Nuclear Development

Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles

A Comparative Study

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

7. R&D NEEDS

7.1 Introduction

Chapter 5 gave an overview of the development and the required figures of merit in the technology for fast reactors and accelerator-driven systems while Chapter 6 addressed the safety constraints on ADS. This chapter focuses on the perceived needs for research and development (R&D) by briefly describing the ongoing and planned R&D-projects, and aims at identifying the possible gaps in R&D activity.

A lot of research was started in the early 1950s on the development of fast reactors and continued until now, however at a slower pace. This initial development was essentially based on the perception that uranium resources could become scarce after a significant deployment of nuclear energy. As history has shown, this initial argument faded over the past decades and today only a few countries remain active in the field of fast reactor development, while the transfer and consequently the build-up of expertise in this field has come to a halt in most of the OECD Member countries. In addition, the experimental facilities, e.g. fast irradiation reactors, have been closed down or have come under strict operating conditions which make further R&D difficult.

As today's society is particularly concerned about the waste management aspects of nuclear energy, a renewed interest in accelerator-driven systems emerged in the 1980s and especially in the 1990s, benefiting from the similarity with fast reactor technology and the existing experience base. While in essence being fast reactors, these accelerator-driven systems aroused interest in re-launching past activities in the fields of cross-section measurements, benchmark and integral experiments, materials research and irradiation programmes, as well as increased cross-disciplinary research with the nuclear physics and accelerator community. Especially since the early 1990s, this revived interest has crystallised in new R&D programmes on ADS and related fields, even in OECD Member countries that took little part in the fast reactor scene.

Several assessments of ADS technology requirements have been undertaken since these early 1990s, the most relevant being the review of the OMEGA project in Japan, the ATW roadmap exercise in the US and the European TWG roadmap. Other countries undertook national evaluations in order to analyse the opportunities for new experiments or even new research infrastructures for ADS development. Some additional funding was granted by Japan, US and the EC to launch several activities in the field but most of these efforts have so far remained less extensive than the funding for FR technology in the 1970s and 1980s.

This chapter aims to give an overview of the different issues to be raised for further development of ADS or FR in the context of the fuel cycle schemes discussed, the ongoing and planned activities as well as the perceived need for increased focus in future R&D-programmes. It will address some elements of the discussion on the need for a new dedicated ADS infrastructure while highlighting the potential interest in increased international collaboration. As in the previous chapters, use will be made of an overview Table 7.1 showing the field of activities and perceived R&D needs.

7.2 Technology goals for P&T, and especially ADS development

This study has focused on the integration of P&T in advanced nuclear fuel cycles and the specific issues relating to the different steps in the fuel cycle and especially to the reactor part, be it ADS or FR. It has become obvious from Chapter 3 that developments in the reactor system are closely connected to the fuel cycle. The significant difference in residual decay heat for comparable fuel types used in different fuel cycle schemes, and the difference in doses and activity during fuel fabrication, are examples of this dependence. Chapters 5 and 6 also raised important issues for further R&D.

In the context of this study, two main blocks of R&D requirements may be identified:

- *R&D related to the fuel cycle,* which is to a large extent the same whether FR or ADS systems are to be used in such fuel cycles. However, some differences appear, such as the type of fuel that may need to be fabricated and reprocessed, the residual decay heats, etc. Main items for consideration in this block relate to:

  – *Adequacy of separation of uranium, TRU, and long-lived fission product* elements from LWR-UOX or MOX spent fuel and FR or ADS transmuter fuel. The separation efficiencies of 99.9% still need to be proven on an industrial scale. As was shown in Chapter 3 and Chapter 7, achieving these high efficiencies is crucial to attaining a significant reduction in mass going to waste. The cost analysis in Chapter 7 indicated that improvements in separation technology have a direct impact on the mass reduction while cost-effectiveness is crucial.

  – *Quantification of total long-lived radioactivity generated* in the FR or ADS transmuter system, including spallation products from the ADS, and the implications for waste streams and waste forms. The quantities actually generated will be functions of the processes used and the separation efficiencies. Design features and scale of operations will determine how much residual waste will still require disposal in a geological repository or other waste facility. Assessing the amounts and compositions of the secondary LLW, ILW and HLW streams may help future assessment studies by indicating where investments for improvement may be most appropriate.

  – *Performance assessment for a geological disposal site using a P&T source term* is necessary to clarify the cost-benefit analysis of a P&T scenario including this geological disposal. Only such a complete assessment can tell whether P&T is really effective. Identifying criteria for future P&T work should be a key driver for such assessment studies. In general, a study looking to new options for repository design, taking into account developments in advanced fuel cycles, would be a welcome endeavour. In fact, the overall P&T issue addressed by this study splits in economic, administrative, ecologically, and social terms into those of plutonium management (mainly an economic and proliferation issue) and minor actinide (MA) management (mainly an ecological and biological hazard issue of longer range).

Table 7.1. **Outline R&D matrix for P&T technology**

	Technological objectives	(2) Pu-burning	(4) Double strata	(3b) TRU burning in ADS	(3a) TRU burning in FR (5) All FR
Partitioning	**99% recovery**	*1st Stratum*	*2nd Stratum*	**Dry reprocessing: 99.9% TRU recovery**	
		Wet reprocessing 99.9% U, Pu, (Np) recovery	Dry reprocessing 99.9% TRU recovery		
	R&D needs	Reprocessability of high-Pu-content fuel with high recovery	Separation of U from TRU?		
		Separation of actinides from lanthanides			
	Short cooling times	Needed in order to keep low inventory in cycle			
	R&D needs	FR-MOX reprocessing High residual decay heat requires changes in Purex process: pin-choppers, centrifugal contactors, laser cutting; alternatively, longer cooling times, dilution with LWR-UOX feed	– Material corrosion by salts and high temperature – Batch process: development of transport and loading techniques for material – Pin-choppers or laser cutting techniques in head end		
	Additional or alternative processes	Dry reprocessing of oxide fuel	– Wet reprocessing may remain possible to co-extract Am + Cm – Dilution with LWR-MOX or FR-MOX to reduce mean decay heat	Wet processing: Purex or Urex	
Fuel fabrication	**High burn-up fuel**	Burn-up limitation due to swelling rates and gas pressurisation: modelling, development and irradiation under normal and power transient conditions needed			
	High TRU/MA loading	***Oxide fuels***	***Nitride fuels***	***Metal fuel***	
		– High Pu content (ca. 45%) fuel – Effect of 238Pu on fabrication – MA content reduces margin to melting owing to low thermal conductivity. Limitation to fuels with low residual decay heat	– Reduced stability against decomposition at high temperatures – Fabrication process may be unsuited to "ad hoc" tailoring	– Need to improve thermal properties, adding non-fissile metals with high melting point (e.g. Zr), however low mutual solubility of Np and Zr – Hydriding & de-hydriding behaviour of TRU-Zr fuel as well as its sintering & hot-pressing behaviour to make uniform pellets – Modelling of PCI	
	Fabrication technology	– Vibro-packing or pellet – Maybe need to transform into metal for dry reprocessing	^{15}N enrichment process and recovery needed	– Injection casting – Centrifugal casting	
			Choice of cladding material: its interaction with coolant (LBE) needs especially to be studied		
	Shielding	High neutron source strength demands additional shielding, criticality control, reduced batch sizes			
		High MA loading in fuel; problems in handling Am and especially Cm			
Waste management		High α-contaminated waste	Pyro-reprocessing waste – α-damage to composite glass-ceramic wastes (sodalite) to be studied – Leaching behaviour of pyrochemical ceramic waste in reducing environments to be studied		
		Reduce secondary waste arisings			
		Trade-offs between waste volume and waste form parameters, associated R&D costs, and disposal costs. Various disposal and disposition options for these wastes need to be analysed			
		A complete performance study, using appropriate source terms, should be performed to assess the cost-benefit aspects for the geological disposal site			

Table 7.1. **Outline R&D matrix for P&T technology (cont'd)**

	Technological objectives	(2) Pu-burning	(4) Double strata	(3b) TRU burning in ADS	(3a) TRU burning in FR (5) All FR
Reactor (Safety and O&M)		100% LWR-MOX core (design changes needed)			
		Economy in FR needed because of high fraction in nuclear park			
		Exploration of possibility to re-use radioactive sodium in new fast reactors			
	Sub-critical part				
	Thermal hydraulics		Thermo-hydraulics of liquid metals, especially LBE: Assessment of different coolants, make and compare different engineering designs for an ADS, gas- or LBE-cooled		
	Neutronics		Validation of simulation codes and nuclear data for new fuel, new reactor designs and new burnups per batch. MC and deterministic calculation codes to analyse kinetics and core dynamics		
	Target		– Thermal shocks on materials and fuels due to beam variations – Radiation damage to structural materials: (currently limited to 20 $\mu A/cm^2$; should be increased for more flexibility in design)		
			– Investigation of the effects of spallation products on the structural materials of an ADS target		
			– Experimental feasibility demonstration of LM-cooled target		
			– Blanket design studies to understand trade-offs between characteristics of beam delivery and blanket – Coolant chemistry: LBE conditioning, cover gas control, impact of spallation products		
			Window: – Dynamics analysis of diffusion and migration mechanisms for chemical species as functions of the temperature – Out of the beam axis, most interactions are with neutrons and generate more dpa than gas release		
	Basic science needs	Basic nuclear data: need for better cross-section values for MAs in thermal and epithermal spectra			
			Better nuclear data for target/ADS – Spallation product yields and distribution in (A,Z) * Intermediate energy data to meet needs of accuracy * For transmutation: cross-section measurements needed in the 1ev-250MeV range (capture & fission for Ac; capture for LLFPs) – For ADS engineering design: cross-section measurements above 100 keV needed (inelastic collisions, (n,xn) for structural, coolant and fuel materials but also (p,x) reactions)		
			Data are needed on the relatively high solubilities of Pu and Zr in Pb and Bi		
	Safety analysis and demonstration		– Safe shut-down – Decay heat removal – Containment of radioactivity		

– The *fabrication of very specialised, dedicated, fuels* needs further research. Several new aspects come into play. While the fuel form must be compatible with the reprocessing scheme, its selection also depends on the constraints imposed by interactions between pellet and cladding, cladding and coolant, etc. While oxide fuel forms may be preferable in the short term, others such as nitride and metal may be more suitable in the longer term but need significant development during the coming 10 to 20 years. In particular the presence of large amounts of curium is a new challenge for fuel fabrication and may need completely new designs of plants. In case of nitride fuel, specific processes are also needed in order to recover the costly enriched ^{15}N. Besides development of the fuel form itself, attention should be paid to the fabrication process, i.e. the need for dedicated fabrication plants, increased requirements for shielding and criticality control, optimisation of processes for small batch sizes, possible co-location of fabrication and reprocessing plants at the FR or ADS site, and so on. These considerations may need, after an initial concept screening exercise, a detailed assessment before further specific R&D can be undertaken.

- *R&D related to the reactor,* whether FR or ADS. The development and demonstration of FR or ADS technology will require several technological challenges to be overcome:

  – *Lifetimes of proposed materials and components in the radiation, thermal, and chemical environments anticipated*. Understanding the behaviour of fuel and structural materials in complex and aggressive environments is a prime R&D activity before any other development can be considered. In addition, R&D in this domain is expensive in time and resources as corrosion tests and irradiation tests should be performed in experimental rigs or facilities that may still need to be constructed. In the case of ADS, such material irradiation tests should be undertaken in existing fast MTRs (i.e. Monju, FFTF, Phénix, BOR-60, … etc). It is therefore essential that these facilities remain available and so irradiation programmes are proposed to keep them in use. At a later stage, especially when more detailed ADS designs are emerging, additional irradiation tests may be needed in dedicated ADS irradiation test facilities and set-ups (e.g. ADTF, XADS, …), for instance, to test window materials in complex geometries. The challenges posed by materials development are particularly harsh for FR or ADS transmuters, where very high neutron fluxes, liquid metals, and high temperatures may co-exist. This will have a significant influence on design evaluations relative to system life, requirements for maintaining or replacing equipment, licensing, and life-cycle costs. On top of this, the primary and secondary proton damage to these fuel and structural materials in an ADS is an additional and essentially new domain that has only limited resemblance to the proton damage experienced in existing spallation target sources for neutron physics research.

  – *Reliability and availability of ADS systems*: ADS systems may be expected to operate with high availability for 60 years. All ADS subsystems would consist of newly designed equipment operating at higher temperature or higher loads than current equivalents. New equipment and components must be designed and tested to assure lifetime reliability and availability. In addition to the reliability and technological feasibility of several parts of an ADS, more important technological trade-offs may need to be made, e.g.:

    ♦ *Core physics*: recent neutronic benchmarks by OECD/NEA [188] indicate that the modelling of such sub-critical systems needs further development as significant differences still exist in static and especially in dynamic responses. Basic science requirements in this area relate to the need for better cross-section libraries extended to minor actinides and higher intermediate energies. Besides these data, continuous benchmarking of calculational tools is needed in order to reduce the margins of uncertainty in any future design work.

- *Accelerator type and power level*: the technological feasibility of high-power proton accelerators needs further investigation, especially in relation to the desired reliability. Depending on the specific ADS design and depending on its use as MA or TRU burner, a variable beam power may be needed in order to compensate for burn-up,control the power level, and so on. These requirements are specifically relevant in the case of a TRU burner where the decline in k_{eff} could be very significant and where a trade-off is needed between fuel core management and accelerator operational characteristics.

- *Accelerator beam trips*: as was mentioned in Chapters 5 and 6, proton beam trips occur frequently on current linear accelerators. They would cause thermal stresses in fuel and structural materials, and if frequent, cause low cycle fatigue failure of the structures to become a safety and operating issue. R&D is therefore necessary in order to reduce the impact of these beam trips on the core by reducing their number or by designing a "forgiving" core.

- *Cooling and decay heat removal:* the proposed use of relatively new type of coolants (lead, LBE or gas), especially in combination with new fuel types and cladding materials, demands specific attention to the thermal-hydraulics and core mechanics in normal and abnormal conditions. Sodium cooling is another option that might benefit from the existing rather extensive experience base. Again, a trade-off is needed between the level of sub-criticality, accelerator characteristics and the core management and its impact on the thermal-hydraulics. Safety authorities will demand structural integrity of fuel, cladding and core as a whole while the very high residual decay heat of the fuel may add serious constraints to the cooling needed during handling, transport and core refuelling. Next to the cooling considerations for the core, specific attention is needed to the target region and its integration with the reactor core. Basic science requirements relate to developing and benchmarking thermal-hydraulic codes (with coupling to neutronic codes), studying the compatibility of coolant and its operational regime with the fuel and cladding constraints, and to understanding corrosion mechanisms in such coolant and material combinations.

- *Safety analysis of ADS* should identify the possible ways to exclude HCDAs in ADS. If such a HCDA has to be taken into account in the safety analysis, a prompt negative feedback mechanism for quenching such an accident has to be developed. The technology questions related to the integration of a target with the sub-critical core as well as their safety implications need more precise study, for instance of the dynamic response in case of beam-tube flooding.

- *Instrumentation:* New techniques and tools must be developed to control the coolant chemistry, the sub-criticality level monitoring (by beam power or moving control rods), the coupling between power level and accelerator beam power, etc., and especially to increase the reliability of the accelerator.

- *In-service inspection and repair:* Besides instrumentation, providing operating and maintenance tools suited to highly radioactive environments, mostly not visually transparent and in contact with hot fuel, presents a technological challenge already very familiar from the case of sodium-cooling.

7.3 Perceived R&D needs in the short to medium-term

The above description itself shows the need for continuous development of basic science and technology in essentially four domains:

- *Nuclear data, neutronic calculations and kinetic and dynamic core behaviour* for better modelling of core physics, safety, radiation shielding and so on in order to reduce the design uncertainties.
- *Materials research for fuels and structural materials* (cladding, window, etc.) in various coolants and in radiation fields (including protons) where a phased approach may be appropriate.
- *Reprocessing technology,* aqueous as well as pyro-reprocessing technology.
- *Performance assessment* for a geological disposal site using a P&T source term as is necessary in order to clarify the cost-benefit analysis of a P&T scenario including this geological disposal.

While the above domains may need to be approached differently in various countries (for instance, some countries need more technology transfer on pyrochemistry than others), these basic science requirements are recognised universally as necessary steps to be taken in order to perform detailed system studies. Other R&D requirements in more

7.3.1 Nuclear data and neutronic calculations

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 the interest in thermal and fast neutron reactors. Although the currently existing nuclear databases are sufficient for a first evaluation of dedicated transmutation ADS and critical reactors, a detailed assessment requires more precise and complete basic nuclear data.

The first point to take into account is the large fraction of the minor actinides and high mass plutonium isotopes in the fuels proposed for the transmutation devices. These isotopes with little relevance for the operation of present reactors will play an important role on the neutronics of the transmuters. Second, the use of innovative coolants like lead will also make to increase the role of the isotopes contained in that material (mainly lead and bismuth). Third, the operation of many transmutation devices in fast spectrum requires to complete the nuclear data (cross-sections, fission yields, isomer production, etc.) for many fuel and structural material isotopes in the region from 1 keV till several MeV. Finally, the eventual transmutation of fission fragments will require a better determination of the associated transmutation (normally capture) cross-sections.

Present knowledge of the spallation reaction mechanism is not yet accurate enough for any technical application at the scale of the anticipated ADS for transmutation. Two main aspects play a major role in designing and constructing the target assembly of the spallation neutron source: the neutron yield (with its energy and spatial distribution) and the residual nuclei produced in the reaction.

The work on basic nuclear data is largely driven by a few national laboratories that have started extensive programmes on various accelerator-driven projects. However, there is also a more widespread effort to determine data related to transmutation. One may distinguish between conventional nuclear data, below 20 MeV, and intermediate energy nuclear data, above 20 MeV. The first set is necessary for fast reactor cores, i.e. fuel and structural materials, while the intermediate energy data are essentially needed for the structural materials in ADS applications. In general, the initial focus is on assessing priorities, including sensitivity and uncertainty analysis, and on evaluating key data which may not have received sufficient attention in the past. The actual provision of intermediate energy data to the users is progressing rapidly. Although present uncertainties may allow reasonable pre-conceptual design assessments, future detailed studies will require more accurate data, with drastically reduced uncertainties. The relevant sensitivity studies have started, but they have not yet tackled satisfactorily the problem of accuracy in the intermediate (i.e. $20\ \text{MeV} \leq E \leq 200\ \text{MeV}$) energy range. However, sensitivity studies for the different parts of the whole device are indispensable as a parallel area of research in the field of intermediate energy nuclear data. They may provide a valuable guideline on isotopes and reactions to be measured and evaluated.

Several high-energy transport codes exist containing an intra-nuclear cascade model that is mainly successful for the primary stages of the reaction, including the production of several types of hadron. For energies below about 150 MeV, when the predictive power of the high-energy transport codes becomes suspect, nuclear data libraries are required.

The general recommendation is that for more materials, the available data libraries should be extended from thermal and intermediate energies to 150 MeV. This will require a significant effort from both the experimental and the theoretical nuclear physics communities. It is therefore necessary to revisit the evaluation process over the whole energy range, which should ensure a smooth transition from low to high energies. Some new experiments are proposed or under way in order to fulfil this task.

Japan

JNC has organised, together with Japanese universities, several projects on nuclear data measurements for LLFPs and MAs over recent years. These researches include for instance fast neutron induced fission cross-sections of americium isotopes, and capture cross-sections of ^{237}Np, ^{99}Tc among others [189]. JNC is now planning to extend the nuclear data measurements to capture and fission cross-sections and decay data for important LLFPs and MAs from the thermal energy region up to a few MeV. In particular, more precise determinations of the capture cross-section in nuclides such as ^{99}Tc and ^{129}I are intended.

EC[70]

A large experimental programme was initiated in Europe a few years ago in order to improve our knowledge of the spallation reactions. These experiments are set-up in order to provide accurate data to benchmark more reliable model calculations. Neutron multiplicities were investigated using liquid-scintillator-based detectors with a large angular acceptance in the Berlin Neutron Ball [190] and ORION [191] used by the NESSI collaboration (Berlin – Ganil – Jülich). This collaboration has conducted a large experimental programme to determine the neutron yields produced in thin and thick targets by a large range of primary projectiles and energies. In addition, the unique and essential GSI experiments derived the (A,Z) distributions of spallation products by using the inverse kinematic technique. Spatial and energy distributions of spallation neutrons were measured at Saturne [192].

70. A more complete overview of the EC’s programme of work is given in [193].

New experiments have been proposed and are to be conducted within the EC 5th Framework Programme within the n-TOF and HINDAS projects.

n-TOF

The main goal of the n-TOF project is to produce, evaluate and disseminate high precision cross-sections for the majority of the isotopes relevant to waste incineration and design of the ADS, i.e. capture and fission cross-sections for the MAs, capture cross-sections for the main FPs and (n,xn) reactions for structural and coolant materials. Most of the measurements will be performed using the CERN (Geneva) accelerator complex. The experiment will cover low as well as intermediate energies, 1 eV – 250 MeV.

HINDAS

In the HINDAS project (sponsored by EC), nuclear data in the 20-2 000 MeV region will be provided by a combination of nuclear models and appropriate intermediate- and high-energy experiments. A whole panoply of European accelerators will be utilised to provide complete sets of experimental data for key elements and energies. Nuclear model codes will be improved and validated by these new experimental data and then used to generate enhanced ENDF-formatted data libraries below 200 MeV, and cross-sections for high-energy transport codes above 200 MeV. The impact of new data libraries and high-energy models will be directly tested on some important parameters of an accelerator-driven system.

USA

Neutron total cross-sections have been measured at LANSCE from 5 to 560 MeV on 31 elements and isotopes covering the range from hydrogen to uranium. These measurements were supported by the APT project as part of a programme to improve the physics in the modelling codes for neutron transport up to several hundred MeV. For nearly all of the target materials, the data are accurate to better than 1% (both statistical and systematic) in 1% neutron energy bins. These data are essential for neutron transport codes and for nuclear modelling.

7.3.1.1 Spallation product analysis

Besides developing better cross-section libraries for fuel and structural materials, other required nuclear data relate to spallation products in the target and coolant material. These data are very important in material selection to improve, for instance, the target window lifetime, the arisings of secondary wastes in the target area, etc. During the irradiation of an ADS target with protons a large number of spallation products are formed. Most have short lifetimes and no significant impact on the behaviour of the system. However, a considerable number of spallation products or their successors have longer lifetimes and must be taken into account with respect especially to consequences for waste arisings and thus for the back-end of the system. Recently a Russian study has been published with a comparison of long-lived residual activity characteristics of liquid metal coolants for advanced nuclear energy systems [153]. This study emphasises the importance of ^{205}Pb and of ^{210m}Bi with lead and LBE coolants respectively.

The significance of spallation products in a fast spectrum ADS has been investigated in some detail. It has been shown that in a fast spectrum, neutron absorption in the spallation products competes only weakly with nuclear decay as long as the half-life is less than about 30 days. The most important spallation products have been listed in IABAT and show that quite a large number of isotopes are missing from the evaluated data files, e.g. ^{205}Pb. Some of the most outstanding experiments to measure residue production are performed by the German-Spanish-French collaboration at GSI. The technique used in these experiments takes advantage of inverse kinematics and the full identification in mass and atomic number of the reaction residues by using a magnetic spectrometer [194].

7.3.1.2 Neutronics

The further development of calculational tools is as important as the previous action on basic nuclear data and the experimental benchmarking of these codes is especially necessary. Calculational benchmarks have been undertaken at laboratory and international levels, co-ordinated by OECD/NEA or IAEA. Experimental benchmarks are ongoing where one of the most important experiments is performed in CEA Cadarache.

The MUSE experiments

The MUSE experiments, launched in 1995, simulate the neutronics of a source-driven sub-critical system, using the physics characteristics of the separation of the effects due to the presence of an external neutron source from the effects of the neutron multiplication. In fact, for a wide range of sub-criticality values (e.g. k_{eff} = 0.9 - 0.99), the space dependence of the energy distribution of the source neutrons is quickly (in approximately one mean free path) replaced by the fission-dominated neutron energy distribution.

In practice, external known neutron sources have been introduced at the centre of a sub-critical configuration in the MASURCA reactor. The more recent of these experiments is made of a deuton accelerator and a target (deuterium or tritium) at the centre of a configuration where actual target materials (like lead) are loaded in a buffer close to the target, to provide the neutron diffusion representative of an actual spallation source. The neutrons issued from (d,d) and (d,t) reactions, after crossing the lead buffer, provide a reasonable simulation of the spallation neutrons, in terms of energy distribution. Static (e.g. flux distributions, spectrum indexes, importance of source neutrons) and kinetic parameters (e.g. time dependence of neutron population, effective delayed neutron fraction, with appropriate weighting, etc.) have been or will be measured. Sub-criticality itself is measured by static and dynamic techniques. Continuous monitoring of sub-critical reactivity in future accelerator-driven systems will become important. Several core monitoring techniques, including noise related techniques (Feynman-α), would also be tested in this MUSE-experiment.

Finally, the proposed experiment MUSE-4 start-up procedure with:

- A critical configuration with accelerator hole but no beam.
- A sub-critical configuration with accelerator hole but no beam.
- The same, but with beam on.

allows a precise reactivity scale to be established in Step 1, and then used both to calibrate control rods if needed and to measure in a standard way (e.g. with the modified source multiplication, MSM, method) the level of sub-criticality in Steps 2 and 3.

The TRADE experiment

The present basic experiments do not provide the validation of the concept at low but significant (~1 MW) power and with the coupling of an accelerator with a sub-critical core. On the contrary, to demonstrate the feasibility of stable operation and dynamic behaviour as well as to investigate the safety issues of an ADS, it is of primary importance to perform a first global experiment to demonstrate the coupling a proton accelerator with a spallation target and a sub-critical system of sufficient size to produce a sizable power. Moreover, operational experience in this domain, along with the definition of licensing procedures for such a system, could be extremely beneficial to the realisation of a future fast neutron demonstrator.

A joint ENEA-CEA working group has recently launched the idea to carry out this pilot experiment, first example of ADS component coupling "at real size", in the TRIGA reactor at the ENEA-Casaccia Centre. This reactor is an existing swimming pool reactor of 1 MW thermal power, cooled by natural convection of water in the reactor pool. The TRIGA reactor, made sub-critical by removing the innermost ring of the fuel core, will be coupled with an upgraded commercial proton cyclotron (proton energy of 110 MeV and current in the range 0.5-2 mA) through a tungsten solid target

This experiment – actually called TRADE, i.e. TRIGA Accelerator-driven Experiment, could be performed at levels of several hundred kW sub-critical core power and few tens of kW in the target, thus providing, among other, valuable insight into the dynamic behaviour of an ADS in presence of reactivity feedback effects.

The experiments of relevance to ADS development to be carried out in TRIGA could concern:

- The dynamic regime: the possibility to operate at some hundred kW of power and at different sub-criticality levels (0.95÷0.99) will allow to validate experimentally the dynamic system behaviour versus the external source effectiveness and to obtain important information on the optimal sub-criticality level both for a demonstrator and, by extrapolation, a transmuter.
- Sub-criticality measurements at significant power.
- Correlation between reactor power and proton current. This correlation can be studied at different sub-criticality and power levels.
- Reactivity control by different means and possibly by neutron source importance variation, keeping the proton current constant. In principle, this can be obtained changing the neutron diffusion proprieties of the buffer medium around the spallation source (e.g. using different materials in the empty innermost fuel ring close to the target).
- Start-up and shut-down procedures, including suitable techniques and instrumentation.

Moreover, an important feature of the TRIGA layout is the possibility to carry out, before the coupling with the accelerator, a propaedeutic experimental campaign by inserting into the current central thimble a known standard fixed neutron source, and performing static and dynamic measurements for different sub-criticality levels. For example, such a configuration of the TRIGA reactor allows the application of a wide variety of techniques devoted to the determination of the sub-criticality level, like source jerk, pulsed neutron source analyses, rod drop, Modified Source Multiplication. Such set of experiments will provide a link with the MUSE experiments and characterise the sub-critical core from a safety point of view.

The preliminary studies have been completed and a first feasibility report has been issued on June 2001; analysis have been performed on neutronics, power and temperature distributions, structures damage, thermal-hydraulic of the target, safety parameters, general lay-out of the facility and some licensing issues.

The preliminary analysis and results show no major obstacles, even if some more detailed studies should be performed. The feasibility report shows that all relevant experiments (at different power levels in a wide range of sub-criticalities) can be performed, with only relatively limited modifications to the existing TRIGA reactor.

7.3.2 Materials research

Materials research may be subdivided into three domains, i.e. fuel, structural materials including cladding and window materials, and the coolant. It should be remarked that these are mutually interacting and a cross-disciplinary approach is needed, to cover also the reprocessing technologies for fuel and cladding research.

7.3.2.1 Fuel research

For both critical and sub-critical dedicated cores, the major issue in the path towards feasibility demonstration is the development of fuel. Many candidates have been considered (see for example Table 7.2), but limited experimental work has been done, in order to characterise the basic properties of these potential fuels, their fabrication processes and their behaviour under irradiation. See also Chapter 3, Section 3.4.1. for a more complete discussion of fuel and target fabrication and behaviour and the interaction with their reprocessability.

Practically all the major transmutation programmes lack well-structured coverage of fuel development. A significant exception is the JAERI programme, focused on nitride fuels.

Table 7.2. **Dedicated Pu + MA fuels**

Metal fuels	– Need to improve thermal properties ⇒ add non-fissile metal with high melting point (e.g. Zr) ⇒ Pu-MA-Zr alloy – However: mutual solubility of Np and Zr may be troublesome
Oxide fuels	– Mixed transmutation oxides as a logical extension of MOX – However: smaller margin to melting (low thermal conductivity)
Nitride fuels	– Good thermal behaviour – However: need enrichment in ^{15}N – Lower stability against decomposition at high temperatures
Composite fuels: the role of Zr	Ad-hoc "tailoring": – MgO + (Zr, An)O_{2-X} (CERAMIC-CERAMIC) – Zr + (Zr, An)O_{2-X} (CERAMIC-METALLIC) – Zr + (An, Zr) alloy (METAL-METAL) However, fabrication can be difficult (also: size and distribution of the dispersed actinide phase)
Coated particle fuels	Special form of composite fuels. However in the case of fast spectra, little is known on potential candidates (TiN?) ⇒ A generic problem: the high production of helium under irradiation.

Irradiation performance issues

The primary performance criteria for a fuel rod in general are that for all anticipated conditions the fuel should retain its position in the core, contain fission products and maintain a coolable geometry. Experience with various fuel forms has proved the following characteristics to be important to fuel performance and lifetime:

- *Dimensional stability*: the dimensions of the fuel can change dramatically if the material swells or grows significantly on irradiation. Such effects have implications for the neutronic performance of the core and can introduce stresses into the cladding that lead to a breach.
- *Fission gas pressurisation*: some fuel types, especially metallic, release large amounts of fission gas into the fuel rod plenum. Therefore, if the plenum is not adequately sized to

accommodate this fission gas content, then pressure-induced stresses can lead to cladding failure, particularly during transient-induced temperature increases.

- *Phase stability or micro structural evolution*: the high-temperature, high-flux environment of the reactor core (which also induces temperature gradients) typically alters the microstructure or local composition of a fuel material from its initial state. Such changes include development of porosity that can vary in morphology across the radius of a fuel rod, establishment of different phases and redistribution of fuel constituents through the fuel material. Accumulation of fission products during irradiation can also contribute to these effects. Ultimately, they manifest themselves by degrading thermal conductivity, by introducing local high-power zones in the fuel, by enhancing chemical interaction between fuel and cladding, or possibly by affecting gas release or swelling phenomena.

For many fuel forms, contact of the fuel or fission products with the interior cladding surface leads to interactions that embrittle the cladding or otherwise compromise its ability to withstand stresses. This is particularly true for some metal alloys, in which fuel constituents and fission products interdiffuse with cladding constituents, resulting ineffective thinning of the cladding and incorporation of low-melting phases or compositions in the fuel, cladding or the interaction zone at the fuel-cladding interface; formation of such zones often has implications for fuel reliability during high-burn-up, steady-state operation and during certain transients. Experience shows that fuel performance almost always degrades as the plutonium content of the fuel is increased. The proposed fuels employ an actinide alloy that is primarily plutonium. Furthermore, the incorporation of such a large quantity of minor actinides into the fuel alloy has never before been tested.

A major complication to the irradiation test programme is the lack of an appropriate test reactor in which to conduct the irradiations. Furthermore, no LBE test loop exists at any irradiation facility in the world. However, it should be remarked that more intensive research should be conducted towards simulating materials behaviour under irradiation conditions in order to shorten the necessary irradiation campaigns. Such a modelling of materials behaviour, under proton and neutron irradiations, would also permit a better focusof the experiments in the scarce and expensive irradiation devices.

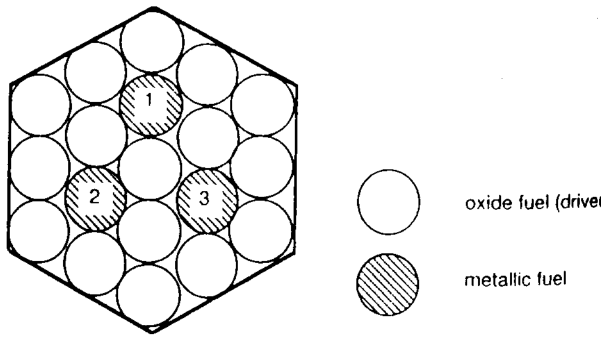
Compatibility between the fuel and stainless steel cladding must be confirmed. Considerable data exist in this area for metallic, plutonium-containing EBR-II or IFR fuels and a variety of stainless steel claddings. Of particular interest will be the class of stainless steel alloys in use by the Russians in LBE applications, and the effect of the MAs on compatibility. For the dispersion fuel form, compatibility between the fuel alloy and the zirconium matrix must be demonstrated. Additionally, compatibility between the fuel and the LBE must be characterised. Although little data currently exists in this area, the relatively high solubilities of plutonium and zirconium in lead and bismuth indicate the need to consider dissolution of fuel material into coolant after a breach of cladding. The major issues in this area must be resolved before beginning the irradiation test programme.

A number of issues related to the fuel-cladding gap must be resolved before fabricating the initial fuel for irradiation testing. For the primary dispersion fuel form, it must be determined whether fabrication techniques allow for co-extrusion of the fuel and cladding, thus eliminating the need for an open gap and a thermal bond material. Should these be required or desired, a thermal bond material must be selected that is compatible with the fuel, cladding and coolant; this material will probably be a liquid metal, such as LBE or sodium.

While many material properties may be conservatively estimated for the purposes of obtaining approval for the initial irradiation experiments in test reactors, this will not be enough to prepare a sound technical safety case for an ADS core. This is because the material properties may be very conservatively estimated for the purposes of irradiation testing, relying on the fact that only a small amount of the test fuel is being introduced into the reactor core, thus limiting the consequences of any failure to an acceptable level. Such consequences are generally not acceptable when failure is extended to a significant fraction of the core. Thus, a fairly comprehensive experimental programme to measure the important fuel properties directly must reduce the large uncertainties associated with the conservative estimates of material properties.

Besides the developments in the USA that could be re-started in the context of the AAA-programme, other countries and international laboratories have undertaken comparable experiments. Activities started at CRIEPI (Japan) and have now extended to TUI-Karlsruhe. These new activities also cover fuel reprocessing. In particular, an experiment (METAPHIX) is planned, in order to irradiate metal fuel pins, loaded with MA and rare earths (RE).

Figure 7.1. **Arrangement of fuel pins in a rig for the METAPHIX experiment (CRIEPI-TUI)**



Nine metallic fuel pins have been prepared for the METAPHIX irradiation study: three pins of UPuZr, three pins of UPuZr-MA2%-RE2%, three pins of UPuZr-MA5%, and UPuZr-MA5%-RE5%. They are planned to be inserted in the positions 1, 2 and 3, respectively, in the rig. Three rigs consisting of three sample metallic fuel pins and sixteen driver oxide pins will be prepared, one for each of the burn-up values 1.5, 5 and >10%.

On homogeneous recycling in standard oxide fuels, some experimental knowledge has been obtained with the SUPERFACT experiment. More will come from experimental programmes conceived at JNC to take place in JOYO beyond 2003. However, no experience exists on MA-loaded oxide fuels in standard light water reactors.

In the context of a heterogeneous recycling mode, apart from conceptual studies at JNC and CEA, experimental activities have been launched in Europe (e.g. the EFTTRA collaboration) and some useful indications have been gathered. The EFTTRA-T4 and T4-bis experiments concern ^{241}Am, at a 12% volume fraction, in a matrix of $MgAl_2O_4$, for a maximum fission rate of 28%. Swelling due to the decay of the ^{242}Cm produced by neutron capture has been significant, and triggered further research on the form of inert matrix-actinide fabrication (e.g. micro-dispersion versus macro-dispersion). It is worth noting that experiments performed up to now did not cover the presence of ^{243}Am and curium. Further experiments are planned in France, and in particular the ECRIX experiment, which should take place in PHENIX, and the CAMIX and COCHIX experiments also planned in PHENIX. The CAMIX experiment will provide information on "micro-dispersion" of a $(Am, Zr, Y)O_{2-x}$ compound in MgO, and COCHIX information on the same compound "macro-dispersed" in MgO or $(Zr_{0.6}\,Y_{0.4})O_{1.8}$. All three experiments are planned to reach a fission rate equivalent to 30 at%.

A significant global experiment is presently planned in the framework of the collaboration between MINATOM (Russia) and CEA (France) with FZK and TUI-Karlsruhe, as partners of CEA. In this experiment (AMBOINE), americium targets of $AmO_2 + UO_2$ and $AmO_2 + MgO$ will be fabricated at RIAR by the VIPAC process. These targets should be irradiated in BOR-60 and reprocessed by pyro-processing after further irradiation at RIAR, so providing a full validation of the whole fabrication – irradiation – reprocessing cycle for CER-CER targets.

The CONFIRM project, sponsored by the EU 5th FWP, is devoted to nitride fuels ((Pu,Zr)N and (Am,Zr)N). The project aims to fabricate, characterise and irradiate these fuels, and addresses also the issue of ^{15}N enrichment.

7.3.2.2 Structural materials research

Besides issues related to selecting an appropriate cladding material, materials research is focused on the choice of window material for the target of an ADS. Regardless of the technology chosen, the major research and development activities that are required for the successful development and demonstration of a target include:

- Establishing requirements for design data (material properties such as strength, ductility and fracture toughness as a function of displacement damage, in-beam and out-of-beam corrosion resistance, swelling tendencies, etc.).
- Performing irradiation and corrosion tests to provide the design data.
- Conducting irradiation tests on near-prototypical structures and components designed, fabricated and irradiated to simulate anticipated service situations.
- Post irradiation examination and analysis of test samples, structures and components.
- Acquiring spallation physics data and developing methods to predict yields of spallation neutrons and products.

Perhaps the most significant issue with regard to the target design, and certain the most costly to address, is the change in materials properties due to irradiation (proton and neutron) and exposure to LBE coolant. Iron, chromium and nickel, components of many structural steels, are soluble in liquid LBE and experience corrosion or erosion when exposed to streams of it. However, compatibility with the liquid LBE can be significantly improved by adding silicon to steel and controlling the oxygen content in the LBE alloy. Using silicon modified steels and oxygen control measures apparently provide the basis for successful application of LBE coolant technologies to several Russian nuclear systems, including Alpha-class nuclear submarines. There is little or no data on the effects of high-energy proton beams and spallation neutrons on materials properties at the temperatures of interest to ADS. Therefore, an irradiation test programme is necessary to quantify the effects of displacement damage, hydrogen and helium build-up and the accumulation of spallation products on material properties. Recent studies of candidate materials for the APT, irradiated and tested at or near 130°C, have shown that fission reactor data do not accurately represent the effects of irradiation by high-energy particle beams. These studies also confirmed the accumulation of high levels of hydrogen and helium in the irradiated materials. The temperatures anticipated for the LBE coolant in ADS are in the range where helium embrittlement of steels is well documented. These observations illustrate the necessity for irradiation testing under anticipated ADS temperatures and proton or neutron spectra.

Target window lifetime[71]

The window of the spallation target is a critical part of this device. It is directly exposed to the proton beam, it must be transparent to protons so it cannot be thick, and being an interface between accelerator and reactor environment, it will most probably be an interface between low and normal or high pressure. Moreover, it will also be exposed to back-scattered spallation neutrons and neutrons coming from the surrounding sub-critical core.

The following Table 7.3 presents the main parameters applied to assessing the lifetime of the window for each of the target types, using lead, mercury or tungsten plates for a 1 GeV beam. This table shows that lead and mercury targets suffer similar damage to the window; however, the mercury and tungsten targets have been designed for a higher power. Interstitial atoms of phosphorus and sulphur migrate towards grain boundaries at high temperatures and might cause local embrittlement. These phenomena still require more investigation from the materials standpoint and should include dynamic analysis of diffusion and migration mechanisms for chemical species as function of the temperature. The lifetime of the window is essentially determined by its mechanical properties. Here, two arbitrary limits in the deterioration of the material are used: maximum helium production (2 000 appm He corresponds to the dose accumulated in the Inconel window tested at LANL) and maximum dpa (100 dpa is half the objective for FBRs in order to be conservative). The second Table 7.4 indicates the lifetime of the window in a beam current of 33 mA for the different targets.

Table 7.3. **Factors affecting the lifetime of windows**

	Pb	**Hg**	**W plates**	**Units**
Neutron yield	28.2	24.6	15.5	n/p
Gas release				
H,D,T	740	790	680	appmH/mA.y
^{3}He, ^{4}He	40	43	39	appmHe/mA.y
Interstitials				
Phosphorus	6	5	5	appmP/mA.y
Sulphur	4	3	4	appmS/mA.y
dpa	0.92	0.94	0.68	dpa/mA.y

Table 7.4. **Limiting lifetime of windows with various target materials**

Limiting factor	**Liquid Pb**	**Hg**	**W**	**Units**
^{3}He, ^{4}He	1.5	1.4	1.6	Years
dpa	3.3	3.2	4.5	Years

The previous tables do not include "reactor range" neutrons and as these account for more than 50% of the overall damage, they should clearly be taken into account.

Radiation damage to the window ofthe spallation target and enclosure walls

Table 7.5 gives an evaluation of the damage by high-energy particles in the main system components as well as of gas production by spallation particles in the main target components. We

71. See also the description of spallation target technology in Chapter 4, Section 4.3.3.

allow for 4.6 nuclear interactions per incident proton, 0.5% of which take place in the window, 50% in the liquid target, 37% in the core and 12.5% in axial and radial shielding. An upper neutron shield is twice as much exposed (4%) as a lower shield.

Table 7.5. **Effects of high-energy particles on system components**

Component	**H, D, T**			**He**		
	appm/mA.day	appm/mA.y	appm/ dpa	appm/mA.day	appm/mA.y	appm/ dpa
Beam tube	1.165	425.52	644.73	0.032	11.7	17.27
Core	0.017	6.21	34.5	0.003	1.1	6.11
Dummy belt	0.56	204.54	401.06	0.022	8	15.69
Radiation damages to ADS components induced by high-energy particles						
dpa/mA.y	Core	Beam tube	Window #2	Dummy test belt		
	0.18	0.66	20.93	0.51		

The analysis shows that off the beam axis, most interactions come from neutrons. These interactions generate more dpa than gas release, as indicated in the previous table.

In Europe, the Fifth Framework programme has included a specific programme, entitled SPIRE, to investigate irradiation damage on such structural materials. This programme addresses the effects of:

- Spallation elements on microstructure and mechanical properties before irradiation.
- Spallation elements on microstructure and mechanical properties via ion implantation.
- Fast neutron irradiation on mechanical properties to complement existing data.
- Irradiation in a mixed neutron-proton prototypical spectrum on mechanical properties and microstructure. In addition, modelling is dedicated to characterising irradiation damage, predicting hardening and computing segregated boundary cohesion energy.

The main outputs are a validated data-base on tensile, Charpy, fracture toughness and the selection of a reference steel, for design studies.

Experiments

TC-1

The TC-1 loop is being designed, fabricated and pre-tested by IPPE, funded by ISTC. This loop is designed to the physical constraints and beam specifications of the LANSCE Area A. The TC-1 will be an in-beam test of LBE as a spallation neutron source target. It will be used to demonstrate operation and control of the LBE target, both in and out of beam; to investigate spallation product accumulation via cover gas sampling and post-irradiation examination of LBE; and to investigatedegradation of component performance with accumulation of spallation products, corrosion and radiation effects. This loop was planned to be installed in-beam in the second half of 2001.

LiSOR experiment

One of the major unknowns in liquid metal target development is related to whether liquid metal – solid metal reactions are enhanced under irradiation in the presence of static or cyclic stress. 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 cyclotron to irradiate stressed steel specimens in contact with flowing liquid metal. Currently the rig is being designed by SUBATECH with support from CNRS and CEA. LiSoR was originally planned as a stand-alone investigation. Owing to its immediate relevance for MEGAPIE, it is intended to be incorporated into the initiative, but for the time being it is still pursued on an independent basis. This is mainly due to the temporal restrictions which result from PSI's intention to discontinue operation of 72 MeV cyclotron in 2001 and from the time when results are needed to affect the MEGAPIE design. Support for LiSoR is being sought under the first phase of the EU 5th Framework Programme.

MEGAPIE

MEGAPIE is an international experiment undertaken by CEA, PSI, FZK, CNRS France, ENEA, SCK·CEN, US-DOE and JAERI. It is to be carried out in the SINQ target location at the Paul Scherrer Institute in Switzerland and aims at demonstrating the safe operation of a liquid metal target at a beam power in the region of 1 MW. The minimum design service life will be 1 year (6 000 mAh).

The target material will be the LBE mixture. Existing facilities and equipment at PSI will be used to the largest possible extent. In fact, the MEGAPIE target will be used in the existing target block of SINQ.

The target will be designed for 1 MW of beam power at a proton energy of 575 MeV, i.e. a total beam current of i_p = 1.74 mA.

The major objectives of the MEGAPIE initiative are:

- Full feasibility demonstration of a spallation target system.
- Evaluating radiation and damage effects on structures and beam window in a realistic spallation spectrum.
- Testing effectiveness of the window cooling under realistic conditions.
- Investigating interactions between liquid and solid metal under radiation and stress.
- Post irradiation examinations (PIE).
- Demonstration of decommissioning.

Two EU contracts established in the framework of the 5th FWP, SPIRE (material irradiation) and TECLA (physico-chemical properties of lead alloys, corrosion etc.), provide a relevant R&D back-up to the MEGAPIE project. Moreover, experimental laboratories have been launched in support of these activities (like the KALLA laboratory in FZK-Karlsruhe) or re-oriented (like the ENEA laboratory in Brasimone, the CHEOPE loop). In addition, a specific experiment is under way to study the possibility of early embrittlement under irradiation and inthe presence of LBE (the LISOR experiment).

7.3.2.3 Research related to liquid metals, particularly as target materials

The advantages and drawbacks of different coolants have been described in Chapter 4. Some experiments are currently under construction or already performed in order to test basic aspects of coolant behaviour, besides some technological development tests in relation to specific system designs. Moreover, at present most ADS target designs are based on LBE and this is the driving force for most of the R&D programmes indicated below.

Several groups have proposed R&D-programmes in this field and some test loops have been constructed:

Japan

As part of the R&D for the Accelerator Material Irradiation Facility, a liquid LBE loop for material testing was installed in JAERI/Tokai at the end of January 2000. The loop was successfully operated at 450°C with 50°C of temperature difference for more than 1 200 hours. For the safety analysis of the ADS physics experimental facility, a preliminary evaluation of a hypothetical accident showed that the dose rate around the facility can be controlled at a low level by the emergency shutdown mechanism. The groups for the experimental facility design and for research on the transmutation system were merged in April 2000. This new group, named as "Nuclear Transmutation Group", will undertake broad research and development for P&T technology as well as the development of an ADS Experimental Facility.

USA

In 1997-98, a first test loop to develop LBE technology was built at LANL. The objectives were to acquire experience in constructing and operating an LBE system, to collaborate with Russian experts on technology transfer, to implement and demonstrate reliable instrumentation for thermal-hydraulic parameters and to implement control systems for safe operation of the loop. The loop allowed temperatures in the range of 250-400°C and flow velocities of about 5 m/s (36 m^3/h capacity). A new test loop, integrating more Russian technology and experience, was constructed in 2000. This new loop is designed to study material compatibility and thermo-hydraulics. A higher temperature range (350-500°C), higher temperature changes (delta T = 100°C) and the possibility of natural convection makes this new test loop appropriate for experiments on corrosion control and coolant quality maintenance, material compatibility, thermo-hydraulics and heat transfer, equipment performance and natural convection.

EC

KALLA Lab (FzK, Germany)

In Germany, the HGF Strategy Fund Project aims at developing new methods and technologies to design and manufacture thin-walled thermally highly-loaded surfaces (such as the beam window) which are cooled by a corrosive heavy liquid metal (LBE). The results of this project will be the basic scientific-technical tool for the conception and the design of an ADS spallation target and later on a European Demonstrator of an ADS systems. Three fields are covered by this project (see following Table 7.6):

- *Thermal-hydraulic investigations*: if necessary for experimental thermal-hydraulic physical models of conductive and convective heat transfer along thermally highly-loaded surfaces such as a beam window in turbulent LBE flow. In parallel, a thermal-hydraulic computer programme isbeing validated for fluid LBE at low Prandtl numbers. Finally, a complete spallation target isto be numerically designed.

- *Material specific investigations*: using physical methods to define corrosion mechanisms in flowing LBE and ways to overcome their effects on potential structure and window materials, with and without surface treatment.

- *Oxygen control*: in the field of reaction kinetics, a physico-chemical method to measure and control the oxygen potential in a LBE loop is being developed in order to prevent corrosion of the materials used.

Table 7.6. **Experimental investigations performed in the KArlsruhe Lead LAboratory (KALLA)**

Technology loop	Thermal-hydraulic loop	Corrosion loop
Oxygen measurement	Single-effect investigations	Corrosion mechanisms
Oxygen control	Solid beam window	
Measurement techniques	Windowless design	Protective layers
Heat transfer and turbulence	Closed target module	Mechanical tests
High-performance heaters	Fuel element	
	Steam generator	
	Heat exchanger	
	Integral investigations: Core heat removal Decay heat removal	
Fluid volume: 0.1 m^3	Fluid volume: 0.5-4.0 m^3	Fluid volume: 0.03 m^3
Temperature: max. 550°C	Temperature: max. 550°C	Temperature: max. 550°C
Flow rate: max. 5 m^3/h	Power: 0.3-4.0 MW	
	Flow rate: max. 100 m^3/h	Flow rate: max. 3.5 m^3/h

TERM experiments

In order to study some of the unresolved problems related to the design of liquid metal targets in the context of the ESS project and in preparation of a data base for thermal hydraulic studies for a possible later SINQ liquid metal target, a Test Experiment at the Riga Mercury Loop (TERM) was set up. The main goal was to study experimentally questions of heat transfer between the window and the fluid and related flow distributions in various geometrical configurations. The first phase, which used the geometry of the SING target, has been finished. Methods developed and used include Ultrasonic Velocity Probes (UVP), based on a through the wall measurement of the Doppler effect in the fluid, Heat Emitting Temperature Sensitive Surfaces (HETSS) and Surface Thermography. Data from this phase of the experiment are still being evaluated. Ongoing experimental work now concentrates on the geometry of the ESS target and the effect of gas in the fluid on the cooling of the beam window. The full-scale SINQ target model is also still available for further investigations.

PSI LBE loop

In order to be able to carry out experiments even more realistic for SINQ than were possible at the Riga Mercury Loop, an LBE loop has been constructed and is being commissioned at PSI. Without a test section attached, the loop contains 0.12 m^3 of LBE and has a total height of 5.1 m. Operating temperatures are rated at up to 250°C. It is equipped with an EM pump (32-58 kVA) with a head of 1.5 m LBE and a capacity up to 200 l/min. The pressure rating of the loop is 1 to 2 bar. Test sections can be added to the loop depending on the problem under investigations. The loop is intended for testing of individual components as well as studies of flow configuration and heat transfer problems.

CIRCE

ENEA, though its ADS Project Team and in collaboration with Ansaldo, has decided to build CIRCE – a Pool Test Facility based on LBE – carrying out R&D in support to the ongoing ADS design activity. In particular, CIRCE will allow testing the key operating principles of the LBE Experimental Accelerator-Driven System (XADS) currently being designed in Italy. The size, the LBE load of 100 tonnes, the layout, and the basic features of the CIRCE facility have been set to meet the aforementioned R&D needs and utilise the former PEC building structures and components in Brasimone. The facility has been conceived to feature basically natural and enhanced circulation of LBE in a fairly large pool with a controlled and instrumented environment, electrical heating of the test volume and removal of 1 MW. The wide access to the test pool from the top with dedicated test sections supported by the cover plug makes the facility suitable for different tests: thermal-hydraulic, LBE purification and material compatibility, special instrumentation and remote blind operation in a LBE environment, integral component prototype, and benchmarks for scaled system analysis. Table 7.7 provides the main parameters of the facility.

Table 7.7. **CIRCE Facility Main Parameters**

Parameters	Value
Main vessel	
Outside diameter, mm	1 200
Wall thk, mm	15
Height, mm (from bottom head to top flange)	8 500
Material	AISI 316L
LBE inventory, kg (max)	~90 000
Electr. Heat tracing, kW	47
Cooling air flowrate, N-m^3/s	3
Temperature range, °C	200 to 550
Main vessel cover gas pressure	
Operating, kPa (gauge)	15
Design, kPa (gauge)	450
Argon gas	
Flowrate, N-liter/s	15
Injection pressure, kPa (gauge)	600
Electr. heaters (prospective) for core power simulation, MW	1.1

Test results from CIRCE can intersect a wider interest on HLM, the basic features of the CIRCE facility offer flexibility to conceive test on a more general frame of interest related to the HLM use. The tests with the CIRCE facility could give confirmation on: material corrosion in oxygen-controlled eutectic in “pool” configuration, effectiveness of different filtering elements for the Pb-Bi purification, Pb-Bi natural circulation, Pb-Bi enhanced circulation by gas injection system, performance of a secondary loop with low-vapour pressure organic diathermic fluid, overall plant performance and systems interaction during operational and accident conditions, hydraulics of a windowless target eutectic Pb-Bi, kinematic links of the fuel handling machine in cover gas and in the melt, ISI technology, instrumentation operating in Pb-Bi.

The basic configuration of CIRCE, including the first test section, has been completed and commissioned at the site of Brasimone (Italy) in October 2001.

TECLA

This EC 5th FWP-funded programme aims at carrying out several investigations in order to demonstrate the applicability of LBE technology or develop new systems. Moreover, thermal-hydraulic experiments on fundamental topics typical of any ADS system have to be performed in order to define analytical correlations for lead alloys and to validate codes for design. The final goal of this activity is to demonstrate the feasible use of lead or LBE as spallation target and coolant.

Several additional and smaller Pb and Pb-Bi loops had been build in some of the institutions participating in this TECLA program.

VICE

VICE (Vacuum Interface Compatibility Experiment) is intended to answer questions on the direct coupling of an accelerator to a liquid LBE target in a windowless design for the MYRRHA-project. The objectives of VICE are to:

- Clarify the possible interaction of the accelerator, demanding a high vacuum, with material emanating from the LM in the windowless design.
- Qualify and test corrosion protection methods for the loop wall (protective coating or oxygen control).
- Assess initial out-gassing rates of the LM and vessel as a function of temperature and other parameters affecting diffusion and cleanliness of the LM.
- Assess the migration of material towards the accelerator, whether gases or metal vapours under quasi-operational conditions.

7.3.3 Reprocessing research

Chapter 3 introduced the description, and especially the applicability, of the two main categories of process that might be applied to the separation of long-lived radionuclides: hydrochemical and pyrochemical processes. It was indicated that, to avoid radiolysis effects, pyrochemical processes are the better suited to the TRU and MA recycling schemes. This section will therefore briefly review the two processes where some emphasis will be given to the R&D requirements for the pyrochemical processes. Additional information with extensive descriptions of these processes and the R&D programmes is given in the literature [8,9,2,195].

Numerous concepts have been consolidated or newly developed during the last few years, both in hydrochemical and pyrochemical processing of HLWs or spent fuels and targets for advanced nuclear systems. Tests on “real objects” were carried out successfully in several countries, including the EBR II demonstration test at Argonne-West (USA) on pyro-processing of spent FR fuels. In the domain of hydrochemical processes, development is flourishing. Multi-step processes look promising but most of the systems developed so far appear complex and probably need to be simplified. In the domain of pyrochemical processes, interest has strongly revived in “old concepts” including fluoride volatilisation.

Hydrochemical processes

Extending the current industrial Purex processes towards improved separation of neptunium, and further to the other minor actinides, is a research topic in many countries. The future R&D tasks to develop such advanced aqueous reprocessing technology may be summarised as:

- Reducing the size of head-end equipment.
- Enhancing and optimising equipment with respect to corrosion resistance, extraction performance, etc.
- Improving the efficiency of MA recovery processes to reduce waste.

It also seems important to simplify the hydrochemical MA and LLFP separation processes, and reduce their space requirements. Some routes for improvement can be proposed:

- Single-cycle operation.
- Considering High Active Concentrates instead of High Active Raffinates as source material (large volume reduction factor).
- Integrating MA and LLFP separation processes.
- Considering less familiar LLFPs for possible partitioning.
- Maintaining the "CHON principle" to minimise secondary solid wastes.

Table 7.8 gives a brief overview of the status of R&D on the various aqueous partitioning techniques as was reported in the first-phase P&T systems study "Status and Assessment Report of Actinide and Fission Product Partitioning and Transmutation" [2].

Three phases were distinguished:

- *Phase 1* corresponds to research on the principles of the process. In many cases, it overlaps the basic research conducted in the laboratory (for example, research on new extractant compounds). Its completion demonstrates the scientific feasibility of the process.
- *Phase 2* is the process development step. It includes all research designed to develop the complete flow chart, describe its application, and guarantee its performance. The conclusion of this step demonstrates the technical feasibility of the process.
- *Phase 3* relates to the industrialisation of the process. It is aimed to ensure overall active operations in industrial conditions. In practice, these studies are essentially conducted by engineering design. It terminates in the industrial feasibility of the process and its potential application in an industrial installation.

For all these processes the development of new extractant molecules and the improvement of existing ones is carried out world-wide. In particular the most challenging separation, that of actinides from lanthanides, has inspired work on diphosphines in Russia, research on dithiophosphinic acid derivatives in China and Germany, the improvement of TPTZ and BTP derivatives in France and in India the examination of sulfoxide-type extractants.

For the sake of process industrialisation, the economics and the radiation resistance of the organic molecules are important R&D issues. The aim is to develop sustainable, environmentally friendly processes. A direct selective extraction of actinides from the Purex raffinate would reduce the number of process steps, and pre-concentration of the raffinate by a factor of ~10 the volumes of liquid to be handled. Cost-effective, robust and simple processesare needed with either well-established technologies (pulsed columns, mixer settlers and centrifugal contactors) or new technologies such as hollow fibre modules. In all cases it is important to keep a good balance between fundamental chemical research, process development and qualification using genuine high active wastes originated from real spent nuclear fuels.

Table 7.8. **Status of R&D on aqueous separation techniques**

	Phase 1	**Phase 2**	**Phase 3**	**Remarks**
U and Pu separation (PUREX)	–	–	–	Achieved industrially
Np separation (PUREX)			X	95% separation
(PUREX)		X		>95% separation

(DIDPA)		X		
(HDEHP)		X		
(TRUEX)		X		
Am + Cm separation:				
– based on An/Ln co-extraction				
(TALSPEAK)			X	
(DIDPA)		X		
(TRUEX)		X		
(TRPO)		X		
(DIAMEX)		X		
– based on An selective extraction				
(TPTZ)	X			
(Picolinamides)	X			
(CYANEX 301)	X			SF=5900
(BTP)				
– based on precipitation	X			
(Ferricyanide)				
Am separation in the oxidised state				
(SESAME)		X		Am/Cm separation
Tc separation				
(PUREX)			X	Soluble Tc
(PUREX)	X			Insoluble Tc
Tc-PGM separation				
(Denitration precipitation)		X		
(Active carbon adsorption)		X		
I separation(PUREX)			X	95% separation
Zr separation (PUREX)		X		
Cs separation (Calixarenes)		X		
(Zeolite)		X		
Sr separation (Titanic acid)		X		
Cs and Sr separation (Dicarbollides)			X	
Pd (PGM), Se, Ru separation				
(Electrolytic extraction)	X			Soluble Pd, Se, etc.

Pyrochemical processes

With the completion of the demonstration review by the NRC and a positive non-proliferation assessment, the Department of Energy (DOE) decided to use this technology to process the remaining EBR-II fuel (approximately 25 tonnes) and some sodium-bonded metal fuel from the Fast Flux Test Facility (FFTF). After completion of an environmental impact statement, these production operations started in September 2000. The work performed to date on the treatment of nitride and oxide fuels has been on either the laboratory or engineering scale. The feasibility of the processes has been demonstrated, but large-scale tests have not been performed with irradiated spent fuel.

The Spent Fuel Treatment Program at ANL demonstrated many parts of the pyroprocess fuel cycle, but there are still key aspects that have yet to be demonstrated on a large scale with radioactive materials. The main outstanding issue is the recovery of transuranics. Large-scale equipment has been fabricated for transuranic recovery, but with the termination of the IFR program, the equipment and process was never tested beyond the laboratory scale.

The remote fabrication of IFR fuel was not part of the Spent Fuel Treatment Program, but the same technology was used to fabricate cold fuel for EBR-II and a demonstration of another pyroprocess (melt refining) for recycling EBR-II in the 1960s employed remote fabrication for 34 500 fuel elements.

One challenge for a pyroprocessing system is selecting the appropriate materials of construction for the high temperature processes. Material improvements are needed in order to lessen the formation of dross streams and increase material recovery and throughput.

The quantity of waste generated that requires geological disposal from pyroprocessing appears to be comparable at present to modern commercial aqueous processes. Advancements are being pursued to further reduce the disposal volumes through zeolite ion exchange processes. This technology has not been demonstrated beyond the laboratory scale.

Most of the radioactive work performed to date has been on the pyroprocessing cycle for metal fuel. Laboratory work has been performed on the head-end operations for oxide reduction and on the nitride fuel cycle. Demonstrations of these technologies with actual spent fuel are still needed. Additionally for nitride fuels, demonstrating the recycle of nitrogen is critical since ^{15}N is specifically required for the fuel in order to eliminate the formation of radioactive ^{14}C.

Further work is required in a number of areas related to process design and equipment. Actual irradiated fuel should be used to verify the behaviour of the TRUs and fission products. In addition, much work needs to be done to understand the fundamentals of the salt-recovery step to provide a basis for construction of more efficient cells and to understand the behaviour of fission products in this step. Alternative, lower-cost oxygen-evolving electrodes must be developed for the salt-recovery step.

Directions for improving the pyrochemical processes appear to be:

- Minimisation of TRU losses in wastes and increase of the purity of the separated fractions.
- Actinides that can be obtained through the combined use of several separation techniques and multi-stage techniques.
- The waste problem, which is mostly corrosion related owing to the aggressive process media.
- Character of the media and the high process temperatures, needs to be precisely estimated.
- Consideration of the possible separation of LLFPs.

Table 7.9 shows the current status of dry methods in analogy to the Table 7.8 for the aqueous reprocessing techniques.

Table 7.9. **Status of R&D on dry separation techniques [196]**

Process/Fuel type	Phase 1	Phase 2	Phase 3	Remarks
Pyroprocessing (LWR oxide fuel)				
Fluoride volatility		X		Process operated in Czech Republic in 1980s; experimentation in US. in 1960-1970s; supplemental experience via enrichment process
Electrorefining (U-Zr metal alloy fuel)				
U recovery		X		From EBR-II fuel treatment application
TRU recovery	X			Laboratory-scale work with liquid cathode (Pu only)
TRU separation	X			Cadmium distillation process (Pu only)
Noble metal fission product extraction		X		From EBR-II fuel treatment application
Ln, Cs, Sr fission product extraction	X			Laboratory-scale zeolite process
Tc, I recovery	X			Not considered

Electrorefining (U-Pu-Zr metal alloy fuel)				
U recovery	X			Not tested with irradiated fuel
TRU recovery	X			Laboratory-scale work with liquid cathode (Pu only)
TRU separation	X			Cadmium distillation process (Pu only)
Noble metal fission product extraction	X			Not tested with irradiated fuel
Ln, Cs, Sr fission product extraction	X			Laboratory-scale zeolite process
Tc, I recovery	X			Not considered
Oxide electrowinning (RIAR Process)				
U recovery		X		LWR fuel processed for BOR-60 MOX fuel production
Pu recovery		X		LWR fuel processed for BOR-60 MOX fuel production
MA recovery	X			At early development stage
Noble metal fission product extraction	X			At early development stage
Ln, Cs, Sr fission product extraction	X			At early development stage
Tc, I recovery	X			Not considered
Pyroprocessing (Non-fertile metal alloy fuel)				
TRU recovery	X			Laboratory-scale work with Pu only
FP extraction	X			Laboratory-scale work with lanthanides only
Tc, I recovery	X			At early development stage
Pyroprocessing (Non-fertile oxide fuel, inert matrix)				
Direct electrochemical reduction/electrorefining	X			Laboratory-scale work (U, lanthanides only)
Pyroprocessing (Non-fertile nitride fuel, inert matrix)				
Electrorefining process	X			At early development stage
Pyroprocessing (Non-fertile graphite particulate fuel)				
Fluoride volatility	X			Some experience with aqueous processing applies
Pyroprocessing (Molten salt fuel)				
Fluoride volatility		X		Work at NRI-Rez (Czech Republic), and Oak Ridge National Laboratory

Collaborations

It seems a pressing necessity to maintain, or best to increase, the collaborations in this complex field of reprocessing research at:

- National levels: maintain or create network(s) between academic and applied research bodies. As an example, in France, two networks exist working under the auspices of the December 1991 Nuclear Waste Act: the so-called PRACTIS and NOMADE Groupes de Recherches.
- Bi-national levels: numerous collaborations exist, e.g. CRIEPI-ANL, CEA-JNC, CEA-JAERI etc.
- Regional level. As an example, at the European level common works exist which are partly financed by the EU, e.g. the PARTNEW, CALIXPART and PYROREP programs within the EC 5th Framework Programme (2000-2003). The role of ITU at Karlsruhe is also very important for European and wider collaborations,
- At the International level, the roles of OECD/NEA for Workshops and Working Parties and also of IAEA appear essential.

7.3.4 Technology development

Where the previous paragraphs discussed the needs on basic R&D, the path towards testing, demonstration and finally deployment of such MA or TRU transmuters will be a long one where technological development will increasingly be needed. In particular, heat removal and ancillary systems meeting stringent licensing conditions will need further exploration once a basic concept has been accepted.

Several systems will need to be developed where, today at least, only limited experience and limited infrastructure are available to test the components. Therefore, technological development will need to be considered in the fields of:

- Primary and secondary pumps.
- Intermediate heat exchangers and steam generators.
- Vessel features, such as head, support structures and fuel handling equipment.
- Ancillary systems such as the coolant cover gas system, cold trap and filter.
- Penetration of the proton beam line through the reactor building and vessel.

As the development of such advanced nuclear fuel cycles with TRU/MA-transmuters is a long undertaking, it is to be envisaged that technology development, e.g. the building of pilot or demonstration plants, will most probably have to be initiated by R&D-organisations within an international context and, most probably, is a phased programme.

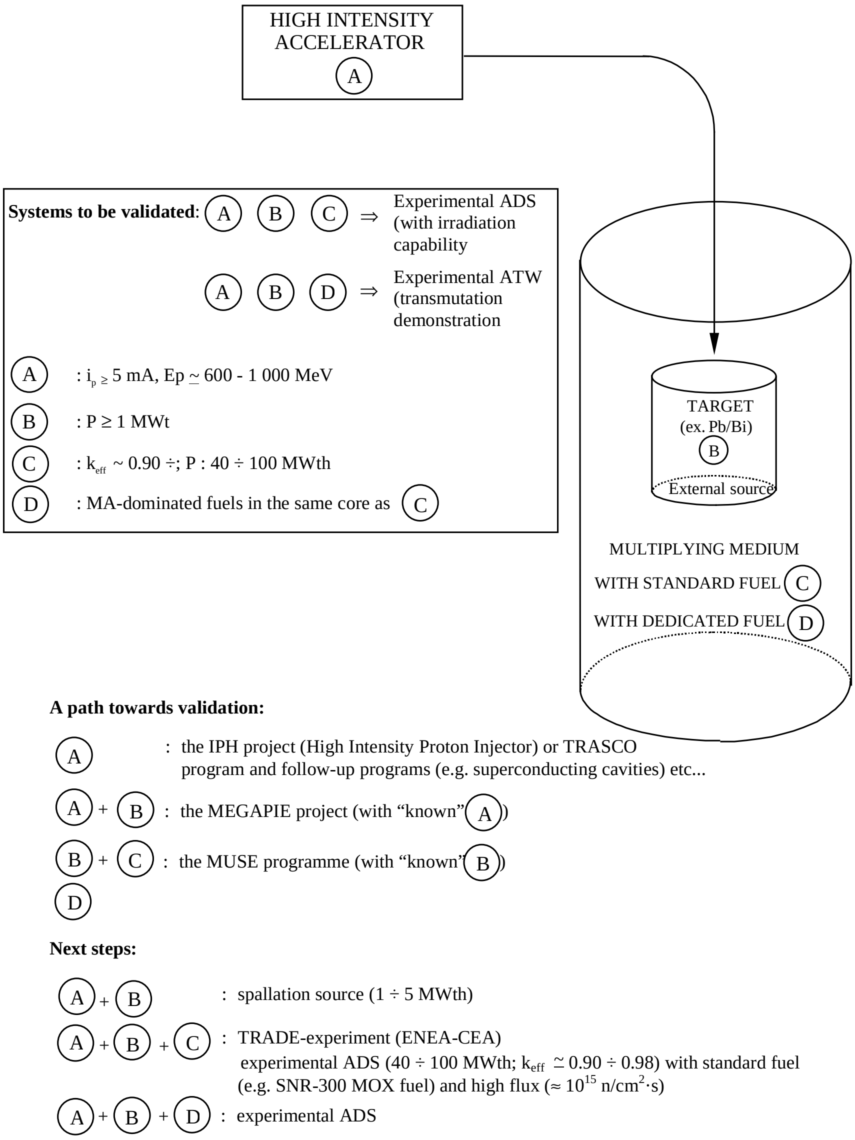
7.3.4.1 Pilot plants and demonstration facilities

The previous sections have already indicated the different activities needed to develop ADS facilities. Some of these projects are integrated in an R&D programme oriented towards developing a prototype, pilot or demonstration plant. Some examples of these initiatives are ADTF (USA), ADS Experimental Facility (Japan), XADS (Europe), Gas-cooled ADS (France), Lead-bismuth cooled (Italy), MYRRHA (Belgium), HYPER (Korea) and others.

As was indicated above, some very specific R&D issues, associated with experimental requirements, are to be handled first as a means to finalise detailed designs or, at least, to respond to the stringent licensing demands for such pilot plants. The continuous availability of irradiation devices in existing MTRs will therefore be very important. The neutron fluxes and/or the irradiation conditions in such critical (fast) MTRS, if available at all, may not always be representative enough for the mixed irradiation fields in the ADS field. For those countries embarking on the technology development of ADS, a demonstration ADS-type irradiation facility in an international programme may be needed.

A phased approach to the development of ADS may therefore be highly recommended while maximising the use of existing research facilities world-wide. Such a phased approach is schematised in Figure 7.2. Some of the ongoing programmes, for instance the KEK/JAERI programme in Japan, work through the intermediate and multi-purpose phase of a multi-megawatt spallation neutron source.

Figure 7.2. **A step-by-step approach to validating and demonstrating the ADS concept**



7.3.4.2 Multi-purpose facilities?

The "transmutation" community has recently become involved in discussing multipurpose facilities, based on a high power proton accelerator which provides neutrons by spallation on one (or several) target(s) for different applications. Some synergy may be sought between the development of ADS and FR but also between ADS and other fields of nuclear science and technology, e.g. spallation neutron sources, medical applications, radioactive beam facilities, and so on. Some OECD Member countries have envisaged such synergy, i.e. the joint KEK/JAERI programme in Japan, while other countries are studying proposals, e.g. the AAA programme in the USA.

There may be some good reasons to search for such synergy between the ADS-development for transmutation purposes and other uses, e.g.:

- More effective use of scarce financial and human resources.
- Phasing the development while better managing the inherent risks involved.

- Sharing technological development among different disciplines.
- Optimising the learning-curve process in developing ADS.

However, other considerations from a scientific and technical perspective counterbalance these advantages for synergy and may even jeopardise the prospects of a dedicated ADS development for transmutation purposes, i.e.:

- *Sharing of the available beam*. In some cases, technical measures can be used to change the time structure of beams to optimise them for particular applications.[72] Total available intensity must be considered. Clearly, there are limits to the ability to share a finite proton flux, however large, among users who require maximum intensity for their experiments. In addition, acceleration of negative ions and of protons may have to be supported in the same accelerator.
- *The needs and characteristics of the user communities*. The size and operating modes of user communities are important factors in deciding whether a shared large facility is warranted. In general, dedicated, longer-term projects cannot be easily combined with those where scientists from many disciplines come to the facility to perform short experiments (as is the case for many users of neutron sources). In addition, ADS-transmuter applications may have special safety and regulatory constraints that would pose particular organisational problems at a shared facility. In some cases, especially for those machines that are at or beyond the state of the art, accelerator physicists would need frequent access to the machine, with unscheduled down-times and frequent modifications. In addition, most of the other users do not require the high reliability demanded by ADS and may therefore not accept the over-design, and thus costs, for such a shared accelerator.
- *The time-scales of the various scientific programmes*. Long-range plans for the applications are in various stages of maturity at national and regional levels. Besides the difficulties of adding yet another level of co-ordination, there is the simple observation that each field should proceed according to its own optimum pace, which may not be compatible with the concept of multipurpose facilities.

In addition, the successful implementation of any of the facilities, whether for single or especially for multiple purposes, will depend on the ability of scientists and engineers to design and operate High Power Proton Accelerators (HPPA) with beam energies in the Giga electron-volts (GeV) region, and power levels ranging from 1-5 megawatts for some applications to 50 megawatts for others. In several critical areas, the necessary levels of performance greatly exceed the state of current knowledge and technological capability (see Chapter 4).

The notion of combining several HPPA applications at one facility deserves serious attention, with a realistic appraisal of the needs, benefits, and difficulties. Opportunities for joint R&D should be exploited whenever possible, even when separate facilities are in order. While ADS for transmutation purposes would definitely benefit from sharing the technological development of HPPA with other users, other users are not always receptive to such sharing of facilities for the reasons given.

It may therefore become accepted that ADS may need to develop its own accelerator, including all aspects related to licensing, over-design, high reliability etc adding to the costs. This may remain true until such high power and high reliable accelerators become readily available in the market-place.

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72. Intermediate options are worth considering, viz., a single site with more than one accelerator and shared infrastructure such as power distribution and cooling systems, or office space.

As a conclusion, these developments are grounds for the nuclear community to look for further increased international collaboration if developing such ADS is considered a priority.

7.4 Conclusions

Based on the above considerations and supported by the conclusions in the previous chapters, we may conclude that:

- *Basic R&D* is needed for the new FR and ADS in the fields of nuclear data and neutronic calculations, fuel technologies, structural materials, liquid metals, reprocessing technologies, target materials and high power accelerators (the last two only for ADS).
- *Experimentation on fuels is a priority*. No concept can be considered seriously unless the appropriate fuels are defined, which means characterised, fabricated, irradiated and reprocessed.
- Since fuels play a central role in all scenarios of waste minimisation and nuclear power development, an international sharing of efforts on nitrides, oxides and metals should be organised in order to ensure an optimum use of resources in the few existing laboratories to handle very active fuels.
- In that connection, *the availability of irradiation facilities, in particular able to provide fast spectra and high damage rates, is a key point and a major concern*. Again, an international initiative could be envisaged to harmonise programmes and to allow the best use of existing resources. Identifying the experimental irradiation needs in such a shared international facility would be a worthwhile undertaking.
- *Demonstrating at the appropriate scale the performance of pyrochemical processes* (level of losses, secondary waste, etc.) is needed in order to assess the technico-economic viability of certain fuel cycle scheme options.
- In the field of basic R&D supporting FRs as well as ADS, the discussion of *coolants for FR or ADS* would benefit from a better international agreement on the advantages and drawbacks of the different options.
- *Improved modelling tools to simulate the materials behaviour* under (mixed) irradiation conditions, and possibly high temperatures, may prove to be a very valuable approach and a sharing of expertise and benchmarking within an international context may be advocated.
- *Safety analysis of ADS* should identify the possible paths to exclude HCDAs in ADS. If such a HCDA has to be taken into account in the safety analysis of an ADS, a prompt negative feedback mechanism for quenching such an accident has to be developed.
- And last but not least, *performance assessment studies for a geological disposal site using a P&T source term* are necessary in order to clarify the cost-benefit analysis of such advanced fuel cycles, including this geological disposal.