8
Pu burning in MOX - LWR	61.9
Np Production in MOX - LWR	0.5
Am Production in MOX - LWR	9.6
Cm Production in MOX - LWR	2.6
TRU burning rate in ADS	120

Approximately six UOX-LWRs are needed to produce the necessary inventory for one MOX-LWR (193.8 kg/TWh_e shown in table 2.2). In this case an ADS fraction of 15% of the reactor park would be sufficient to burn all the MAs and the remaining Pu from the MOX-LWR reactors as shown schematically in fig. 2.5. From the remaining 85%, 74% are of the UOX type and 11% of the MOX type.

Strategy 2: ADS and continuous use of nuclear energy

- Pu and MA transmuted together

Some countries prefer not to separate the Pu. The Pu and the actinides stay together and are sent to the ADS to be transmuted. The energy production is in UOX-LWR reactors. The production and burning rates for UOX–LWRs and ADS given in table 2.2 again are assumed. The share of ADS must be increased to 21% in this case as shown schematically in fig. 2.6.

Different nuclear methods had been proposed to achieve this type of incineration, including fast neutron spectra ADS (Pb, Pb-Bi or gas cooled) and ADS pebble bed reactors.

In this latter case, it has been proposed to tailor the neutron spectra for eliminating Pu and MA.

Strategy 3: ADS and phase-out.

The phase out scenario presently envisaged in Germany is taken as an example (shown schematically in fig. 2.7). From the operation of the existing reactors, there is an amount of about 80 t of Pu and 8 t of MA. It is foreseen that another 2600 TWh_e will be produced in the present reactors prior to their final shut down. This means a further 17 years operation at the present level. Reprocessing and recycling will not be allowed from 2005. This will lead to an additional mass of spent fuel of 7700 t containing a mass of Pu of about 78 t and 12 t of MAs.

In total, in 2025 there will be about 15,000 t of spent fuel, 160 t Pu and 20 t of MA in Germany which will have to be disposed off in one way or another.

We assume that ADS with a total capacity of 4-5 GW_e would be installed to burn this material. Under these assumption about 50-70 years would be needed to burn the TRUs.

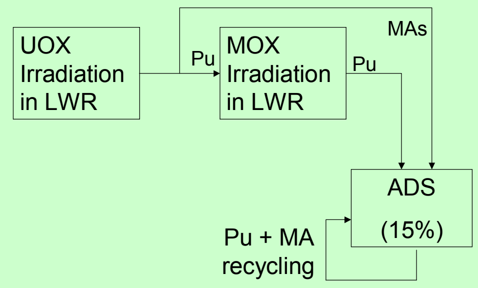


Figure 2.5 Strategy 1: double strata fuel cycle, Pu recycling in the 1st stratum

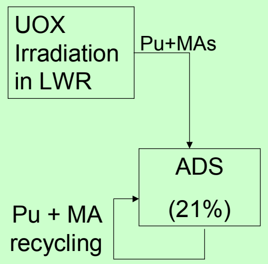


Figure 2.6 Strategy 2: Pu and MA transmuted together

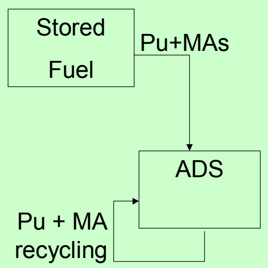


Figure 2.7 Strategy 3: nuclear phase-out

Summary

In summary it can be stated that the ADS can play a very important role in the P&T perspective and allows a very high level of radio-toxicity reduction.

It must be emphasised, that the same goals could be reached by a strategy implementing an electro-nuclear system of advanced fast reactors (AFR), which would provide the same level of radio-toxicity reduction performance as a double strata system (see figure 2.2). A good example of such a system is the IFR concept proposed by ANL in the 80s. However a large fraction of the reactor park would have to consist of burner reactors (40 – 50 %). The competitiveness and full feasibility has not yet been demonstrated.

Because of this and taking into account the fact that fast reactors (FR) suffer serious public objections, it seems reasonable to develop an alternative. Therefore it is important to proceed with the R&D and a stepwise demonstration of the technology and of the ADS system, for an industrial prototype implementation about 2030 and a full industrial large scale deployment starting around 2040.

The demonstration has to be carried out stepwise. In a first step, a test facility will be built in which the basic physical principles will be studied and demonstrated. This eXperimental ADS (XADS) will use conventional MOX fuel and therefore the capability of the transmutation process will not be demonstrated. This will be done in a second phase where either the XADS will be converted to an eXperimental accelerator driven transmuter (XADT) by exchanging the conventional fuel with dedicated fertile-free fuel or – should this not be feasible - by constructing a new facility. In this report it is assumed generally, that the stage of XADT can be reached by exchange of the fuel. These two phases will be followed by the construction of a prototype ADT which will be of industrial scale and have all the properties of the facility to be deployed later on.

2.4. From R&D to Demonstration

The development and qualification of the main components.

Accelerator: requires early demonstration, taking into account the very non-linear nature of critical problems related to reliability, space charge, stability, etc. Starting from IPHI and TRASCO programmes, a (potentially polyvalent) accelerator of about 10 mA (or more if a multipurpose facility has to be supplied by this high intensity accelerator) can be built and started about 2010 (see section 4.3.2).

Spallation module: a first prototype of 1 MW will be tested in PSI/SINQ in 2004 (the MEGAPIE project, see section 4.4.1). A 5 MW target would be required for the XADS and could be coupled to the accelerator around 2010 for tests, tuning and neutron supply to first experiments with spallation neutrons. A 12 to 40 MW spallation target must be developed till 2030.

Sub-critical reactor: the principles of sub-critical operation are currently being checked on MASURCA (MUSE program, see section 4.5.1) with a liquid metal coolant representative core. Further stages of the program will be realised with configurations representative of a gas-cooled core. A global, small scale experiment (like the one presently explored at TRIGA reactor in Italy) could also represent a relevant step towards the XADS. A larger scale experiment is the MYRRHA project (approximately 20 MW_{th}: see section 4.5.2). A choice of the reference coolant – fuel option should be made around 2003, followed by a preliminary design. European Framework Programme activities foresee a co-operation in this area.

A detailed design would be available around 2007 – 2010. An XADS could be built starting in 2008 and, after a phase of tuning, low beam power, low fission power experiments, could start full power operation about 2013. Efficient irradiation of samples and fuel subassemblies could be carried out after that date.

Fuel: large amounts of TRUs, and specifically MAs, in fuel form using advanced technology, will not be available until 2020 – 2025. The main reasons for this are:

- the need to design and qualify advanced fuels, well suited to the chosen coolant;
- the need to fulfil the additional requirements due to a TRU composition with large amounts of MA (see section 3.4);
- the need to install pilot plants for this advanced “hot” fuel fabrication and reprocessing.

From now until 2025, only “driver” plutonium fuels for an XADS are needed (and available). Moreover, before 2015 – 2020, it is probably too optimistic, even in the case of plutonium dominated fuel, to consider the availability of a completely new fuel technology. Thus the XADS, which is to operate well in advance, will have to start its operation with conventional fuel elements. This fact leads to the critical issue of the “convertibility” of the XADS core to new, incremental or revolutionary fuels. If the convertibility is attainable, the XADS will be transformed into an XADT (eXperimental Accelerator Driven Transmuter) with a limited effort in terms of delay and cost. If a new facility has to be built to burn the new generation fuel, delay and cost will be significantly increased.

Fuel Cycle (separation and fabrication). Finally, in order to “demonstrate” a double component or double strata ADS utilisation, the operation feedback of processing and fabrication facilities (at the pilot plant scale) is required. These facilities will be used later for a prototype ADS plant (see section 3.5).

2.5. Time Schedule and Milestones for XADS and XADT

The time schedule and milestones for this “step by step” approach for ADS technology development is given in table 2.3. 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 2008;
- 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 and prototype with fuel and targets;
- obtain feedback for further development of industrial scale facilities.

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

Phase 1 which uses available fuel technology and is devoted to the demonstration of the ADS concept and possibly for irradiation purposes in particular fuels dedicated to transmutation (XADS);

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, a full demonstration of accelerator driven transmutation should occur. This requires successful development of the fuel and the fuel cycle facilities till about 2020!

Table 2.3. Time schedule and milestones for the development of ADS technology in Europe

Year 2000+	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	25	30	40	50
Phase-1 XADS/XADT																								
Basic R&D	■	■	■	■	■	■	■	■	■	■	■	■												
Choices of Options	■	■	■	■																				
Preliminary design			■	■																				
Design + Licensing					■	■	■	■	■															
Construction								■	■	■	■	■												
Low power testing													■	■										
Full power testing														■										
XADS Operation															■	■	■	■	■	■				
XADT Conversion																	■	■	■					
XADT Operation																				■	■	■	■	
Phase-2 Prototype ADT																								
Basic R&D	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
Constr., Operation																				■	■	■	■	■
Phase-3																								
Industr. Application																								■

Milestones
2005: Start of detailed design of XADS
2008: Start of construction of XADS
2015: Operation of XADS
2017: Decision on how to go to XADT
2025: Operation of XADT
2030: Operation of PROTO-ADT
2045-2050: Industrial Application

Key requirements for the XADS:

- The XADS will have the double role of an irradiation tool and an ADS technology demonstrator (e.g. coupling of the components). The key requirements as for irradiation are a fast neutron spectrum and a high fast flux level (goal: neutron flux $\geq 1 \times 10^{15}$ n/cm².sec).
- *Irradiation volume*: in order to perform the irradiation of fuel subassemblies, a minimal irradiation flux is required. Moreover, the capability for testing reference and alternative core technologies (fuel and coolant) means that test loops should be integrated into the design. The annular geometry of the ADS core and the minimal power density related to a minimal flux level, leading for approximately 100 MW_{th} core to a few hundred litres core, require an optimised design. Moreover, in order to avoid a high flux gradient across the core, operation at a limited sub-criticality level is required.
- *Availability*: a yardstick as for accelerated irradiation capability is the number of dpa per year of operation. A high fast flux and a high availability are thus required. An XADS is not probably as efficient, from this viewpoint, as a critical fast flux experimental reactor could be. In order to limit the associated drawback for accelerated irradiation, the design of the XADS and its operation and maintenance procedures have to be optimised in this respect.

The above mentioned requirements lead to specifications about fuel, coolant, unit power (see below). Finally, transmutation samples can be burned in the XADS, during the first phase of the demonstration. Transmutation cores, available about 2025, will be demonstrated later.

The power of the XADS has to be fixed in the 60-100 MW range (see section 3.6), depending on the:

- choice of the fuel – coolant technology (which influences the concentration of fissile material in the core and its scattering characteristics);
- compactness of the spallation module which influences the leakage;
- quality of the plutonium available for the “driver” fuel.

A minimal “quasi-critical” mass of fissile nuclei is needed. A minimal unit power is thus required for a fixed objective of fast flux level (assuming a fast neutron spectrum).

In summary, the choice of the fast flux level depends on the very objective for the XADS as an irradiation tool as well as on the ASAP fuel – coolant technology adopted, which defines the thermal – hydraulic limit of power density. The overall issue is thus a classical problem of optimisation under constraints, several constraints depending on external options or opportunities. A mean total flux level of about 1×10^{15} n/cm^2.s and a peak flux of about 2.5 to 3×10^{15} n/cm^2.s with a limited flux gradient giving access to a reasonable irradiation volume, should be attainable. These numbers have to be confirmed after a detailed safety design study. They are relevant for an objective of fuel qualification and transmutation demonstration and, probably, for “representative” irradiation of advanced fuels for future nuclear systems.

2.6. From Demonstration to Prototype and Beyond

This tentative schedule is illustrated in table 2.3 by the “skeleton” of the last phases:

- Prototype-ADT phase.
- Industrial application phase.

After successful operation of XADT it can be imagined, that the construction of a prototype ADT, which basically would have the technology used in XADT but would be larger in size, could be started early in 2030. After a successful construction and operation of this prototype large scale industrial deployment of ADS could be started late in 2040.

These phases cannot be forecast with precision, even if each step is related to specific requirements. If several favourable conditions are fulfilled, and if the nuclear R&D effort is well supported, the schedule could be shorter by a decade, in the most optimistic case. It has to be reminded that technological “barriers” have still to be lifted in several independent areas, from accelerator technology (with very high reliability) to advanced processing and fabrication plants for “hot” TRU fuels, including the topics concerning the technology and safety – design optimisation of advanced fission plants.

Finally, in an extended double strata scheme, the considered schedule does not hamper the integration of ADS in the nuclear parks of the future. This is because the fraction of power dedicated to these burners is limited and can be programmed and built without jeopardising the optimisation of the whole electro-nuclear plant implementation.

3. XADS AND XADT ROADMAP

3.1. Key Issues, Main Technical and Safety Options

In order to set up a credible path towards the realisation of the XADS, and eventually the XADT, the individual plant components together with the key R&D issues need to be identified. In addition, the costs involved at each stage require estimation. ADS technology shows several specific innovative features which need to be developed in detail and assessed to confirm efficient and safe performance. As discussed in more detail in the following sections, the key issues and main technical and safety options to be investigated are related to the following ADS main components:

- Accelerator (section 3.2);
- Spallation module (section 3.3);
- Fuel and fuel cycle (section 3.4 and 3.5);
- Sub-critical system (section 3.6).

In addition, the interfaces and coupling of these components need to be analysed. Current trends in nuclear engineering emphasise simplicity in the system configuration and the use of proven technology. Multiple physical barriers are used between the radioactive products and the environment and the integrity of these barriers must be protected to the maximum possible extent by means on inherent engineered design features.

3.1.1. Accelerator

As described in more detail in section 3.2 the most relevant issues related to an ADS-class accelerator development and operational deployment are:

Performance. While an energy of the order of several hundred MeV (600-1000 MeV) is well within the state of the art, an intensity ranging from several mA to 10-15 mA requires a significant increase of the presently available capabilities. In principle both linacs and cyclotrons can fulfil these demanding requirements; only linacs, however, can be eventually upgraded to an industrial machine for which currents of the order of 25-40 mA are presently envisaged.

Reliability and availability. The reliability requirements are essentially related to the number of allowable beam trips which can heavily load the reactor structures, the spallation target, or the fuel of the sub-critical core and, also, decrease the ADS plant availability. Trips in the millisecond timescale do not imply damage for fuel, target and reactor structures. Longer beam interruptions (> 1 s) can on the contrary cause transients affecting the structural behaviour of the reactor components. The allowable number of these longer duration beam interruptions depends on the technology of the components (e.g. spallation module, core structures and materials, primary coolant).

Operation and safety. The ADS plant is optimised to operate at nominal power. But, it has also to be capable to operate at partial load (from around 20% to 100% of the nominal power) without significant penalties. Moreover, during the plant commissioning and after a refuelling shutdown state, operation at very low power (< 3%) may be requested.

Three basic safety functions concern the accelerator:

i) the control of the power and the monitoring of the reactivity of the core - this requires a reliable, safety related beam shutdown system to be implemented;

ii) the containment of radioactive materials, in particular of the radioactive products in the spallation target;

iii) the radiological protection of the operators in normal operating conditions (beam losses and X-rays resulting from electron motions and collisions in RF cavities).

3.1.2. Spallation Module

The spallation module or target unit is one of the most innovative components of the ADS as it constitutes the physical and functional interface between the accelerator and the sub-critical reactor. It is simultaneously subject to severe thermal-mechanical loads and damage due to high-energy heavy particles. The spallation module design should be based on a balanced optimisation between neutronic efficiency, material properties (physical, chemical) and thermal-hydraulic performances under the conditions imposed by safety and reliability, including life-time.

Different target concepts are presently under investigation: a) a configuration with window and b) a windowless configuration, both with a liquid lead-bismuth eutectic (LBE) target. In principle, also solid targets can be considered (e.g. W). Each concept has its own specific issues and, as described in section 3.3, the most relevant of these related to the ADS-class spallation module development are:

Target materials. An important issue common to both conceptual designs is the assessment of the behaviour of the module structural materials in contact with the liquid eutectic. The concerns relate to corrosion and erosion, in particular, at high temperature and flow velocity.

Lifetime. The spallation module should, in principle, have a lifetime comparable with the fuel elements (e.g. 2-3 years, not a strong requirement for XADS) while, in the case of the windowed target, the beam window will probably have an expected life of not longer than six months.

Spallation product confinement. A significant number of highly radioactive isotopes will be produced by the proton and neutron interactions with the LBE. A safe confinement of these isotopes needs to be assured to avoid releases to the reactor building and possibly to the environment.

3.1.3. Fuel and Fuel Cycle

In a first phase of operation, the XADS will use conventional fuel, e.g. fuel of SNR-300 or Superphénix (SPX) reactors. In a second phase advanced fuel pins or elements, characterised by a high content of plutonium and minor actinides, will be introduced into the core of the XADS for irradiation tests. Finally, the new fuels will be introduced into the XADT core for transmutation capability demonstration.

As discussed in more detail in sections 3.4 and 3.5, the most relevant issues are the following:

Conventional fuel options. For the conventional fuel to be utilised in the XADS (phase 1), two possibilities exist: i) MOX fuel elements fabricated for SNR-300 and SPX. In that case, however, the core design has to be adapted to the fuel element design. ii) The fabrication of new MOX fuel elements. This has the advantage that the design can be adapted to the core design of the XADS.

Advanced fuel options. The choice for the advanced fuel (for the second phase of XADS and XADT) is not obvious at present. Oxides and nitrides are considered the most promising fuel materials, oxides (either as mixed transuranium oxide or as inert matrix oxide) being the primary candidate for the XADS. Composites (ceramic-metal or ceramic-ceramic) may be an alternative.

Fuel elements cladding and structural material compatibility with coolant. The austenitic cladding materials of the SNR-300 and SPX elements are compatible with He cooling. Compatibility with Pb-Bi coolant has to be demonstrated. For advanced fuel, an extensive programme on the determination of the properties of the proposed fuel materials and fuel form is needed.

Fabrication, irradiation and qualification. In Europe facilities for the fabrication of americium and curium fuel for R&D purposes exist at the Institute for Transuranium Elements (JRC, Karlsruhe) and in ATALANTE (CEA, Marcoule). The first irradiation tests of the advanced fuels can be performed in existing irradiation facilities. In Europe this will mainly be the PHENIX reactor and materials testing reactors.

Reprocessing capabilities. Two types of processes can be applied to the separation of long-lived radionuclides: hydrochemical (“wet”) and pyrochemical (“dry”) processes. The hydrochemical reprocessing techniques should be modified/extended for the extraction of minor actinides. Pyrochemical processes offer more possibilities to reprocess advanced fuels but extensive development programmes are needed.

3.1.4. Sub-critical System

As described in more detail in section 3.6, the sub-critical system is the part of the plant where the demonstration of the transmutation capabilities of the ADS occurs. Some options of the XADS sub-critical system have in principle already been agreed:

- power level of the order of 100 MW thermal;
- fast neutron flux (with a flux level10^{15} n/cm^{2}s);
- spallation medium separated from primary coolant;
- no electricity production.

Starting from the above reference choices, the study and the assessment of several other key issues will be the goal of the demonstration programme. In particular:

Coolant. In order to obtain a fast neutron spectrum, the choice of the primary coolant medium is restricted to liquid metals (Pb, Pb-Bi, Na) or gas (He, CO_2). Liquid metals are eligible candidates thanks to their attractive thermal properties and to the possibility to operate close to atmospheric pressure. On the other hand, they also exhibit adverse chemical properties such as corrosion for Pb or Pb-Bi or strong chemical reactivity with air and water for Na and may result in positive reactivity feedbacks from voiding. The use of gas as coolant favours the in-service inspection and repair, does not result in potential adverse reactivity feedbacks, and does not raise issues of chemical compatibility with structural materials. However the use of gas coolant requires high primary system pressures (50 to 70 bars), mechanically loading the vessel, and the target assembly.

Core sub-criticality. The degree of sub-criticality directly affects, for a given XADS or XADT design, key accelerator system parameters (e.g. the proton beam current). Low sub-criticality implies low proton beam current but increased risk of approaching or attaining criticality under abnormal or accident conditions; higher sub-criticality implies higher proton beam current but reduced risk of approaching criticality. The selected level of sub-criticality must therefore be determined by a balanced approach.

Radioactivity confinement and radiological protection. In addition to commonly known radioactive isotopes characterising the contamination of the nuclear power plant systems, some new contaminants have to be considered. In particular spallation products generated through the collision of the high-energy proton beam against the target material.

Safety Approach and Path to the Licensing. The XADS and XADT design development should follow the general objectives in nuclear safety, i.e. the protection of individuals, population, and the environment. This is to be achieved by establishing and maintaining an effective defence against radiological hazards consistent with current licensing approaches for new nuclear plants.

3.1.5. Tentative Schedule Towards XADS

Making reference to table 2.3 - Time schedule and milestones for the development of ADS technology in Europe - and taking into account the above key issues, the steps toward the XADS operations are:

i) ADS class accelerator (I > 5 mA, E = 600-1000 MeV) R&D, design and construction;

ii) 5 MW class spallation module design and construction;

iii) accelerator and 5 MW class spallation module coupling and operation;

iv) XADS detailed design, including licensing process, and construction.

The first two steps are somehow independent and will stem from parallel activities on accelerator and spallation module design. In the third step both the accelerator complex and a prototypical spallation unit must be assembled and coupled together for the demonstration of their correct and safe operation on the way to the XADS. The design and the realisation of the sub-critical system can proceed in series/parallel with the three above steps. All steps are envisaged to be performed at the site which will host the XADS shown in figure 3.1.

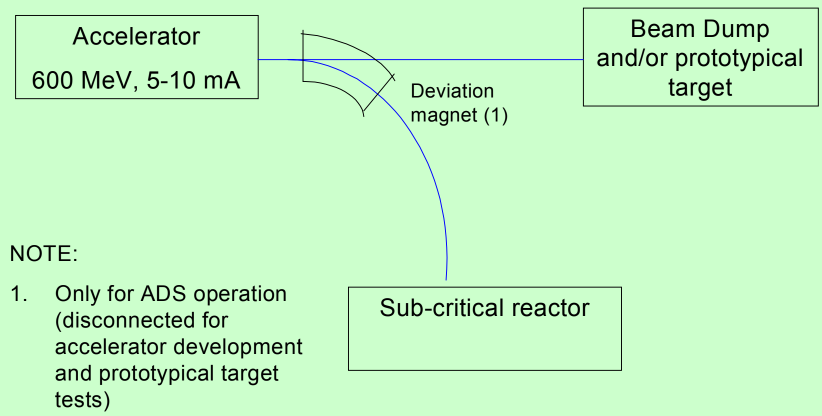


Figure 3.1 XADS schematic layout

Table 3.1 Envisaged time schedule for the realisation, commissioning and operations of the key component of the XADS

Year 2000 +	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
ACCELERATOR															
- R&D	■	■	■	■											
- Design			■	■	■	■									
- Construction						■	■	■	■						
XADS Site and Infrastructures Preparation					■ (1)	■	■								
SPALLATION MODULE															
Prototypical Target - connection to accelerator						■	■	■	■						
Operation of accelerator & target combined										■ (2)	■	■			
SUBCRITICAL SYSTEM															
- Choice of Options (coolant and fuel)		■ (3)	■	■											
- Detailed Design and Licensing					■	■	■	■	■						
- Construction								■	■	■	■	■			
- Commissioning and operations													■	■	■

(1) Nuclear island foundations and infrastructures for accelerator complex
(2) Refer to figure 3.1 for plant configuration
(3) PDS-XADS activities within 5th FWP

The design steps leading to the construction of the whole XADS facility are consistent with the phases leading to the realisation of the main components in which the plant is functionally and physically divided (i.e. accelerator, spallation module and sub-critical reactor). Making reference to the time schedule of the table 3.1 the relevant activities and milestones can be summarised as follows:

- year 2004 selection of main XADS options (e.g. coolant medium, fuel and primary system configuration);
- years 2003-2009 accelerator design and construction;
- year 2006 selection of spallation module configuration;
- years 2006-2009 prototypical spallation module design and construction;
- years 2010-2012 accelerator and prototypical target coupling and commissioning operations;
- years 2005-2009 sub-critical reactor design and licensing;
- years 2006-2012 MOX fuel fabrication;
- years 2008-2012 sub-critical reactor construction;
- year 2013 sub-critical reactor and accelerator coupling and commissioning operations.

The choice of the main technical options, including accelerator technology (linac vs. cyclotron) and sub-critical system (gas cooled or LBE cooled reactor) are assumed to be made within the frame of the 5th FWP or early at the beginning of the 6th FWP. For the spallation module, the choice between the window and the windowless concept is assumed to be deferred to the conclusion of the planned experimental campaigns of MEGAPIE and MYRRHA.

A preliminary overnight vendor cost evaluation, subject to confirmation when a complete and consistent XADS configuration will be available, leads to the following figures:

- Linac accelerator and sub-critical system engineering design: 150 M€
- Linac accelerator and sub-critical system components: 250 M€
- Civil works and infrastructures (nuclear island and balance of plant): 80 M€
- Site engineering for erection and commissioning: 70 M€
- Indirect costs: 50 M€

The above estimate has to be increased of the fuel cost. Owners' costs, including operations, are not included.

3.2. Accelerator Roadmap

3.2.1. Performance of the XADS Accelerator

The main characteristics of the proton beam, i.e. the energy and intensity, are mostly influenced by two physical quantities: i) the neutron yield rate per proton and per unit of energy in the target and ii) the fraction of beam energy deposited in the entrance window of the target. The first quantity reaches its optimum value for protons of energy equal to or higher than 1 GeV. The second quantity, for proton energies of interest (< few GeV), is a rapidly decreasing function of the beam energy.

For a given number of spallation neutrons (as required by the characteristics of the chosen sub-critical core), higher energies imply smaller intensities and therefore a reduction of both the technical challenge and the mechanical/thermal stresses on the target window. Thus, aside from technical, cost and construction time considerations, the physics of spallation and of energy deposition favours the choice of an energy of the order of 1 GeV or more.

While an energy of the order of several hundred MeV (600-1000 MeV) is well within the state of the art, a related intensity ranging from several mA to 10-15 mA requires a significant increase of presently available capabilities. In principle both linacs and cyclotrons can fulfil these demanding requirements; only linacs, however, can eventually be upgraded to an industrial machine for which currents of the order of 25-40 mA are presently envisaged.

However, as the mission of the XADS plant is a global demonstration of the operation and safety and not the industrial operation for waste transmutation, cost considerations could favour the choice of a lower energy. In any case, a lower limit of about 600 MeV can be set in order to have a reasonable efficiency in neutron production and an affordable beam load on the target window.

Given the kinetic energy T_p of protons, the required beam mean current is determined by the maximum thermal power and the range of variability of the neutron multiplication factor k_0. For the power P_{max} = 100 MW and $k_{eff} = k_{max}$ = 0.98, the current needed at the energy T_p = 600 MeV is 1~2 mA. With $k_{eff} = k_{min} \approx$ 0.90 the current rises up to ~10 mA.

However, while the studies already done have shown that there are no fundamental obstacles to reach beam powers up to 100 MW or more by a 1 GeV (or several GeV) proton linac, the ADS kinetic energy and beam current are near to the limiting values for a cyclotron, put by experts at ~1 GeV and ~10 mA. A 600 MeV accelerator, if of the linac design, would be upgradeable to 1 GeV or more.

Beam currents higher than 10 mA should in principle also be considered for the XADS accelerator, in order, for instance, to demonstrate not only the basic principles of an ADS for waste transmutation but also the feasibility of industrial operation of this kind of plant and to study ageing effects of components. Moreover, in such an experimental facility, it is advisable to design the accelerator in such a way to allow a wider range of operability, particularly if it does not imply significant over-costs and has not significant impact on work schedule.

Such an approach can essentially rule out a single cyclotron operated XADS facility. A multi-cyclotron plant is conceivable although it would need the additional development and installation of appropriate "funnelling" devices in order to merge the beams prior to the spallation target.

Based on this, the ease of construction, the flexibility, the energy and power expandability favour the choice of a linac. The design current can be set at 15-20 mA, applying a factor 1.5-2 over-design with respect to the maximum estimated current for XADS. The energy can be set, at least for the first experimentation phase, to 600 MeV but it will be highly advisable to design the accelerator and related infrastructures in order to allow an easy future upgrade to 1 GeV.

The time structure of the proton beam is still under discussion inside the scientific community in the field of ADS. In principle, to avoid thermal stresses on the beam window, target and sub-critical assembly, a continuous wave beam (CW linac) would be the best solution. However a pulsed operation of the accelerator is feasible, since the time scales of thermal inertia of the different components of the target and the reactor are much longer than that of the beam period. Pulsed mode would prove more flexible for beam power adjustments and would enhance the compatibility of the XADS plant with other applications.

3.2.2. Accelerator Reference Concept

The linac scheme for a high power proton beam is based on the accepted solution which foresees super-conducting radio frequency (SCRF) elliptical accelerating structures above about 100 MeV.

The linac is divided into three major sections.

The *first section*, called injector, provides a proton beam of the wanted intensity at an energy of approximately 5 MeV. The injector is made of an ion source providing the protons and a radio-frequency quadrupole (RFQ). The special challenge for all these components is to cope with the strong space-charge effects (due to the repulsive Coulomb forces between the beam particles) which are preponderant at these low energies. The theoretical and experimental progress which has been accomplished for the beam dynamics of very intense beams during the last few years, shows that currents at the 100 mA level can now be handled.

The *second section* accelerates the low energy beam up to the value of ~100 MeV - thereafter, elliptical SCRF cavities can be used. This part can be conceived basically in two alternative ways. One is a room-temperature drift tube linac (DTL), a conventional and well-understood accelerating structure basically of high transmission, but of somewhat low efficiency if the high energy gain and low operating costs are of importance. For achieving high transmission, the quality of the design and the precision of the manufacturing of the focusing elements are of prime importance. Alternatively, the new and challenging possibility of an independently phased super-conducting cavity linac (ISCL) can be considered. Studies of this solution are going on, including fabrication and test of prototypes. Once eventually qualified through the development of the required SC cavities, this solution should have the advantage of a high flexibility.

The *final section*, which brings protons from about 100 MeV up to the maximum energy, is a super-conducting linac, derived from the experience gained at CERN, TJLab and DESY and their collaborating laboratories, where high performances super-conducting electron linacs are in reliable operation. Indeed, because of several advantages compared to the classical approach using copper cavities at room temperature, the SCRF cavity solution has been retained, worldwide, by other HPPA projects now under construction, such as SNS or the KEK-JAERI joint-project. The high efficiency of SCRF cavities and their high electrical gradient result in very favourable economical consequences. Moreover, at the envisaged frequencies, the SCRF cavities have quite large opening for the beam which reduces drastically the activation due to lost particles from the beam halo. In fact, extremely low losses have been predicted even for very large intensities. This feature is very important because it will allow hands-on maintenance, and, consequently, minimise the downtime due to servicing. A second valuable aspect from the operational standpoint is the great flexibility that is associated with SCRF cavities. This will help for an easy change of the beam power level and may even provide fault-tolerance up to a certain degree.

3.2.3. Reliability and Availability

The reliability requirements are essentially related to the number of allowable beam trips. Frequently repeated beam trips can significantly damage the reactor structures, the spallation target or the fuel of the sub-critical core and, also, decrease the ADS plant availability. Some beam trips have duration sufficiently large that they would lead to a variation in the plant parameters (thermal power, primary flow, pressure, temperature) or to a plant shutdown. Accelerators are known for sudden interruptions, the duration of which ranging from a few milliseconds to a failure requesting a repair before restart. During such a transient, the power output of the reactor fuel drops to a few percent. If the transient duration is small, the energy stored in the fuel will allow a restart without noticeable change of the fuel temperature. Those transients are insignificant. If the transient lasts a few seconds, the fuel temperature will begin to drop and the restart will have to be performed at a given rate. The fuel behaviour under this kind of transient will have to be examined in detail, to determine the allowable transient duration and the allowable power increase rates after transient.

On the basis of current results, the order of magnitude of the allowable duration of the beam trips is 1 second. Regarding the damage on the reactor structures, the spallation target and the fuel, the allowable number of long beam interruptions (> 1 s) depends on the technology of these equipments (window concept, materials, primary coolant). Nevertheless, in any case this number can be quite large. The order of magnitude is hundred's per year, depending on ADS type and design, assuming the plant is designed for a life-time of 40-60 years.

From the point of view of availability (and cost), in the perspective on an industrial application, the tolerable number of long-term beam interruptions is much lower. The number of unexpected shutdown for the present nuclear plants dedicated to the electricity production is a few per year (1 or 2). For an ADS burner which target is not electricity production, a higher value, about ten times higher, might be accepted. Hence the availability of the accelerator of the industrial ADS burner, expressed in term of allowable number of long-term beam losses, should be less than about 10 per year.

In existing accelerators, beam trips normally exceed by far the above numbers. This means that operating an accelerator at a high beam power and requiring, at same time, relatively few beam trips of short duration and a negligible amount of time lost for longer beam interruptions, poses new challenges in accelerator field. There is considerable potential for improving accelerators from the point of view of reliability and availability.

Short and medium length beam trips are usually caused by sparking of high voltage components and quenches in the SCRF cavities. In principle, modern controls, based on fast electronics, allow to move these trips to the millisecond scale, i. e. in a duration range where no damage is foreseen for fuel, target and reactor structures. It is well known that an even moderate over-design would lead to a greatly improved performance for such components.

Longer beam interruptions are due not only to sparking high voltage components and quenches but also to the failure of other accelerator components such as magnets, power supplies, vacuum and cooling systems, controls. A certain amount of over-design would increase the stability and the life-time of critical components; on the other side, the availability of ready-to-operate back-up units together with a fast interchangeability of accelerator components would greatly reduce downtime.

3.2.4. Operation and Safety

The ADS plant is optimised for operating at nominal power. But, it has also to be capable to operate for long periods at partial load (from around 20% to 100% of the nominal power) without significant penalties. Moreover, during the plant commissioning and after a refuelling shutdown state, operations at very low power (< 3%) may be requested.

Therefore, the accelerator has to be capable to produce also a stable and reliable low intensity proton beam, which is also needed for the starting process. This can be achieved by varying the current at the injector in a CW accelerator while, for a pulsed mode of operation, it can be achieved also by adjusting the pulse width or the repetition rate. An automatic regulation system will assure the beam stability for operation with stable thermal power.

The accelerator operation, similar to a reactor, is governed by the following three basic safety functions.

The first concerns the control of the power and the monitoring of the reactivity of the core even if, for a given source-target configuration, the proton beam has little or no direct influence on core reactivity, which is an intrinsic property of the nuclear system. In the event of unpredicted transients a reliable, safety related beam shutdown system has to be implemented in order to decrease reactor power level to the decay heat value. This system has to shut down the beam if an abnormal variation of the core parameters (neutron flux, primary flow, temperature, etc.) is detected, and to avoid the restarting of the proton beam after a spurious loss if the core parameters are not in an acceptable value. The accelerator control system has to be designed in order to exclude any large and fast beam power increase which could damage the sub-critical core, the spallation target or the window.

The second safety function addresses the containment of radioactive materials. The main safety concern due to the implementation of the accelerator is the containment of the radioactive products in the spallation target. This safety function is achieved by several barriers implemented between the radioactive materials and the environment. The beam window(s), the portion of the vacuum pipe of the accelerator itself from the window(s) to the isolation valves of the reactor building, and the building housing the reactor will provide three successive barriers.

The third safety function is the radiological protection of the operators in normal operating conditions. The main accelerator concerns result essentially from beam losses (and consequent induced activities) and X-rays resulting from electron motions and collisions in RF cavities. The proton losses have to be very low. For example, for a linear accelerator, the possibility of hands-on maintenance operations requires a linear proton loss lower than 50 pA per meter, for a 1 GeV proton beam. This represents, for a 10 mA proton beam, a loss rate of 5×10^{-9} per meter. Such a loss can be achieved by a careful design of the beam optics.

3.2.5. Step to Industrial Scale

The main technical constraints requested for the accelerator have to be consistent with the requirements for the system as a whole and are related to the economy, the operability and the safety..

Concerning the economical and the operating constraints, the accelerator has to be considered as a part of the whole ADS plant and the optimisation has to be found in a global way.

Even if the goal of an industrial nuclear waste burner is not to produce electrical power, the industrial plant should produce electrical power as economically as possible. From the cost investment viewpoint, an optimisation has to be found between the size of the reactor and the size of the accelerator. From the point of view of reactor operation, a preliminary assessment for the power of the sub-critical core is in the range of 500 to 1500 MW_{th}. An additional impact on the cost investment concerns the expected life duration of the plant. For the future nuclear plants, 40-60 years is expected. The life duration of the accelerator should be similar, including the maintenance capabilities.

Concerning the operating costs, compared to a critical plant, the ADS has an operating over-cost due to the spallation neutron generation. In order to minimise this over-cost, the proton beam energy should be optimised regarding the number of generated neutrons per proton and the accelerator efficiency. As already said, the optimised value of the energy is about 1 GeV. Regarding the accelerator efficiency a careful balance between over-design, as possibly required by reliability considerations, and cost minimisation must be aimed for.

For a power in the range of 500 to 1500 MW_{th}, assuming a minimum value of k_{eff} of the order of 0.95, the requested beam current of a 1 GeV accelerator is in the range from 12 mA to 40 mA, well within the reach of a linear accelerator.

In normal operating conditions, the requirements concerning the accelerator operability are related to the accelerator reliability and availability, the partial load conditions and the interaction with the reactor operations. The XADS experimental phase will be essential for assessing these vital functions eventually affecting ADT operation.

3.2.6. Milestones, Estimated Schedule, and Cost

The investment cost of a 15-20 mA, 600 MeV linac, adapted to the XADS needs, is estimated to be around 200 M€. Its development (R&D and construction) requires around nine years. An extension to 1GeV would require an additional investment cost of about 100 M€. Cost estimate of the cyclotron option (multi-cyclotron) is given in annex 4.

At present, there are a number of design studies and prototype constructions that are going on at a national level. Further, certain successful collaboration already exist within Europe. These constitute the basis for the initial phase of the accelerator roadmap.

An important initiative has been started by the TWG within the 5th Framework Programme (FWP). An XADS conceptual design proposal jointly presented by European industries and research agencies has been submitted to the Commission. It contains the accelerator as one of the major working packages. It is the first step to the construction of an XADS which should be envisaged as a joint European effort.

It is planned that the general conceptual layout, in particular including the choice of the accelerator can be performed within the 5th FWP so that the necessary R&D is identified and can be accomplished during the 6th FWP. A typical example for this R&D and its financing needs are fully equipped SCRF cavities, which would need about 20 M€ over a 4 years period. Simultaneously the engineering design can advance during this period so that the construction can start at the end of the 6th FWP and completed during the 7th FWP. Table 3.2 summarises this roadmap.

Table 3.2 Accelerator development time schedule

Year 2000 +	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
ACCELERATOR															
General Conceptual Design	■	■													
R&D	■	■	■	■											
Technical Design			■	■	■	■									
Site and Infrastructures preparation					■	■									
Construction						■	■	■	■						
Commissioning & coupling with prototypical target										■	■	■			
Full ADS Operation													■	■	■

3.3. Spallation Module Roadmap

3.3.1. Spallation Module Performance

The spallation module or target is perhaps the most innovative component of the ADS as it constitutes the physical interface between the accelerator and the sub-critical reactor. It is a sensitive component since it is simultaneously subject to severe thermal-mechanical loads and damage due to high-energy heavy particles (protons, spallation and fission neutrons, irradiation and spallation products). The spallation module design should be based on a balanced optimisation between neutronic efficiency, material properties (physical, chemical) and thermal-hydraulic performances under the conditions imposed by safety and reliability including life-time.

The conversion yield of an accelerated proton beam into spallation neutrons is most efficient with high-Z nuclei target material and high kinetic energies of the colliding protons. The specific neutron yield reaches an asymptotic trend (of about 32 - 34 neutrons per proton) in the energy range of 1 - 2 GeV. However, even at energies of around 0.6 GeV approximately 22 - 25 neutrons are produced per incident proton.

In order to obtain the required neutron supply of 10^{17} - 10^{18} n/s, necessary for compensating the subcritical core, beam intensities of up to tens of milliamps are required corresponding to a power of tens of megawatts. Such a high beam power is released by the proton beam through the spallation reactions with the heavy nuclei of the target material inside a rather small (an overall few litres) volume. This poses significant challenges for the cooling of the target material so that it may be expedient to rely on the use of low-melting heavy-metal mixtures such as those based on lead or lead-bismuth (for which the above-mentioned neutron yields are based on).

A molten heavy-metal based target material such as the LBE, while characterised by fairly good general compatibility with most of the engineering structural materials, requires to work out some relevant corrosion-erosion aspects which are fundamental for the thermal loading performances and life of the mechanical target components. The advantage of using a LBE target may also reside on the full compatibility with the core system when the same coolant is used in the primary loop; also, the temperature levels may be kept at comparable values in the target and core system to avoid possible mismatches, both for chemical compatibility and enthalpy rating, in case of coolant leaks between the two systems.

3.3.2. Technical Options

The design of a spallation target for an ADS goes some way along with the target design for spallation neutron sources for physics investigations. While the physicists are asking for higher and higher source strengths – towards 10 MW and above (required for ADS) - the common route is to leave the solid target technology. The next best choice is to go for a heavy liquid metal (HLM, in particular Pb-Bi eutectic) as the target material for the proton beam and use its flow for convective cooling.

The inter-linking of cooling requirements for the core with that of the target loop presents an additional difficulty in the design of such systems. In core schemes with assemblies of fuel rods, the spallation source is restricted to an on-axis hole or arrangement of holes whose diameter should be as small as possible to warrant high coupling and minimise the core volume in the interest of performance. The HLM flow main orientation is chosen mostly vertical, driven by emergency cooling requirements of the core, although other orientations have been discussed (e.g. KEK project). For a pebble bed type core a horizontal target flow in the environment of a main vertical flow cooling loop is not, a priori, excluded but is likely to constitute a major local disturbance in the pebble cooling pattern.

A second requirement is that the sub-critical core permits a channel through which the proton beam can be coupled to the target. Since the sub-critical core design cannot usually account for a second channel, e.g. perpendicular to the target flow, the majority of the designs have the main direction of coolant flow in line with the proton beam.

The target/coolant fluid of choice is either Pb or Pb-Bi eutectic with the latter having clear advantages in engineering terms because of its low solidification temperature of 123°C (against 326°C for Pb) whereas its higher levels of Po production (spallation product) have clearly to be taken into account.

The basic choice that has to be made is to either couple the proton beam through a solid window into the HLM flow (window option) or to directly let the beam impinge on the HLM (windowless option) which has to present either a curtain or gravity controlled free surface interface. In both cases, the main problem is not that the global balance for heat removal cannot be fulfilled for reasonable flow parameters, but that the creation of hot spots near flow stagnation points could either jeopardise the window or produce localized boiling which would worsen the vacuum conditions at the free surface.

Present development projects for window spallation targets at power levels of around ~1 MW power (MEGAPIE, LANL-ISTC 559) try therefore to cool the window in a cross flow, thereby avoiding the risk of stagnation points in an axis-symmetric arrangement. This option may represent a key challenge for extrapolation to larger target volumes in an even more crowded environment. The design of an adequate window to separate the forced flow of several bars from the vacuum of the proton beam line is one of the major challenges of the ADS design.

A successful design asks for an optimisation process in which to choose:

- A window of a material of high strength, ductility, fatigue resistance that can be made sufficiently thin to permit the removal of the beam deposited heat, resisting the HLM coolant pressure and possible vibrations. These properties should not lead to a degradation of more than 100 dpa/year from protons as well as neutrons.

- A proton current density of up to 50 μA/cm^2 which is believed possible for virgin materials in the energy range under consideration, and more exotic materials might enable to increase this level.

- A loop flow with a suitable flow velocity/temperature field – its design perhaps aided by proton beam profile shaping - which also generates a suitable cooling pattern for the window.

Engineering means such as techniques for joining the window rim to the pipe-work, easy replacement schemes in case the above material properties cannot be fulfilled for the full lifetime of an ADS (as is to be expected). A windowless design development, also in the ~1 MW power range (such as planned for the MYRRHA development project) can avoid the above difficulties. In this case however new difficulties are introduced:

The free surface, being the beam vacuum interface, has to fulfil the requirements that metal and spallation product evaporation and de-gassing do not unsuitably increase the vacuum pressure in the first few meters of the beam line adjacent to the sub-critical core. Indeed no effective vacuum pumping can be installed in this region of the core. A too high particle density would eventually lead to thermal loading of the beam line from secondary plasma formation with run-away character and even beam blocking. The difference to a solid interface beam line is the access to particle reservoirs potentially orders of magnitude higher than in solid interfaces. However, material considerations are here limited only to the spallation loop pipe-work which is under similar loading in the above window case.

Although the criteria for judging the flow are somewhat different for the windowless design the main rule is still the avoidance of hot spots and the difficulties of doing so are of similar nature as above. If such optimised flow conditions can be achieved, this will permit in principle to increase the window design current densities by a factor in the range of 3 to 5.

If a successful scheme can be found the replacement/maintenance problem of the critical component (namely the window) is solved. With respect to engineering problems, an additional one arises from the fact that the pressure at the free surface is zero and that therefore the suction head of the spallation loop pump is now to be referenced accordingly.

The window material as well as other material for the spallation loop are already in the catalogue of materials to be used for the sub-critical core; the 5^{th} FWP programmes SPIRE and TECLA contain already candidates also with regard to possible window use. For special parts of the loop, window or nozzles, exotic materials could and should be considered where costs are of secondary importance (e.g. ductile variants of refractory metals may have to play a special role). It is very unlikely that the results of these programmes will be sufficient to warrant the design of a reliable target from the onset and additional development is likely to be required before a target can be brought with some confidence into service in the XADS. Window lifetime assessment attempts are highly speculative with the present knowledge of material properties, under the joint influence of liquid metal corrosion and embrittlement, mechanical stressing and irradiation embrittlement.

There are at present two forerunners in Europe for a 1 MW class spallation target:

In the MEGAPIE project, carried out by a partnership of laboratories interested in ADS technology, a Pb-Bi target will be irradiated to create a pure spallation source by the SINQ proton beam of PSI at 590 MeV and 1.8 mA. The target design uses a window for which the highest irradiation dose will be of the order of 10 dpa in the 6 months of the actual experiment planned for 2004. The results of the post-irradiation examination will become available in 2005/6 (see also section 4.4.1).

In the MYRRHA project, a small ADS irradiation facility, under design at the SCK·CEN, a windowless Pb-Bi target will be irradiated to serve the ADS as a primary neutron source. The windowless design had been chosen to cope with the geometrical constraints to achieve high performance of the sub-critical core. A 350 MeV, 5 mA proton beam will generate the neutrons in the target subjected to a current density around 150 µA/cm2. Experimental activity to verify the physical and thermal-hydraulic behaviour of the windowless configuration are already being performed in water and planned in LBE. The MYRRHA facility is intended to become operational in 2008. Sound operational records and additional experience may be expected for 2010 (see also section 4.5.1)

3.3.3. Operation and Safety

In the operation of the target, the frequency and duration of beam trips caused by partial failure of one of the many accelerator components will play an important role which can only be answered by analysis of the chosen design. It might be possible to expect (see section 3.2.3) the number of trips to be lowered to a level of 1/day whereby the number to be counted depends on their duration of importance to the particular target design. One may assume a duration threshold in the several 10 millisecond domain below which the thermal inertia of the components may prevent such a trip to be adverse in terms of cycle stress and shocking, but generally all system have to be analysed in this respect, e.g. the sub-critical core.

For the operational target reliable beam position, intensity monitors and beam steering elements have to ascertain that target loadings are within high precision to design specifications. Their development and the achieved reliability will determine the specifications of passive/active safety features, in principle with redundancy, to switch off the beam and to cope with the direct consequences of the breaking of a window or loss of the position of the free surface in case of the windowless design. It is expected that multiple vacuum valves in series on the beam line, with a hierarchy of interlocks, should be capable to provide as many reliable barriers as are required by the safety philosophy. Furthermore the pumping (mainly cryo-pumping in connection with sorption pumps to be considered here) can limit the possible releases towards the accelerator to negligible levels.

3.3.4. Waste / Decommissioning

Independently of the configuration (with window or windowless) which will be chosen, the concerns about spallation module waste storage/disposal and decommissioning are mainly related to the spallation products generated by protons and neutrons impingement into the LBE and by the activation of the structural materials under the beam of protons and generated neutrons.

Since the expected lifetime of the module is in the range of few months to one year, the design of the XADS shall take into account the need to storage (e.g. in the fuel building, through casks and/or canisters, in principle in dry conditions) a certain number of modules waiting for final disposal.

Furthermore adequate provisions shall be considered to treat or storage the activated LBE contained in the removed spallation modules.

3.3.5. Milestones, Estimated Schedule

Given the relevance of the spallation module for a safe operation of the XADS and the technical concerns related to the design and performances of such an innovative component, the choice of the final configuration (with window or windowless) has to be determined through the experimental evidence already planned in the MEGAPIE and MYRRHA projects. Considering the specific test schedules and the XADS overall planning, the choice has to be made around the year 2006. It is furthermore envisaged to test a prototypical 5 MW-class target under the accelerator beam before the final installation in the sub-critical reactor. Then two main steps are planned on the XADS site:

- Prototypical target realisation and insertion on the beam line in the area provided for beam dump (see figure 3.1) for commissioning and verification of a safe and effective coupling with the accelerator.
- XADS target fabrication, based on the results of the prototypical target experimental commissioning, and assembling within the sub-critical reactor for first operations.

As a consequence of the above approach, the schedule of the spallation module has been brought in line with the intended accelerator development schedule (assumed to be ready for commissioning at the end of the year 2009) such that the tests and the operations of the prototypical target with the accelerator could start in 2010. Then a three years period will be available, before XADS starts of operations, to assess the real behaviour of the target under the beam and consequently implement experimental feedbacks into the design of the final target to be inserted into the first sub-critical core.

Given this programme, provisions have to be made with regard to the shielding and housing of this prototypical target which could serve as a pure spallation neutron source in its own. Since the pure target costs are likely to be negligible in comparison to this experimental target facility building, the "hot" target at the end of that period could stay there for further development work and eventually for final disposal (see section 3.3.4).

Table 3.3: Spallation module: time schedule and milestones

Year 2000 +	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
R&D (MEGAPIE and MYRRHA)	■	■	■	■	■	■									
Selection of the technical design (window vs. windowless)						▼									
Prototypical target design						■	■								
Prototypical target construction								■	■						
Prototypical target coupling with accelerator and test operation										■	■	■			
XADS target design and fabrication											■	■			
XADS commissioning and operations													■	■	■

3.4. Fuel Roadmap

3.4.1. Specifications for XADS

The fuel cycle for the XADS is complex and should be divided into several phases. In a first phase the XADS will be operated with a conventional fuel, most suitably a mixed oxide of the type of SNR-300 or SPX, which eventually can be reprocessed with hydro-chemical techniques. Conventional fuels allow to test most of the ADS characteristics, in particular those related with the coupling of the spallation target and the sub-critical assembly and the operability of the whole ADS. In a second phase advanced fuel pins or elements will be introduced into the core of the XADS for irradiation test. These advanced fuels, characterised by a high content of Pu and minor actinides (MA), are preferably uranium-free and will be irradiated to relatively high burn up to achieve a high extent of transmutation. The fuel material (metal, oxide, nitride, etc.) and the fuel form (pellet, particle) will be subject to extensive research and must take into account reactor coolant medium (gas or liquid metal) and, in case of a recycle strategy, the possibility of reprocessing.

3.4.2. Conventional Fuel Options

For the conventional fuel of XADS (phase 1), two possibilities exist:

MOX fuel elements fabricated for SNR-300 and SPX can be used for the XADS. In that case, however, the core design and related vessel internals structures have to be adapted to the fuel element design. This is in principle the case for the SNR-300 elements, which would need to be used as complete elements because the ^{241}Am content in the fuel is already significant. More possibilities exist for fuel elements of SPX. The elements can be re-assembled into assemblies of a new design, or, eventually, the fuel pins can be re-fabricated into new fuel pins.

The fabrication of new MOX fuel elements. This has the advantage that the design can be adapted to the core design of the XADS. There it seems not to be technical problem for the fabrication of new MOX fuel elements. It can be done in existing industrial facilities although their future availability cannot be guaranteed.

For the design and modelling of the oxide fuel of phase 1, research is needed on the interaction between cladding and coolant (in case of Pb-Bi coolant), the effect of americium on the fuel behaviour, and further analysis of the thermo-hydraulics.

3.4.3. Advanced Fuel Options

The choice for the advanced fuel is not obvious at present. Oxides and nitrides are considered the most promising fuel materials, oxides (either as mixed transuranium oxide or as inert matrix oxide) being the primary candidate for the XADS. Oxide phases have the advantage of high chemical stability and thus relative simple handling and fabrication, which is very important for MA containing materials. However, the relatively low thermal conductivity of oxide materials will lead to a high operating temperature. Composites (ceramic-metal or ceramic-ceramic) may help to improve this. Nitride fuel, on the other hand, has much better thermal properties and, hence, a low(er) operating temperature but is more difficult to fabricate. However, the relatively low chemical stability of the transuranium nitrides may lead to severe safety problems during power/temperature excursions (nitrogen pressure build-up, actinide metal vaporisation/redistribution).

A general problem for fuel with high MA content is the helium that is produced in the transmutation scheme (see figure 3.2). To deal with this, the standard pellet form may need modification or other fuel forms, e.g. particles, may be considered.

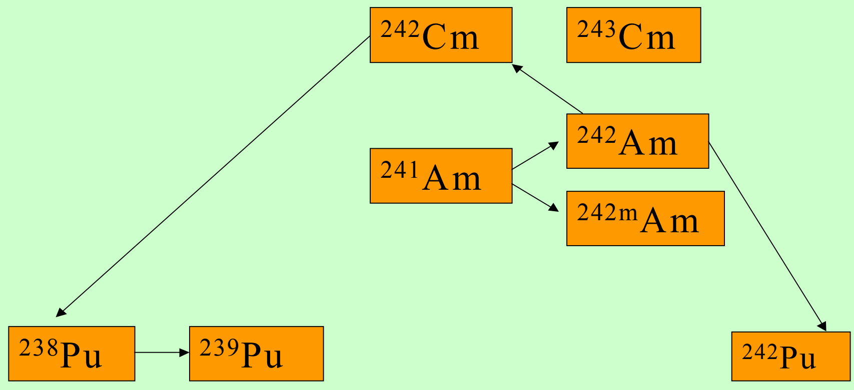


Figure 3.2: Transmutation of ^{241}Am gives rise to ^{242}Cm. This in turn decays by alpha emission to ^{238}Pu with the associated production of helium (from the alpha particles).

The primary or reference option for the advanced fuels for the XADS is based on the $(Pu,MA,Zr)O_2$ material: a homogeneous phase or a composite with steel (CERMET) or MgO (CERCER). An optimisation of this fuel type needs to be performed in the coming 5-10 years in a European research and development programme, during which a selection of the fuel form (standard pellets, modified pellet, or particle) will be made. The back-up options for the advanced fuels for the XADS are $(Pu,MA,Th)O_2$ and (Pu,MA,Zr)N.

For advanced fuel, an extensive programme on the determination of the properties of the proposed fuel materials and fuel forms is needed to facilitate the design. Safety analysis of these fuels should be included in the XADS design phase.

3.4.4. Cladding Material Compatibility with Coolant

The austenitic cladding materials of the SNR-300 and SPX elements are compatible with He cooling. Austenitic cladding can also be used in case of Pb-Bi coolant but the oxygen content of the liquid metal needs to be controlled at a low level. Scoping thermo-hydraulic calculations have shown that for the SNR-300 fuel elements a set of acceptable operational parameters (system pressure, linear heat rating, and temperature increase along the fuel pin) can be found.

3.4.5. Fabrication

In Europe facilities for the fabrication of Americium and Curium fuel for R&D purposes exist at the Institute for Transuranium Elements (JRC, Karlsruhe) and in ATALANTE (CEA, Marcoule). In these facilities the fuel pins for characterisation and the first irradiation tests can be made. The capacity is presently limited to a few grams of Curium and tens of grams for Americium. For larger scale irradiation tests a (small) dedicated fabrication facility needs to be constructed.

3.4.6. Irradiation and Qualification

The first irradiation tests of the advanced fuels can be performed in existing irradiation facilities. In Europe this will mainly be materials testing reactors, in which spectrum tailoring can help to achieve a representative neutron spectrum. In the longer term, test in fast systems are, however, unavoidable. This could be realised outside Europe (Russia, Japan), but ideally these tests should be performed in the XADS.

3.4.7. Principles of Reprocessing Capability

Because hydro-chemical reprocessing of the proposed advanced oxide fuels is difficult, it is clear that pyro-chemical reprocessing techniques must be considered. This means that a conversion process must be developed to convert the oxide to a chloride that can be dissolved in the molten salt.

3.4.8. Convertibility from Conventional to Advanced Fuels Based Cores

An important issue which have technical and economical implications is related to the convertibility of the XADS in the XADT. In the XADS the main goal will be the demonstration of the functional and safe coupling between the accelerator and the subcritical system (through the spallation module) and a conventional MOX fuel will be adopted. The demonstration of transmutation capabilities is deferred to the XADT which will utilize MA based fuel elements. Given the high investment cost related to the realisation of the plant, there are strong incentives to maintain the same structures and main non replaceable reactor components (vessel and internal structures) in the two demonstration phases to avoid to be obliged to build a new facility. The key-stone of the transformation is the possibility to adapt the core configuration to the two fuel types without major modifications in the primary system both in terms of fuel coolability and compatibility with coolant medium. It is envisaged that the decision how to proceed from XADS to the XADT will be taken around 2017 after a minimum years of operations of the XADS. In such a perspective the design of the XADS core (and related supporting structures and systems) shall take into account from the preliminary phase this flexibility/convertibility option, adapting if possible the technical solutions to this relevant goal.

3.4.9 Milestones, Estimated Schedule and Costs

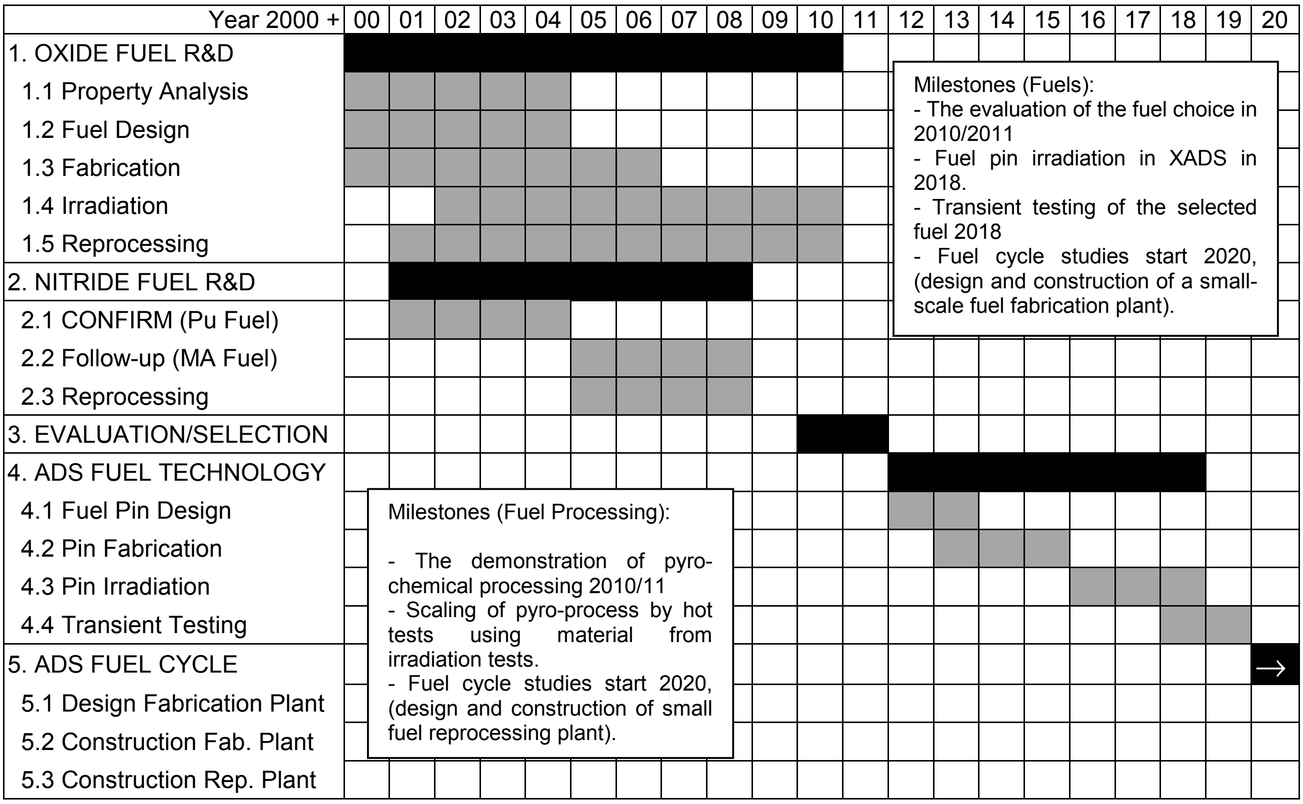
Considering the availability of SPX or SNR-300 fuel elements and the present fuel fabrication capabilities in Europe (in the case of utilization of the existing fuel pins or pellets), the conventional MOX fuel for XADS, to be chosen around 2004, is assumed to be available in time for plant operations scheduled for the year 2013.

A tentative planning for the advanced fuel development to be used in the second phase of XADS (in a limited number of core positions for fuel irradiation and qualification) and extensively in the XADT for the demonstration of the transmutation capabilities is shown in table 3.4. Important milestones in this diagram are:

- evaluation of the fuel choice in 2010/2011 after the completion of an extensive research programme on the reference fuel and the backup solutions;
- fuel pin irradiation of the selected fuel materials in XADS in 2018;
- transient testing of the selected fuel.

A rough estimate of the cost of the fuel development is 200 M€.

Table 3.4 Fuel and Fuel Processing: time schedule and milestones



3.5. Fuel Cycle Back-End Roadmap

3.5.1. Hydrochemical and Pyrochemical Processing Capabilities

Two major types of processes can be applied to the separation of long-lived radionuclides: hydrochemical (“wet”) and pyrochemical (“dry”) processes.

The PUREX process is the most important hydrochemical reprocessing technique to separate U and Pu from spent fuel and is based on the dissolution of the fuel in nitric acid. For the extraction of minor actinides, the process should be modified/extended for which extensive research is being currently performed. Neptunium could be extracted in a modified PUREX process, americium and curium in the extended PUREX process in which additional extraction steps follow the standard process. This extension must include the separation of minor actinides from the lanthanides, which are generally co-extracted due to very similar chemical properties.

An alternative to hydrochemical processes are pyrochemical processes in which refining is carried out in molten salt. In nuclear technology, they are often based on electrorefining or on distribution between non-miscible molten salt-metal phases.

The major advantages of pyrochemical techniques to reprocess advanced fuels, in comparison to hydrochemical techniques, is a higher compactness of equipment and the possibility to form an integrated system between irradiation and reprocessing facility, thus reducing considerably transport of nuclear materials. Especially for advanced oxide fuel (mixed transuranium, inert matrix or composite) and metal fuels, but also nitride or thorium based fuels, pyrochemistry is to be preferred. Nitride fuels can be processed by both methods without problems. In addition, the radiation stability of the salt in the pyrochemical process compared to the organic solvent in the hydrochemical process offers an important advantage when dealing with highly active spent MA fuel. Shorter cooling times reduce storage costs.

3.5.2. R&D Needed / R&D Planning

For the reasons stated in the previous section, pyrochemical techniques, and in particular electrorefining and reductive extraction, are the preferred technologies for the back-end of the ADS fuel cycle. The technology of pyrochemical reprocessing of (U,Pu) metal fuel is available on a semi-industrial scale for metal fuel in the USA and for $(U,Pu)O_2$ oxide fuel in Russia. However, before such technology can be applied to fuels for transmutation in ADS three important issues have to be solved through an extensive research programme:

- The feasibility of the separation of the minor actinides with sufficient efficiency and the required decontamination from lanthanides.
- The applicability of pyrochemical techniques to the reprocessing of the fuel form(s) selected for ADS, which are characterised by an a-typical composition (high content of actinides) and potentially by an a-typical form (composites with refractory metals of ceramics).
- The possibility to transform for instance oxide or nitride fuels into metal in the head-end step of the process (e.g. by electrolytic reduction), in case that electrorefining of minor actinides would be possible only in a metallic form.

A 10-year research programme is envisaged for these studies, in parallel to the fuel research (see table 3.4). After this research programme, a development programme is required in which a gradual upgrading of the scale of the process is foreseen. During this development phase, large-scale hot tests will be performed.

3.5.3. Small-Scale Reprocessing Facility

At present no facility for pyrochemical reprocessing of spent nuclear fuel is available in Europe but research facilities are or will become available at several research institutes in the coming years. In these facilities unirradiated and irradiated materials can be handled in modest quantities. An extensive R&D programme in the field of pyrochemical reprocessing is foreseen up to 2020. If this proves to be successful, the design of a small-scale reprocessing facility can be started. Such a facility should have a capacity of a few tons per year, dedicated to the demonstration of the process using the fuel of the XADS.

3.5.4. Milestones, Time Schedule, and Costs

The important milestones for the development of this innovative technique are:

- The demonstration of the feasibility of pyrochemical reprocessing in 2010/11 after the completion of an extensive research programme.
- Further development and scaling of the pyrochemical technology by hot-tests using material from irradiation tests.
- The fuel cycle studies starting in 2020, which will include the design and construction of a small-scale (prototype) pyrochemical reprocessing plant.

The cost of pyrochemical reprocessing development is estimated to be 150 M€.

3.6. Sub-critical Fission Reactor Roadmap

3.6.1. Specifications of XADS and XADT

The mission of the XADS is to demonstrate the safe and efficient operation of the ADS concept dedicated to the transmutation of long life highly radioactive wastes (specifically actinides and long lived fission products) generated within the fuel of the current nuclear power plants for electricity production. This demonstration implies the detailed design of the facility and its component and to perform the evaluation of the plant response to design transients in order to obtain the construction permit by the licensing authority, to build the plant, to obtain the start-up permission and finally to operate the complex coupling an accelerator, a spallation target and a sub-critical core.

The demonstration and the qualification of the technology of future ADS has to be performed in the XADS even if the qualification of some separate aspects, as already in progress (see chapter 4), could be (and in some cases, is already) performed in other smaller facilities.

Furthermore, given the neutron flux characteristics, the reactor of the XADS could constitute a unique capability in Europe for irradiation with a fast neutron spectrum. Therefore additionally to the transmutation, the irradiation capability could be the second main objective of the XADS.

The goal of XADT, assuming that the basic principles (mainly the coupling) of ADS will be demonstrated in the XADS, and given the availability of qualified MA based advanced fuels, will be to demonstrate the capability of an effective and efficient transmutation. No specific economical constraints will be superimposed to XADT. Such constraints will be left to the prototype plant on the way to the industrial deployment of ADS dedicated to the transmutation.

Based on the main objectives presented above, the main specifications for the XADS reactor are:

Sub-critical core power of the XADS. The objective of the demonstration of operation with a high-power accelerator, and the irradiation objective, requests a significant neutronic power of several tens of megawatts. On the contrary, in order to facilitate the licensing and in order to limit the consequences of unpredicted behaviour of advanced technological options, the power must not be too high. In line with previous experimental facilities size it is proposed for the sub-critical core a power around of 100 MW**.**

Primary system temperatures. The production of usable (and economic) energy is not a goal of the XADS, therefore, there are no specifications concerning a high temperature level in the core and the sub-critical system. The use of liquid lead-bismuth as primary coolant or spallation material needs to operate the system in normal and abnormal conditions, to avoid freezing, with a temperature level significantly higher than the melting temperature of lead-bismuth.

Core characteristics. The operation with a core totally dedicated to transmutation is not a primary objective for the sub-critical core of the XADS; for this reason in the first phase an existing conventional MOX fuel as the SPX or SNR-300 fuels will be adopted. Nevertheless, the capability for irradiation of advanced MA based fuels (to be made available in a second phase) representative of the fuel of the future ADS dedicated to the transmutation, is requested. The possibility to convert the core to a MA based fuel, with limited impact on internals configuration, is to be considered a high priority.

The XADS must allow one to test different technological options, in particular concerning the fuel and the spallation target. The design of the primary circuit must allow flexibility, in terms of geometry, operability, and material compatibility. Use of proven solutions is, however, highly recommended; this will, at least in principle, also facilitate the licensing of the XADS.

The spallation module, regardless of the configuration which will be selected, has to provide a safe interface between the accelerator and the sub-critical system. The structural materials behaviour, under the combined loads coming from irradiation and thermo-mechanical operating conditions, must guarantee a spallation module lifetime of at least several months. Also, due to the lack of knowledge of the spallation process, particularly the impact of the spallation products, it is preferred to provide a dedicated spallation-module cooling medium separated from the primary coolant.

Several provisions must be included in the design if the XADS/XADT is to be used also as an irradiation facility. In such a perspective the XADS shall provide a neutron flux in excess of 10^{15} n/cm^{2}s^{-1}, also with the capability to reach high (> 20-30) dpa.

The XADT will be dedicated to transmutation and therefore the core will be loaded with fuel containing a high fraction of minor actinides.

All attempts should be made in the XADS design phase to provide the maximum practical flexibility in order to possibly convert the plant to XADT without major modifications; this is in particular related to the core configuration and to the heat removal capabilities.

Even if not directly superimposed to the XADT design, considerations shall be given, specifically in the perspective of the prototype and industrial ADS, to the definition of the optimum economical size. This should include the cost of the plant (reactor and accelerator), the cost of the fuel cycle (taking into account for instance the strategies for fuel recycling plants, active material transportation), and the cost of the deposits for the residual wastes. The optimisation has to be performed at a European level. Preliminary considerations lead to consider that the size could be similar to that of present nuclear power plants (i.e. several hundreds of thermal megawatts). In principle no electricity production is envisaged even if some consideration could be given to this possibility to limit operational costs; in such a perspective attention should be devoted to improve the thermodynamic efficiency of the primary coolant cycle.

3.6.2. Coolant and Fuel Options

Coolant. In order to obtain a fast neutron spectrum (see section 3.6.3) the choice of the primary coolant medium is restricted to liquid metals (Pb, Pb-Bi, Na) or gas (He, CO_2). More “exotic” coolants such as molten salts, which would require extensive technological developments, are presently considered well beyond the state of the art and are then neglected for application to the XADS.

Liquid metals are eligible candidates due to their attractive thermal properties and to the possibility to operate close to atmospheric pressure. On the other hand they exhibit disadvantages (e.g. adverse chemical properties such as corrosion for Pb or Pb-Bi or strong chemical reactivity with air and water for Na) and may result in positive reactivity feedbacks from voiding. They also cause difficulties with regard to in-service inspection and repair due to the opacity of the medium.

The high liquid metals boiling point (actually very high, in excess of 1700°C for Pb or Pb-Bi) and the high thermal inertia are very favourable to defer or even prevent core cooling problems also in the case of unlikely events leading to complete loss of heat removal. Their melting points, on the other hand, pose constraints on XADS/XADT operating temperatures during shutdown and refuelling, in order to avoid primary coolant freezing. From this point of view the use of pure lead requires the plant to be operated at temperatures in the range 400°C – 600°C and would consequently increase the structural material corrosion issues. The use of the Pb-Bi eutectic would allow a significant decrease in the operating temperatures (200°C – 400°C), reducing the challenges for structural materials; however, the generation of polonium (an alpha emitter with a half-life of 138 days) with associated radioactivity confinement, is a concern. Furthermore, the limited availability of bismuth prevents the deployment of a large number of ADS based on the eutectic. Experience on lead-based coolants exists in Russia, but the application to ADS needs to be supported and validated by on-going extensive R&D campaigns (see chapter 4).

The use of gas as coolant has the advantage to facilitate the in-service inspection and repair; moreover it does not result in potential adverse reactivity feedback coefficients in the case of voiding and does not show issues of chemical compatibility with structural materials. A thermal cycle based on gas cooling, however, requires high primary system pressures (50 to 70 bars), mechanically loading the vessel and the target assembly and thus increasing the probability of failures leading to loss of coolant. In this case, decay heat removal is anticipated to be more troublesome (and possibly not adequate) in natural circulation with consequent need of mitigating active systems which would increase plant complexity and related costs.

Fuel and Core. The first core design of the XADS will be based on exploitation, to the maximum possible extent, of already existing highly enriched MOX fuel (ranging from 18% to 35% Pu enrichment) of present liquid metal fast breeder reactors (LMFBR). As anticipated in section 3.4, consideration will therefore be given to the exploitation of SPX or SNR-300 fuel pellets, pins and sub-assemblies (possibly with modified pin pitch, active length, number of pins per sub-assembly, cladding material, etc.).

Considering the availability of fuel reprocessing and manufacturing capabilities presently existing in Europe, and the very expensive fabrication costs, the use of the already manufactured SPX and SNR-300 fuel sub-assemblies without re-assembly or refabrication should also be investigated. However, it is to be expected that the size and the composition of the assemblies will not be ideally suited to the XADS.

The fuel sub-assemblies will be arranged in an annular layout made of several rounds surrounding the central spallation target unit. The requirements for dummy assemblies (empty duct structures or assemblies filled with inert (steel) fuel pins) or core positions reserved for test assemblies shall be taken into account in the core design. The capability to burn and transmute minor actinides (MAs) and long-lived fission products (LLFPs) in special assemblies, located in regions of the outer core with adequate neutron flux spectrum, is required. In the perspective of the XADT, the XADS core (and supporting structures) must be designed, at least in principle, to cope with “flexible/convertible cores”.

The behaviour of the core strongly depends on the performance of the accelerator/target unit in operating and accident conditions. The relationship between the system multiplication factor with the spallation neutron source and k_{eff}, the core intrinsic neutron multiplication factor, needs to be quantified for the adopted core configuration and its evolution with burn-up reliably predicted. This is important in order not to unnecessarily oversize the accelerator system while ensuring that the core will remain sub-critical over its lifetime during normal, abnormal and accident conditions. The core behaviour during the operational transients such as start-up and shutdown and along the evolution of conceivable accidents needs to be analysed.

The possibility to include reflecting/moderating materials to improve burn-up and to reduce fast neutron damage to relevant structures, while fulfilling the neutron spectrum requirements, should be considered.

The fuel management scheme shall be established. Fuel burn-up and fuel residence times shall be computed. The decay heat removal flow path and mode from the core assemblies shall be determined for the safety studies, in particular under natural convection conditions and for the design of the spent fuel handling equipment and installations.

The conceptual design of the ADS core (as well as the main vessel internals) will include adequate provisions (such as shielding, geometry, distance) to satisfy the safety requirements and to limit the fast neutron damage to the relevant adjacent structures.

3.6.3. Core Spectral Zone Strategy

The fast neutron spectrum is considered as a reference for the XADS. The fast spectrum allows a maximum transmutation of minor actinides, because of a better fission efficiency, and the high neutron flux. This solution would have to be optimised for the different nuclear fuel cycles strategies considered in the Europe.

A value in the core of 10^{15} n/cm².s can be used as a reasonable objective. This would be adequate even in the case of materials irradiation with the capability to reach also high (> 20-30) dpa.

Concerning LLFPs, the transmutation is performed through capture processes which are most efficient at energies typical of a thermal or epithermal spectrum due to the presence of resonances. Then LLFP targets should be preferably located at the periphery of the core.

The references above could also be applied to XADT. The need to implement several enrichment zones could be investigated. The objective is to improve the thermal uniformity in the core and at the core outlet. This will allow to avoid an over sizing of the coolability capacity, and to limit the thermal damages on the primary circuit structures.

3.6.4. Power Level

A reference level of 100 MW_{th} for the XADS core power has been selected.

Given the XADS missions, this value was selected to mediate a number of competing requirements, ranging from significant core performances and incineration capabilities, to the sustainability of the fission reaction cascade with adequate sub-criticality margins. The generated thermal power can be discarded with modest economical loss, yet making available more flexible design options in the selection, for instance, of the operating parameters of the primary loop (such as temperature levels and flow rates) as no particular requirement is demanding or binding for exploiting the plant thermal cycle efficiency.

Much smaller power levels (< 20 MW_{th}) would match substantial problems either in reaching, by sizeable fuel core loading, significant fuel duty in reasonable dwelling times with low power densities, or in sustaining, by practicable accelerator and spallation target power, sufficient core reactivity and cycle length by low core mass with high power densities.

3.6.5. Sub-Criticality Level

The degree of sub-criticality directly affects, for a given XADS or XADT design, key accelerator system parameters (e.g. the proton beam current) required to sustain the predefined power level. Additional requirements can derive from the selected approach to compensate fissile material burn-up (e.g. increasing the proton beam current vs. keeping it constant and moving neutron absorbing devices).

Small sub-criticality levels imply low proton beam current (and hence "moderate" accelerator system performances) but increased risk of approaching or attaining criticality under abnormal or accident conditions; higher sub-criticality levels imply higher proton beam current (and hence "demanding" accelerator system performances) but reduced risk of approaching criticality. The selected level of sub-criticality must be therefore determined by a properly balanced approach.

From the point of view of safety, it is mandatory that the nuclear design ensures that criticality conditions are not attained, with adequate margin, under any foreseeable occurrence pertaining either to design basis conditions or beyond design conditions. The above can be achieved, in principle, with or without reliance on neutron absorbers.

In the former case, it should be considered that, due to the external spallation neutron source, the fission power generation in the sub-critical system cannot be terminated but just reduced by inserting neutron absorbers into the fission core. Fission products decay heat level can be attained only by turning off the external neutron source that is, ultimately, by tripping the accelerated proton beam.

In the latter case, the provision of an adequate level of sub-criticality can be achieved by conservatively estimating the positive reactivity insertions associated with abnormal and accident conditions (such as from fuel, coolant and structural materials temperatures variation, coolant voiding, geometrical changes, ingress of foreign fluids into the fissile material region) and, consequently, properly choosing the allowable range of normal operating conditions.

An exhaustive demonstration of adequate sub-criticality under any foreseeable condition would be the key challenge for a design not including "shutdown" absorbers.

3.6.6. Coupling Specifications

The most innovative feature of the ADS concept relies on its basic property of coupling a sub-critical nuclear core system with a powerful particle accelerator.

The accelerator-core coupling is realised through a spallation target whose chief function is to convert the beam of high-energy protons into a high intensity neutron source, which feeds the core. The spallation neutrons supply, as high as some 10^{17}-10^{18} n/s, must be capable of maintaining operational the otherwise inherently lacking core neutron multiplication, such to “compensate” for the intrinsic core sub-criticality.

In order to exploit the neutron spallation yield, the spallation material has to be made of heavy nuclei. Furthermore, it must well sustain thermal loading and irradiation damage. In this context the benefit of the choice of LBE is twofold: LBE is able in fact of exploiting highly efficient proton-to-neutron conversion yields while allowing the direct removal of the intense spallation heat. Moreover, the lead-based materials are stable enough to overheating (good thermal inertia – at least in respect of the alkali metals – and boiling point) and have sufficient chemical compatibility with most structural materials and mild interaction with the environmental agents. The maximum beam power and the thermal-hydraulic constraints (maximum LBE flow velocity, as related to pumping and corrosion aspects, and temperature increase, as related to thermal-mechanical loading) are readily outlining the target size.

In order to maximise the importance of the spallation neutron source, this is accommodated inside a cavity that, surrounded by fuel assemblies rounds, so as to locate the spallation target at the core mid-plane. The core shape hence assumes the configuration of a hollow cylinder whose size needs to be established based on a set of many different conditions: the target cooling requirements, the hardness of the spallation neutron flux spectrum and the basic geometrical constraints which are related to the cross-section shape and width chosen for the fuel assemblies.

Since the requirements for the cavity size can be substantially different, depending on the spallation target design (windowed or window-less), the maximum beam power is determining the cooling needs and the basic target geometrical constraints. Specific mechanical design options and maintenance requirements may also be determining for the whole target configuration and dimensional choices.

The goal to limit the irradiation damage on the inner fuel core structures may concur to widen the spallation cavity as well. This may turn out helpful also for controlling the thermal-mechanical loading on the innermost fuel assemblies and for flattening out the radial core power distribution, which is expected rather peaked at the centre, for XADS designs operating at low core multiplication factors.

A steep decrease of the core multiplication factor occurs in fact with burn-up when the core mass is not large enough for sustaining, through the breeding of new fissile from the fuel fertile material, the loss of the fissioning nuclides. In the case of such “non self-sustaining cores”, a fairly stable core reactivity and power level with time as the fuel burn-up increases, can be only achieved by the management of substantially high fuel enrichments and/or by high beam currents. The upper limit of the multiplication factor needs to be adequately limited below the unity in order to allow enough safety margins to potential inadvertent transients and to make available, at the same time, a practicable operating range for the XADS.

This may make the beam-target power requirements substantial (a few MWs) already with fresh fuel core at BOL. Furthermore, practical and reasonable constraints for the spallation target, as measured against the core size, could otherwise turn out to be enveloping for the maximum beam requirements and for the maximum burn-up in the fuel.

3.6.7. Design and Safety Approach and Path to the Licensing

The XADS and XADT design development should be based on pursuing the general objective of nuclear safety, i.e. the protection of individuals, population and the environment.

This will be achieved by establishing and maintaining an effective defence against radiological hazards. The design and safety philosophy will primarily address the prevention of accidents. Attention must be paid, however, to provide appropriate protective features (i.e. features specifically designed to control and limit the consequences of a given accident) as well as mitigation of the consequences of accidents that could give rise to major radioactivity releases.

The foreseeable accident initiating events shall be systematically identified and grouped either into design basis conditions (DBC) or beyond design conditions. The analysis of their consequences will then be performed to demonstrate consistency with the basic safety principle according to which the most probable occurrences should yield the least radiological release while situations having the potential for larger releases shall be those less likely to occur.

Very low probability accident scenarios, such as those deriving from failure to trip the accelerator proton beam, or from complex sequences involving multiple independent malfunctions or failures will have to be addressed in order to demonstrate that there is no potential for catastrophic accidents. In the event of a highly unlikely accident sequences, no off-site sheltering or relocation action has to be required. This is important for the social and political acceptance of a new technology.

The licensing approach will be based on the defence-in-depth concept, already successfully applied to current nuclear power plants, providing multiple physical barriers between the radioactive products and the environment and protecting their integrity by means of inherent design features as well as simple, reliable and easy understandable engineered features. The licensing of the XADS/XADT will be performed by the authorities of the country hosting the facility. Nevertheless the safety approach has to be elaborated on the largest common basis, but excluding possible national specificity if this has no large influence on the general structure of the plant. The European safety approaches developed for the future nuclear power plants for electricity production should be used as a basis for the XADS. Special developments are needed due to the interfaces with the accelerator and the spallation unit, and due to the operation in sub-critical configuration.

Extensive research and development activities including experimental activities in facilities of different scale will help providing evidence of the performance of the proposed safety features.

3.6.8. Radioactivity Confinement and Radiological Protection

In pursuing the general objective of nuclear safety, that is the protection of individuals, population and the environment, key parameters in the XADS/XADT design development are the requirements related to radioactivity confinement and radiological protection.

In this framework, the identification and the characterisation of the radioactivity inventory resulting both during normal and accident conditions are among the main issues to be addressed and evaluated.

In the XADS in addition to commonly known radioactive isotopes characterising the contamination of the nuclear power plant systems (i.e. fission products, activation products, corrosion products) some unusual contaminants have to be considered. In particular, spallation products generated through the collision of the high energy proton beam with the target material (high “A” medium), and the activation products generated by the collision of a high energy neutrons with the target and coolant eutectic liquid metal (for lead-bismuth concept only). Contaminated and activated heavy metals are produced in the spallation zone, including Hg, Pb, Bi and Po. In windowless designs, a part of the waste is to be found in the vacuum systems.

A very large spectrum of radioisotopes will be involved in plant systems contamination; a major concern is related to the presence of the very highly toxic polonium-210 isotope. For most of the above contaminants it is anticipated that they will remain in the target (and in the coolant for the lead-bismuth option), with no consequential radioactivity confinement concerns. Nevertheless detailed studies and R&D activities need to be performed on their effective chemical and physical behaviour both during normal and accident conditions. This is essential particularly for the isotopes for which potential volatile behaviour (it is the case of polonium-210) could have an impact on interested plant systems design: leak tightness requirements during normal plant operations and confinement in accident conditions.

In normal operation, including maintenance operation, the radiological releases in the environment and the individual and collective radiological doses for the operators have to be as low as possible (ALARA principle), and in any case significantly lower than the accepted international limitations.

According to the defence-in-depth concept, radioactivity confinement in the XADS design is to be achieved through physical barriers (at least two) interposed between radioactive isotopes and the external environment. Design criteria are established to ensure that the occurrence of an abnormal or accident event does not jeopardise the integrity of these barriers. For the liquid metal cooled XADS design, since most of plant systems operate at atmospheric pressure, no significant radioactivity confinement problems are anticipated to occur. For the gas cooled XADS design the operating pressure is expected to be significantly over the atmospheric value and radioactivity confinement concerns are expected in case of primary system leakage or break. For both options detailed safety analyses extended to all potential design basis events (design basis conditions and design extension conditions) that can be postulated to occur, have to be performed to confirm that safety objective are met.

In addition to the risk of radiological releases, the toxicity of the lead-bismuth has also to be taken into account and the risks for the operators, the public and the environment have to be minimised.

As far as radiological protection is concerned, specific provisions for the XADS design that have to be investigated, cover the following aspects:

- shielding and personnel access requirements to areas/room interested by the accelerator system (i.e. design impact by the high proton beam flux shielding);
- airborne contamination of areas/rooms in which polonium-210 (or other volatile isotopes) and/or contaminated systems are localised (i.e. system leaktightness and impact on ventilation system design);
- radiological protection features for handling operations such as refuelling, target substitution, maintenance of peculiar components, etc.

3.6.9. Operations, Lifetime, Waste and Decommissioning

The start-up procedure for XADS has to be optimised in order to limit the delay between the shutdown state and the nominal power. Due to the low efficiency of control rods in a sub-critical core, compared to the case of critical core, the power variations should be performed a priori by proton beam intensity variations while control rod displacement or neutron absorbing elements relocation could be considered to counteract fuel depletion along the cycle. The control of the accelerator has to be designed for that purpose, taking into account the core parameters (neutron flux in the core) and the other plant parameters such as the core and the spallation target cooling which have to be in operation during the start-up phase. In normal operation the power variations in the core has to be limited to a few percent (2%).

Because of the sub-critical level, the ADS cores are less sensitive to the reactivity accidents. Nevertheless, due to the relatively small size of the XADS core, the reactivity consequences of handling errors could be significant. Therefore primary handling in normal operation is forbidden; handling will be done only in the shutdown-state and with a reactivity margin sufficient against all credible error, including fuel and spallation target handling processes.

The fuelling and de-fuelling procedures are driven by the characteristics of the coolant chosen. When fuelled, the reactor cannot be opened: for gas reactors, because gas circulation must be maintained at all times; for heavy metal reactors because the coolant must remain above its freezing point. Thus, the fuel handling must be performed by equipment installed in the reactor vessel an/or through penetrations of the vessel.

The technology and the complexity of the system is close to what has been made for fast reactors. The XADS/XADT will be operated under a cyclic mode, that is a given number of months of operation followed by a shut-down period, for fuel reshuffling and maintenance. The cycle duration will be determined mainly by the purpose of the reactor. An irradiation oriented machine will have cycles of limited duration (a few months) in order to allow periodic recovery of the irradiation samples. A “pure” transmutation machine should aim at operating as much as possible, with reactor cycles extending over periods of at least one year.

Concerning the plant lifetime, no specific and stringent requirements are imposed on the XADS/XADT due to the experimental characteristics of the facilities. Making reference to the planned schedule for XADS and XADT, a lifetime of the order of 20 years for the non-replaceable equipment (reactor vessel and its internals) seems adequate to reach the targeted missions. The damage on the vessel is design dependent and it is a function of the distance between the vessel wall and the core, the efficiency of the in-vessel shielding, the intensity and the spectrum of the neutron flux, the stress level and the operation temperature. Because of its larger diameter, an integrated vessel containing all the components of the primary loop minimises the radiation damage on the vessel. It is particularly suited to heavy metal cooled reactors, which do not require a pressure vessel. The neutron flux on such a vessel is of the same order of magnitude as for a PWR. Hence, comparable lifetime can be expected (up to 40-60 years) provided that the corrosion issue is well mastered. The issue on vessel ageing will be more critical for gas cooled XADS/XADT which will require a pressure vessel, and is more difficult to build with large diameters.

Some internal components, such as the spallation target, will be submitted to an extremely intense neutron flux and will have a limited lifetime. The design of XADS/XADT must allow their extraction from the reactor and their replacement, or the replacement of the spallation target. Because of the likely Po contamination of the spallation module, this operation will have to be performed remotely through a transport flask to permit a safe transfer to the fuel building and eventually in hot-cells, or storage before decommissioning. The spallation module lifetime is expected to be of the order from some months to one year, the lower value being related to the adoption of a window design while the higher value is related to a windowless design approach. This causes the need to provide a storage capacity adequate to the number of modules substituted during the ADS lifetime.

Concerning the waste production and management, as a target the amount of waste produced divided by the thermal energy generated in the core has to be similar and even lower than the comparable parameter in the current nuclear power plant. Given the high-level waste transmutation duties of the XADS/XADT, the reduction of the radiotoxicity of the radioactive wastes should be compared with the radiological and chemical toxicity of the waste produced in operation and during the decommissioning of the plant (reactor, spallation target, and accelerator). Such a comparison is a complex task and a methodology has to be developed.

The decommissioning of the plant has to be taken into account at the conceptual stage, in order to minimise the amount of radiological and non-radiological waste and the risk of release of these materials during the decommissioning phase.

3.6.10. Irradiation Capability

If the XADS/XADT is to be used also as an irradiation facility, several provisions must be included in the design. In such a perspective the XADS should provide a neutron flux > 10^{15} n/cm^{2}s, also with the capability to reach high (> 20-30) dpa.

The XADS/XADT can be used to validate new fuel types, transmutation target designs, or new reactor materials to be used in future reactors of the same type. In this case, the irradiation samples (fuel, transmutation targets, materials) can be included in ‘standard’ fuel assemblies and irradiated with them. The design must allow an easy recovery and replacement of the samples after the irradiation, which influences the design of the fuel casing. This influences also the spent fuel path, which will have to be transferred in hot cells, for the recovery of the irradiated samples, and possibly reconstitution of the fuel assembly for further irradiation.

If the irradiation targets are relevant of other designs, like pure lead cooled reactors, the irradiation temperature and the coolant can be different. The sample must then be isolated in a dedicated device, which provides the adequate environment (pressure, temperature, coolant type and flow rate, etc.) and instrumentation. The device must be inserted in the core or close to the reactor, in a position where it will be submitted to the adequate neutron flux. Therefore, irradiation positions in the core and suitable penetrations in the XADS/XADT vessel must be foreseen. The design of the XADS/XADT building must also foresee the extraction of the irradiated device and its transfer to a hot cell where the samples will be recovered.

3.6.11. Control and Instrumentation

Driving an XADS/XADT sub-critical system with an external neutron source has substantial consequences on its operation and control since it results in an effective decoupling between the core kinetics and its response to normal operation source or reactivity changes.

The nuclear core and the spallation source fed by means of a proton beam accelerator have in fact quite separate dynamics, so that an XADS/XADT cannot be a self-stabilising system such as an ordinary critical reactor core whose kinetics are controlled by means of a small, but crucial, delayed neutrons fraction and a number of reactivity coefficients.

The XADS/XADT core, normally designed many dollars sub-critical, is characterised by prompt-neutrons kinetics with very small mean generation time ($\Lambda \sim 10^{-7}$ s) and fast response from external neutron source or reactivity changes due to small time constants.

This is a direct consequence of the fact that the sub-criticality level, besides making the system sub-delayed critical, is ordinarily chosen with adequate safety reactivity margins such as to prevent reaching criticality in any foreseeable transient and accident occurrences. Conversely, the reactivity changes occurring in the core system during normal operation are instead much lower than the pre-set sub-criticality level, such to make their direct feedback on core total reactivity essentially ineffective.

Also, the reactivity changes which stem out from variations in the fuel or core medium properties (Doppler, temperature coefficients, voidings etc.) have no direct effect on the spallation source neutrons, which can be driven by the accelerator control system only. In contrast to a critical reactor, source neutrons are in fact not affected by variations in the physical property or geometry of the core constituting materials (fuel, coolant, structure) since the related feedbacks (whatever their favourableness may be) cannot inherently propagate through a connecting medium from core to the accelerator system, if not artificially by means of conversion to signals and electrical connections.

Variations in the total power level for an XADS/XADT can be eventually considered as arising from two independent contributions which are directly proportional to the sub-criticality level related reactivity insertions ($\Delta\rho / \rho$) and to the source strength related source intensity changes ($\Delta S / S_o$). The asymptotic fractional change of power is given by:

$$\frac{\delta P_{th\_core}}{P_o} = \frac{\delta S}{S_o} - \frac{\delta \rho}{\rho_o}$$

so that either a 10% source change (assumed for beam intensity only, since acceleration energy changes would be negligible due to inherent characteristics of the accelerator system) or a 10% reactivity change would produce same amount of variation in the core power level.

The dynamic decoupling between the sub-critical core and the spallation source hence requires, in order to maintain the XADS/XADT at a fixed power level, to compensate the reactivity changes occurring in the core by equivalent interventions on the source strength.

The actions for maintaining the pre-set power level shall be necessarily based on instrumentation readings from the core and the core cooling system. The signals shall be conveyed and displayed to the plant operator console for undertaking the appropriate source strength adjustments through the accelerator control system as needed.

In order to avoid malfunction and/or overshooting of the source intensity control, which could trigger overpowers and/or oscillations in the core, the source-controlling rate should be restricted below a maximum value.

This could be matching the typical thermal time constants of the core system, such to implement a beam-to-core response dynamics which would be more similar to that of a mechanical control rod system, inherently slow, rather than to that of a very fast electric control, such as that one of the source is expected to be.

The rate-controlled source regulation system should be implemented in such a way to make impossible to bypass or otherwise circumvent, whether intentionally or accidentally.

The perspective of the XADS/XADT could be substantially different in case of use of fixed and/or movable neutron absorbers. In such a case, the core power level could be controlled by playing on two different variables, according to the above correlation. In such a scenario, the best procedure optimising core control, safety, and plant efficiency should be assessed for.

The general XADS/XADT architecture, which is mainly based on point-source loading in relatively wide cores, may imply substantial neutron flux decoupling between different core regions, due to predominance of some of the higher harmonics in some cases.

Spatial decoupling requires the use of both wide and local neutron flux monitoring systems in order to assess the core neutron flux and power distributions and for controlling the whole levels through the accelerator control system and, possibly, the distribution forms if movable neutron absorbers may be considered practical by specific designs. Conversely, the adoption of absorber systems, adding extra decoupling and physics complexity in the core, could make the controlling systems and procedures even more cumbersome.

3.6.12. Transition to Transmutation Core Demonstrator

After a few years of operation of the XADS, the main goal will be to perform irradiation with high neutron flux for the development and the qualification of fuels dedicated to the transmutation of nuclear waste (fuels with a high enrichment in minor actinides, targets or special elements containing LLFPs, and other similar fuel concepts).

After these phases, approximately 10 years, the uncertainties will be strongly reduced for assessing the physical and economical performances of the following XADT, considering the whole fuel cycle including waste reprocessing and ultimate disposal and storage. The transition to a transmutation core demonstrator (i.e. XADT) is subject to the qualification of new and innovative MA based fuels (see sections 3.4.3 & 3.4.6). The fuel development constraints and steps (including reprocessing capabilities) will then define the time frame of XADT deployment.

In principle, given a requirement for an XADS core flexibility and convertibility to MA based fuels, the XADT could be adapted to the main components (vessel and internal structures) of the XADS and related buildings and auxiliaries. However, this choice could be made only after a certain number of years of operation of XADS and the decision how to proceed to the XADT is presently foreseen around the year 2017. In the case that the transformation of XADS into a transmuter is not possible, a fully new primary system would have to be built on the same site taking at least benefit from the accelerator complex and the most part of the auxiliaries.

3.6.13. Milestones, Time Schedule, Cost Estimates

Making reference to the overall time schedule of table 3.1, the relevant activities and milestones for the sub-critical system development and construction are shown in table 3.5.

The first period, starting from present and lasting for four years, will be devoted to the preliminary design, the evaluation and comparison of the two different options under study: the gas cooled and the lead-bismuth cooled concepts. This will be accomplished mainly within the 5th Framework Programme (FWP) and will give the possibility to select the main options (e.g. coolant medium, fuel, primary system) of the XADS sub-critical system configuration. Information and feedback relevant for the choice will stem from the parallel supporting R&D activities, as described in chapter 4.

The detailed design of the preferred configuration will be developed lasting for around five years (second half of the 6th FWP and first half of the 7th FWP). This step will also include the licensing procedure which, given the degree of innovation of the XADS, is foreseen to be more troublesome than current procedures for issuing construction and operations permits.

Parallel to the start of the detailed design, the selected site will undergo the preparation of foundations and infrastructures, common also to the accelerator complex. This is needed since the accelerator and the spallation module time schedules are anticipated in comparison to that of the sub-critical system (refer to tables 3.2 and 3.3) in order to allow first the coupling of the accelerator with the prototypical target. The specific construction period of the sub-critical system is assumed to last 5 years, a period which is consistent with margin, with the construction schedule of the current nuclear power plants.

After successful operations of the accelerator and the prototypical target, the sub-critical reactor will be coupled with the accelerator for XADS commissioning and operation tests (low and full power).

Full-power operation is planned by 2015.

Table 3.5: Sub-critical system: time-schedule and milestones

Year 2000 +	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
Preliminary design and evaluation of different options (e.g. fuel, coolant)	■	■	■	■											
Selection of reference design				▼											
Detailed design (including licensing)					■	■	■	■	■						
Site and infrastructures preparation (common to the accelerator complex)					■	■	■								
Sub-critical system construction								■	■	■	■	■			
Sub-critical system coupling with accelerator and spallation target												▼			
XADS commissioning and low power testing													■		
XADS full power testing														■	
Full XADS operation															■

A preliminary overnight vendor cost evaluation, subject to confirmation when a complete and consistent XADS configuration will be available, leads to the following figures:

- Sub-critical system engineering design: 100 M€
- System components procurement: 150 M€
- Civil works and infrastructures (nuclear island and balance of plant): 80 M€ (*)
- Site engineering for erection and commissioning: 70 M€ (*)
- Indirect costs: 50 M€ (*)

The above estimate has to be increased of the fuel cost. Owners' costs, including operations, are not included.

(*) including accelerator complex.

4. CURRENT ADS RELEVANT PROGRAMMES AND FACILITIES IN THE EU

4.1. Overview

In this chapter we describe in detail the various programmes, projects and experimental facilities in the EU of relevance to ADS development.

XADS R&D activities should be properly co-ordinated with national or regional programmes. In the future, the current situation of poorly connected research programmes could change if the European Research Area (ERA) were actually established. The European Commission has announced the idea and structure of this research policy, and it seems that it will dramatically change the way R&D activities are planned and developed for the 6th Framework Programme (FWP) and beyond.

In some cases, the Commission has used the example of Nuclear Fusion as a way to explain the ERA concept, because all activities on this field in all European Union countries are developed in a fully co-ordinated way. The EU Nuclear Fusion programme combines well a major activity of reactor-oriented nature (aimed at ITER or a similar machine) and several minor activities receiving the so-called preferential support. Although the Nuclear Fusion programme has received several criticisms because of its very high level of expenses and a certain lack of compromise with a given work schedule, Nuclear Fusion is a good example of how to co-ordinate R&D basic research.

For XADS, the first need is to establish a properly defined coherent and co-ordinated programme that could be managed in an efficient way. Institutional issues are therefore a first fundamental problem to be settled with two main types of actors: the member countries and the Commission. Although at a lower budget level, a structure similar to that of Nuclear Fusion could be the first step in organising the XADS programme. A second step would afterwards be needed to build and run an XADS.

The aforementioned sectors do not convey the same degree of attention for ADS development and have different impacts on the critical route to an XADS. For instance, the development of a new specific nuclear fuel can take over ten years, but an XADS can start with fuels already available. Similarly, technology available in the accelerator field seems to be sufficient to launch an ADS programme. In some cases, it is cited that accelerator reliability has to be improved by two orders of magnitude or so, but this point mainly relates to accelerators built with technologies twenty years old. New devices would take advantage of recent advancements in the field of material sciences and electronic equipment (including power electronics).

From the point of view of an ADS programme, there seems not to be any critical item that could actually be a "showstopper", from the point of view of R&D. Nevertheless, licensing an ADS facility would have to face new challenges which are not standard in the Nuclear Regulatory domain, as is the case of radioactivity confinement in spallation targets.

Of course, any licensing process must be based on previous experiences and sound calculations, and some sort of feedback must be devised to carry out a step-wise licensing process according to the results of the successive stages of the research programme. From this viewpoint, licensing becomes an important ingredient in the R&D plan, which will have to foresee how to interact with Regulatory Authorities and how to develop the aforementioned step-wise licensing process.

Basic Research

<u>Fuels</u>: The XADS can start with an existing fuel. Therefore, there is not an urgent need for basic research in this area. Nevertheless, basic research is needed for:

- Reprocessing and partitioning methods to treat LWR spent fuel and ADS recyclable fuel.

- Fuel fabrication (including suitable cladding) for minor actinides containing fuel and other specific fuels, according to the transmutation scenarios given by nuclear waste agencies and national authorities. TRU-fuelled pebble bed and high-temperature gas-cooled fuel in a fast spectrum would also need an R&D research programme.

Accelerators: Higher reliability electronic equipment would be needed for the deployment of ADS on an industrial scale, but it is not a critical problem for an XADS, which can be built on the basis of available technology.

Target: This is a point where basic research is still needed and urgent. Neutron yields from spallation targets are a well-characterised and calculations can replicate experimental results. On the contrary, more knowledge is needed on spallation products yield, where experimental results do not form yet a total and comprehensive body of data. Moreover, calculations from the available codes (FLUKA, GEANT, HETC, etc.) give different results to an extent which is not actually acceptable for licensing procedures. This is a very important point because radioactivity confinement, operational doses, and radiological protection as a whole, critically depend on the spallation products yields.

Sub-critical system: For molten-metal ADS, cladding and structures corrosion is a fundamental issue that needs urgent clarification by R&D activities. It is known that standard cladding materials for sodium-cooled FBR are not suitable for lead or lead-bismuth cooled reactors.

Gas cooled ADS are not affected by this important problem, although they need a target for the neutron source, and the first candidate is based again on lead (or Pb/Bi). An alternative could be a solid tungsten pebble-bed target also cooled by gas, but gas pressure can convey very high mechanical demands in the accelerator tube window. This point needs also basic R&D attention.

System Integration: Basic research needs are in this case connected with reactor maintenance and routine operation surveillance. Proper counters and recorders of all relevant magnitudes must be developed. Of course, they have to be suitable for working in the chemical and radioactive environment of the XADS.

Components

Three main components are identified in an ADS: the accelerator, the intense neutron source and the sub-critical reactor.

Basic research for accelerators will mainly have to address the problem of reliability and operability. Accelerator physics is quite well known due to a long-standing research in this field for more than 70 years, and standard basic problems have already been solved.

Research for the accelerator source of protons has already been carried out in several laboratories because of standard requirements of hadron accelerators. Additional research has been done specifically in the field of highly intense proton injectors, as in the IPHI Project in France (aimed at generating a high-quality, low-emittance beam of the order of 100 mA protons) which is one order of magnitude larger than the beam current foreseen for ADS, and TRASCO (TRAsmutazione SCOrie) in Italy.

A field where basic research is still needed is the technology to improve the electromagnetic feed of RF cavities, in order to avoid beams trips due to components damage prevention which would be associated to very high-voltage sparks.

Improvements on the technology of power supply, vacuum and beam control will also need basic research, to develop new elements for high-reliability accelerators. Recent advancements on fast electronics and ultra-fast computation will help meet the requirements for designing, constructing and operating the new accelerators to fulfil ADS requirements on proton beam intensity and reliability.

The second fundamental component is the intense neutron source. In this context, the projected MEGAPIE experiment at PSI (Switzerland) with the collaboration of some countries of the European Union is a fundamental milestone, where basic research will have to be mastered to a high extent. MEGAPIE will make use of previous basic research in the field of molten metal chemistry, provided by the KALLA (see § 4.6.3) and CIRCE (see § 4.6.5) projects, to be carried out under the auspices of the EU 5th FWP.

A special case of basic research will be needed for the beam tube window, if such a window is foreseen in the tube-target coupling. This point is particularly addressed in next section.

In the long term, ADS could use other options to increase the reliability of the neutron source, including redundancy of some of the elements - but they are out of the scope of basic research, which must be targeted at solving the fundamental pending problems of the whole system.

Basic research for the sub-critical reactor can be considered from different viewpoints.

In order to start operation of an experimental ADS, basic research must only take into account the clad-coolant compatibility, which in turn can consider either standard clad or newly developed clad. For molten metal cooled ADS, the KALLA and CIRCE projects will have to provide the appropriate materials for fuel cladding. The situation will be much less demanding for gas-cooled ADS, where standard cladding could be used.

For a new fuel specifically developed for transmutation purposes, basic research will be very complex, including irradiation tests both for the fuel itself and the cladding material. Most of the work to be carried out will be in the field of physico-chemical processes. Nuclear properties of the XADS relevant nuclides are well known for most of the neutron energy range under consideration. Better knowledge is required for fuels with high content of high mass MA, as expected in ADS re-circulating TRU fuel. These data will come out from the nTOF project at CERN (see § 4.2.1) and the HINDAS project (§ 4.2.2), both to be carried out during the 5th FWP.

Overall, it seems that most of the basic research needed for ADS experimental development has been addressed within the 5th FWP, with the exception of high-reliability elements for specially suited accelerators for ADS.

System Integration

As any multi-component system, an ADS will depend critically on effective system integration. In this context, the neutron source plays a fundamental role because it has a double interface, with the accelerator – on the one hand, and with the reactor - on the other hand.

A first attempt at ADS integration was made at CERN in 1994 in the FEAT project (First Energy Amplifier Test) where the physics of sub-critical multiplication in natural uranium reactor was successfully checked.

A more comprehensive experiment on a source-driven sub-critical reactor will be carried out in MUSE (see § 4.5.1), within the 5th FWP.

For the future, two additional projects will have to provide relevant information: MEGAPIE and MYRRHA, which are described in § 4.4.1 and 4.5.2, respectively.

Moreover a first experiment of ADS component coupling could be envisaged using the TRIGA reactor at Casaccia (Italy). This experiment can be run at several hundred kW_{th} power in the reactor and few tens kW_{th} in the target, thus providing e.g. a demonstration of the dynamic behaviour of an ADS in presence of reactor feedback effects.

Basic research on system integration must take into account the standard requirements of nuclear safety. Those requirements are mainly connected to two issues:

- criticality (in ADS, this means sub-criticality in any conceivable reactor state);
- radioactivity confinement.

Both sets of problems will be fundamental points in the licensing process for ADS, particularly for ADS prototypes and experimental reactors.

In relation to radioactivity confinement, an ADS presents a specific problem because of the spallation products generated in the neutron source. In the most standard approach, a molten metal target will be used as a spallation source, and the inventory of a large set of radioactive products will be increasing with time. Cleanup and purification systems can help reduce the build-up inventory in the target, but some basic research is needed in this context with regard to product generation, and chemical systems for target purification. Projects such as MEGAPIE and MYRRHA can be considered as important elements of the R&D in support for addressing these problems. MYRRHA could also provide a sound experience in site selection and licensing procedures for ADS, which are basic items to system integration.

4.2. Neutron Data

Neutron cross section data is available mainly for uranium and plutonium isotopes, reflecting the interest in the U-Pu fuel cycle, and for neutron energies ranging from thermal to fast reflecting interest in thermal and fast neutron reactors. Although the currently existing nuclear databases are sufficient for a first evaluation of ADS and dedicated transmutation devices, a detailed assessment require more precise and complete basic nuclear data.

The main data requirements can be classified as follows:

- Measurement of the basic cross-sections (elastic, capture, fission, total and inelastic) of many high-mass transuranic isotopes which arise in the partitioning and transmutation scenarios. In many cases, there is either no data or just a single experimental data set. The most important energy range covers from thermal energies to 20 MeV.
- Measurements of the basic cross-sections of medium and long-lived fission, activation, and spallation products. For most of these isotopes there are very few measurements and the available data is uncertain. Improvements are required to evaluate the possibility of their transmutation in dedicated devices. The most important energy range for these measurements is again from thermal to 20 MeV.
- Evaluation of available experimental data to compute cross-sections, and dissemination of the evaluated cross-sections results through the international agencies co-ordinating the distribution of this data.

- Measurements of neutron cross-sections at higher energies (from 10 MeV to several hundred MeV) and improvement and evaluation of nuclear models for the processes appearing in the interactions of neutron and charged particles, during the operation of spallation neutron sources.

The largest activities in Europe are co-ordinated within the nTOF and HINDAS projects, and cover experimental measurements and cross-sections and model evaluations.

4.2.1. The CERN neutron Time Of Flight, nTOF

Objectives

The nTOF project objective is the measurement, evaluation and dissemination of neutron cross sections relevant for the nuclear waste transmutation, ADS design, and the development of the thorium cycle. The project is organised as a Shared Cost Action (SCA) within the 5^{th} FWP of the EU, with wide participation of groups from many countries (Austria, France, Germany, Greece, Italy, Portugal, Spain and Sweden) plus CERN and the IRMM laboratory of the EC JRC.

To perform the measurements, a facility is being set-up at CERN (see fig. 4.1) which will be used initially by an international collaboration extended to groups from the Russian Federation and the USA. The IRMM facilities and other smaller accelerators will also be used for the experimental campaign. Measurements will, in addition, provide useful information for the developments in nuclear astrophysics, nuclear physics and neutron dosimetry.

The CERN facility will be based on the existing CERN Proton Synchrotron (PS), to send 20 GeV/c protons onto a lead target surrounded by a 5 cm water layer.

A fraction of the neutrons produced by spallation and moderated in the water will be diverted through a 200 m long, wide vacuum pipe to an experimental area. In this area, the samples to be measured will be exposed to those neutrons and the secondary particles produced by the neutron interactions will be detected. An optimised set of neutron collimators and shielding elements has been introduced in the neutron path from the spallation target to the samples, to maintain the neutron beam shape and position and to minimise the neutron and photon background in the experimental area.

The time of flight of the neutrons along the 185 m, i.e. the distance between the spallation target and the sample position, is measured with 1 ns precision. This allows one to determine the neutron energy with a resolution better than 10^{-4} for neutrons of energies up to 1 MeV, and with a resolution better than 10^{-3} up to 100 MeV. The identification of the reactions taking place in the sample is based on the secondary particle measurements. The counting rates of different types of reactions allow a computation of the cross sections, using the previously determined neutron flux, both as a function of the neutron energy.

The PS is able to provide 7×10^{12} protons per pulse with an FWHM pulse duration of 5 ns. This, together with the high proton energy, will provide a suitable pulsed neutron source available for cross-section measurements. The maximum repetition rate is one shot every 1.2 s, although nTOF will normally take one pulse every 4.8 s.

These characteristics will make nTOF a worldwide unique facility for neutron cross section determination in the intermediate energy region, from 1 keV to many MeV, especially for radioactive, expensive or rare material samples. In addition the facility has the possibility of reaching up to several hundred MeV, albeit with smaller intensity.

Several innovative detectors have and will be developed and installed in the experimental area. Parallel plate avalanche chambers (PPAC) for observing the fission of standard isotopes, and advance Si detectors plus one micromegas chamber for observing (n,α) reactions in ^{10}B and ^{6}Li, will allow a precise absolute determination of the neutron flux intensity, energy distribution and beam profile. Additional BF_3 detectors, working with the long-counter principle, will allow the fast monitoring of these parameters.

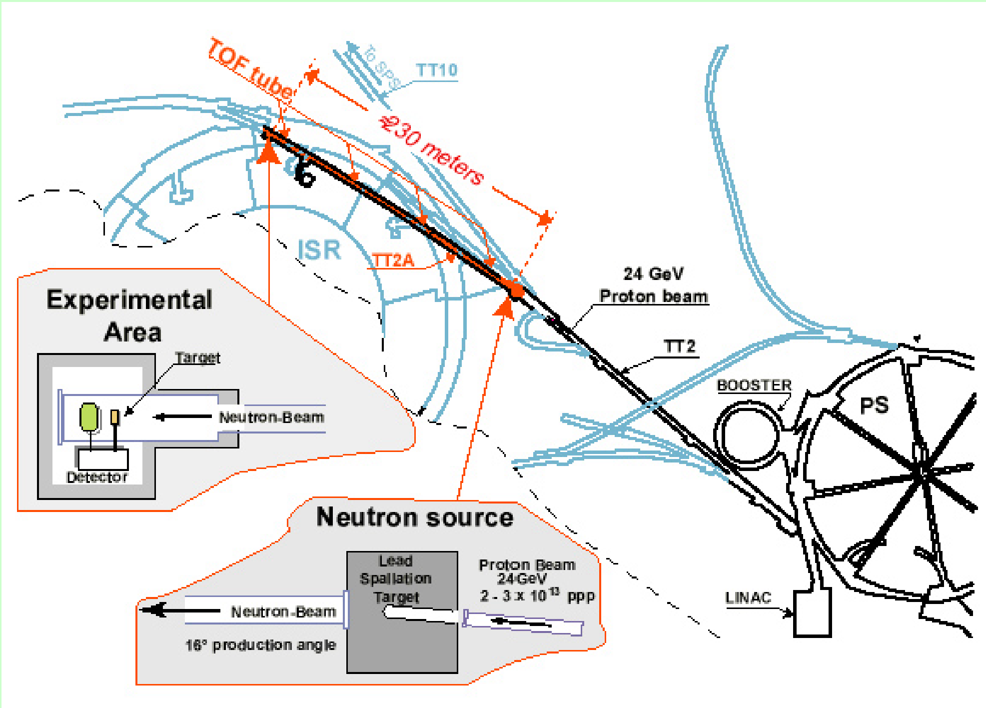


Figure 4.1: Schematic Layout of the CERN nTOF Facility

In a first phase, PPACs will also be used for the measurements and tagging of fission in the samples. The capture reactions in the samples will be studied with newly designed C_6D_6 detectors. Outside beam spectroscopic Ge detectors and activation methods will be used for the measurements of (n,xn) reactions. All these advanced detectors will be handled by fast, pile-up resistant DAQ system, based on Flash ADC specifically designed for the experiment.

In a second phase, scheduled for years 2002 and 2003, specific detectors will be installed to improve selection quality and maximum information recording of fission and capture events. The main component will be a 4π calorimeter based on fast, neutron insensitive, inorganic scintillators. This calorimeter is the key element for the capture cross section of the transuranic isotopes, where the separation of the capture events from fission and radioactive decay in the sample is a difficult task.

The program of measurements for the duration of the EC contract (presently 2000 to 2003) is organised in a set of work-packages:

- *Fission cross-sections for the Th-cycle and transuranic isotopes*: the main isotopes considered are ^{237}Np, ^{239}Pu, ^{241}Am, ^{243}Am, ^{244}Cm, ^{245}Cm, ^{232}Th, ^{233}U, ^{234}U and ^{236}U (plus ^{235}U and ^{238}U as reference standard isotopes). The main objective will be to cover the energy range from 1eV to 20 MeV, but the higher energy limit will be extended as much as allowed by statistics.

- *Capture cross-sections for transuranic isotopes:* limitations in sample availability and intrinsic radioactivity have restricted the present list of samples to: ^{237}Np, ^{240}Pu, ^{241}Pu, ^{241}Am, ^{243}Am, ^{245}Cm and ^{238}Pu. The energy range of measurements will be from 1eV to 20 MeV.

- *Capture cross-sections for Th-cycle isotopes*: including measurements of ^{232}Th, ^{231}Pa, ^{233}U, ^{234}U and ^{236}U in the range from 1eV to 20 MeV.

- *Capture cross-sections for non-fissionable isotopes*: both long-lived fission products and possible coolant isotopes are of interest e.g. ^{151}Sm, ^{129}I, ^{99}Tc, ^{79}Se, ^{206,207,208}Pb and ^{209}Bi, again in the range from 1eV to 20 MeV.

- *Total cross-sections*: performed by transmission, most probably in the IRMM facilities. The isotopes are ^{237}Np, ^{129}I, ^{239}Pu and ^{240}Pu.

- *(n,xn) cross-sections*: performed in two ways, by TOF at CERN and by activation methods in several facilities at Europe providing mono-energetic neutrons. Measurements are proposed for ^{237}Np, ^{232}Th, ^{231}Pa, ^{239}Pu, ^{241}Pu, ^{241}Am, ^{243}Am, ^{233}U, and ^{207}Pb.

The facility is expected to operate at CERN for a much longer period of time after the EC contract and the above list of measurements is expected to grow with time.

In addition to the facility preparation and calibration, and the cross-section measurements, two specific work packages have been set-up. The first is for the cross-section evaluation in collaboration with the NEA-OCDE and IAEA. The second is to design and implement a new dissemination mechanism that can replace the present plain text files by a more efficient, reliable and traceable platform with tools for interfacing with the simulation, visualisation and analysis programs.

Project Schedule

The nTOF CERN facility has been completed in the winter 2000, up to the experimental area, and is presently in the commissioning phase. The first measurements are scheduled for April 2001. PPACs, C_6D_6 detectors, and neutron beam measuring detectors will be installed from the beginning of the nTOF facility operation in April 2001. However the 4π calorimeter and some other advanced detectors will only be available by the end of year 2002.

The complete program of measurements included in the EU contract is expected to be finished by the end of 2003. The distribution of the measurements during this period will be progressively designed by CERN and the nTOF collaboration, taking into account the availability of PS protons. The capture cross-section measurements, for the more demanding isotopes, will have to wait till the 4π calorimeter is operational (end of 2002).

The evaluation of cross-sections is expected to follow the measurements with a typical 6 months delay.

4.2.2. HINDAS Project: High and Intermediate Energy Nuclear Data for ADS

The objective of the collaborative effort of the 16 partners involved in the HINDAS project is that the essential high-and intermediate-energy nuclear data, required for the ADS application, will be available in an energy range where at present almost no data exists. This essential goal can only be achieved by means of well-balanced combination of basic cross section measurements, nuclear model simulations and data evaluations. The three elements, Fe, Pb and U have been chosen to give a representative coverage of the periodic table, of the different reaction mechanisms and, at least for lead and iron, of the different materials used in ADS. The overall objective of this project will be achieved through the following eight work-packages (WP) list in table 4.1

Table 4.1 Work packages of the HINDAS project

WP 1. Light charged-particle production induced by neutrons or protons between 20 and 200 MeV (Used experimental facilities: *UCL, RuG, UU*).

WP 2. Neutron production induced by neutrons and protons between 20 and 200 MeV (Used experimental facilities: *UCL, UU*).

WP 3. Residual nuclide production induced by neutrons and protons between 20 and 200 MeV and production of long-lived radionuclides (Used experimental facilities: *PSI, UU, UCL*).

WP 4. Light charged-particle production above 200 MeV (Used experimental facility: *FZJ*).

WP 5. Neutron production induced by protons above 200 MeV in thin and thick targets (Previously used experimental facility: *CEA-DSM*).

WP 6. Residual nuclide production above 200 MeV in inverse kinematics (Used experimental facility: *GSI*).

WP 7. Nuclear data libraries and related theory (theoretical work at intermediate energies).

WP 8. High energy models and codes (theoretical work).

In WPs 1, 2 and 3, experimental data will be measured below 200 MeV, using the most recent experimental techniques, at the European facilities that are the best equipped for the reactions under consideration. These data will constitute a benchmark set for nuclear reaction models developed in WP 7.

The WP 4 and 5 will be devoted to the collection of data above 200 MeV concerning the production of light charged-particles and of neutrons, measured recently by different partners of the project in thin and/or thick targets. The experiments performed in the framework of WP 6 will provide reliable and comprehensive data on cumulative yields, from which long-lived activities and final element yields can be deduced.

Theoretical nuclear models (WP 7 and 8) will be developed and/or improved (dedicated optical model, pre-equilibrium, fission, direct and statistical models at energies in the 20-200 MeV region, intra-nuclear cascade, fission and evaporation models above 200 MeV) and benchmarked against the new experimental data.

4.3. Accelerators

4.3.1. VICE - The Vacuum Interface Compatibility Experiment

VICE is an accompanying research activity of the Belgian Nuclear Research Centre SCK•CEN at Mol to answer problems occurring from the direct coupling of an accelerator to the liquid Pb-Bi eutectic target in their windowless design for the spallation source of the MYRRHA-ADS. This coupling connects the accelerator and proton beam transport tube (beam line) vacuum directly with the target liquid metal (LM) that, in principle, constitutes potentially a rather huge particle reservoir.

The vacuum pumping speed in the immediate vicinity of the sub-critical core is very limited due to geometrical constraints. The high level of radiation and temperature causes difficulties for the implementation of vacuum supporting measures. Since MYRRHA is the first experiment to choose the windowless solution, in order to avoid related engineering and maintenance problems, an attempt is necessary to assess the situation in quantitative terms.

VICE, which is under construction at SCK•CEN, resembles the 4 m or so of the beam line adjacent to the LM target in the confined geometry of the reactor environment. The LM target is being provided in a ca. 1.5 m high crucible, forming the lower part of the vessel and being of ca. 13 l content ≈ 135 kg LM or 3-5% of the content of the foreseen MYRRHA spallation loop.

A schematic drawing of VICE vacuum vessel is shown in fig. 4.2.

In its upper part the 6 m high column contains a baffle similar to that intended in MYRRHA whose purpose is to limit (slow down) the migration of metal vapours and to give a conduction limitation for the assessment of flow rates. The entire vacuum vessel can be baked to 500°C in service for coating and experimental purposes. A turbo-pump at the top end is to match the geometrically given pumping speed of order 100 l/s and can provide the vessel with initial ultra-high vacuum (UHV) conditions. The entrance to the turbo-pump will be throttled by a variable conduction valve over almost 4 orders of magnitude down to almost zero again for the purpose of flow rate measurement. A commercially available, high quality mass spectrometry, with a triple-quadrupole of high mass resolution at the top of VICE, will be the main diagnostic in connection with the vacuum pressure gauges along the beam line, but not exclusively. Mass flow rates of the emanating gases will be measured by comparison to measured gas flow rates of calibration gases intentionally injected at the same pressure regime; their composition will be resolved with the quadrupole.

The entire vessel is made of austenitic stainless steel (AISI 316L) the inner surface of which has been finished by electro-polishing to best UHV standards. The flanges are metal sealed in CF technique. Ohmic wire heaters will be applied to outside of the vessel as well as thermo-couples to permit fine tuning of temperatures up to 500°C and gradients. The LM will also be heated by induction heating with a low frequency (ca. 50 Hz) generator and the induction field will simultaneously serve to stir the LM (quasi MHD pump). Since it is likely that despite of the foreseen gettering oxide or other layers might obstruct possible emanation processes (layers which the proton beam would later on "clean up"), glow discharge cleaning with deuterium (one of the few gases not expected in "natural" out-gassing) will be applied.

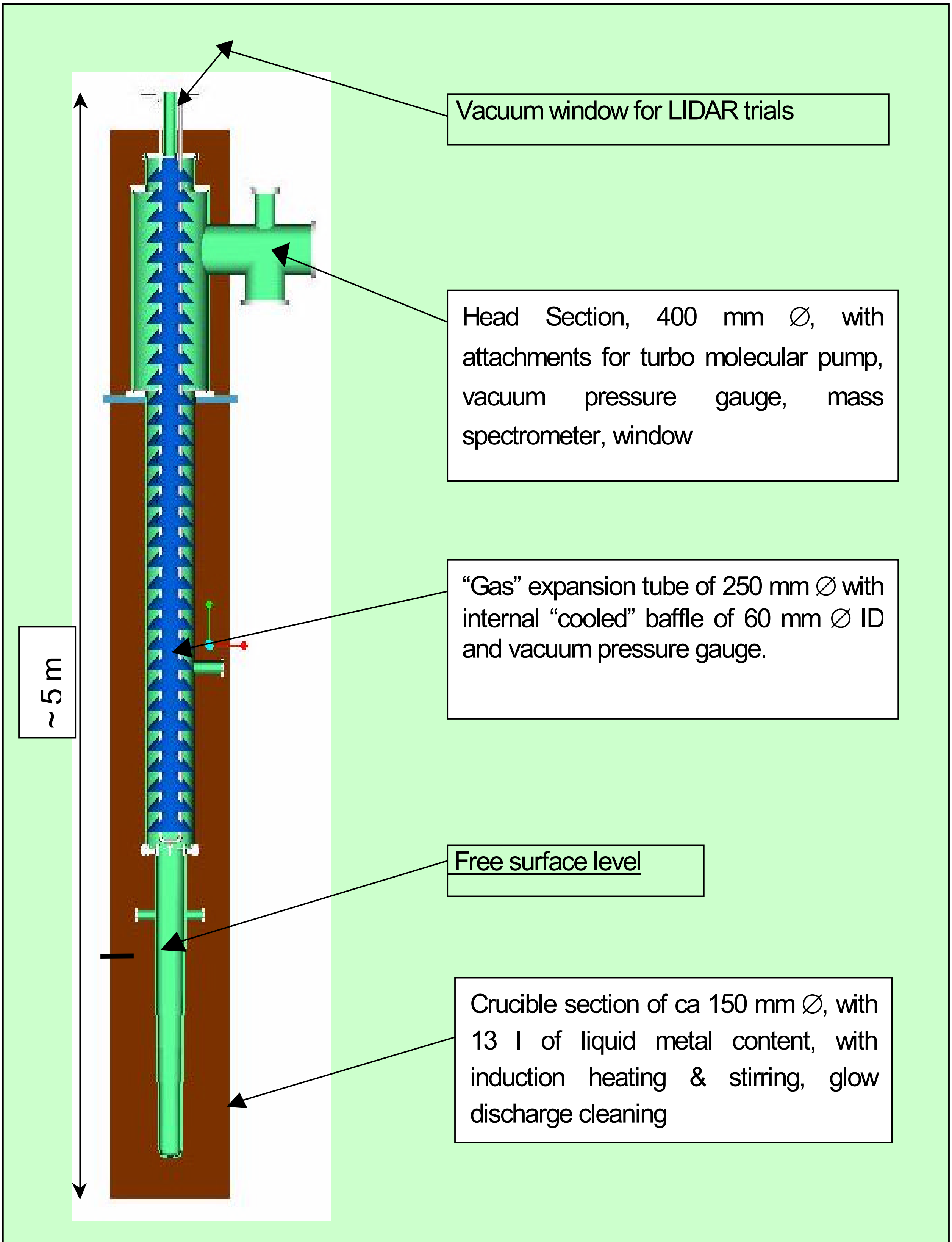


Figure 4.2: MYRRHA – VICE Vacuum Vessel Schema

The two methods of corrosion protection against the LM that would attack in the metal composition of the stainless steel (SS) – the oxygen control and the protective coating by low solubility materials in the absence of oxygen – will be considered. They both need to be vacuum compatible during long operational periods under vacuum and are mutually exclusive. The oxygen control cannot be made by contact of the LM with process gases but rather only with solids like PbO.

The objectives of VICE are thus:

- To clarify the possible interaction of the accelerator, with its high vacuum requirements, with the material emanating from the LM in the windowless design of the MYRRHA ADS and the walls in the temperature range chosen for MYRRHA.
- To qualify and test the proposed corrosion protection method for the loop wall; without the application of which no vacuum compatible LM corrosion resistant containment solution can be demonstrated convincingly for the MYRRHA target loop.
- To qualify for the second option of corrosion protection the oxygen removal ("gettering") and/or control process without which the wall will not withstand the LM corrosion.
- To assess initial out-gassing rates (LM conditioning) of the LM (of gases in solution) and vessel as a function of temperature and other parameters affecting diffusion and cleanliness of the LM but also operational cycle time if out-gassing turns out to be a tedious process.
- To assess the migration of material towards the accelerator, whether gases or metal vapours under quasi-operational conditions. This includes at a later stage the simulation of volatile spallation products like mercury and polonium by admixture of mercury and a simulation element for Po still to be determined.
- To verify a suitable and relevant method of LM surface level detection under relevant geometrical conditions that is needed to regulate the free surface position in operation.

4.3.2. IPHI, TRASCO, and ASH

IPHI (Injecteur de Proton Haute Intensité)

In-depth studies on the development of robust high power proton accelerators has been going on in Europe for some time. Two projects, IPHI in France and TRASCO (TRAsmutazione SCOrie) in Italy, are of particular interest in view of the design and construction of the XADS and XADT. A well structured collaboration (CEA-CNRS-INFN) between the two projects has been formally established in such a way that, even though each project has its own programme, many important choices are common in order to obtain the maximum profit from the investments made by the two teams.

IPHI is a 1 MW, 10 MeV demonstrator accelerator, that could be used as front end for a high power proton linac, as shown in fig. 4.3. It consists of:

- An ECR source (SILHI, Source d'Ion Légers Haute Intensité), operated at 2.45 GHz with an ECR axial magnetic field of 875 Gauss, able to deliver a 95 keV, 100 mA proton beam;

- A normal conductive radio-frequency quadrupole (RFQ) able to provide a 500 kW, 5 MeV CW beam;

- A drift tube linac (DTL) tank that brings the proton energy up to about 11 MeV.

Both the RFQ and the DTL are fed by RF power provided by three 352 MHz, 1.3 MW klystrons. The source is driven by a 1.2 kW magnetron, but it will be replaced by a generator based on a 3GHz, 1 kW klystron for a better flexibility in pulsed mode.

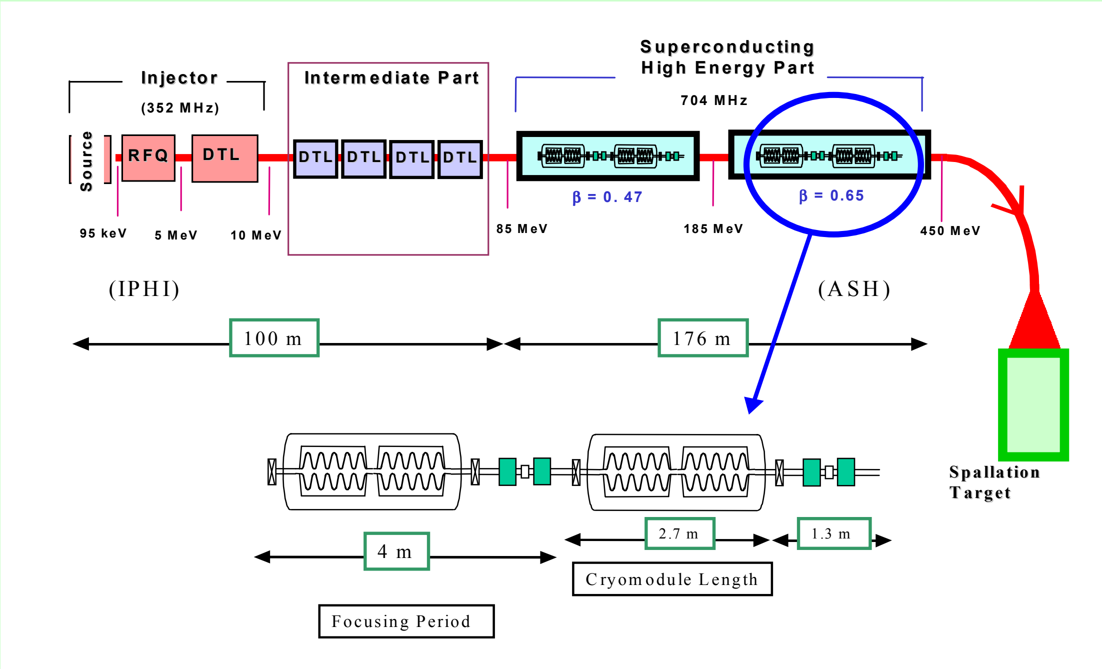


Figure 4.3: Typical layout of a high power proton LINAC – the IPHI Injector

The SILHI source has already been built, as well as the low energy beam transport (LEBT) line, which includes a set of diagnostics. The source fulfils all the main requirements to inject the beam into the RFQ. Long uninterrupted runs have demonstrated a very good availability (99,96%).

The design of the RFQ has been completed; the beam dynamics was studied using several complementary codes. The construction is now going on and should be completed by next year. The definition of the vacuum system and the cooling system are practically completed. A cold model is in operation to validate the codes and optimise the RF tuning procedures.

The construction of a short DTL tank, equipped with three drift tubes, is in progress; this prototype cavity will allow the validation of the technological choices, the RF codes as well as the magnetic measurements and the alignment procedures.

The definition of the high-energy beam transport (HEBT) has almost been done and diagnostics are under development, with R&D work focussed on the conception of non-interceptive diagnostics. IPHI is planned to deliver the first beam by 2004.

TRASCO (TRAsmutazione SCOrie)

TRASCO is a basic R&D program aiming at study the physics and developing the technologies needed to design an ADS for nuclear waste transmutation. It consists of an accelerator (fig. 4.4) and the sub-critical system and covers all the main sub-systems of an ADS.

The objectives of the first part of the research programme are:

- A conceptual design of a 1 GeV, 30 mA proton linear accelerator (linac);
- The design and construction of the proton source and of the 5 MeV, 352 MHz CW RFQ;
- The study of possible alternatives for the linac part from 5 MeV (the output of the RFQ) up to about 100 MeV;
- The design of the high-energy section of the linac, based on super-conductive elliptical type accelerating structures, as well as the construction of some prototypical super-conducting RF cavities.

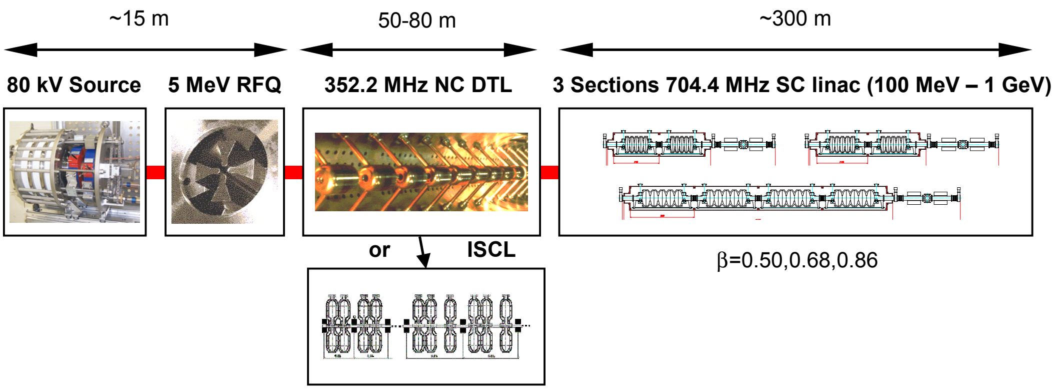


Figure 4.4: Conceptual block diagram of the TRASCO LINAC

The TRASCO intense proton source (TRIPS) is a 2.45 GHz microwave source that can produce a 50 mA – 75 keV proton beam. The main goal of TRIPS is to achieve the required current and voltage stability as well as a satisfactory controlled low-beam emittance, taking into account the state-of-the-art of such devices, in particular SILHI.

TRASCO considers and compares different options for the part of the linac from 5 MeV up to about 100 MeV: 1) a standard drift tube linac (DTL) at 352 MHz, 2) an independently phased super-conducting cavity linac (ISCL) made of $\lambda/4$ or $\lambda/2$ super-conductive cavities or super-conductive elliptical re-entrant cavities.

For the high-energy part of the linac, two operating frequencies have been considered and compared for the design: the LEPII (CERN) 352 MHz frequency and its doubled value of 704 MHz. The choice of the operating frequency implies a different choice of fabrication technology for the super-conducting cavities: for the LEP 352 MHz, it is possible to use the relatively "cheap" Nb sputtering on copper cavities – that has been proven to be able to provide acceleration gradients of about 8 MV/m for cavity with a proton velocity ß close to unity – while the 704.4 MHz allows to take advantage of the outstanding performances of the bulk Nb cavities set by the recent developments driven by the TESLA/TTF Collaboration. Both technologies have been investigated in the prototypical activities of the TRASCO programme.

The TRASCO programme started in 1998 and a number of activities have been carried out. A reference conceptual design of the proton source and medium energy section - the 352.2 MHz RFQ and a DTL - has been determined, for a nominal accelerated current of more than 30 mA. The TRIPS source has been built and is under commissioning. A detailed design and engineering work of the 352 MHz RFQ has started and a 3 m long aluminium model of the RFQ has been built and measured for RF field stabilisation tests. Technological tests on a short copper section have been done and the first section of the RFQ is in construction.

Preliminary studies of an ISCL - to be used instead of the traditional DTL - have been also done. The ISCL is similar to the accelerators used for low-energy heavy ions in several nuclear physics laboratories. In the present case the structures need to be designed for much higher beam intensities and for wider particle velocity range. Various approaches have been checked, like single and double gap cavities, at the frequencies of 176 and 352 MHz. A promising design of a 352 MHz ISCL ranging from 5 MeV up to 100 MeV, is based on the so-called "re-entrant cavities", that are modified cylindrically symmetric pillbox cavities and, therefore, theoretically guaranteed to be dipole free. Many points of this design work are, however, preliminary but will be used for cavity R&D activities.

The conceptual design of the 352 MHz super-conducting LINAC, able to bring the 30 mA proton beam from 100 MeV up to 1700 MeV, has already been worked out and is mostly based on the LEPII technology. The design of the cavities has been performed investigating carefully all the electromagnetic and structural performances. The construction and the tests of the Nb-sputtered copper ß=0.85 single-cell and multi-cell prototypes cavities has been done at CERN, under a collaboration agreement between CERN and INFN.

Starting from a study of linac design frequency scaling laws, and in order to take advantage of the bulk Nb cavity fabrication technology set by in the last few years by the TESLA/TTF International Collaboration, a linac design based on the use of 704 MHz frequency for a super-conducting section from about 100 MeV to nearly 2 GeV and for beam currents in excess of 30 mA, has been carried out.

The choice of bulk niobium cavities allows an increase in the cavity gradients and shortening the super-conducting linac length by nearly a factor 2.

ASH (Accélérateur Superconducteur pour Hybride)

This last part of TRASCO is being done in close collaboration with the French ASH, which is a CEA-IN2P3 specific program for the development of super-conducting cavities applied to high power proton accelerators. A common reference design has been developed as well as a common program for prototypes design and construction.

4.4. Spallation Targets

4.4.1. MEGAPIE, a Megawatt Pilot Experiment

Background, Goals an Time Schedule

MEGAPIE is a joint initiative by six European research institutions and JAERI, Japan, to design, build, operate and explore a liquid lead-bismuth spallation target for 1 MW of beam power, taking advantage of the existing spallation neutron facility SINQ at PSI, Switzerland

A liquid metal spallation target based on the lead-bismuth eutectic mixture with a melting point as low as 125°C and a boiling point as high as 1670°C is the preferred concept in several studies aiming at utilising accelerators to drive sub-critical assemblies. In this context, the test of a 1 MW liquid metal target is a crucial milestone.

It is the goal of the MEGAPIE experiment to explore the conditions under which such a target system can be licensed, to accrue a design database for liquid lead-bismuth targets and to gain experience in operating such a system under the conditions of present day accelerator performance. Furthermore, design validation by extensive monitoring of its operational behaviour and post irradiation examination of its components, are integral parts of the project. An extensive pre-irradiation R&D program will be carried out in order to maximise the safety of the target and to optimise its layout.

As for the MEGAPIE target, a period of 2 years (2000 and 2001) has been allotted to carry out the research and engineering work necessary to decide what the final design should be and to prepare the preliminary safety analysis report. At the end of this period a decision will be made whether to go ahead with the detailed design and construction, for which another two years are foreseen, including testing without beam. This sets the beginning of the year 2004 as the goal for putting the MEGAPIE target into SINQ.

A standby target will be ready in case some unforeseen difficulty arises. This target will be used at the end of the operating period of the MEGAPIE target, unless a follow-up liquid metal target will be available. The duration of the irradiation period will be decided upon, based on the results obtained up to that point from supporting research, but the design goal was set to 6000 mAh, which corresponds to 1 year of full power operation at 1 MW.

Target material will be the Pb-Bi eutectic mixture. The design beam power is 1 MW at 600 MeV. Existing facilities and equipment at PSI will be used to the largest possible extent. Cooling water loops of the target station will be left largely unchanged and will be ready for use with a solid target again within less than 1 month after termination of the MEGAPIE irradiation.

Boundary Conditions of the MEGAPIE Target

The MEGAPIE target will be used in the existing target block of SINQ.

The beam enters the target block from underneath and passes through a collimator system. The collimator system on the one hand prevents the proton beam from hitting the central tube of the moderator tank surrounding the target and, on the other hand limits the intensity and angular divergence of the evaporation neutrons streaming back from the target into the beam transport system. A special, heavily shielded catcher device is located beneath the last bending magnet to avoid soil activation by the remaining neutrons and, in case of a catastrophic target failure, hold the debris that would eventually fall down. This part of the beam line is designed for use with a solid target only and some retrofitting will become necessary for use with a liquid metal target.

The target and its handling operations must be conceived such that α-contamination of accessible areas in the SINQ facility is excluded under all conceivable conditions. The target design shall follow the present SINQ target philosophy that includes a separately cooled safety enclosure around the regions affected by radiation damage.

The safety shell shall be able to withstand a spill of the target material into the inter-space until solidification of the target material has occurred. The inter-space between the safety shell and the target container shall be surveyed for leakage of either one of the two components.

Double enclosure of all volatile or potentially volatile radioactive materials shall be foreseen.

The outer dimensions of the target must be such that it fits into the target position of the SINQ facility, the existing target exchange flask including its contamination protection devices and the existing target storage positions.

Sufficient shielding must be provided towards the top of the target to allow personnel access for disconnecting the coolant piping, electrical supplies and other media transport lines prior to removal of the target from its operating positions.

Pressure level, pressure drop and temperature level at the secondary side of the heat exchanger must be within the specifications of the existing cooling loops.

The target will be designed for 1MW of beam power at a proton energy of 575 MeV, i.e. a total beam current of I_0 = 1.74 mA. The beam on target has elliptical distribution with Gaussian intensity profiles characterised by σ_x = 19 mm and σ_y = 33.1 mm.

Technical Baseline

The MEGAPIE target at SINQ is shown schematically in Fig. 4.5, with the main components of the target unit and the required new auxiliary systems.

The original concept for the SINQ target was to move the liquid metal from the beam interaction zone to the heat exchanger by natural convection. However, in order to avoid the risk of local overheating the concept of a pumped bypass flow of 1 l/sec to cool the window was adopted as a reference for MEGAPIE.

Although this flow from the bypass pump might be sufficient to avoid overheating during transients, the technical baseline for MEGAPIE was chosen to include a pump also for the main flow. Its estimated capacity should be 4 l/sec at a pressure head as required by the flow resistance in the target. Although an EM-pump has been selected as reference concept, other alternatives will still be evaluated.

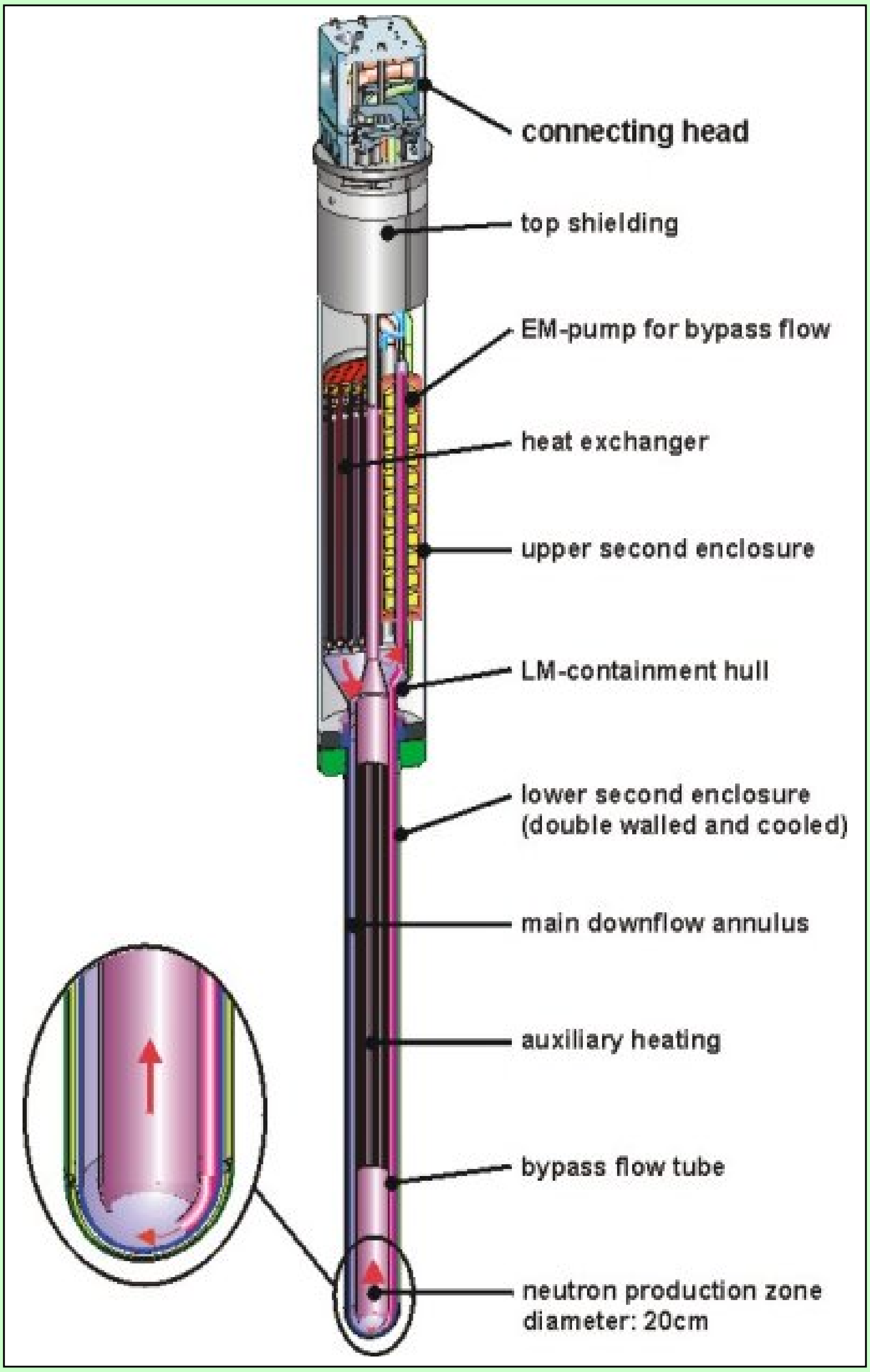


Figure 4.5: Conceptual Design of the MEGAPIE Target

The heat exchanger system must be designed such that freezing of the liquid metal can be safely avoided everywhere in the system even in cases of variable beam power or extended shutdown periods (e.g. the weekly 1-2 days of accelerator maintenance and beam development). Several options to achieve this have been identified. The one selected as the reference concept includes a double walled heat exchanger with an intermediate heat transfer fluid whose level can be varied (e.g. by pressurising a gas volume connected to it).

The structural material for the target container is foreseen to be martensitic (French designation T91 type) steel, at least in its lower part. For the upper part the use of austenitic (316L type) steel is being considered, which is more readily available and easier to weld. This is contingent upon sufficiently high liquid metal corrosion resistance, because the highest temperature gradient in the system will occur along the heat exchanger. In order to facilitate the transition between two different materials the two parts will be joined by a flange system. The whole target container will be surrounded by a second enclosure with an insulating vacuum between. In the lower part this enclosure will be double walled with heavy water cooling as is the present target shell. The material for this part will be chosen for minimum neutron absorption and sufficient strength at any temperature the shell might reach in the case of a breach of the target container. Presently Zircaloy 2 is the favoured material, but this needs to be studied in detail. Again, as in the present target concept, the upper and lower parts of the outer shell will be joined by a flange. The upper part of the outer shell will be stainless steel. Sufficient shielding shall be provided in the top part of the target to avoid excessive radiation levels in the target head room from direct gamma radiation from the liquid metal. Whenever possible, the feeds through this shield should be designed to avoid direct sight.

Supporting R&D at the Participating Laboratories and in International Collaborations

While the MEGAPIE collaboration aims directly at designing, building and testing a Pb-Bi liquid metal pilot target in a 1 MW proton beam, it is embedded in and will profit from a variety of different related research activities its members are involved in.

The most important of these collaborations and activities are the STIP collaboration (radiation effects on materials); the TERM experiments (thermal hydraulics and heat transfer experiments at the Riga Mercury Loop); the PSI Lead Bismuth loop ; the Karlsruhe lead Laboratory (KALLA); the SPIRE project (material irradiation effects) of the 5^{th} FWP; the TECLA project (Lead Alloys Technologies) of the 5^{th} FWP; the French GEDEON network. Furthermore, a proposal to fund design support and integral testing of the MEGAPIE target is under preparation for the second call of the 5^{th} FWP.

The LiSoR experiment

One of the major unknowns in liquid metal target development is related to the question, whether Liquid metal-Solid metal Reactions (LiSoR) in the presence of (static or cyclic) stress are enhanced under irradiation. Since this is a problem that must be solved before a liquid metal target can be irradiated in a proton beam for an extended period of time, an experiment has been initiated to use PSI's 72 MeV Phillips cyclotron to irradiate stressed steel specimens in contact with flowing liquid metal.

Scoping calculations have shown that, while much less radioactivity is produced, the damage levels and gas production in thin specimens by 72 MeV protons are, within reasonable limits, comparable to those on the inside of the proton beam window at 600 MeV. Also, the beam parameters can be adjusted in such a way that relevant heating rates at the solid-liquid interface are obtained. A proposal to carry out such an experiment has been received positively by the Experiment Review Committee and irradiation time has been set aside for the operating period of the year 2001. Currently the rig is being designed by SUBATECH and PSI with support from CNRS and CEA.

LiSoR was originally planned as a stand-alone investigation. Due to its immediate relevance for MEGAPIE, it was incorporated into the project, but, for the time being, is still pursued on a largely independent basis. This is mainly due to temporal restrictions which result from PSI's intention to discontinue operation of the Phillips cyclotron after 2001 and from the time when results are needed to affect the MEGAPIE design. Support for LiSoR has been granted under the first phase of the EU 5th.

4.5. Sub-Critical Systems

4.5.1. The MUSE Experiment

Objectives

The neutronics of sub-critical systems driven by an external source is characterised by the de-coupling of the external source and the sub-critical multiplying medium.

This can be achieved by the availability of the GENEPI (Generateur de Neutrons Pulsé Intense) accelerator based on (D,D) and (D,T) reactions producing two different well-known neutron sources (in terms of intensity and neutron energy) and the MASURCA (Maquette Surgénératrice Cadarache) facility in which different fast multiplying sub-critical media, in term of fuel and coolant nature and arrangement, can easily be loaded. Fig. 4.6 shows a schematic view of the GENEPI-MASURCA coupling.

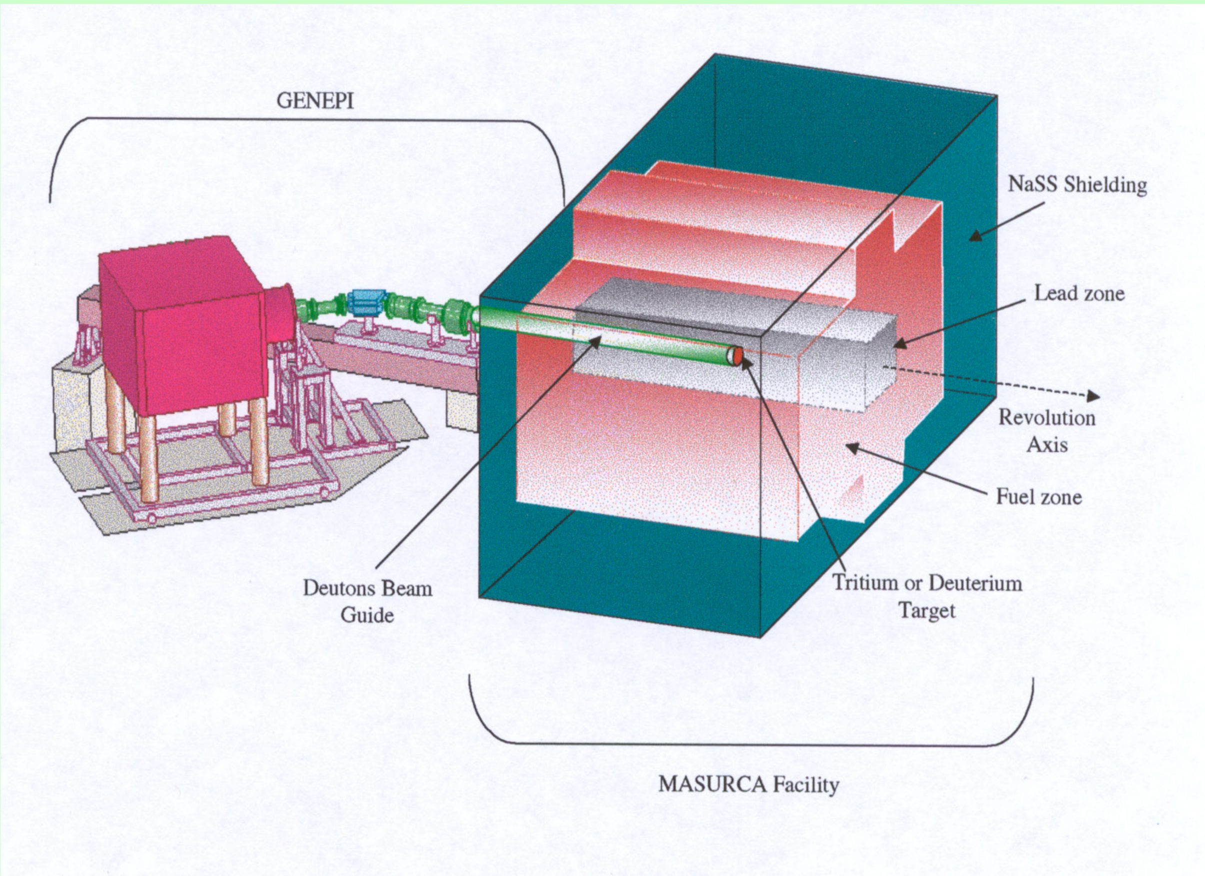


Figure 4.6: Schematic View of the GENEPI-MASURCA Coupling

The main topics are to:

- define sub-critical experimental configurations of interest in terms of fuel, coolant, geometric arrangement, external source type and operating modes (pseudo-continuous and/or pulsed modes);
- experimentally characterise these configurations, in terms of neutron flux level and neutron spectra, by integral experiments using standard or new experimental techniques;
- develop new specific experimental techniques mainly in support to the operation of sub-critical systems, but also for standard integral parameters to obtain a wide range of experimental results to define accurate experimental uncertainties;
- analyse these experimental results by use of different nuclear data files and calculation methods (deterministic and Monte-Carlo tools);
- define a reference calculation route (including nuclear data and calculation tools) for the neutronic predictions of an ADS;
- associate to this reference route a set of residual uncertainties to be compared to the equivalent set for equivalent fast critical system.

Complementary experiments - the SAD experiments: sub-critical assembly in combination with the proton accelerator in Dubna - will be performed, using different spallation neutron sources (Pb, W, Pb-Bi targets) produced by a synchrotron.

A limited number of three main experimental configurations will be studied in the MASURCA facility by the way of a parametric approach, based on the use of the same fuel (MOX fuel) with three different coolant materials:

- sodium: MUSE-4 Experiment;
- lead: MUSE-5 Pb Experiment;
- void (simulating gas): MUSE-5 Gas experiment,

which are the actual retained coolant materials in the analysis of ADS designs.

The well-known external neutron sources issued from the GENEPI accelerator by (D,D) or (D,T) reactions, will be successively used in “pseudo-continuous” mode for all the static measurements and in the pulsed mode with different frequencies (from 50 to 5000 Hz) for the dynamic measurements.

For each previous configuration, a reference critical state will be loaded for the reactivity scale determination by standard reactivity calibration measurement, and for core characterisation in terms of neutron flux level and neutron spectra determination. At minimum, two sub-critical states to be determined for each type of core configuration (i.e. loaded successively with sodium, lead and void - simulating gas - coolant) will be studied with the GENEPI generator out and in operation. Static measurements using the “pseudo-continuous” mode of GENEPI will be performed to characterise the sub-critical media driven by well-known external sources by way of different experimental techniques proposed by the different partners of the consortium.

Using the pulse mode of GENEPI (with various frequencies), dynamic measurements will be performed and different experimental techniques allowing the sub-critical states determination of the different multiplying media will be developed. These measurements will be performed in the frame of an experimental benchmark among the different partners. This last point is of interest for the development of an operating reactivity meter which can be envisaged for a future plant.

These experimental data sets will be then analysed by each partner with their own calculation tools (nuclear data and calculation methods using both deterministic and Monte-Carlo codes). Inter-comparison of the analysis results will be made in the frame of a calculation benchmark exercise between each partner and trends on methods and data will be determined.

Finally, a reference calculation route will be proposed (including nuclear data, methods and residual bias factors) for the predictions of neutronic parameters of ADS. A validated experimental technique (including experimental uncertainties) will also be proposed for the development of an operating reactivity meter which can be envisaged for a future ADS plant.

4.5.2. MYRRHA: A Multipurpose Accelerator Driven System for R & D

SCK•CEN, the Belgian Nuclear Research Centre, and IBA s.a., Ion Beam Applications, are developing jointly the MYRRHA project, a multipurpose neutron source for R&D applications on the basis of an ADS. This project is intended to fit into the European strategy towards the XADS facility for nuclear waste transmutation.

The R&D applications that are considered in the future MYRRHA facility can be grouped as follows:

i) continuation, and extension, towards ADS of ongoing R&D programmes at various European research organisations in the field of reactor materials, fuel and reactor physics research;

ii) enhancement and triggering of new R&D activities such as nuclear waste transmutation, ADS technology, liquid metal embrittlement;

iii) initiation of medical applications such as proton therapy and PET production.

The present MYRRHA concept, as described below, is determined by the versatility of the applications it would allow. Further technical and/or strategic developments of the project might change the present concept. The contribution of the MYRRHA project to the XADS development will be mainly in the field of safety operation of a Pb-Bi based ADS, the licensing of such an innovative system.

The design of MYRRHA needs to satisfy a number of specifications such as:

- achievement of the neutron flux levels required by the different applications considered in MYRRHA:

  $\Phi_{>0.75\,MeV} = 1.0 \times 10^{15}$ n/cm².s at the locations for minor MA transmutation,

  $\Phi_{>1\,MeV} = 1.0 \times 10^{13}$ to 1.0×10^{14} n/cm².s at the locations for structural material and fuel irradiation, $\Phi_{th} = 2.0$ to 3.0×10^{15} n/cm².s at locations for long-lived fission products (LLFP) transmutation or radioisotope production;

- sub-critical core total power: ranging between 20 and 30 MW;
- safety: $k_{eff} \leq 0.95$ in all conditions, as in a fuel storage, to guarantee inherent safety;
- operation of the fuel under safe conditions: average fuel pin linear power < 500 W/cm.

MYRRHA Present Design Status

In its present status of development, the MYRRHA project is based on the coupling of an upgraded commercial proton cyclotron with a liquid Pb-Bi windowless spallation target, surrounded by a sub-critical neutron multiplying medium in a pool type configuration (Figure 4.7).

The spallation target circuit is fully separated from the core coolant as a result of the windowless design presently favoured in order to utilise low energy protons without reducing drastically the core performances.

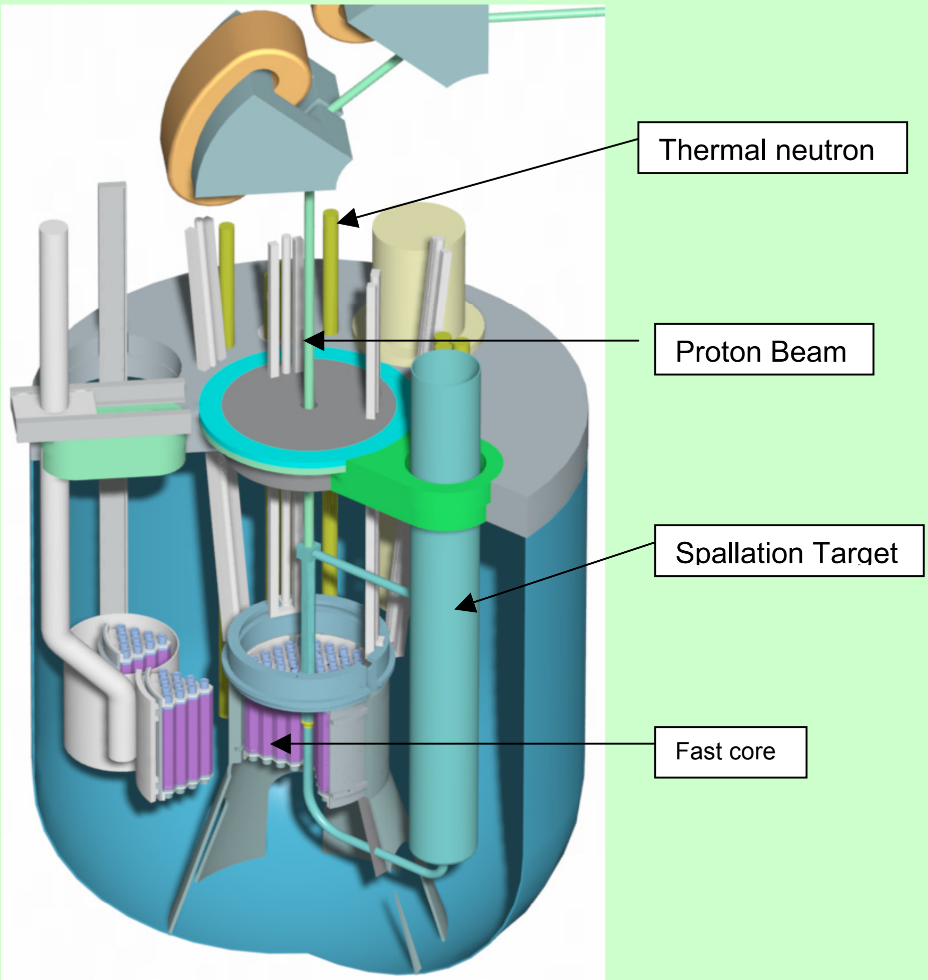


Figure 4.7: Global View of the Present Design of MYRRHA

The core pool contains a fast spectrum core, cooled with liquid Pb-Bi, and several islands housing thermal spectrum regions located in In-Pile Sections (IPS) at the periphery of the fast core. The fast core is fuelled with typical fast reactor fuel pins with an active length of 600 mm arranged in hexagonal assemblies of 122 mm plate-to-plate. The central hexagon position is left free for housing the spallation module. The core is made of 18 fuel assemblies of which 12 have a Pu content of 30% and 6 a Pu content of 20%.

The MYRRHA design is determined by the requirement of versatility in applications and the desire to use as much as possible existing technologies. The heat exchangers and the primary pump unit are to be embedded in the reactor pool. The accelerator is to be installed in a confinement building separated from the one housing the sub-critical core and the spallation module. The proton beam will be impinging on the spallation target from the top.

Accelerator

IBA, a company that has designed the world reference cyclotron for radioisotope production and other machines, is in charge of the design of the accelerator. The accelerator parameters presently considered are 5 mA current at 350 MeV proton energy. The positive ion acceleration technology is envisaged, realised by a two-stage accelerator, with a first cyclotron as injector accelerating protons up to 40 to 70 MeV and a booster further accelerating them up to 350 MeV. This option is not yet frozen: a trade-off of higher proton energy against current is being explored. Other designs, to go in one step from the ion source energy injection up to the 350 MeV desired energy, or accelerating H_2 molecules with stripping at the final energy stage for beam extraction, are in the assessment phase.

This 1.75 MW CW beam has to satisfy a number of requirements, some of which are unique in the world of accelerators up to now. At this level of power, it is compulsory to obtain an extraction efficiency above 99.5% and a very high stability of the beam. In addition, the ADS application needs a reliability well above that of common accelerators, bringing down the beam trip frequency (trips longer than a few tenths of a second) to below 1 per day. The design principles are based on the following lines of thought.

- Statistics show that the majority of beam trips is due to electric discharges (both from static and RF electric fields). Hence the highest reliability requires minimising the number of electrostatic devices, which favours a single stage design.

- In order to obtain the very high extraction efficiency, two extraction principles are available: through a septum with well-separated turns, or by stripping.

- The beams are dominated by space charge. Therefore one needs careful transverse and longitudinal matching at injection, and avoiding of cross talk between adjacent turns (by an enhanced turn separation) if a separated turn structure is required for the extraction mechanism.

The space charge dominated proton beam needs a 20 mm turn separation at 350 MeV if a septum extraction has to be implemented. This solution requires the combination of a large low-field magnet and of very high RF acceleration voltages for realising such a large turn separation, and also an electrostatic extraction device.

In view of what precedes, this solution is not well suited for very high reliability operation. Extraction by stripping does not need separated turns. It may be obtained by the acceleration of H^- ions, but the poor stability of these ions makes them extremely sensitive to electromagnetic stripping (and hence beam loss) during acceleration. The use of H^- would, therefore, lead to the use of an impracticably large magnetic structure. The other solution is to accelerate 2.5 mA of HH^+ ions up to 700 MeV, where stripping transforms them into 2 protons of 350 MeV each, thus dividing the magnetic rigidity by 2 and thereby allowing extracting. This solution reduces the problems related to space charge since only half the beam current is accelerated.

However, the high magnetic rigidity of a 700 MeV HH^+ beam imposes a magnetic structure with a pole radius of almost 7 m, leading to a total diameter of the cyclotron of close to 20 m. The cyclotron would consist of 4 individual magnetic sectors, each of them spanning 45 degrees. At the present stage of R&D the last option appears to be the most appropriate one.

Spallation target

The spallation target is made of liquid Pb-Bi. The Pb-Bi is pumped up to a reservoir from which it descends, through an annular gap ($\varnothing_{outer}$ = 120 mm), to the middle of the fast core. Here the flow is directed by a nozzle into a single tube penetrating the fast core ($\varnothing_{outer}$ = 80 mm). At about the position of the nozzle a free liquid metal surface is formed, which will be in contact with the vacuum of the proton beam guideline. No conventional window is foreseen between the Pb-Bi free surface and the beam in order to avoid difficulties in engineering this component and to keep the energy losses at a minimum. When the Pb-Bi has left the fast core region, it is cooled and pumped back to the reservoir.

The choice of a windowless design was influenced by the following considerations:

- At about 350 MeV, an incident proton delivers 7 MeV kinetic energy per spallation neutron. Almost 85% of the incident energy exits the target in the form of “evaporation” energy of the nuclei. The addition of a window would diminish the fraction of the incident energy delivered to the spallation neutrons.

- A windowless design avoids vulnerable parts in the concept, increasing its reliability and avoiding a very difficult engineering task.

- Because of the very high proton current density (> 130 μA/cm²) and the low energy proton beam we intend to use, a window in the MYRRHA spallation module would undergo severe embrittlement.

A thorough R&D support programme is presently devoted to the demonstration of the feasibility of the windowless design included an experimental design programme with H_20, Hg and in a late phase Pb-Bi.

Sub-critical system

The design of the sub-critical assembly will have to yield the neutronic performances and provide the irradiation volumes required for the considered applications. In order to meet the goals of material studies, fuel behaviour studies, radioisotope production, transmutation of MA and LLFP, the sub-critical core of MYRRHA must include two spectral zones: a fast neutron spectrum zone and a thermal spectrum one.

Fast zone description

The fast core will be placed centrally in a liquid Pb-Bi or Pb pool, leaving a central hexagonal assembly empty for housing the spallation target. It consists of hexagonal assemblies of MOX FR-type fuel pins with a Pu-content, Pu/(Pu+U), ranging from 20% to 30%, arranged in a triangular lattice with a pitch of 10 mm. The fuel pins have an active fuel length of 50 cm (but could be increased to 60 cm to achieve the requested performances) and their cladding consists of 9% Cr martensitic steel.

The fuel pins are arranged in typical FR fuel hexagonal assemblies with an assembly dimension of 122 mm plate-to-plate. The fast zone is made of 2 concentric crowns, the first one consisting of 6 highly enriched fuel assemblies (with 30% Pu content) and the second one of 12 fuel assemblies of which 6 are 30% enriched and 6 are 20% enriched. The table 4.2 below illustrates the preliminary results we obtained for a particular configuration.

Table 4.2 Achievable performance in the MYRRHA sub-critical core

	Neutronic Parameters	Unit	Value
Spallation Source	E_p	MeV	350
	I_p	mA	5
	n/p - yield		4.40
	Intensity (E_n < 20 MeV)	10^{17} n/s	1.23
Sub-critical Core	K_{eff}		0.948
	K_s		0.959
	IF		1.29
	MF = 1 / (1 - K_s)		24.51
	Thermal power	MW	32.2
	Average power density	W/cm^3	232
	Peak linear power	W/cm	475
	n Flux > 1 MeV	10^{15} n/cm^{2}s	
	around the target		0.83
	first fuel ring		0.73
	n Flux > 0.75 MeV	10^{15} n/cm^{2}s	
	around the target		1.14
	first fuel ring		1.03
	Number of fuel pins		2286

Thermal zone description

The initial design, with a water pool surrounding the fast core zone and housing the thermal neutron core zone, has been completely changed for evident safety reasons (water penetration into the fast zone). In the present approach the thermal zone will be kept at the fast core periphery, but it will consist of various In-Pile Sections (IPS) to be inserted in the Pb-Bi liquid metal pool from the top of the reactor cover. Each IPS will contain a solid matrix made of moderating material (Be, C, $^{11}B_4C$) on which a total leakage flux of 1 to 3 10^{15} n/cm².s will impinge.

Local boosters made of fissile materials can be considered depending on the particular performance needed in the thermal neutron IPS. Black absorbers settled around the IPS could ensure the neutronic de-coupling of the thermal islands from the fast core.

In addition to the spallation target, the fast core and the thermal islands, the pool will contain other components of a classical reactor such as heat exchangers, circulation pumps, fuel loading and handling machines, and emergency-cooling provisions.

4.6. Material studies

4.6.1. Lead-Bismuth technology: material developments and R&D support

Introduction

Liquid eutectic lead-bismuth is considered to be an adequate spallation material for an ADS. Besides the well-known advantages, lead and lead-bismuth have a high corrosion potential to most common alloys. The fundamental mechanism of this physical-chemical interaction is the so-called liquid metal corrosion, which is characterised as follows:

- Solution of metal components of the structural material in the liquid metal;
- Mass transport of structural materials within the loop due to temperature gradients, e.g. dissolution in the hot parts and deposition in the cold parts of the loop;
- Change in the structure and the morphology of the materials surfaces;
- Influence on the mechanical properties of the structural materials;
- Reaction of the structural materials with non-metals that are dissolved in the liquid metal, e.g. oxygen.
- Synergic effect between neutron/proton radiation and corrosion (i.e. Liquid Metal Embrittlement).

An ADS specific phenomenon concerns the isotope production in presence of high-energy protons and neutrons because of the spallation and fission reaction of heavy elements. These isotopes can change the physical-chemical characteristics of the liquid metal and thus the corrosivity, considerably. As for possible window materials this chemical attack is combined with the thermal load due to the internal heating by the high-energy proton beam.

It is known that austenitic steels with a high amount of nickel can be severely corroded as long as they are unprotected. Ferritic-martensitic and low-alloyed steels, however, show a very much more favourable corrosion resistance. Although there is no corrosion data available in the literature for tungsten and tungsten-rhenium, only limited corrosion is expected due to their low solubility in lead and lead-bismuth. However due to high affinity to oxygen and the poor quality of the oxides of those materials, only the use in virtually oxygen free liquid metal should be envisaged.

Another possibility to improve the corrosion resistance of materials is the control of the oxygen concentration in the liquid metal within a well-defined range, in order to produce at the interface stable oxides able to act as corrosion barriers. In the case of steels, the oxygen concentration has to be set in such a way, that a stable Fe-Cr-Mn-Oxide scale can be formed on the metal surface, whilst the lead-bismuth loop is not plugged by oxides that are removed from the metal surfaces.

R&D Support

As far as material development, the objective of future R&D must be to elaborate the scientific-technical fundamentals of the corrosion/erosion behaviour of metallic structural and window materials that are in contact with flowing eutectic lead-bismuth.

The main interest should be focussed on nickel-free, ferritic-martensitic steels of the 12% Cr-type and, due to the high temperature strength, on the high chromium/high nickel austenitic steels. In order to limit corrosion of structural materials the following scientific aspects have to be considered:

- Chemical-physical effect of inhibitors in lead-bismuth;
- Long-term stability of scales on the structural materials that are formed by a pre-oxidation under air atmosphere;
- Development of coatings and/or superficial treatments able to act as a surface protection to improve the corrosion resistance;
- Metallurgy of the proposed steels and the effect of the alloying elements.

As far as fundamental aspects of Pb-Bi technology, the most important issues are:

Impurity control and removal: In order to assure the safe operability of a lead-bismuth system and its components over a satisfactory life-time it is necessary to investigate the consequences of the presence of impurities. The initial impurities before start-up and the sources of impurity production during operation (corrosion products, spallation products, ingress of impurities) have to be quantified. Efficient methods to control and remove the main metallic and non-metallic impurities have to be developed: mechanical filters, EM traps, getters.

Oxygen measurement: The control of the oxygen concentration is of major importance for the long-term operation of a lead-bismuth system, e.g. prevention of corrosion attack on structure materials, and thermodynamic equilibrium of the system and prevention of plugging in cold zone. The direct measurement of the oxygen potential can be done with an electro-chemical oxygen probe. Criteria such as long-term stability, resistivity to thermal cycling, aging of the ceramics and the reference material are of major importance and have to be considered for these components.

Oxygen control: The main requirement of an oxygen control system is to establish a stable oxygen potential within the Pb-Bi system for a given temperature gradient under steady-state and transient operational conditions. This, in turn, establishes oxidic protection layers on the structure materials which effectively slow down the corrosion attack. This is the case as long as the oxygen potential is high enough in order to prevent the dissolution of the oxides from the steel surface and the oxygen potential is low enough to prevent the formation of lead oxide.

Thermal-hydraulic measurement techniques: Thermal-hydraulic measurement techniques and calibration instructions are needed for in-situ and on-line measurement and control of operational parameters such as temperature, flow rate, velocity, heat flux, pressure, void. Measurement techniques, which are well-known for a liquid metal such as sodium, have to be adapted and improved for application to high temperature lead or lead-bismuth. These are: permanent-magnet flow meter probes, ultrasonic velocity measurement technique, pressure transducers with coupling fluid, impedance void meters. Important aspects to be considered are: surface modification due to corrosion (e.g. change in heat transfer characteristics), wetting, and the influence of impurities.

The objectives of these issues are to work out the scientific-technical fundamentals to characterise the impurities and to define purification systems; to measure and to control the oxygen concentration in flowing lead-bismuth; to provide an instruction on how to guarantee the corrosion resistance of structure materials; and to develop and calibrate measurement techniques for lead-bismuth.

The whole R&D work must include all technologies necessary to handle and to operate a lead-bismuth loop safely and without unscheduled interruptions for many years.

Application to demonstration facility

In a first step, the R&D issues have to be investigated and verified with small and medium-scale experimental test facilities being available within the EU.

In a second step, a strategy and the functional requirements have to be set up to scale-up and implement the achieved results to a large-scale demonstration facility.

Programmes and main dedicated facilities

Due to the complexity of the work, a strong and intense collaboration on an international level has to be set up. In Europe a well co-ordinated R&D programme – TECLA - has been launched under the auspices of the European Commission within the 5th FWP. The several experiments scheduled under the TECLA programme have been performing (and will be performed) in the various Pb-Bi loops and facilities, already installed or in construction in some various research centres. The large flexibility and broad application of these facilities will allow further extensions of the experimental tests, well beyond the end of TECLA programme (2003), in particular for the specific needs of Pb-Bi XADS development.

4.6.2. TECLA - Technologies, materials and thermal-hydraulics for lead alloys

TECLA, the R&D European programme on heavy liquid metal technology for ADS, was approved by the EC in mid-2000. The main goal of the programme is to assess the use of lead alloys both as spallation target and coolant for an ADS. Three major fields will be investigated: corrosion and protection of structural materials, physico-chemistry, and technology of liquid lead alloys. One of the most important deliverable is the production of a reliable corrosion database at the end of the experimental activity. Moreover, taking into account the existing experiences and the outcomes of the ongoing activities, different solutions aimed at protecting materials against corrosion will be developed and validated. At the same time the effects of the presence lead alloys on the mechanical properties of structural materials will be evaluated. A preliminary assessment of the combined effects of proton/neutron irradiation and liquid metal corrosion will be performed.

As far as mechanical property degradation and effects of irradiation on corrosion, special attention will be devoted to the problem of liquid metal embrittlement. Analytical correlations and numerical computational tools, to be used in lead alloy systems, will be developed and validated.

A close co-operation among the EU laboratories is foreseen: 16 organisations (industry and research bodies) from 6 different countries.The work is divided into six work packages, sub-divided in several specific tasks. The work packages (WP) are related to the main items of the research as follows in table 4.3.

Table 4.3 The TECLA work packages

WP 1. *Corrosion of materials in lead alloys*: basic corrosion studies to pre-select promising materials and to investigate the basic mechanisms of corrosion; determination of the corrosion kinetic of steels in flowing Pb-Bi as function of different parameters; effect of spallation products on Pb-Bi corrosion.

WP 2. *Structure protection and corrosion resistance enhancement*: evaluation of methods of protection by "in situ" oxide formation (Russian technology) and by deposition of coatings, protection obtained by using metals and alloys with high corrosion resistance. A special attention will be given to evaluate the possible counter-measures able to reduce the effects of spallation products.

WP 3. *Mechanical behaviour of structural materials in contact with lead alloys*: generation of thermodynamic data base for multi-constituent systems, calculation of equilibrium phase diagrams for steels in contact with Pb or Pb-Bi with special emphasis on spallation residuals, wettability studies, grain boundary penetration and liquid metal embrittlement studies; mechanical characterisation.

WP 4. *Effects of irradiation on lead alloys corrosion*: preliminary investigations on corrosion and LME under proton/neutron irradiation (including LiSoR experiment);

WP 5. *Impurity control and removal*: characterisation of impurities and definition of purification systems, development of electrochemical cells for on-line oxygen measurement.

WP 6. *Thermal-hydraulic experiments*: production of a thermal-hydraulic data base for code validation in the field of local heat transfer, turbulence and thermally highly-loaded surfaces such as the beam window; demonstration of design critical flow configurations for an ADS, simulating natural circulation, two-phase flow and mixing phenomena in a geometrically similar configuration.

The main expected results are:

- Creation of a data-base on Pb-Bi corrosion and development of protection systems;
- Demonstration that the steels are not unacceptably injured in presence of LM and proton/neutron irradiation;
- Development of techniques able to maintain the required LM purity for a safe operability of the ADS;
- Development/validation of analytical correlations and numerical computational tools for thermal-hydraulic;
- Evaluation of design solutions for the window and the core.

4.6.3 KALLA - Karlsruhe Lead Laboratory

In a first step, experiments in stagnant lead-bismuth have to be performed. The oxygen control can be done via the gas atmosphere. But corrosion investigations in stagnant liquid metal systems can only give a rough estimation for a material selection, as the corrosion kinetics are mainly influenced by fluid dynamic parameters such as the flow velocity. Thus, corrosion tests in flowing lead-bismuth are crucial. Such experiments will be performed in the CORRIDA (CORRosion In Dynamic lead Alloys) Loop of KALLA (fig 4.8).

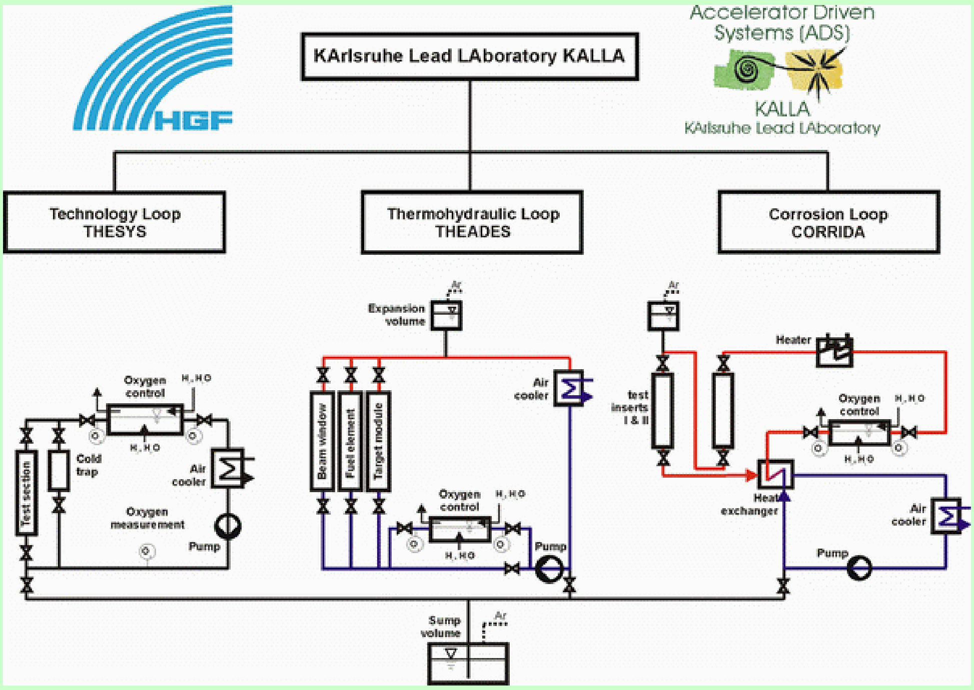


Figure 4.8: The Karlsruhe lead laboratory KALLA: Sketch

The important data of CORRIDA are:

- Piping and components: austenitic high temperature steel
- Total volume of the liquid metal: 0.15 m³
- Maximum temperature: 550°C
- Reynolds number within test section: > 2300 (turbulent flow)
- Flow velocity within test section: 2.0 m/s
- Number of test sections: 2
- Specimen geometry: Cylindrical probes
- Oxygen measurement: Zirconia based oxygen sensor
- Oxygen control: via gas phase
- Mode of operation: continuous

The design and construction of the corrosion loop was done in 1999-2000; the erection will be finished in the middle of 2001.

The reliable investigation of the corrosion attack kinetics requires a minimum of one year experimental time (approximately 8000 h). In order to develop time dependent physical relationships, probes are withdrawn from the test sections after 1000, 3000 and 5000 hours. The specimens are micro-analytically investigated, using metallography, SEM/EDX, AES and microprobe analysis.

4.6.4. LECOR & CHEOPE-III: metal corrosion facilities at ENEA-Brasimone

In the framework of the Italian activities related to corrosion of steels and refractory metals for ADS application in presence of flowing and stagnant lead and lead bismuth liquid alloy, three relevant facilities are already available at the ENEA site of Brasimone. The LECOR (lead corrosion) and CHEOPE-III (chemical and operational) loops were designed and constructed to study corrosion related phenomena in flowing lead-bismuth under different operative conditions. Moreover, a system to characterise the corrosion of different materials in presence of stagnant lead and lead-bismuth alloy was developed and used to achieve the first experimental results.

LECOR – lead corrosion loop

The main objective of the experiments to be carried out in LECOR (sketch in fig. 4.9) is the quantitative study of corrosion phenomena and related mechanical effects affecting steels and structural materials, in presence of flowing lead bismuth alloy under different operative conditions such as temperature, velocity of the flowing liquid metal, oxygen concentration. In particular, the behaviour of materials and coatings at low oxygen activity, simulating the presence of a reducing environment in the spallation target of an ADS system, will be tested.

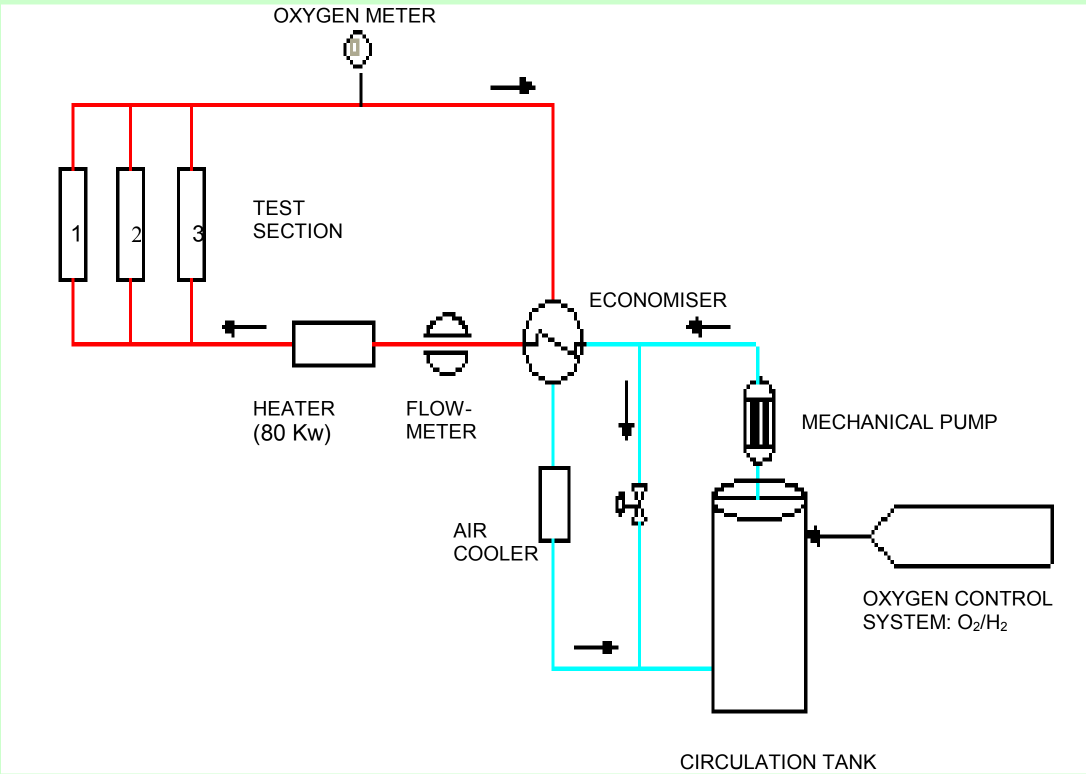


Figure 4.9: Sketch of the LECOR Loop

The LECOR loop was designed and constructed in co-operation between ENEA and F.N. S.p.A. and has been made available at the ENEA site of Brasimone since July 2000. LECOR has a figure-of-eight configuration with a high and a low temperature leg which allows a continuous transport of corrosion products from the hot section zone to the cold one, simulating the actual behaviour of coolant fluid in a power plant.

The reference working conditions during the experimental phase in LECOR and its characteristics are as follows:

- Piping and components: Ferritic and Austenitic (cold part) steels
- Cold branch temperature: 250÷350°C
- Hot branch temperature (test sections): 350÷450°C
- Number of test sections: 3
- Liquid metal velocity within test sections: 0.3÷0.8 m/s
- Liquid metal flow rate max.: 4 m^3/h
- Lead bismuth volume: 0.480 m^3
- Oxygen content: < 10^{-9} wt/%
- Materials investigated: Martensitic and Austenitic steels, W alloys, Mo coating, Ta and Nb.

The experimental conditions foreseen for this loop are defined in order to investigate the behaviour of relevant materials to be used in target systems (MEGAPIE, MYRRHA).

A special care is taken in operating the oxygen control system since the corrosion rate of the materials is a strong function of the oxygen concentration in the molten alloy.

The CHEOPE-III loop

CHEOPE-III is a part of the multipurpose facility CHEOPE and it has the following main characteristics:

- Piping and components: Martensitic steel T91
- Total volume of liquid metal: 50 l
- Maximum Temperature: 500 °C
- Flow velocity within test section: 0.5-1 m/s
- Oxygen concentration: 10^{-4} – 10^{-7} wt%
- Materials investigated: Martensitic and Austenitic steels

This loop is equipped by a Russian oxygen meter and a Zirconia based sensor developed in ENEA.

The main goal of this loop is to prove the “in-situ” oxidation technology taking into account the Russian technology and in close co-operation with IPPE. A system for the oxygen control in the whole loop has been designed in ENEA in collaboration with IPPE and is under qualification in this loop.

Glove-Box

A laboratory device was used for the compatibility tests in stationary liquid metals. These compatibility tests are relevant as they give information on the basic mechanisms of corrosion, while tests in flowing liquid metals are necessary to evaluate the corrosion behaviour of the material when erosion and mass transport are involved. At present the dependence of the basic aspects of the liquid metal corrosion/oxidation from temperature is under investigation in the case of steels. The aim of the work is to define the temperature limits for the applicability of the “in-situ” oxidation protection technique.

4.6.5. CIRCE – Circuito Eutettico

CIRCE is the largest facility for heavy liquid metal technology development, and will provide experience on thermal-hydraulic and material behaviour in a pool configuration, as well as full-scale tests of the critical components of the spallation target and the XADS - Pb-Bi option. CIRCE components are provided by Ansaldo in the ENEA Research Centre of Brasimone (Italy), and will be filled with Pb-Bi and operated at the end of 2001. After the testing planned in the frame of the Italian national programme, CIRCE will be proposed as a European facility for component testing and qualification within a European programme.

CIRCE is designed to operate with different test sections, including a full-size spallation target, core sectors with fuel elements and moving parts of refuelling mechanism.

The CIRCE test facility, of which fig. 4.10 shows a schematic view, has been designed using the following scaling ratios respect to the XADS (Pb/Bi option):

Scale 1:1 in height of the main vessel;

Scale 1:5 in diameter of the main vessel (1:25 in section and volume);

Scale 1:80 in power

The resulting Pb-Bi volume capacity is 10 m^3, the height of the main vessel 9 m and the power supply of 1.1 MW (1/80 of the nominal power of XADS).

The main parameters for CIRCE are:

- Test Vessel size (m): Ø1.2 x 9.0 high;
- Total Pb/Bi load: 100 Tons;
- Electric power for the test section 1.1 MW;
- Max operating temperature 500 °C;
- Pb/Bi flow rate in the pool up to 70 kg/sec;
- Argon vol. flow rate ~20 Ndm^3/sec;
- Argon pressure 0.4 MPA;

- Diathermic oil flow rate on secondary circuit 10 Kg/sec;
- Heat sink Air Cooler.

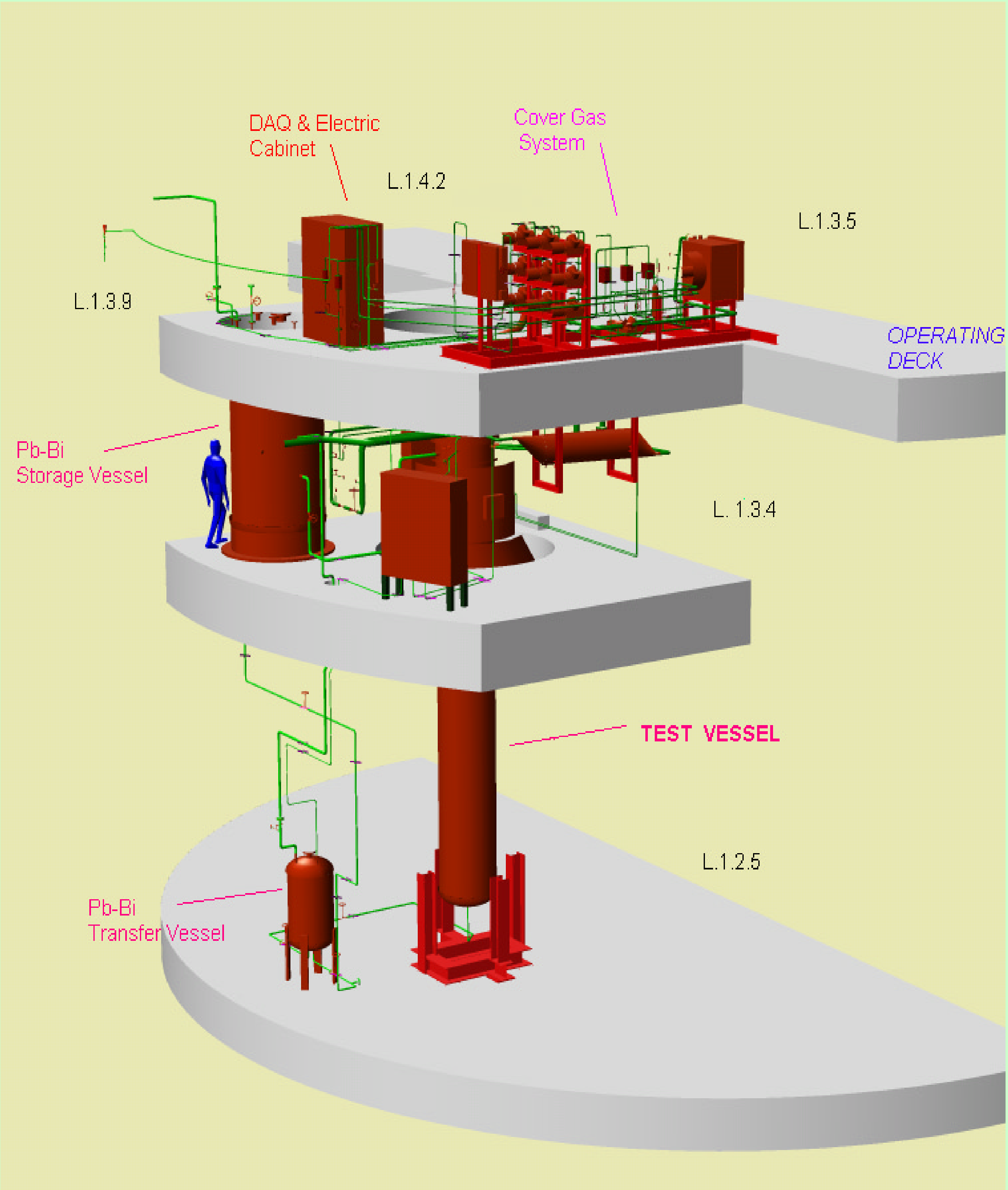


Figure 4.10: Global View of the CIRCE Facility

The experimental tests to be performed in CIRCE are the followings:

Eutectic Circulation Enhanced by Gas Injection. Goals of this experimental activity are: to test the performances of the circuit; to evaluate possible instabilities; to optimise the gas injection system; to verify gas carry-under and to obtain thermal-hydraulic data for code validation.

Control of the oxygen activity. The aim is to study the change of the oxygen activity in LBE as function of the PO_2 content in the cover gas, within the temperature range of the test.

Eutectic purification. The two goals of this test are: to study the efficiency over time in removing the suspended particles by means of filtering elements or concentration of suspended particles at the LBE free level of a dedicated component; to assess different pumping systems to drive the by-pass flow through the filter (electromagnetic pump, gas lifting, etc.).

Corrosion tests. The activity is aimed at evaluating the behaviour of the materials under operating conditions typical of a pool-type ADS. Tests will be performed in the temperature range of 250-450 °C and the use of an oxygen control system is foreseen.

Hydraulics of the windowless target. The scope is: to study the main thermal-hydraulic phenomena; to perform the geometrical optimisation of the target; to evaluate the main parameter range to prevent LBE stagnation in the target region; to determine the requirements of LBE flow rate control system and requirements of the pipe vacuum control system.

Fuel element pressure losses. The main goals are: the assessment of the fuel element pressure losses and the fuel element bypass flow; the collection of data for code validation. The activity will be carried out in isothermal regime (200-450°C) and in a flow-rate range of 5-100 kg/sec.

Mechanical equipment working in Pb/Bi. This test will be devoted to the operability of the basic kinematics of various mechanical equipments working in Pb/Bi. At the same time an assessment of the evolution of functional clearances and corrosion effects in these components will be performed.

Integral system. The test goals are the study of the fuel clad/coolant heat transfer, the primary/secondary system heat transfer and the plant performance evaluation in normal and accident conditions (i.e. loss of enhanced circulation). Moreover, plant operating conditions effect on corrosion and thermal-hydraulic data for code validation will be determined. The activity will be carried out in steady state as well as in transient and accident conditions.

4.6.6. SPIRE – Spallation and Irradiation Effects

The SPIRE project – Spallation and Irradiation effects in martensitic steels under neutron and proton mixed spectrum - involves ten European organisations and foresees a close co-operation with other scientific communities (i.e. Materials for Fusion and Intense Neutron Sources).

One of the most critical components in ADS is the target. The structure of the spallation target is commonly seen as a container with a window to tightly separate the vacuum of the accelerator from the spallation liquid metal.

The irradiation conditions in the structure of the target are expected to be severe. Assuming a maximum proton current density of ~70 µA/cm^2 and a full calendar year of operation, the present estimates of atomic displacements and spallation elements production in martensitic steels, derived from HETC computation, are the following: the atomic displacements amount to ~100 Displacements Per Atom (dpa) in the window and ~50 dpa in the container structure of the target. This will result in the formation of point defects clusters, dislocation loops and possible phase instability and precipitation, all phenomena that generally contribute to harden and embrittle the structural steels.

In the window, the direct impingement of the proton beam results in the production of H (~90,000 appm), He (5,000 appm) and other spallation elements (Ca :~1,000 appm, Ti :~1,000 appm, V :~1,000 appm, P : ~200 appm, S : ~600 appm) that will induce significant changes in the in-service properties, especially hardening and embrittlement of structural steels.

In order to resist such irradiation conditions, high Cr martensitic steels have been selected as prime candidates. The main issues concerning the integrity and the lifetime of the spallation target structures are expected to be brittle fracture by decrease in ductility and fracture toughness, as well as loss of dimensional stability by swelling or irradiation creep.

The SPIRE project addresses therefore the effects of irradiation specific of spallation target on basic in-service properties (tensile, creep, Charpy, fracture toughness, irradiation creep and swelling), with the following general objectives in the perspective of a XADS:

- Determine the properties of selected structural steels under spallation target irradiation conditions;
- Provide the basic mechanisms and modelling for the phenomena observed under spallation conditions;
- Specify a reference material and give a path for the development of an advanced window material;
- Provide basic data and guidance for conceptual design purposes.

From a design point of view the data obtained in the proposed programme will permit to calculate the allowable stresses and deformations defined for irradiated materials developed for example in the ITER design rules. In addition, it is to be noted that the programme remains generic and does not address critical issues more directly dependent of a specific design, such as fatigue under irradiation or physical stability of coating if required against corrosion.

As above mentioned, on the basis of several considerations, the following structural materials for the window and the target container have been selected:

- Conventional 9Cr and 12Cr martensitic steels: 9Cr1Mo, 9Cr1MoVNb and 12Cr1MoVW;
- Experimental alternative clean martensitic steels: 7-9Cr1-2WTa.

The analytical approach selected to meet the objectives of technical feasibility of the target of an ADS has resulted in dividing the SPIRE programme into six work-packages (WP) including a co-ordination tasks shown in table 4.4.

Table 4.4 The SPIRE work packages

WP 1: *Co-ordination*

WP 2: *Metallurgy before irradiation*. Most of the spallation elements are either not present in the initial chemical composition or exist in a very low and well controlled concentration range as it is the case for P and S (typically P < 350 appm, S < 100 appm). The changes in physical metallurgy, microstructure and mechanical properties under thermal ageing, resulting from the spallation elements, namely P, S, and Ti, will allow a better understanding of the results obtained from simulation, neutron and proton-neutron mixed spectrum irradiations.

WP 3: *Experimental simulation of irradiation effects in a spallation spectrum.* The major aim of the WP is to simulate, via implantation of appropriate elements, the microstructure evolution, hardening and possible changes in fracture mechanisms, induced by energetic spallation particles.

WP 4: *Neutron and Post-Irradiation Examination (PIE).* This work-package is devoted mainly to complete the assessment of the effect of neutron irradiation on (i) mechanical properties (tensile, Charpy, fracture toughness) in the range of low temperature between 200 and 400 °C where the existing data on hardening, embrittlement and fracture toughness are to be completed and (ii) long term evolution of mechanical properties and loss of dimensional stability due to possible onset of swelling at high dose and for temperature in the range 400 to 550°C.

WP 5: *Irradiation under mixed proton-spectrum and Post-Irradiation Spectrum.* The objective is to characterise microstructure and mechanical properties of structural materials after irradiation in a prototypical mixed flux of protons of energy in the range 500 keV to 1 GeV and neutrons produced by spallation.

WP 6: *Basic studies : numerical simulation of irradiation effects*. The irradiation effects in spallation target structure materials can only be studied up to limited dose under prototypical neutron-proton mixed spectrum. At the high dose relevant to the XADS, the irradiation effects are to be simulated by charged particles and neutron irradiation. The objective of this work-package is to provide the basic understanding and tools for reliable understanding and prediction of the irradiation damage and its consequences on hardening and solid cohesion, in order to extrapolate the high dose neutron simulation data to the relevant spallation spectrum.

4.7. Advanced fuel and fuel processing studies

4.7.1. Overview

As far as advanced fuel cycles to be implemented in future ADS transmutation devices, many different types of fuels or targets for transmutation of actinides have been suggested in the recent years, mainly depending on fuel cycle strategy considerations. Two general approaches can be distinguished in this context:

i) The mixing of small quantities of minor actinides (MA), up to about 2.5 w%, together with plutonium to the fuels of standard cores. This has, however, a big impact on the fuel cycle because the number of MA-containing sub-assemblies would be relatively high and the effect on the core reactivity coefficients would be considerable.

ii) The use of dedicated fuels/targets, which have a high content of plutonium and minor actinides, in special actinide “burners”, such as an ADS. The number of sub-assemblies required for the same mass throughput is much less than that for i). In addition, the impact on the core reactivity can be reduced by optimising the design of the subassemblies. For a fuel the isotopic composition gives rise to a critical or a reasonably subcritical core, whereas a target, in contrast, does not contribute significantly to the reactivity of the reactor core.

It is obvious that when a fuel or target does not contain uranium or thorium, the transmutation efficiency is higher because no new actinides are formed. In that case a non-fissile (inert) matrix may be considered as support or diluent of the actinide phase. In a homogeneous fuel or target, the diluent forms one phase (a solid solution) with the actinides, in a heterogeneous fuel or target the actinide phase coexist with the diluent (a dispersion). Of course, combinations of the two concepts or non-diluted fuels or targets need to be considered as well.

Significant experience exists for uranium-based fuel forms but there is a lack of knowledge about the characteristics and fabrication technology for the corresponding uranium-free fuel forms. However, qualitatively the physico-chemical properties of homogeneous uranium-free fuel forms are generally poorer than the corresponding uranium- and also thorium-based forms as relevant properties (melting point, thermal conductivity and chemical stability) decrease systematically for most compounds going from Th to Am. These poor(er) properties might be compensated by the choice of the matrix of the fuel, but only a limited number of adequate materials have been identified, none of them being ideal in all respects and compromises thus have to be found.

It is therefore felt that thorium compounds, though fertile and thus not “inert” with respect to neutron capture, should be considered as a matrix for MA, at least as a back-up solution. For example, the properties of ThO_2 are very promising in this respect: it has a high melting point and a thermal conductivity close to that of UO_2.

Moreover, ThO_2 is very radiation resistant and thus allows reaching high burn-up. The fabrication of thorium oxide pellets, spheres, or coated particles is well known. It needs to be extended to $(Th,MA)O_2$ but this technology has been partially developed for $(U,Pu,MA)O_2$ in the past.

Also with respect to the irradiation behaviour, almost no information is available on uranium-free fuel forms. The EFTTRA-T4 experiment is the only known case in which minor actinide in a non-fertile matrix has been irradiated. This experiment has demonstrated the importance of the helium gas accumulation in the fuel, leading to intolerable swelling if no engineering measures are taken. This helium accumulation in the fuel, is considered to be the Achilles heel of MA fuels. In this respect some lessons can also be learned from the SUPERFACT experiment on the $(U,MA)O_2$, which has shown a satisfactory behaviour of fuel containing 20 wt% Np plus 20 wt% Am, though the burn-up was relatively low. This seems to support the suggestion to consider ThO_2 as matrix for MA fuels.

R&D support – On going and future programmes

Because of the general lack of knowledge on the properties and behaviour of uranium-free fuels, it is not possible to reach firm conclusions on the best fuel forms for an ADS transmuter at this moment. However, the most promising areas on which the European research should be focused can be identified.

It is evident that oxide and composite fuels, and to a lesser extent nitride fuels, are the most promising candidates for further research. Composite fuel is considered the most innovative of these because the properties can be tailored to the application. However, the limitations of this fuel type need to be investigated thoroughly. Mixed transuranium oxide fuel is the closest to current European MOX fabrication technology and for this reasons it is an important candidate to consider. It has clearly advantages with respect to fabrication and thermo-mechanical stability but less promising thermal properties may limit its application. Mixed nitride fuel forms is a reasonable alternative for the (homogeneous) mixed oxide if the high temperature stability can be dealt with, for example by addition of ZrN.

In order to test an advanced fuel for transmutation of the transuranium actinides in the XADT, a careful planning of the development phase is required. It is also known from past experience that fuel development is very time consuming because long irradiation tests are involved. To test fuel pins or fuel assemblies of advanced fuel forms in the XADT around 2020, a carefully co-ordinated European effort is required, for which the following suggestions are made:

1. A specific irradiation experiment in combination with a dedicated out-of-pile programme on the determination of the basic properties of mixed transuranium oxide fuel should establish the limits of the use of this fuel form for ADS. A period of 4-5 years is required for the out-of-pile part, provided the necessary infrastructure is available. For irradiation tests, a longer period (8-10 years) would be required. The ongoing activities of the EFTTRA collaboration and of CEA (ECRIX and CAMIX experiments) should be integrated in this.

2. The research on composite fuels for ADS transmuters must be focussed on the MgO-$(Zr,An)O_{2-x}$ ceramic-ceramic and the steel-$(Zr,An)O_{2-x}$ ceramic-metal fuels. Many aspects of these fuels need to be investigated in detail such as fabrication, irradiation behaviour and fundamental properties. A period of 6-10 years is required for a systematic research programme on these topics. It is of key importance that the first screening tests (in-pile as well as out-of-pile) are started as soon as possible.

3. Because MA-containing nitride fuel is studied extensively for the ADS concepts in Japan and Russia, it should not become a major topic of the European research. It is recommended to seek a collaboration with the Japanese and Russian activities in this field. The CONFIRM project in the 5th FWP (irradiation of (Zr,Pu)N fuel – see above) should be starting point for such a collaboration.

4. It is recommended that thorium-based mixed oxide will be considered as back-up solution for the fuel of the ADS transmuter. Some research in this field should therefore be initiated.

5. In about 10 years, the primary fuel form for the European ADS development could be selected on the basis of the experimental results of the proposed activities. However, it should be clear that more details about the system design of the ADS must be fixed rapidly. Especially the type of cooling has a big impact on the fuel: operating temperatures in gas-cooled cores will be higher than in liquid-metal cooled cores, and the possible corrosion by the coolant needs to be considered in liquid-metal cooled cores. Also the safety approach has an impact of the fuel selection and fuel design, and different scenarios need to be considered.

6. The research on targets for iodine transmutation should be continued, taking into account the specific conditions in the ADS core. No clear incentive exists for the study of targets for transmutation of caesium.

7. There are only two fabrication laboratories in Europe able to handle americium and curium for R&D on fuels and fuel processing: ITU (JRC, Karlsruhe) and ATALANTE (CEA, Marcoule). Taking into account the volume of basic data needed to demonstrate the feasibility of dedicated fuels for ADS in a lot of fields, it is obvious that both laboratories at least are needed to manage a complete programme over a period of 10 to 15 years. Complementary actions have to be taken between the two laboratories to cover such a programme. This is an additional argument to focus in Europe the R&D on MA-based oxide fuels (homogenous or composite fuels), as MA-based nitride fuels have been already investigating at JAERI, Japan for about 10 years and metallic fuels have been recently proposed by US as a promising candidate for the ATW.

8. For the testing of the irradiation behaviour of fuels and targets for transmutation in ADS, the XADT is an important instrument as no fast reactor will be available in the EU after 2004. It is felt that the XADT must be integrated with a fuel fabrication facility and hot cells at one site to avoid time-consuming transports and enhance the efficiency of the research.

Along these lines, some important R&D programmes on new fuel matrices have been already launched within the 5th FWP.

4.7.2. ITU Fuel Cycle Facilities

In the Institute for Transuranium Elements in Karlsruhe two unique facilities for the study of advanced fuel cycles will be available in the near future: a laboratory for the fabrication of minor actinide containing fuels and targets (the so-called MA-lab) and an istallation for pyrochemical studies on active and irradiated materials. A short description of the two facilities is given below.

The MA-lab

The Minor Actinide laboratory consists of two glove-box chains that are built to fabricate fuels and targets containing significant quantities of minor actinides such as americium and curium. A schematic layout is shown in fig. 4.11.

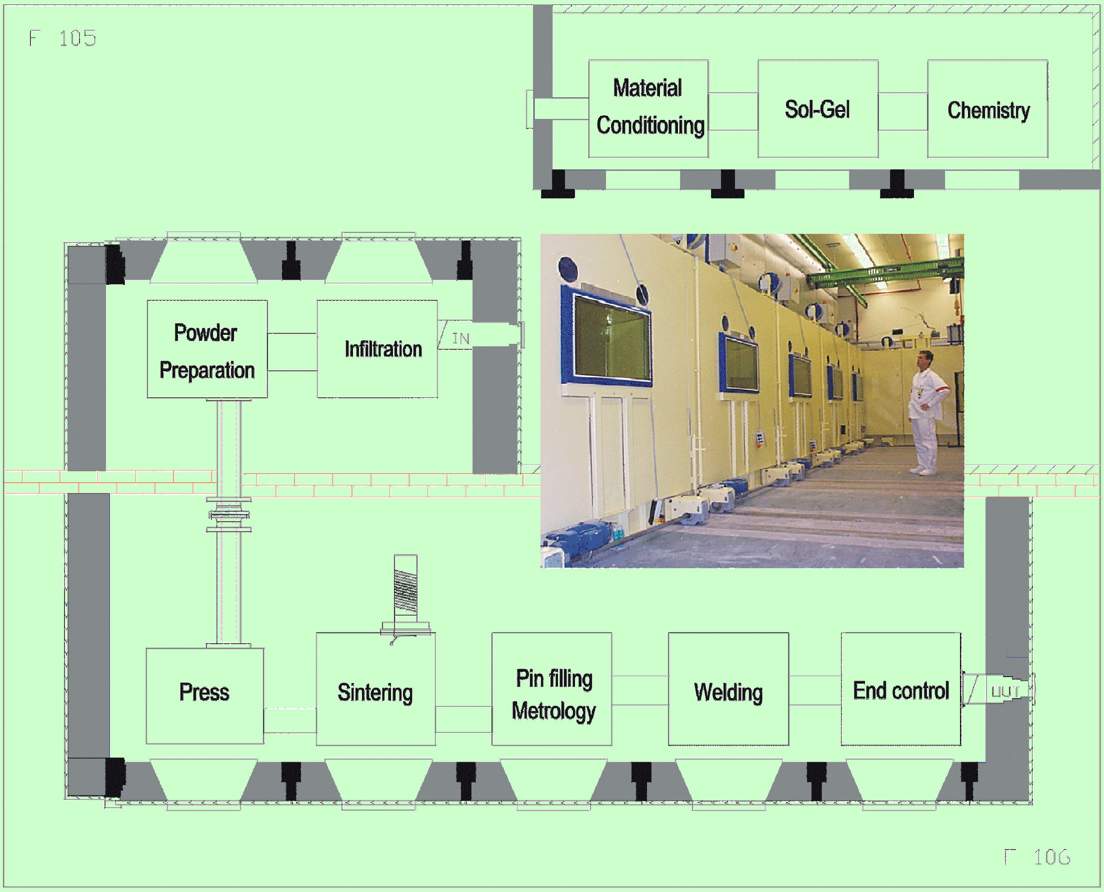


Figure 4.11: The Minor Actinide laboratory at the Institute for Transuranium Elements, JRC Karlsruhe

The main chain consists of 7 glove boxes that are shielded by a thick stainless steel protection wall containing 50 cm water (neutron radiation) and 5 cm lead (gamma radiation). The limiting masses are 150 gram of ^{241}Am or 5 gram of ^{244}Cm. The processes in the glove boxes are partly automated by the use of robots and remote control, but actions are also carried out using telemanipulators.

The reference fabrication processes are based on dust-free techniques such as SOL-GEL and infiltration. The installation is equipped with an infiltration device for powder preparation, calcination furnace, a bi-axial press, a sinter furnace (1650 ^{o}C) for reducing, inert and oxidising conditions, pellet inspection and metrology, pin filling and pin welding of fuel pins up to 100 cm, and fuel pin characterisation (X-ray).

In addition to the seven glove boxes that form the core of the MA-lab, a separate chain of three glove boxes for preparation of powders containing americium or dirty plutonium by SOL-GEL technique will be installed. The shielding of these glove boxes, which are also operated with manipulators, is much less: 5 mm lead and 20 cm polyethylene. The limiting mass is 50 grams of ^{241}Am. The powder produced in this chain can be transferred to the main MA-lab chain where it can be processed further.

The pyro-processing facility

At ITU an installation is being set up to demonstrate the technical feasibility of the electro-refining - reductive extraction concept, and also look for conditions to improve the electro-refining of Am from lanthanides (fig. 4.12). The installation will be the first to operate in the gram-scale (the facility at Argonne National Laboratory in Idaho separates only uranium by electro-refining and disposes off the transuranium elements unseparated from each other, together with the fission products).

Figure 4.12: The stainless steel caisson for the pyro-processing installation at the Institute forTransuranium Elements, JRC Karlsruhe

The installation at ITU consists of a stainless steel box, which fits behind the lead shielding of the hot cells. The atmosphere inside is pure Argon with less than 10 ppm H_2O and O_2 each. We are prepared to process MA containing alloys, described below, but also high level liquid waste from the PUREX process, which we will convert into dry halides. In order to process also oxide fuels, the actinides have to be converted into chlorides or, possibly by reduction with Li, directly to the metals. In preparing the fuel for reprocessing or during different process steps, the separation of long-lived radiotoxic fission products can be achieved. If a voloxidation of the spent oxide fuel is included in the pre-treatment, several fission products are distilled off including ^{129}I, which could be collected with 99.9 % yield. During the electro-refining process, 95% of the ^{99}Tc is collected together with the noble metal fission products in the bottom Cd layer of the electrolysis cell. For the transmutation of the two fission products, special targets have to be fabricated.

4.7.3. EFTTRA - Experimental Feasibility of Targets for Transmutation

EFTTRA, is a network of research organisations in France (CEA, EdF), Germany (FZK), Netherlands (NRG) and the JRC (IAM, ITU) that was formed in 1992. The goal of EFTTRA is the study of transmutation of americium as well as of the long-lived fission products technetium (^{99}Tc) and iodine (^{129}I). The work of the partners of the EFTTRA group is focused on the development and testing of targets and fuels, taking into account the scenarios developed in Europe for P&T strategies.

To that purpose fabrication routes are being investigated, irradiation tests are performed, and post-irradiation examinations are made. Effective use is made of the unique facilities of the EFTTRA partners such as the Minor Actinide fabrication laboratories (MA-lab), irradiation facilities (HFR, Phénix) and the hot-cell laboratories. Table 4.5 gives an overview of the EFTTRA irradiation experiments performed up to now. Results can be found in the literature.

Table 4.5 The EFTTRA irradiation experiments.

Name[a]	Reactor	Description	State of the art
T1	HFR	Technetium and iodine	Completed
T2	HFR	Technetium	Completed
		Neutron damage in inert matrices	Completed
T2bis	HFR	Neutron damage in inert matrices	Completed
T3	HFR	Neutron damage in inert matrices	PIE ongoing
		Dispersion inert matrix fuel using enriched UO_2	PIE ongoing
T4	HFR	Americium in spinel	PIE ongoing
T4bis	HFR	Americium in spinel	PIE ongoing
T4ter	HFR	Central fuel temperature of spinel/UO_2	PIE ongoing
T5	HFR	Americium in Zr-based targets	planned
F1	Phénix	Neutron damage in inert matrices	To be continued
		Dispersion inert matrix fuel using enriched UO_2	PIE ongoing
F1A	Phénix	Neutron damage in inert matrices	To be continued
		Dispersion inert matrix fuel using enriched UO_2	To be continued

[a] Some of experiments known under different names such as RAS or MATINA.

4.7.4. CONFIRM - Collaboration on Oxide & Nitride Fuel Irradiation & Modelling

The CONFIRM project, which involves seven European organisations, was approved by EC in mid-2000 and will last 4 years. The main scope of this European programme is to develop uranium free nitride fuels to be irradiated, in particular, in ADS.

While nitride fuels may operate at higher linear ratings and therefore are of interest as an advanced alternative to the oxide reference fuel in the development of ADS, there are a few drawbacks associated with the nitride fuel form that needs to be addressed in terms of a basic research program before a larger effort on qualifying the nitrides as an ADS fuel could be launched. The main expected problems related to the use of nitride fuel are:

- High temperature stability in terms of dissociation. In particular, dissociation of AmN is expected to occur at comparatively low temperatures;
- Relatively high pellet clad mechanical interaction at high burnup, due to a combination of higher solid fission product swelling rate and lower plasticity of nitrides as compared to oxides;
- The production of C-14 due to (n,p) reactions in natural nitrogen, that significantly deteriorates the reduction of long lived radiotoxic inventories.

In addition, helium production due to alpha-decay of Cm-242, causing fuel swelling, will be a problem for all fuels containing high fractions of Am-241.

Hence, within the present project, simulations of uranium free nitride fuel irradiation up to and above 20% burnup fraction will be made with improved versions of a nitride fuel simulation code, in order to optimise pin and pellet designs. Scoping calculations on advanced bonding options like nitrogen and sodium will be made. An in-depth safety analysis of nitride fuel performance during power transients will be performed. Vaporisation, liquid metal formation and pin pressurisation will be modelled theoretically. An experimental investigation of UN dissociation will be made to validate the models.

Fabrication of (Pu,Zr)N and (Am,Zr)N pellets and characterisation of important properties like thermal conductivity and high temperature stability will be made. (Pu,Zr)N pins of optimised design will be fabricated and irradiated at high linear power (~ 70 kW/m) with a target burnup of about 10%.

Evaluation of whether use of 99% N-15 enriched nitrogen is sufficient to reduce C-14 accumulation in a P&T scenario to acceptable levels is part of the project.

Design work on a boron carbide poisoned fuel assembly will be made in order to assess the possibility of reducing helium production rates in fuel pins.

The main results of the project are a significantly extended database on important properties of plutonium and americium nitrides, a comprehensive safety evaluation of uranium free nitride fuels, and an optimisation of (Pu,Zr)N pellet and pin geometry and composition enabling a high linear power, high burnup irradiation of (Pu,Zr)N pins.

4.7.5. FUTURE – Fuel for Transmutation of Transuranium Elements

The objective of the FUTURE project is to study the feasibility of oxide actinide compounds $(Pu,Am)O_2$, $(Th,Pu,Am)O_2$ and $(Pu,Am,Zr)O_2$ to be irradiated as homogeneous or composite fuel (diluted in an inert matrix) for ADS. Because of the poor knowledge on such innovative compounds, the R&D programme is largely devoted to the synthesis of the compounds, their characterisation (thermal and chemical properties up to high temperatures) and the development of fabrication and pyrochemical reprocessing processes.

Modelling codes will be developed to calculate the fuel performance of these homogeneous and composite fuels and will be fed with the experimental results. Assessment of their behaviour under accident conditions will be analysed using experimental date obtained at high temperatures. All this information should allow to define the best design concept(s) of ADS fuels, taking into account the whole fuel cycle and a suitable qualification and validation tests programme in European reactor(s) beyond this programme.

Several technical issues have to be addressed to demonstrate the feasibility of Accelerator-Driven System to transmute long-life radionuclides. One of the most critical is the fuel and fuel cycle issue. This project aims at giving all the basic elements which are sorely lacking to design fuel and fuel cycle dedicated to the transmutation. So, it is essentially focused firstly on experimental work: synthesis and characterisation of new actinide-based oxide compounds, development of fabrication and reprocessing processes, and, secondly on modelling calculation: design optimisation, performance prediction, and safety behaviour. An irradiation programme is also proposed to be realised, however beyond this programme, to qualify and validate the selected fuel and design option(s).

4.7.6. Thorium cycle

Development Steps for PWR and ADS Applications

The use of the thorium cycle offers challenging options for nuclear waste reduction, both at the back end and the front end. The general objective of this project is to supply key data for application of the Th-cycle in PWRs, FRs and ADS, related to Pu and TRU burning and reduction of the lifetime of nuclear waste. To achieve this, the irradiation behaviour of Th/Pu fuel at high burn up and for relevant neutronic conditions will be examined. The very high Pu/TRU consumption in Th/Pu fuel will be validated by full core calculations.

Following the conclusions of the 4th FWP Thorium project, the following items were recommended for further study: (i) Behaviour of Th-based fuel at extended burn up under respectively PWR, FR and ADS conditions. (ii) Geological disposal and related leaching behaviour of the Th-based fuel, in particular the release and mobility of Iodine and Protactinium (Pa). (iii) Reprocessing of Th-based fuel, in particular less waste producing extractants and an update of the THOREX process flow sheets. (iv) Core calculations for Th-based fuel, validation of previous results from 4th FWP work. (v) Experimental determination of nuclear data for Th-232 and Pa-233 and incorporation of these data in a consistent library. In the present proposal for the 5th FWP the items (i) and (iv) are selected for further study.

To investigate the fuel behaviour under relevant neutronic conditions, two irradiation experiments will be performed.

Four targets $(Th/Pu)O_2$, $(U/Pu)O_2$, UO_2 and ThO_2 will be fabricated, and irradiated in the HFR up to a high burn up. Detailed post-irradiation examinations will be performed on all four targets.

One $(Th/Pu)O_2$ target will be irradiated in KWO Obrigheim under PWR specific conditions in a MOX neutron spectrum. This target will be irradiated in this programme up to a burn up of about 35 GWd/t.

The full core calculations will be performed to validate the conclusions drawn from the pin cell burn-up results in the 4^{th} FWP and to give more precise results for the voided core especially at higher fuel burn-ups (80 or 100 MWd/kgHM) applying Th/Pu-MOX fuels in a PWR. Core burn-up and layout on full core level will be determined for $(Th/Pu)O_2$ and compared with $(U/Pu)O_2$ fuel.

Important milestones are the start of irradiations and the transports of target material. The project should result in key data of Th-based fuels, specifically for the irradiation behaviour at high burn-up full core PWR behaviour, and thereby provide experimentally based information for the application of the Th-cycle.

4.7.7. PYROREP – Pyrometallurgical processing Research Programme

The partitioning of minor actinides is still subject of research. Hydrochemical and pyrochemical techniques are under investigation. Hydrochemical processes have a high potential to separate the minor actinides from spent fuels as demonstrated by extensive research, especially in Europe. However, the major drawbacks of this technique for uranium-free fuels for ADS are:

- The limited solubility of many fuel forms considered.
- The limited stability of the organic extraction molecules in high radiation fields expected for spent ADS fuels/targets.

As a result, the hydro-chemical processes are considered to be more relevant to the first stratum reprocessing of LWR or FNR fuel than for the second stratum reprocessing of ADS fuel/targets.

Pyro-chemical techniques seem to offer the highest potential for reprocessing of ADS fuels/targets due its good compatibility with most fuel forms and its high radiation resistance. In addition, the compactness of the technique is an important advantage. Electro-refining is generally considered to be the most promising pyro-chemical method and it is being investigated world-wide, especially in US, Japan and Russia.

The research activities on pyro-chemical reprocessing in Europe should be intensified. Its use for the processing of mixed transuranium oxide and composite fuels, which have been identified as the main candidate fuel forms, has to be demonstrated. It is important in this respect that facilities will become available.

A specific project has been launched on this field within the 5^{th} FWP, PYROREP. This R&D programme, which involves six European organisations as well as CRIEPI (Japan), was approved by EC in mid 2000 and will last up to 2003.

PYROREP should yield sufficient basic data to assess pyrometallurgical processing flow sheets for use with irradiated fuels and targets. The experiments carried out will provide an opportunity to develop specific methods and apparatus, identify materials compatible with pyrometallurgical process constraints (high temperatures and corrosive media).

Each elementary chemical process will be investigated: oxide fuel conversion to halide form, radionuclide separation by electrolysis or metal/salt exchange, recycling of process reactants, liquid and solid process waste treatment. The performance of each step (yields, decontamination factors, etc.) will be assessed.

The project comprises three work packages (WP) shown in table 4.6.

Table 4.6 The PYROREP work packages

WP 1. *Separation*: the possibility of separating the actinides and the lanthanides will be assessed by two methods, salt/metal extraction and electro-refining. The experiments will be carried out in inactive and active conditions. The media will be molten fluoride salt and molten chloride salt. The recovery yield and purity of each actinide will be measured.

WP 2. *Subsidiary steps*: subsidiary process steps necessary to implement a full separation process will be also assessed:

Salt decontamination: the goal of this step is to recover the actinide traces contained in the saline phase in order to reduce MA losses into the final waste. Two methods will be evaluated: liquid-liquid extraction in active conditions between a molten fluoride salt containing actinides and a metallic phase, and electrolytic methods in a chloride medium with active material. Decontamination factors of alpha emitters will be given at the end of these tests.

Material selection and testing: all these operations use corrosive reagents at high temperatures; suitable metallic construction materials compatible with molten fluoride salt media will be selected and tested.

WP 3. *Waste and system studies:* leach tests will be carried out on inactive sodalities. The performance of various pyrochemical processes will be compared with regard to segregation factors, decontamination factors, final product compositions and characteristics, recycling of reactants, waste quantities and characteristics and economics assessments (at preliminary stage).

4.8. PDS-XADS – Preliminary Design Study of an XADS

The purpose of this project is: to perform "Preliminary Design Studies of an XADS" in the 5th FWP; to identify and study a minimum set of design activities which are considered mandatory for assessing the engineering feasibility of the reference options; to contribute to the selection of one solution to be further developed in detail within the 6th FWP.

Preliminary design studies of the XADS will allow:

- Selection of the most promising technical concepts;
- Address the critical points of the whole system (i.e. accelerator, spallation target unit, reactor housing the sub-critical core);
- Identify the research and development (R&D) in support;
- Define the safety and licensing issues, to preliminary assess the cost of the installation;
- Consolidate the road mapping of the development of the European XADS.

Further, these studies will allow to focus the R&D programmes priorities on the needs for the development of the ADS. European nuclear engineering companies associated with major nuclear research organisations propose to elaborate the technical specifications for a European XADS, and to perform its preliminary design studies.

The preliminary design studies developed in different EU member countries are concentrated mainly on three concepts of the nuclear reactor part:

- a small-scale XADS (20-30 MW thermal) cooled by a lead-bismuth eutectic (LBE);
- a larger (about 80 MW thermal) LBE-cooled concept;
- a gas-cooled concept with two alternatives: a fuel-element reactor devoted to burn MA, which will receive the higher priority in this context, and a pebble-bed reactor devoted to burn all types of transuranics, including plutonium.

An alternative candidate is the sodium-cooled concept, but because of the considerable existing knowledge and validation on sodium technology, similar preliminary design studies would have a lower priority. Therefore, the sodium-cooled concept is not considered in these preliminary studies.

The spallation target is preferably a liquid heavy metal. Two main concepts are envisaged: liquid heavy metal separated or not from the accelerator by a window.

For the accelerator, the two envisaged concepts are the cyclotron and the LINAC.

The purpose of the proposal is to develop these configurations to a level sufficient to define precisely the supporting R&D needs, to perform objective comparisons, and eventually to recommend the solution to be engineered in detail and realised.

Also, the proposal will allow to develop a close working organisation, useful for a future realisation and operation of the XADS, (i) between the engineering companies and the R&D organisations on the one hand, and (ii) between the design experts for the reactor, the spallation target, and the accelerator on the other hand.

The preliminary design studies of the different reactor concepts of the XADS are a necessary step for objectively assessing the feasibility of an industrial ADS series for transmutation of nuclear wastes.

The engineering activity needed for the XADS preliminary design studies will be mainly focused on the engineering analysis of the critical points of the whole XADS concepts: the reactor and the sub-critical core, the spallation target unit, and the accelerator.

To facilitate the preliminary engineering (and later the detailed engineering, the procurement, construction and operation) of a complex facility such as the XADS the plant is functionally divided into systems. Within each system, sub-systems and components will be defined.

The main systems, which essentially determine the XADS configuration and cost, are described hereunder as reference concepts. These concepts originate from scoping studies carried out so far. The outcome of the preliminary engineering proposed herewith, may lead, however, to replace these first-reference concepts with alternative solutions.

The project is split in five main work-packages (WP) shown in table 4.7.

The project will be split into three main phases. The first phase, with duration of about six months, will be dedicated to the definition of the main technical specifications of XADS. The second phase is the preliminary engineering design studies of the different concepts. Its duration is about two years. The third phase is the evaluation and comparison phase of the different XADS concepts. Recommendations will be elaborated for implementation in the European XADS road mapping.

Table 4.7 The PDS-XADS work packages

WP 1: is dedicated to the objectives and specifications of the XADS. It will define the methodologies and criteria for evaluation and comparison of the concepts.

WP 2: concerns the safety studies. It is divided into three sub-WPs: WP 2.1 will define a common safety approach for all the concepts; WP 2.2 concerns the phenomenological studies, and WP 2.3 the application to the XADS design concepts.

WP 3: is dedicated to the design studies of the accelerator and the comparison of the accelerator concepts. It will allow to organise the consistency of the accelerator studies and the reactor studies.

WP 4: is related to the core design studies. There are three sub-WPs: WP 4.1 related to the LBE-cooled core; WP 4.2 related to the gas-cooled studies including the pebble-bed fuel concept; WP 4.3 related to the spallation target unit studies.

WP 5: the design studies of the primary circuit and the implementation of the main components together will be done in the WP 5 which is sub-divided in three sub-WPs: WP 5.1 related to the 80 MW LBE-cooled concept; WP 5.2 related to the gas-cooled concept; WP 5.3 related to the system integration of a “Small scale concept”.

4.9. Possible Transmutation Strategies based on Pebble Bed ADS Reactors for a Nuclear Fuel Cycle without Pu recycling in critical reactors

A proposal to transmute the waste, particularly the transuranics (TRU), in a multi-spectral gas cooled pebble bed reactor (see fig. 4.13) is being studied by some research groups in Spain (U. Polytechnic of Madrid, LAESA, et al.).

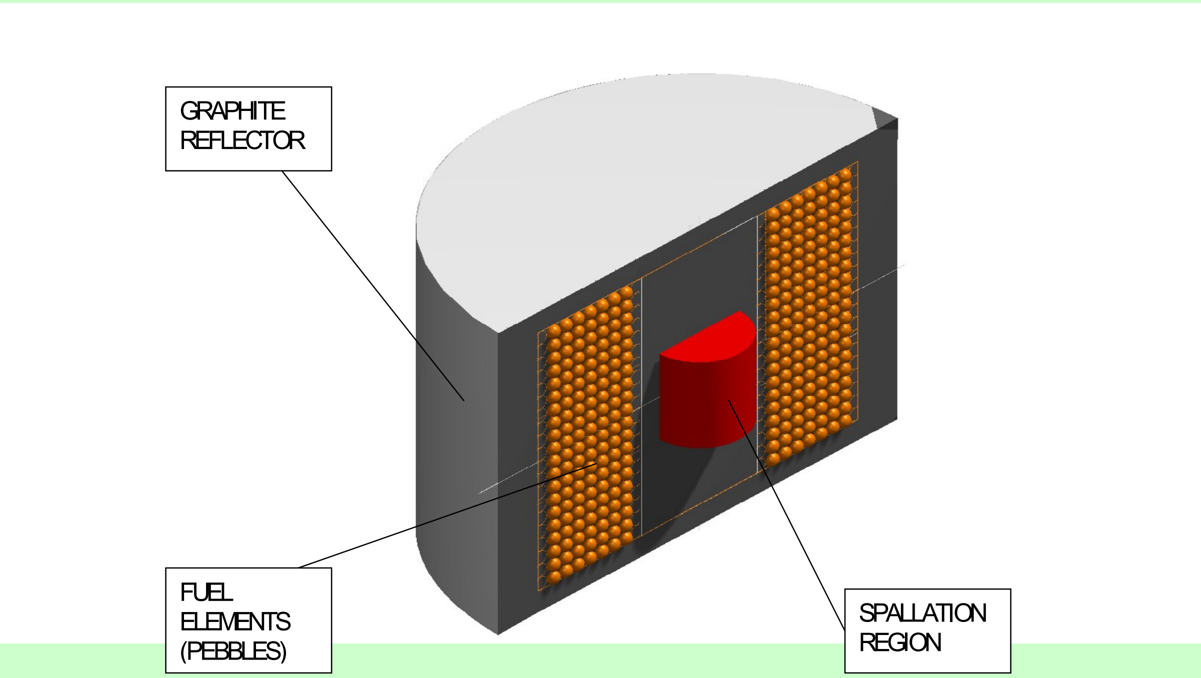


Figure 4.13: Sketch of a Pebble-Bed ADS, showing the main elements

Due to the presence of MA, this reactor will be sub-critical, its power operation being achieved by using an external neutron source, which also permits the creation of a hard neutron spectrum region, advantageous in the transmutation of MA. Three basic strategies for waste transmutation have been identified. These strategies have not been optimised so far, but they can be taken as scenarios to assess the nuclear technology capability to meet this objective. In all cases, it is assumed a constant power level of 1 GWe in LWR, i.e., it is a picture of an equilibrium case, where all variables are kept in a constant value and the systems work in a steady state.

By choosing a power level of reference (1 GWe) this hypothetical study could be applied to any country or set of countries. The nuclear fuel variables chosen for completing the frame of reference are in agreement with this power level plus additional hypothesis that are explained below. In particular, the isotopic composition of the spent fuel considered for this study is just the one reported in table 1.1 of chapter 1.

In the reference option - the once-through cycle - the spent fuel is not treated at all. In the transmutation strategies reported here, the spent fuel is reprocessed and transuranics (TRU) are eliminated in ADS. Each strategy has a specific definition. Of course, these strategies are purely theoretical for the moment, and a large R&D effort would be needed to implement any of them.

Strategy A: **Single pass TRU transmutation in ADS**. Following a 15 year cool-down period, the LWR spent fuel is reprocessed once and all the actinides are transformed into TRISO fuel particles embedded in a graphite sphere. The fuel is circulated in the reactor, (or reactors), until a burnup (BU) of 700 GWd/t is achieved, which is considered the maximum burnup achievable with technologies proven in the past. This strategy requires that the transmuting reactors have a total power of 0.207 GWe, that is, ~ 17% of the total nuclear park (LWR+ADS). The spent fuel from the transmuters will not be reprocessed again, but buried after a suitable cooling period. The materials flow and the radiotoxic consequences of this strategy are shown in fig. 4.14 and 4.16 respectively. The resulting Pu composition can be considered non-proliferant, as the quantity of ^{239}Pu is less than 1% of its initial value, and about 2% of the total residual Pu. A very sophisticated technology would be required to separate the residual Pu, because of the radiotoxicity of the waste. However after several thousand years ^{243}Am will decay into ^{239}Pu and its fraction will increase significantly again. There could be several variants to this strategy based on the inclusion or exclusion of the Long-Lived Fission Products (LLFP) and Np in the transmuted fuel.

Strategy B: **Pu-239 minimisation by multiple reprocessing.** In this strategy 99.5% of the most offending proliferation prone material, namely ^{239}Pu, will be transmuted. This strategy requires that the transmuting reactors have a total power of 0.26 GWe, which is about 21% of the total nuclear park (LWR+ADS). This strategy requires the reprocessing of the irradiated TRISO fuel particles, and the reinsertion of the reprocessed actinides, containing mainly MA, either into a special transmuting fast spectrum ADS or as an additive to the new TRISO fuel elements into the pebble bed core. The radiotoxic consequences of this strategy are shown in fig. 4.16. Using this strategy the amount of ^{243}Am will be much smaller than in strategy A. There could also be several variants to this strategy.

Strategy C: **TRU minimisation by multiple reprocessing**. In this strategy 99.5% of all the actinides will be transmuted. This strategy requires that the transmuting reactors have a total power of 0.27 GWe, that is, about 22% of the total nuclear park (LWR+ADS). This strategy also requires the reprocessing of the irradiated TRISO fuel particles. The materials flow and the radiotoxic consequences of this strategy are shown in fig. 4.15 and 4.16 respectively. Several variants to this strategy could be defined, based on the inclusion or exclusion of the LLFP, the reactor spectra chosen for each irradiation cycle and the fuel compositions to be used.

In figure 4.16, the radiotoxicity of the waste for each strategy is shown. It is measured in relative terms, using natural uranium ore radiotoxicity as the reference point: this value is 19.7 kSv per ton of natural uranium. The reference curve labelled “Waste Fuel. No transmutation” is the radiotoxicity of the spent fuel without any type of nuclear treatment. The “Transmuted Waste” is the fuel unloaded from the transmutator, with a high content of fission fragments, which decay in about 400 y. Because of them, both curves are very similar in the time span between 30 to 100 y. Afterwards, the transmuted waste decays much more rapidly. Contribution of the actinides to the transmuted waste is also shown, as well as the radiotoxicity level of natural uranium ore from which the fuel cycle starts.

Strategy C, in which the maximum amount of actinides is transmuted, will result in the total waste reaching the level of natural U after 400 y. Applying strategy B, this level will be reached after 500 y. If LLFP such as ^{99}Tc and ^{129}I will be separated and transmuted into stable isotopes, the Nat-U level will be reached in 300 and 400 y with strategy B and C, respectively. However strategy C is also the most expensive and requires the largest amount of reprocessing. In order to implement this strategy, some of the transmutation cycles must be performed in a fast neutron spectrum.

A transmutation scheme could be based on a Symbiotic Accelerator Driven System, (SADS), a multi-region multi-spectral reactor (or reactors with different spectral characteristics), so that efficient destruction of all the relevant materials will be possible. The Pu burning is most efficient in the thermal spectrum, while MA can be destroyed much better in the fast spectrum close to the spallation target, or in the regions of resonance absorption. Using multi-spectral gas cooled core for the Pu and MA destruction has the advantage of performing the different transmutation tasks in the spectral region most suitable for the operation.

The proposed Pebble-Bed transmuter (PBT) has the additional flexibility that one can tailor more easily the desired region by a continuous movement of the fuel spheres, from one radial region to the other by reloading the partially burned fuel with fresh fuel, and then inserting them close to the target axis where harder spectrum prevails, achieving the desired degree of actinides elimination. This flexibility results in an equilibrium core, which can operate under a quasi constant power and flux distributions. While the fuel sphere is moving from region to region, different parts of its fuel isotopic composition are destroyed.

Most of the Pu and MA can be burned in the proposed PBT because the TRISO fuel particles can undergo very high BU, as was demonstrated in the Peach Bottom experiment, where BU levels of 700 GWd/t were achieved in samples of TRISO particles, with the ^{239}Pu fraction reduced by 99.9%. The combination of high BU, multi-spectral fluxes, and the continuous movements of the pebbles through the core allows to burn Pu and MA, and to reduce the radio-toxicity of the spent fuel from PBT to very low levels.

The actual regional geometry, and the reactor size(s) were not yet fully determined in this preliminary study. It is not yet clear whether a single core will be sufficient to accomplish the task, because of the need of different neutron spectra. A multi-core system is also a possibility under consideration. A detailed optimization of the multi-parameter PBT system, which is proposed, could be carried out in the future.

Preliminary investigations have shown that the proposed system has good safety characteristics. Shutdown of the accelerator using a simple fail proof method will render the neutronic power to zero within a short period of time. Reactivity effects can properly be featured to guarantee sub-criticality. As relatively small and “slim” reactors are envisaged, the decay heat removal can then be accomplished by natural circulation and heat transport to the vessel walls, which will be air-cooled by natural circulation. This method has been shown to work in several previous designs of the modular pebble bed reactor. In addition, the proposed core has a very large heat capacity, and can withstand very high temperatures.

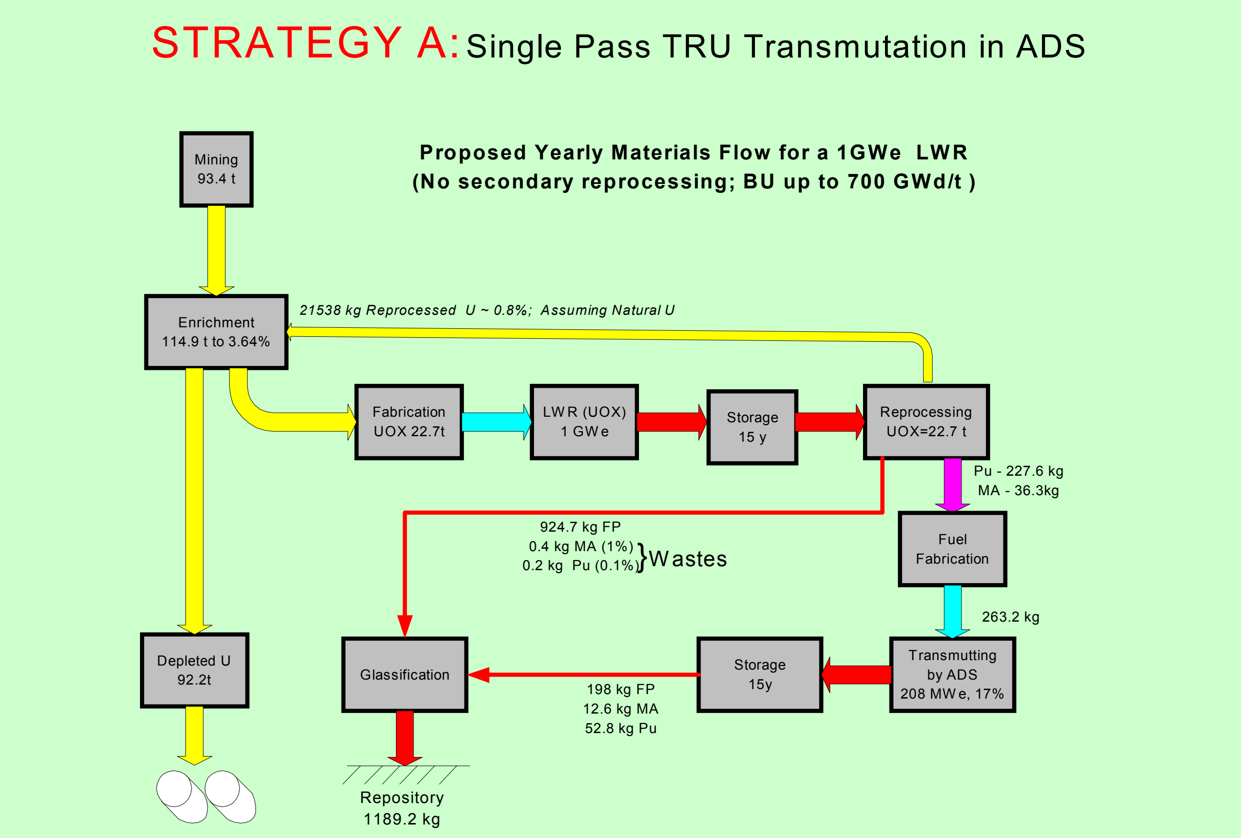


Figure 4.14: Transmutation strategy to achieve a BU of 700 GWd/t

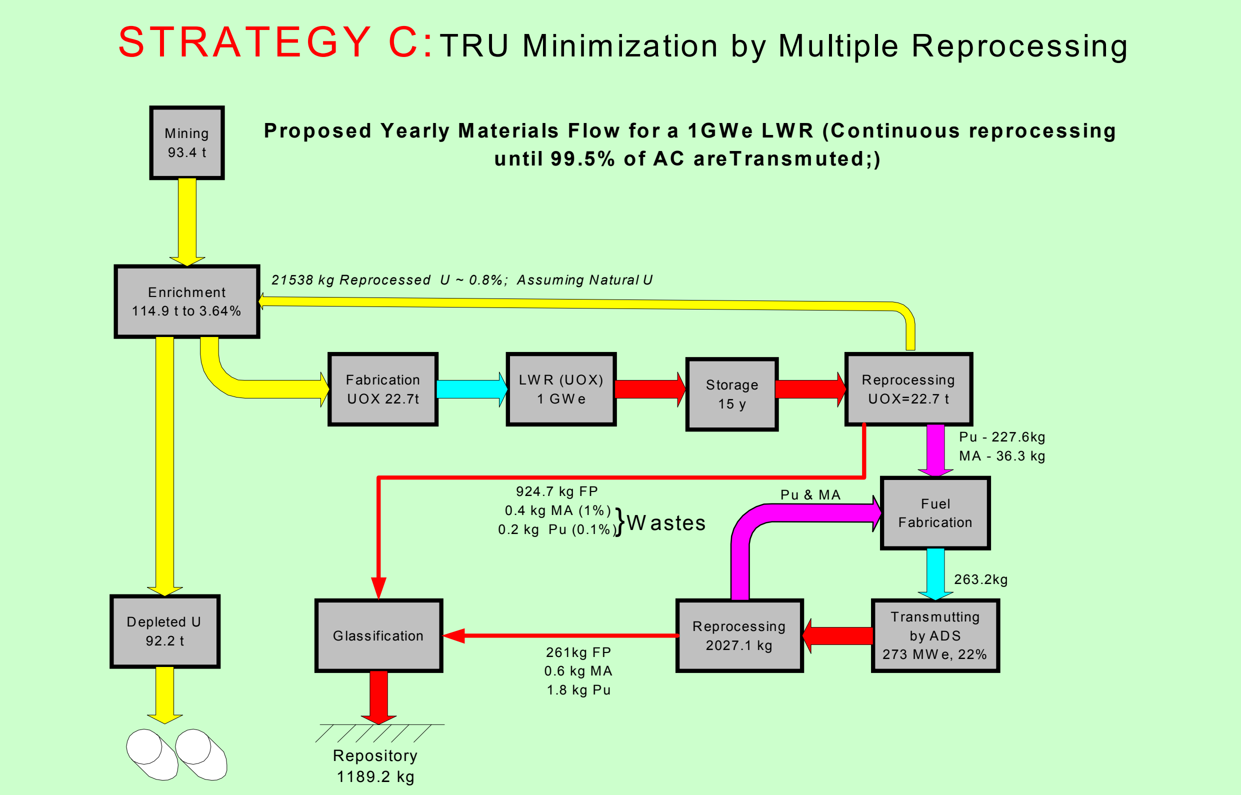


Figure 4.15: Transmutation strategy to minimize long-term radiotoxicity

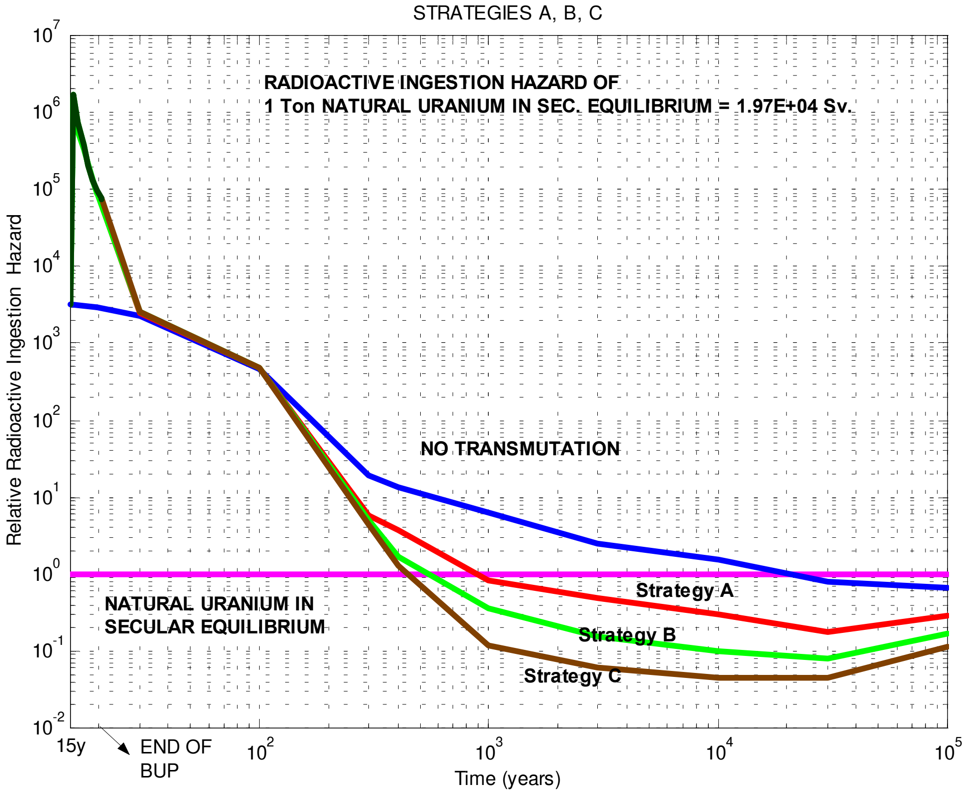


Figure 4.16: Comparing three transmutation strategies

5. SYNERGIES WITH AND POTENTIAL BENEFITS FROM OTHER PROGRAMS

5.1. Synergies with “Generation IV” Fission Reactors

In the event of a revival of interest in nuclear energy, so-called "Generation IV"[4] power systems will come into operation between 2030-2050. These systems should be highly economical, have enhanced safety features, give rise to a minimum of waste, and be proliferation resistant.

Prominent among the performance goals of such reactors is the fact that they should be competitive with other electricity generating sources. Specifically, the cost in euro should not exceed 3 cents/kWh on the basis of year 2000 prices. In addition, plant capital investment costs should not exceed € 1000/kW_e on the same basis.

Another performance goal is that these Generation IV systems should have high proliferation resistance. The fear is sometimes expressed that, in a nuclear revival situation, where many different power systems may be available, one can no longer control the flow of fissile material and the uses to which such systems may be put (e.g. clandestine fissile material production).

5.1.1. Goals for Generation IV Systems and Synergies with ADS

Generation IV advanced nuclear energy systems should be available for commercial construction no later than 2030. A set of seven goals has already been defined for these nuclear energy systems. Generation IV systems should:

i) Advance sustainable energy development. This will ensure that future energy supply options will include nuclear energy.

ii) Provide nuclear energy products in the form of electricity, heat, hydrogen, potable water, etc. whose cost to the customer is competitive with the cost from other sources in the country or region of interest at the time of Generation IV’s deployment.

iii) Have acceptable risk to capital with respect to all other competing energy projects in the country or region of interest at the time of Generation IV systems deployment.

iv) Produce robust designs that are extremely resistant to core damage accidents and support the demonstration of safety that enhances public confidence.

v) Ensure that reactor designs must conform to ALARA radiation exposure over the total system lifetime.

vi) Provide complete technical solutions that are politically and publicly acceptable for all waste streams.

vii) Ensure that the misuse of nuclear materials and facilities should be the least attractive route for potential weapons proliferators. This applies to both indigenous facilities and to exported components of the fuel cycle.

Future ADS should comply with goals i) and iv) to vii); ADS can also contribute to the goals ii) and iii), but these requirements cannot be considered as mandatory for such dedicated waste management plants. Safety requirements for ADS will be identical to those of Generation IV systems.

[4] Generation IV Nuclear Energy Systems Initiative, http://gen-iv.ne.doe.gov/

To improve ADS competitiveness and technology reliability, and to take advantage of current developments, it is essential to exploit synergies with Generation IV advanced nuclear energy systems. An example of this is described in the following section.

5.1.2. Coolant Selection Procedure

To identify the most promising Generation IV concepts, a selection procedure will be implemented using the above goals as criteria; the options are still largely open. Current research is focussed mainly on the following areas:

- water-cooled reactor technologies;
- gas-cooled reactor technologies;
- liquid-metal cooled reactor technologies.

Studies and R&D on gas cooled and liquid metal reactor technologies concerns also fast reactors and could easily be shared with ADS.

5.1.3. Fuel Qualification Process

Fuel development is one of the main challenges for Generation IV plants. Ten to twenty years will be necessary to develop and qualify acceptable solutions. High burnup and resistance to fast fluences are the key issues.

Fuel requirements are not the same for ADS and critical reactors. The large amount of minor actinides in ADS fuels will create specific requirements. Nevertheless much of the basic research, e.g. on fuel matrix, will be similar. As a reference, the following requirements for ADS fuels can be set: a) High content of Pu+MA; b) U-free; c) Capable of high burn-up; d) Pb(Pb-Bi)-Cooled ; e) Gas-cooled ; f) Reprocessing. Items c) to f) are applicable to Generation IV systems.

These characteristics will result in several effects which will be encountered in both ADS and Generation IV systems e.g. high levels of fission gas production, high levels of radiation damage, possible interactions for Pb (Pb-Bi)-cooled concepts, high(er) cladding and fuel temperatures for gas-cooled options, and the requirement of aqueous and/or pyrochemical processing.

With regard to fuel and fuel pin design, ADS and Generation IV systems have several features in common: low smear density, radiation stability, compatibility of cladding with molten lead, compatibility of fuel with molten lead, stability of cladding material, good thermal conductivity of fuel pellets, high melting point fuel material, dissolution ability in HNO_3, conversion ability to metal or chloride.

5.1.4. Demonstration Steps

As already indicated, Generation IV advanced nuclear energy systems should be available for commercial construction no later than 2030. No clear steps for demonstration process are identified yet.

This will be one of the main objectives for the Generation IV Roadmapping[5] that will include identification of research and development activities, sequencing of tasks, initial cost estimates, and opportunities for national and international co-operation.

Nevertheless it seems clear that if synergies are implemented on plant and fuel technologies, this will naturally lead to a merging of efforts not only for the R&D but also for the demonstration steps.

5.2. Synergies in the Development of High Power Proton Accelerators

5.2.1. European Projects

A number of different applications are envisaged worldwide, relying on the performances of a new generation of high power proton accelerators potentially capable of producing beams of several tens of MW.

Besides waste transmutation, there are:

- Radioactive ion beam generation;
- Spallation neutron sources for material science;
- Materials irradiation tools;
- Neutrino (and muon) factories.

European projects are ongoing in all these fields.

Radioactive Ion Beams **-** The possibility to produce intense Radioactive Ion Beams (RIB) of exotic nuclei is recognised by the scientific community as a new frontier for nuclear physics and other disciplines related to RIBs and their experimental techniques. The EURISOL project, a RTD project supported by EU, is aimed at completing a preliminary design study of the next-generation European ISOL radioactive ion beam facility. In the ISOL scenario, intense RIBs are produced by bombarding various targets by protons and fissile targets by an intense flux of spallation neutrons. An ISOL facility requires a high intensity driver accelerator to deliver beam power from hundreds KW to MW and a target-ion source system able to withstand beam intensities and power densities, which are orders of magnitude higher than the current ones. The time scale for such a facility is for the beginning of the next decade.

Spallation Neutron Sources **–** Neutron scattering constitutes a very important technique to study the structure and the dynamics of condensed matter. Although Europe at present has a very effective set of neutron sources, many of these facilities are ageing. There will be the need of both replacing capacity and building new sources offering higher instantaneous neutron fluxes (30-100 times higher), than can be delivered, for technical reasons, from fission reactors.

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[5] Through the Roadmap process, Gen IV technologies will be identified for further development. This work started in October 2000 and it is expected to take 18 to 24 months to be complete. The Roadmap process consists of the following essential steps:

a) Determination of Concept-Independent Gen IV Technology Goals (draft available)
b) Application of the Goals to Nuclear Technology Areas
c) Identification of Most Promising Concepts
d) Development of the Gen IV R&D Plan

Once the Roadmap is complete, it would serve as the organising basis of national, bilateral, and multilateral research and development activities aimed at addressing the technology challenges associated with Gen IV systems.

Also, an accelerator-driven spallation source can deliver pulsed neutron beams with a time-averaged flux similar to the best reactors.

Such high-power spallation sources are under construction in the US (SNS) and Japan (Joint Project). The planned European Spallation Source (ESS) project in Europe aims to design and build a world-class spallation neutron source, based on a 5 - 10 MW, 1.333 GeV, H^- linac accelerator. An R&D programme on the technical key issues is already in place - construction could start in 4 years and the beam available to the users in 2010. This constitutes a somewhat similar roadmap than that of the XADS.

Technological irradiation tools **–** In several fields, there is the need to develop new radiation resistant materials with improved performances and longer lifetimes. Neutron sources able to provide fluxes of some 10^{15} n/cm^2.s, in both thermal and fast ranges, are needed in order to induce annual damage of a few tens of dpa in test samples. Intense spallation sources may be used to this end. The required proton beam power is of the order of 10 MW.

Neutrino factories **-** Neutrinos play a crucial role in particle physics and astrophysics. Detailed studies of neutrinos require fluxes several orders of magnitude greater than those presently available at existing accelerators. In Europe, a neutrino factory is being studied by CERN community. The factory is based on an accelerator complex, using as a driver a high intensity proton accelerator (2 GeV, 2 mA, 4 MW pulsed linac).

These different projects foresee the use of a high power proton accelerator. Power requirements range from hundreds kW to several tens on MW; energy may go from several hundred MeV to about 2 GeV; mean currents are from several hundred µA to tens of mA. Both pulsed and continuous wave accelerators are considered. The most powerful proton accelerators running at present are the Los Alamos linac and the PSI cyclotron. Beam power is, in both cases, about 1 MW. A boost of one or more orders of magnitude is needed. Whereas cyclotrons can provide one order of magnitude, only the linac can allow larger boosts and can be used for all the applications listed above.

5.2.2. Synergies and Competition. A Multipurpose Facility?

Most current applications of accelerators foresee the use of a linac. The various linacs have similar structure and are based on:

- use of microwave source in order to get long-life, stable operation and good reliability;
- RFQ structures made of solid copper and brazed together in order to get very good cooling and thermal stability;
- Super-conducting ellipsoidal cavities at higher energy sections (> 100 MeV).

For the low energy (~ 5-100 MeV) part of the accelerator, there are a variety of different structures, both warm and cold, that are considered.

There are several technical challenges to be overcome before a high power proton accelerator (HPPA) can be built:

- A good ion source and injector, able to assure stable long-term operation and deliver a high-quality low-emittance beam is a necessity for any successful accelerator.

- The thermal management and the related mechanical stability of the normal conducting part of a high current (in particular continuous wave) accelerator.

- Low beam losses (< 1nA/m) are a must for hands-on operation. This requires a good initial beam emittance, excellent matching of the various part of the accelerator, and careful attention to beam halo formation and control.

- The use of ellipsoidal SC cavities in the region between ~100 MeV and ~1000 MeV requires careful design and R&D in order to extrapolate to relatively low particle velocity the techniques applied to β=1 particles.

- Operation reliability - absence or very low number of unexpected beam trips and beam control are of paramount importance for applications such as ADS for waste transmutation or, in general, when serious stresses of high-power targets are to be avoided.

- The need to design new high-power targets and beam stops, as proton beam powers of tens of MWs have no precedents. These targets represent a very challenging thermal design issue as well as a serious radiation environment.

- The high construction and operating cost demand for a careful design and optimisation of the whole machine and related infrastructures.

Studies have been started by the different projects on all these items. In particular, several important R&D efforts are presently underway for high current injectors. R&D activities on the low energy part (< 100 MeV) of the accelerator are concentrating on both warm and cold structures (spoke, re-entrant cavities). Important efforts are going into developing ellipsoidal superc-conducting cavities for the high energy (> 100 MeV) sections of such multi-MW-class accelerators.

To avoid duplication of efforts and a rationalisation of resources, it is necessary to investigate all possible links and synergies, as well as the possibility of combining at least part of various initiatives into a project for a European multipurpose facility. A first technical feasibility study in this direction is proposed by the CONCERT project, jointly launched by ESS and CEA.

The industrial burning of nuclear waste will certainly require dedicated accelerators. Assuming that pulsed operation is feasible, the XADS facility can probably share the accelerator with other applications such as irradiation facilities and radioactive beams.

Clearly, if an accelerator able to deliver a proton beam of sufficient power to several users would be needed, then a proton linac will be the only possibility.

Concerning costs, a multipurpose facility between several compatible users would probably prove beneficial for European countries because of the shared driver accelerator. Moreover, independent of costs, it looks unlikely that Europe has the necessary specialised manpower to build, in parallel, many HPPAs.

However, although the concept of a multipurpose facility seems to look very favourable from several points of view (there are no "a priori" visible technical obstacles), the conceptual design of such a facility needs to be carefully studied, along with an estimate of costs. In particular, concerning ADS, the consequences of abnormal operation of the multipurpose accelerator (e. g. pulse time structure, beam power variations) on the target and core have to be assessed.

An alternate possible route could be that different, dedicated facilities would actually use identical major accelerator components developed in common.

5.2.3. Proposal to Implement Synergies among European Projects

In order to try to start a real and effective collaboration among different European research communities - at present in competition with each other - a European co-ordination group should be set up. The group should be composed of representatives of the different communities. Its terms of reference should be:

- to establish a common base for design work, developments of design tools, and R&D needs;
- to agree the sharing of tasks among the different communities;
- to take care of the follow-up of the various activities;
- to collect results and make them available to the different partners;
- to promote actions for further strengthening of the collaborations and possible common initiatives, including the possible conception of a multi-user facility.

5.3. Co-operation with US, Japan, Russia

Activities for developing partitioning and transmutation technologies for waste management and, in particular, studies on accelerator driven transmutation of wastes have grown considerably worldwide in the last few years. Major programmes are going on mainly in USA and in Japan, in addition to activities in the EU. Important projects are also being carried out in Russia, Korea, Czech Republic. The major programmes cover most or all aspects of an ADS plant for waste transmutation.

In October 1999, DOE in USA presented to the U.S. Congress, a "Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology". That roadmap identified the technical issues to be solved, a way to proceed, and a cost estimate; it, also, assessed the impact that ATW technology could have on the treatment of civilian nuclear spent fuel and estimated capital cost and operating life-cycle costs. The R&D activity proposed by the roadmap has now been funded with $65M in the fiscal year 2000 and has been included in the Advanced Accelerator Applications (AAA) program, which merges the ATW programme with the former Accelerator Production of Tritium (APT) programme.

ATW offers a very good opportunity for collaboration between Europe and USA on all the technologies involved in the accelerator transmutation of wastes. This was also stressed in the roadmap document submitted to the Congress.

Also in the USA, at Oak Ridge, a MW-class spallation source driven by a superconductive proton linac, is being developed. The choice of superconducting cavities rather than the normal conductive cavities, was motivated by the progress made in Europe on niobium cavities.

In Japan, JAERI and KEK have been jointly proposing the High-Intensity Proton Accelerator Project since September 1998 based on the previous two projects, the Neutron Science Project of JAERI and Japan HADRON Project of KEK. At the end of 2000, phase 1 of the Joint Project was approved for construction. It includes a 400 MeV normal conducting linac, a 3 GeV proton synchrotron (PS) at 1 MW, a 50 GeV PS at 0.75 MW, a major part of the 1 MW spallation neutron source (SNS) facility, and a portion of the 50 GeV experimental facility. The total budget of phase 1 is 133.5 billion Yen (about 1335 M€). The phase 1 will be completed within 6 years. A phase 2 will follow, which will include the construction of and ADS experimental facility (including 400 MeV to 600 MeV superconducting linac), in addition to the upgrade of SNS to 5 MW, the construction of a neutrino beam line and the upgrade of the 50 GeV experimental facility. The entire cost, including phase 2, will be 189.0 billion Yen.

The entire partitioning and transmutation studies, other than ADS experimental facility, is being carried out under the OMEGA program and covers aqueous partitioning technology, nitride fuel fabrication and separation technology, and an ADS design study.

Russia also has interests in the field of accelerator transmutation of nuclear wastes. Of particular interest is the unique experience obtained over a period of 40 years on lead-bismuth eutectic (LBE) coolant technology. LBE is foreseen as a possible target for XADS and as a possible coolant. In the past few years there have been many contacts between Russia and several European countries and a number of collaborations have been established. In the event that LBE will be the final choice for XADS, working with Russian experts would prove highly beneficial.

6. SUPPORTING DOCUMENTS AND ANNEXES

ANNEXE 1: Interim Report of the Technical Working Group on Accelerator Driven Sub-Critical Systems – October 5, 1998

ANNEXE 2: Overview of the Ongoing Activities in Europe and Recommendations of the Technical Working Group on Accelerator Driven Sub-Critical Systems – September 6, 1999

ANNEXE 3: Four Page Document: Nuclear Waste Transmutation using Accelerator Driven Systems – The European Technical Working Group on ADS – February 21, 2000

ANNEXE 4: Report of the TWG Subgroup on Accelerators for ADS – March 2001

ANNEXE 5: The Fuel Fabrication and Processing Subgroup of the Technical Working Group on ADS - Fuel of the XADS – March 2001

ANNEXE 6: The Fuel Fabrication and Processing Subgroup of the Technical Working Group on ADS - Advanced Fuel Cycles for ADS: Fuel Fabrication and Reprocessing – April 2001

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A large number of papers and reports have been published on Accelerator Driven Systems and Transmutation Applications in recent years. Some of these have been prepared by international organisations, particularly the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA) of the OECD.

A first summary of ADS information can be found in “Accelerator Driven Systems: Energy generation and transmutation of nuclear waste” IAEA-TECDOC-985 (Vienna, 1997).

NEA-OECD has organised six “Information Exchange Meetings on Actinide and Fission Product Partitioning and Transmutation”, the last of which was held in Madrid, 11-13 December 2000. The official proceedings are expected by summer 2001. The proceedings of the 5th Meeting held at Mol (Belgium) in November 1998 were published in the Euratom Report EUR-18898-EN (1999).

Concerning reprocessing and partitioning, the NEA Nuclear Science Committee Report NEA/NSC/DOC(97)19 “Actinide Separation Chemistry in Nuclear Waste Streams and Materials” can be cited (Paris, 1997).

The NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle initiated an expert group to investigate the possibilities of P&T. This expert group organised their work in two phases. The report of the first phase was published in 1999 with the title “Actinide and Fission Product Partitioning and Transmutation. Status and Assessment Report”. The report for the second phase, where the main variants of the fuel cycles including transmutation in ADS is covered in detail, is expected for the summer 2001.

There are also scientific conference series where the subjects of ADS and P&T are treated specifically. This is the case with the ADTTA conference, the first of which was held in Las Vegas (USA) on 1994. The second was held in Kalmar (Sweden) in 1996 and the third in Pruhonice - Praha (Czech Republic) in 1999.

ADS transmutation has also been an important subject at previous ICENES (International Conferences on Emerging Nuclear Energy Systems) conferences, and in particular at the 9th and 10th ICENES meetings held at Herzeliya (Israel) in 1998 and at Petten (Netherlands) in 2000 respectively.

Similarly, the GLOBAL an ICONE conferences have also paid attention to these subjects, as well as in the SAFEWASTE 2000 conference (held in Montpellier, France).

Other specific meetings devoted to ADS were:

"Specialist Meeting on Accelerator Based Transmutation", Villigen, Switzerland, 1992.

IAEA Technical Committee Meeting on “Feasibility and Motivation for Hybrid Concepts for Nuclear Energy Generation and Transmutation” - Madrid, Spain, 17-19 September 1997.

International Workshop on the “Physics of Accelerator Driven Systems for Nuclear Transmutation and Clean Energy Production” - Trento, Italy, 29th Sept. - 3rd Oct. 1997.

Applications of Accelerator Technology - Gatlinburg, TN, USA, 1998 Long Beach, CA, USA, 1999.

Proceedings of these conferences are available.

Some of the papers and reports that can provide complementary information on the topics described in this Roadmap are listed below. The list is by no means exhaustive because of the very large number of papers available in journals, proceedings and reports from laboratories and research institutions.

1. AEC Research and Development Report, “Facilities for Electronuclear (MTA) Program“. Report LWS-24736, (1953).

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4. E. O. Lawrence, E. M. McMillan, and Luis W. Alvarez, Electronuclear Reactor, United States Patent No. 2,933,442 Apr. 19, 1960.

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ADS RELATED WEBSITES

Accelerator Driven Systems (ADS) - JRC, Karlsruhe
http://itumagill.fzk.de/ADS/

ATW - Accelerator-Driven Transmutation of Waste Project
http://www.pnl.gov/atw/

Karlsruhe Lead Laboratory
http://kalla.fzk.de/

Safety of Nuclear Waste Burners - JRC, Ispra
http://nucleartimes.jrc.it
e-mail discussion group
http://www.egroups.com/group/ads_safety

CRS4 (Centre for Advanced Studies, Research and Development in Sardinia)
http://www.crs4.it/Areas/ea/

FACET Project (Fission driven by Accelerator and Isotopes Transmutation), Spain
http://fachp1.ciemat.es/

HINDAS project (High and Intermediate energy Nuclear Data for ADS), Belgium
http://www.fynu.ucl.ac.be/collaborations/hindas/index.html

ENEA, Italy
http://rin365.arcoveggio.enea.it/ads

TRASCO (TRASmutazione SCOrie) - Joint ENEA-INFN Project for Nuclear Waste Trasmutation.
http://trasco.lnl.infn.it/

JAERI, Japan, Neutron Science Project
http://cens.tokai.jaeri.go.jp/ENGLISH/index.html

The LAESA (Laboratorio del Amplificador de Energia, S.A.) website
http://www.laesa.com/

MYRRHA project, Belgium
http://www.sckcen.be/research/reactorsafety/fuel/myrrha/myrrha_home.html

P&T homepage, NEA, Paris
http://www.nea.fr/html/pt/welcome.html

The Royal Institute of Technology, Sweden
http://www.neutron.kth.se/

C.H.M. Broeders
http://inrwww.fzk.de/~inr487/

Tokyo Institute of Technology
http://www.nr.titech.ac.jp/~hsekimot/HTML1.html

CORDIS: executive summaries of the FP5 projects, dealing with P&T
http://www.cordis.lu/fp5-euratom/src/fp5-proj2.htm

GLOSSARY, ACRONYMS AND ABBREVIATIONS

ADS, Accelerator Driven System
Acronym used to refer to various types of hybrid systems in which a sub-critical reactor reaches its neutron balance by means of an accelerator. A key advantage of ADSs over conventional critical reactors lies in the fact that large amounts of MAs can be transmuted safely.

APT, Accelerator Production of Tritium

ASH, Accélérateur Superconducteur pour Hybride
A CEA-IN2P3 specific programme for the development of super-conducting cavities applied to a high power accelerator.

Actinide (s)
Any nuclide (s) belonging to a series of 15 consecutive chemical elements in the periodic table from actinium to lawrencium (atomic numbers 89-103). As a group they are significant, largely because of their radiotoxicity. Although several members of the group, including uranium (the most familiar), occur naturally, most are man-made.

ATALANTE, ATelier Alpha et Laboratoires, ANalyses, Transuraniens, Etudes de Retraitement (France)

ATW, Accelerator Transmutation of Waste

BOL, Beginning of Life
concerning the operations start-up of the fresh fuel loaded in the core.

BOP, Balance of Plant

CEA-DSM, Commissariat à l'Énergie Atomique-Direction des Sciences de la Matière
A division of CEA whose activity is focused on basic research in physics including nuclear physics.

CERN, Centre Europeen de la Recherche Nucleaire
Joint European laboratory with a mission of furthering knowledge in the fields of particle and nuclear physics. As part of this mission this laboratory has developed a world leading competence in the domain of accelerators.

CHEOPE, multipurpose facility CHEmical and Operational loop
One of three facilities at the ENEA site at Brasimone for the study of corrosion phenomena in stagnant and flowing lead-bismuth.

CIEMAT, Centro de Investigaciones Energéticas Medioambientales y Tecnologicas
Spanish Government Research Centre for the Research on Energy, Environment and Technology

CIRCE, CIRCuito Eutettico
A large scale facility for heavy liquid technology development and thermal-hydraulics assessments in pool configuration; location ENEA Brasimone site (Italy) (see also LECOR and CHEOPE).

CONCERT, ESS-CEA study on a multipurpose HPPA accelerator

CONFIRM, Collaboration on Oxide and Nitride
An EU funded program of the 5th Framework Programme.

CORRIDA, CORRosion In Dynamic lead Alloys

CW, Continuous Wave
This term (originally describing the RF structure driving the cavities providing the energy to the beam) is commonly used as synonym for a 100% duty cycle particle accelerator.

DAQ, Data AcQuisation
Electronic hardware and software required to collect and pre-process data on line.

Deep Geological Repository
An underground site, excavated from the surrounding rock formation, designed to isolate nuclear waste from the biosphere over long periods of time.

DESY, Deutsches Elektronen Synchrotron
A high-energy physics laboratory at Hamburg, Germany, very active in research on SCRF cavities.

Double Strata Fuel Cycle
A concept initially introduced by JAERI, which makes a functional distinction between a power reactor fuel cycle (Stratum 1) and a partitioning-transmutation (P-T) cycle (Stratum 2). In the power reactor stratum, only U and Pu are burned and possibly recycled. In the P-T cycle, the high level waste is partitioned into groups: MAs, I, Tc, … ; most of it is incorporated into fuel elements or irradiation targets, and then transmuted in a dedicated accelerator driven systems. The final high level waste should therefore contain mostly short-lived fission products.

Dpa, Displacement per atom
The displacement per atom, dpa, is a measure of damage accumulation in irradiated material. Elastic collisions of impinging particles/ions on atoms constituting a crystal can result in the displacement of these atoms from their lattice sites if the displacement energy is surpassed. In a normal operating UO_2 fuel, each atom is displaced about once per day, leading to levels of ~1200 dpa after 3 years.

DTL, Drift Tube LINAC
A structure in which the particles are accelerated in the gap between two consecutive drift tubes. Focusing can be made inside the drift tubes. Reliable and well proven design. Since the tubes have to increase length with the particle energy so that the phase in the accelerating gap is kept constant, a DTL becomes inefficient at high energy.

EC-JRC, European Community – Joint Research Centre

ECR, Electron Cyclotron Resonance
One of the most efficient Ionisation methods currently used in high intensity ion sources.

EFTTRA, Experimental Feasibility for Targets and TRAnsmutation

ENEA, Ente per le Nuove tecnologie, l'Energia e l'Ambiente
Italian Government Agency in charge of advanced research in the fields of novel technologies, energy and environment, including in particular also nuclear energy.

ERA, European Research Area

ESS, European Spallation Source

EURISOL
A preliminary design study of the next-generation EURopean ISOL (Isotope Separation online) radioactive nuclear beam facility. A 5th European Framework Programme funded RTD project.

FEAT, First Energy Amplifier Test
Experiment performed at CERN

Flash ADC, Analogue to Digital Converter
Electronic hardware capable of digitising on-line the time evolution of an experimental signal to allow efficient storage and convenient computer post-processing.

FLUKA, FLUctuating KAscade Simulation Programme
for the calculation of electromagnetic and particle cascades induced by particle-into-medium collisions.

FNR, Fast Neutron Reactor

FP, Fission Product

FUTURE, Fuel for Transmutation of transURanium Elements
Project funded partly in the 5th Framework Programme of the EU.

FWP, FrameWork Programme of the EU

FWHM, Full Width Half Maximum
Term used in statistics to describe the characteristic width, around a central value, for a quantity having, instead of a precise value, a distribution.

FZJ, Forschung Zentrum Jülich
German research Centre engaged in basic and applied research in the domain of nuclear science.

GEANT, Montecarlo computer code for high energy particles transport simulation

GEDEON, GEstion DEchets par des Option Nouvelles

GENEPI, GEnerateur de NEutrons Pulsé Intense
A generator of intense neutron pulses used for research on hybrid reactors built by CRSN-IN2P3-ISN Grenoble and installed by the MASURCA research reactor at Cadarache.

GSI, Gesellschaft für Schwerlonenforschung
A laboratory at Darmstadt (Germany) engaged in basic research (nuclear, condensed matter, medicine) performed by means of beams of heavy ions of various proton and neutron numbers over a wide range of energies

HETC, High Energy Transport Code

HLM, Heavy Liquid Metals (e.g. Lead, Lead-Bismuth, Mercury)

HLW, High Level Waste
refers to waste in any form issued from reprocessing which contains highly radiotoxic nuclides (fission products and minor actinides) and, as a result, requires both radiation shielding and provision for cooling.

HPPA, High Power Proton Accelerator.
Term now commonly used. There is no exact definition, but if the power contained in the proton beam exceeds 1 MW, one certainly may speak of a HPPA-class machine.

HADRON, Hybrid Accelerator Driven Reactor with Optimized Neutron spectrum

IABAT, Impact of Accelerator BAsed Technologies
An EU funded program of the 4^{th} Framework Programme.

IAEA, International Atomic Energy Agency

IN2P3, Institut National de Physique Nucléaire et de Physique des Particules
French National Institute of CNRS, promoting and co-ordinating fundamental and applied research in nuclear particle and astroparticle physics through its 18 laboratories.

INFN, Istituto Nazionale di Fisica Nucleare (Italy)
Italian National Institute promoting and co-ordinating fundamental research in nuclear particle and astroparticle physics.

IPHI, Injecteur de Proton de Haute Intensité.
The high-intensity proton injector (100 mA) under construction in France through a CEA-CNRS collaboration.

IPPE, Institute of Physics and Power Engineering (Obninsk)
Russian research institute on nuclear energy with specific experience on liquid lead-bismuth applications.

IRMM, Institute for Reference Materials and Measurement
Institute of the European Commission, Joint Research Centre, in Belgium.

ISCL, Independently phased Super-conducting Cavity Linac

ISOL, Isotopic Separation Online
A fast method to extract radioactivity produced by a nuclear reaction and to mass-separate it on-line in order to provide isotopically pure secondary beams for fundamental nuclear physics experiments and applied research.

ISTC, International Science and Technology Centre, Moscow (Russia)

ITER, International Thermonuclear Experimental Reactor

ITU, Institut für TransUrane
Institute for Transuranium Elements. ITU is a laboratory of the European Commission, Joint Research Centre located at Karlsruhe, Germany.

JAERI, Japan Atomic Energy Research Institute
Japanese Agency in charge of the research covering the entire cycle associated with nuclear energy production

KALLA, KArlsruhe Lead LAboratory
located at the FZK German Research Centre at Karlsuhe.

KEK
High Energy Accelerator Research Organization (KEK) established in April, 1997. The laboratory at Tsukuba Japan engaged in basic research mostly in the domain of particle physics. Site of the future Joint Project in association with JAERI.

LAESA, Laboratorio del Amplificador de Energia, S.A. (Spain)

LANL-ISTC 559
A project involving Russia supported by USA and some European countries within the ISTC programme aiming at the construction of a spallation target in the MW range.

LBE, Lead Bismuth Eutectic

LECOR, LEad CORrosion loop
One of three facilities at the ENEA site at Brasimone for the study of corrosion phenomena in stagnant and flowing lead-bismuth

LEP, Large Electron Positron collider.
CERN accelerator build in the eighties for precise experiments on the standard model of elementary particle physics. Operated very successfully from August 1989 to November 2000.

LEP II
Energy upgrade of LEP by means of additional superconducting accelerating cavities.

LINAC, LINear Accelerator

LLFP, Long-Lived Fission Products

LM, Liquid Metal

LMR, Liquid Metal Reactor

LWR, Light Water Reactor

MA, Minor Actinides

This expression refers mainly to the elements neptunium, americium and curium. These minor actinides (MA) are produced as radioactive by-products in nuclear reactors. The term "minor" refers to the fact that they are produced in smaller quantities in comparison to the "major" actinide plutonium.

MASURCA, Maquette SURgénératrice Cadarache

A modular fast test reactor installed at Cadarache, France.

MEGAPIE, MEGAwatt PIlot Experiment

Project launched by CEA, CNRS, FZK, and PSI with a view to demonstrate the feasibility of a liquid Pb-Bi spallation target at power levels relevant to ADS and to gain experience in designing, operating and disposing of such targets. Scheduled to be operational by 2004.

MOX, Mixed OXide fuel

Containing uranium and plutonium oxides.

MUSE, MUltiplication de Source Externe

A set of experiments performed at MASURCA to validate the physics of sub-critical multiplying systems relevant to ADS.

MYRRHA

A multipurpose neutron source for R&D applications based on ADS, project under development by SCK-CEN (Belgium).

NEA, Nuclear Energy Agency of the OECD

N_TOF, Neutron Time Of Flight

Facility at CERN which produces intense beams of neutrons of high energy resolution over a wide energy spectrum (0.1 eV to 200 MeV) for neutron induced capture and fission cross section measurements.

OMEGA, Option Making Extra Gain from Actinides

The Japanese P&T project, which was started by the Atomic Energy Commission in 1988. Main participating organisations: JNC (PNC at that time), JAERI and CRIEPI.

Partitioning

Refers to aqueous or pyroprocessing methods which are used to separate (partition) the various components of the spent fuel: U, Pu, MA and fission products.

PBT, Pebble Bed Transmuter

PDS-XADS, Preliminary Design Study of an XADS

Project funded in the 5th Framework Programme of the EU

PIE, Post Irradiation Examination

PPAC, Parallel Plate Avalanche Counter

A detector using gas ionisation and subsequent electron collection on a bi-dimensional grid of anodes to detect the position and to some extent the nature of crossing charged subatomic particles

PSI, Paul Scherrer Institute
Laboratory at Vilingen (Switzerland) engaged in basic research mostly on the structure of matter by means of neutron diffraction. Their cyclotron facility routinely runs a 590 MeV proton beam at 1.6 mA intensity which is used for the spallation source SINQ.

PUREX, Plutonium and Uranium Recovery by EXtraction
An aqueous reprocessing technique.
PWR, Pressurised Water Reactor

PYROREP, PYROmetallurgical processing Research Programme
Project partly funded by the 5th Framework Programme of the EU.

RIB, Radioactive Ion Beam

RF, Radio Frequency
Electromagnetic waves used as a mean to transfer energy to the particles in accelerators.

RFQ, RadioFrequency Quadrupole.
A low-energy linear structure which simultaneously assures bunching, focusing and accelerating and thus overcomes space charge effects.

RuG, Reijksuniversität Groningen

SAD, Sub-critical assembly in combination with the proton Accelerator in Dubna

SCA, Shared Cost Action
A project which is partly funded by through EU Framework Programmes.

SCK-CEN, StudieCentrum voor Kernenergie-Centre d'Etude de l'Energie Nucleaire
Belgian national research laboratory on nuclear energy.

SCRF, Super-Conducting Radio-Frequency [cavities].

SINQ
A continuous neutron spallation source, first of its kind, running with a flux of 10^{14} neutrons/ cm^2 s. Based on the high intensity cyclotron operated by the PSI laboratory at Villingen (Switzerland).

SNR, Schneller Natriumgekühlter Reaktor (fast sodium-cooled reactor)
The SNR 300 was the German fast breeder reactor prototype. It was erected at Kalkar (Nord Rhein Westfalen) from 1973 till 1985. After the end of construction, SNR 300 had to face significant political objections. The state of Nord Rhein Westfalen refused to grant the operational licence for the reactor after having granted 13 partial licences. The delay caused significant costs. This finally lead to the decision to abandon the project in 1991.

Spent Fuel
Nuclear fuel which has been used for energy production in a reactor and whose nuclide composition has been (partially) modified by fission and neutron capture processes and subsequent radioactive decays.

SPIRE, SPallation and Irradiation Effects,
a 5th EU Framework Programme funded project on irradiation effects on structural materials, like martensitic steel, under neutrons and protons mixed spectrum.

SNS, Spallation Neutron Source

SPX, SuperPhénix
SuperPhénix, a 1250 MW_e French, sodium cooled, fast-breeder reactor operated in the nineties. It is now at the beginning of the decommissioning phase.

SUBATECH, Laboratoire de physique SUBAtomique et de TEChnologies associés, Nantes (France)

TARC, Transmutation by Adiabatic Resonance Crossing
Experiment at CERN under the 4th European Framework Programme

TECLA, TEChnologies, materials and thermal-hydraulics for Lead Alloys
A 5th EU Framework Programme funded project on heavy liquid technology for ADS applications

TERM, Thermal hydraulics and heat transfer Experiments at the Riga Mercury loop

TJLab, Thomas Jefferson Laboratory
US nuclear physics accelerator facility, formerly known as CEBAF (Continuous Electron Beam Accelerator Facility), one of the pioneering laboratories for the development of SCRF cavities which form the essential component of their accelerator.

TESLA, Tera-electronvolt Energy Superconducting Linear Accelerator
A large-scale facility for fundamental particle physics and applied Research developed by an international collaboration at DESY, Hamburg, Germany.

THOREX, THOrium Recovery by EXtraction
An aqueous reprocessing technique.

Transmutation
The conversion of a nuclide into one or several other nuclides in a reactor or with an accelerator as a result of fission or capture reaction. In practice, the goal of transmutation is to produce more stable and less radiotoxic nuclides.

TRASCO, TRAsmutazione SCOrie.
A joint ENEA-INFN research project for the design of an ADS for nuclear waste transmutation. Location Italy.

TRIGA, Training Research Isotope General Atomic immersed test reactor

TRU, TransUranic elements

TTF, Tesla Testbed Facility
A prototype technology-demonstrating Accelerator for TESLA, built by an international collaboration at DESY, Hamburg, Germany.

UCL, Université Catholique de Louvain-la-Neuve

UHV, Ultra High Vacuum

UU, Uppsala University

VICE, Vacuum Interface Compatibility Experiment

XADS, eXperimetal Accelerator Driven System

XADT, eXperimetal Accelerator Driven Transmuter
XADT will use dedicated fuel for the optimisation of the transmutation efficiency, in contrast to XADS in which conventional MOX fuel will be used.

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