STATUS OF THE TRADE EXPERIMENT

S. Monti[1], L. Picardi[1], C. Rubbia[1], M. Salvatores[2], F. Troiani[1]
[1]ENEA, Lungotevere Thaon di Revel, I-00196 Rome, Italy
[2]CEA, CEN-Cadarache, F-13108 Saint-Paul-lez-Durance, France

Abstract

The paper describes the status and the main technical achievements in view of the preparation of the TRADE experiment to be performed in the TRIGA reactor of the ENEA Casaccia Centre in Italy. The first beam operation is foreseen for early 2007 and the first operation of the full experiment in TRIGA by early 2008.

Substantial improvements have recently been introduced with respect to the original design developed in 2002-2003, both in the functionality of the components and in the general layout of the experiment, within the main target goals already described in previous papers [1,2].

The main additional elements of TRADE with respect to the already-existing TRIGA-1 MWatt reactor are: (1) a high-energy accelerator with a suitable current and conservative, well-proven technologies, (2) a beam transport line to bring the beam in the TRIGA reactor operated as a subcritical system, (3) a solid target inserted in the core of TRIGA with the purpose of producing an adequate neutron source by the spallation reaction, and (4) additional shielding due to the production and injection of a particle beam in order to conservatively ensure an adequate radiation protection of the above new components.

The accelerator chosen is a compact negative ion (H^-) accelerator with an energy of approximately 140 MeV and a variable current with a maximum of about 300 mA. The beam transport has been drastically simplified with respect to previous designs, reducing the integrated bending power to the minimal 90 required by the difference in orientation of the horizontal accelerator and the vertical access tube to the spallation target. The presence of an extracted proton beam introduces significant contributions in terms of beam losses and additional radioactivity in the immediate vicinities of the accelerator, beam transport and target. To this effect additional shields have been introduced both in the regions immediately adjacent to the active elements and some additional conservative shielding in the form of a full “box” around the full reactor building, but physically well separated from the reactor structure.

The present schedule of TRADE foresees the first accelerator operation by early 2007. A period of one year is foreseen for the operation of the beam transport and the spallation target in the so-called “test station” realised in the accelerator building. When all possible certifications of the operability of the target system have been successfully completed the coupling between the accelerator and TRIGA will become operational.

Outline and general layout of the TRADE facility

The *TR*IGA *A*ccelerator-*D*riven *E*xperiment (TRADE), to be performed in the existing TRIGA reactor of the ENEA Casaccia Centre, is an original idea of Carlo Rubbia aimed at a global demonstration of the ADS concept. TRADE will be the first experiment in which the three main components of an ADS – the accelerator, the spallation target and the subcritical blanket – will be coupled at a power level sufficient to encounter feedback reactivity effects. As such, the TRADE experiment represents the necessary intermediate step in the development of hybrid transmutation systems, its expected outcomes being considered crucial – in terms of proof of stable operability, dynamic behaviour and licensing issues – for the subsequent realisation of an ADS transmutation demonstrator.

As already demonstrated in previous papers [1,2], the experiments of relevance that can be performed in TRADE concern:

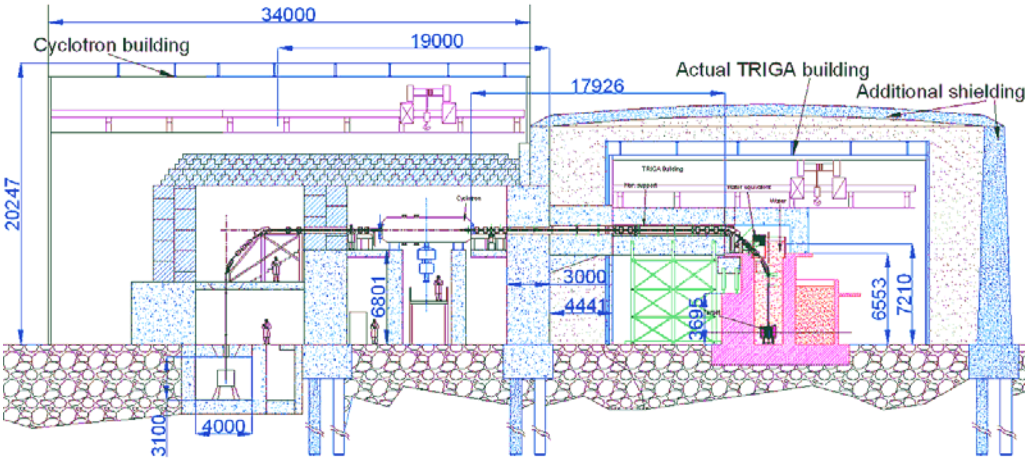
- The dynamic system behaviour of an ADS vs. the neutron importance of the external source at different subcriticality levels, providing important information on the optimal subcriticality level.
- Subcriticality measurements at significant power.
- Correlation between reactor power and proton current.
- Reactivity control by different means and possibly by neutron source importance.
- Compensation of power effects of reactivity swing with control rods movements or with proton current variation.
- Start-up and shutdown procedures, including suitable techniques and instrumentation.

The representativity of the TRADE experiment as concerns the validatation of the dynamic behaviour of a subcritical system over a wide range of subcriticality levels (whatever the neutron spectrum in the core), has been demonstrated [1], and has been the subject of an international workshop, held in Rome on 11 March 2004 (presentations available on the Internet site http://www.trade.enea.it).

The overall layout of the facility – determined after a quite comprehensive comparison among others – is shown in Figure 1 [3]. It foresees the erection of a new bunker, close to the existing TRIGA building, to house the accelerator and the test station for proton beam test and adjustment. The proton beam is transferred from one building to the other via a section of the transfer line that is particularly simple, since the cyclotron is at the same level as the top of the reactor. The beam transport line is protected by a massive shielded tunnel which extends into the TRIGA building up to the reactor top. Through the straight section of the transport line, the beam is transferred to the final bending section composed of two magnetic dipoles and three magnetic quadrupoles, which have the duty of directing the beam, with the correct size, to the spallation target placed in the central thimble of the reactor.

As for the accelerator, several configurations were studied for a suitable proton energy beam of 140, 200 and 300 MeV and with a beam current in the range 100-300 mA. Taking into account the constraints related to the cost and the relatively short time scale for the implementation of the TRADE experiment, a room temperature H^- cyclotron is considered the most affordable solution. In fact, even if the requested performances for TRADE (140 MeV, 2-300 Am) are rather challenging with respect to those of the existing machines, the TRADE cyclotron can be regarded as an evolution of a typical H^- machine for radioisotope production (E_p around 30 MeV) or for hadron therapy (E_p around 60 MeV).

Figure 1. Reference layout of the TRADE facility (vertical section)



The main reference parameters of the TRADE subcritical core are reported in Table 1.

Table 1. TRADE main reference parameters

Global parameters	Symbol	Reference case
Initial fuel mixture	LEU	UZrH
Initial fuel mass	m_{fuel} (kg)	235.2
Initial U concentration	m_U/m_{fuel} (wt.%)	8.5
Initial fissile enrichment	$^{235}U/U$ (at.%)	20.0
Thermal power output	P_{th} (kWatt)	200
Spallation target		Tantalum
Proton beam energy	E_p (MeV)	140
Spallation neutron yield	$N_{(n/p)}$ (n/p)	0.74
Multiplication coefficient	$k = (M - 1)/M$	0.94-0.99
Accelerator current	I_p (mA)	215-35
Beam power	P_{beam} (kWatt)	30-5
Core power distributions		
Avg. fuel power density	P_{th}/V_{fuel} (W/cm^3)	4.9
Spec. fuel power density	P_{th}/m_U (W/g HM)	10.0
Max. heat flux	P_h (W/cm^2)	6.0
Max. linear power	P_l (W/cm)	68.0
Radial peaking factor	P_{max}/P_{ave}	1.3

The studies performed so far by a working group of scientists of ENEA (Italy), CEA (France), CERN (Switzerland), CIEMAT (Spain), CNRS (France), DOE (USA) and FzK (Germany) concern:

- The neutronics of selected possible configurations, along with a neutronic benchmark to define codes and tools to be used for the neutronic design and the interpretation of the experimental measurements.

- The core and target thermal-hydraulics, using natural or forced convection, including the target coupling to the reactor at power.

- The target performances and characteristics as well as the conceptual design of the target, its cooling system and the definition of the tests needed for its qualification.

- A conceptual design of the beam transport line.

- The shielding and activation aspects in order to gain insight on the dose issues.

- The safety and licensing aspects related to the plant modifications induced by the TRADE experiment, including considerations on general safety criteria, possible accident initiators and a preliminary hazards analysis.

- The overall experimental programme to be performed in TRADE.

- The representativity of the foreseen experiments in terms of dynamic behaviour, neutron spectrum, reactivity control, proton current/power relation, operation at start-up and shutdown, external source importance measurements, etc.

- A preliminary cost and time schedule evaluation.

Furthermore, a preliminary experimentation in the TRIGA RC1 reactor was carried out in fall 2002 so as to characterise the TRADE reference core; a new experimental phase – which will include measurements in a mock-up of the TRADE core with californium, DD and DT external sources – is being performed over 2003-2004.

The accelerator

Taking into account the constraints related to the cost and the relatively short time scale for the implementation of the TRADE experiment, a H^- machine is considered the most affordable solution. Moreover, the room temperature H^- cyclotron relies on a well-proven technology. The performance both in energy and in intensity for the accelerator of TRADE is significantly higher with respect to those of the presently commercially available units. However, this cyclotron can be regarded as a logical evolution of typical H^- machines for radioisotope production ($E_p \sim 30$ MeV) or for hadron therapy ($E_p \sim 60$ MeV), the most challenging upgrade being the need of bringing the energy of the protons up to about 140 MeV with an extracted current of at least 300 mA. Further, the accelerator must guarantee a flawless continuity of the beam to be injected in the subcritical subassembly.

In the past, some concern has been expressed as concerns the possible occurrence of erratic behaviour of the delivered current, which could produce adverse effects on the high-power subcritical core. Therefore, all active components of the accelerator and of the beam transport line must ensure the utmost reliability during operation. The simple cyclotron chosen in the design is characterised by an extremely small number of active, very reliable components, in comparison for instance with the number of elements and the size of a linac accelerator with equivalent performance.

A compact geometry is preferable to an open sector geometry because of the geometrical considerations related to the available space and accessibility, as evident from Figure 1. This type of structure also ensures a better shielding against beam losses, primarily due to stripping of negative ions. Such radiation losses, which occur in a narrow radial segment near the last orbits, could eventually be moderated with the help of dedicated small beam absorbers of suitable material.

An indicative list of parameters for the TRADE cyclotron is given in Table 2. Further details of the proposed cyclotron design are reported in another paper at this conference.

Table 2. Main parameters of the TRADE cyclotron

Parameter	Reference value
Output energy	120-140 MeV
Max. nominal current	300 mA
Normalised emittance at 2s	1-4 p mm mrad
Injected particles	H^-
Number of sectors	4
Extraction radius	2.2 m
Cyclotron outside diameter	6.5 m
Cyclotron magnet vertical size	= 2.0 m
Total weight	300-400 tonnes
Total power in main coils	~150 KW
Extraction	Stripping (carbon foil 70 mg/cm^2)
Beam losses due to electromagnetic dissociation	= 1%

The beam transport line and the beam diagnostics

The beam transport line (BTL) has two main purposes: (1) to rotate the beam direction from horizontal to vertical (90); (2) to match the beam emittance from the cyclotron to the precisely circular shape of the size required by the subsequent target.

The BTL is characterised by a straight line to transport the beam nearby the target with the help of a small number of quadrupoles, followed by the 90 achromatic final bend, composed of two dipoles and three quadrupoles. The two dipoles, each of 45 , have been chosen with a relatively conservative magnetic field of 1.3 tesla, corresponding to a curvature radius of about 1.3 m.

The second dipole M4 (see Figure 2) is immersed in the pool water of TRIGA in order to shield the neutron back-streaming from the core through the beam pipe (50 mm diameter), by about 2 meters of water. In the present layout, the water level also includes the quadrupole triplet Q7-Q8-Q9. It may be possible, however, to locally replace water with some other equivalently absorbing material (polyethylene?) in order to avoid insulation problems due to the water of the reactor pool.

The design criteria for the final part of the BTL were characterised by the minimum number of components with which one could achieve a circular spot of nominally 40 mm diameter at the target spot, starting from the actual parameters of the accelerator.

The overall layout of the accelerator and of the beam transport line in the final location is shown in Figure 3.

As for the diagnostics of the beam transport line, these are considered crucial for the TRADE experiment, both for the capability of delivering the correct beam to the target and for a very low loss transport in the BTL part sited in the TRIGA building, where shielding may not be as complete as for the cyclotron bunker. These monitors have to quickly react to beam variations and eventually, whenever necessary, shut off the accelerator in a very short time (microseconds).

They are used in a number of critical positions, both when the experiment is in the location of the target mock-up (i.e. in the test station) and in the final TRIGA position. In particular, during the mock-up phase they are necessary in order to experimentally determine the amount and the position of

Figure 2. BTL final section and beam port into the TRIGA core

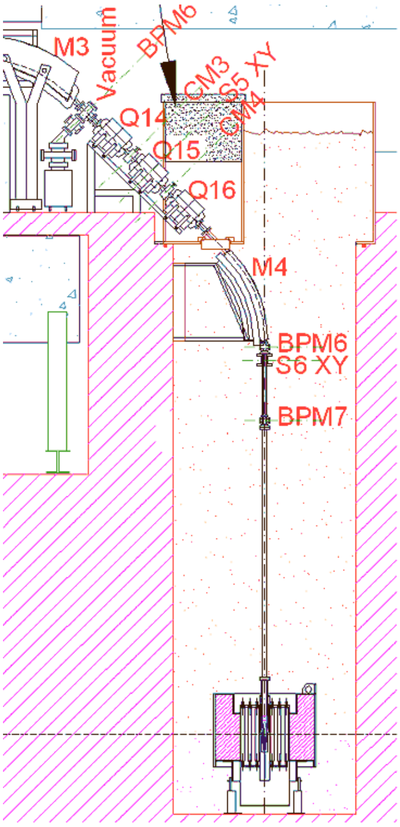
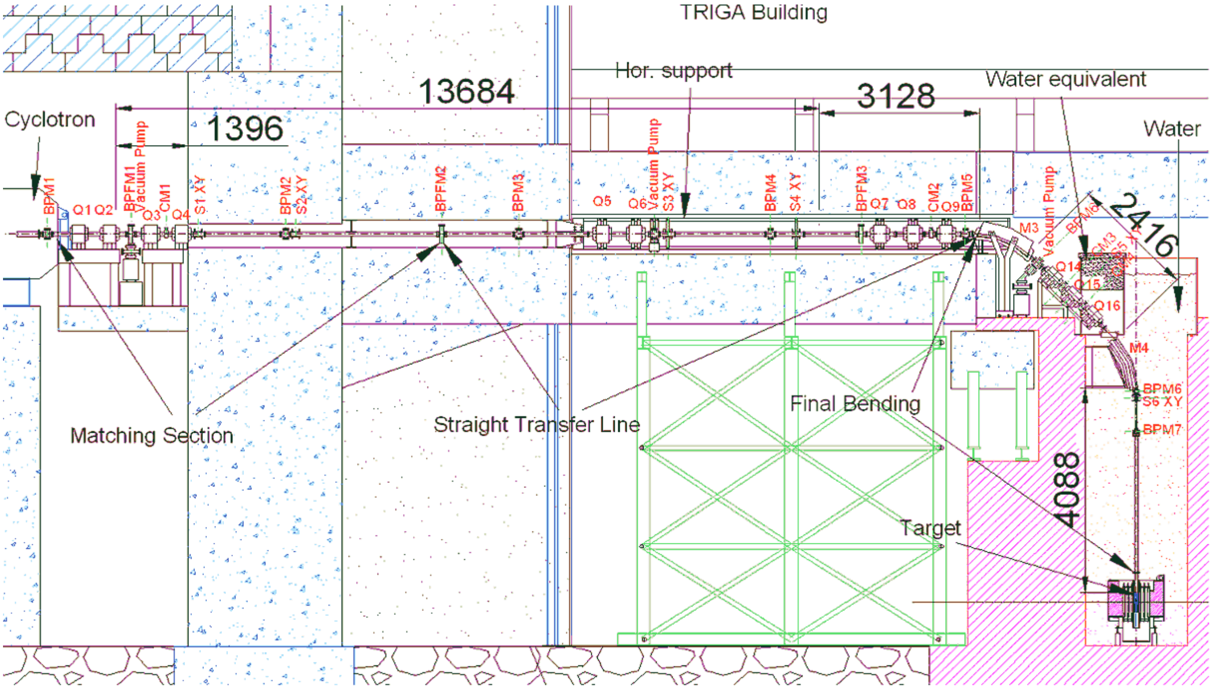


Figure 3. General layout of the accelerator, the beam transport and the TRIGA subcritical assembly with the target inserted in the core



the beam losses, in order to finalise a robust shielding protection. Some of the monitors are still at the detailed design stage, since they have to be checked in particular as to sensitivity and resolution. They are of two types, non-interceptive and interceptive. The non-interceptive are: beam position monitors, current monitors, beam loss monitors and infra-red thermometry.

Most of the beam diagnostics required are of a non-intercepting nature and therefore have straightforward solutions. However, these tools are unable to produce a precise "image" of the proton beam, for which intercepting diagnostics is necessary. In this case the interaction of the proton beam with a suitable detecting method is necessary, with a consequent scattering and hence modification of the beam emittances and eventually of some heat production. Particularly suited are the so-called secondary emission monitors (SEMs), in which secondary electrons, generated by the passage of protons through a thin foil or mesh, are recorded. They are currently under development in several laboratories (CERN, FERMILAB). In our case, however, they must withstand a current which is about an order of magnitude higher (up to 300 mA). These modern methods may replace with significant advantages the classic fluorescent screens viewed by a camera.

The BTL design and its diagnostics are discussed in more detail in another paper of this conference.

The spallation target

The spallation target is the key component of any ADS concept. Even in the TRADE facility, despite the relative small power of the proton beam (< 40 kW), the development and design of the target implies a detailed assessment of different aspects mutually interacting, from the physics of spallation reaction – including neutron generation and distribution, spallation products yields and damage rates – to technological issues, such as choice of the most suitable material, power density distribution, heat removal, thermo-mechanics, fabricability, etc. The guidelines that were followed for the target development, along with the main constraints and interfaces, have been extensively addressed in Refs. [4] and [5]. The target geometry is shown in Figure 4.

The inner geometry is characterised by three conical cavities with different angles and total length equal to the active height of the TRIGA core. The cone tip (lowest cone) is exposed to the highest power density for two reasons:

- The relevant proton current at the centre of the Gaussian distribution.
- The forward scattering of protons as a consequence of the conical angle steepness.

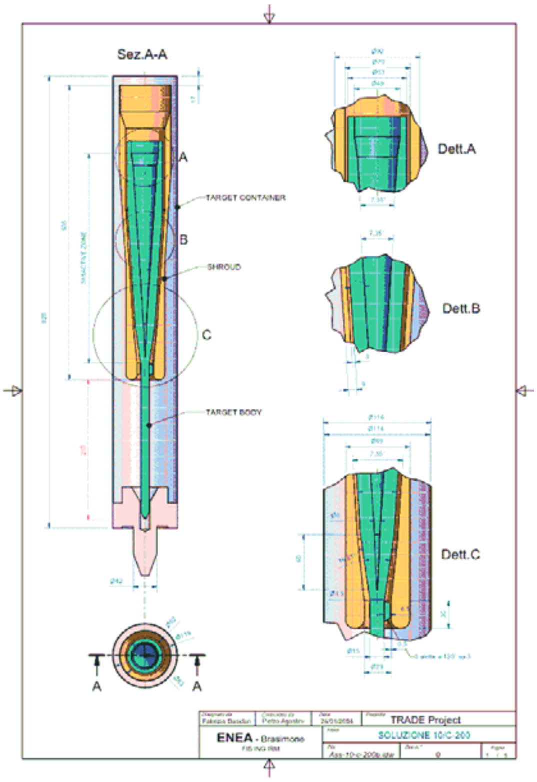
The main choices for the target are the following:

- *Material*: Tantalum has been selected for the spallation target due to its good properties of ductility, machinability and resistance to water corrosion and irradiation.
- *Thermal flux*: It has been decided to maintain the target thermal flux at a level corresponding to one-third of the critical thermal flux.
- *Target cooling mode*: Forced circulation has been selected, rather than natural circulation, in order to facilitate the start-up and shutdown operations as well as to guarantee an efficient heat removal with limited exchange surfaces.

- *Tantalum welding*: No welds are allowed in the zone where spallation reactions occur and/or in high thermal flux regions.

- *Cladding of the target*: No target cladding is foreseen in order to avoid fabrication difficulties and negative effects related to differential thermal expansions of the materials.

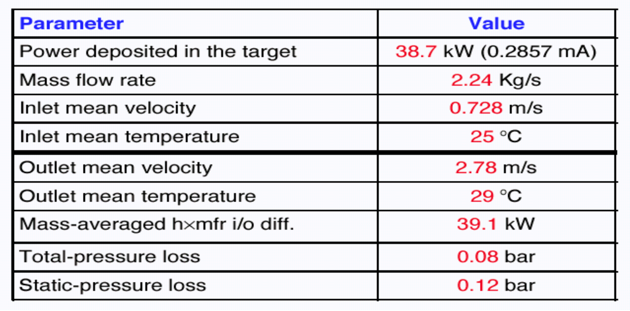
Figure 4. Spallation target configuration



As for maximum admissible loads and the elasto-plastic state of the material, on the basis of the RCC-MR engineering rules for fast reactors, a certain degree of plasticisation of the material is allowed. In any case the licensing of the target is subject to positive results of irradiation integral tests to be performed in the test station.

The thermal performances of the target under the reference operating conditions are reported in Table 3.

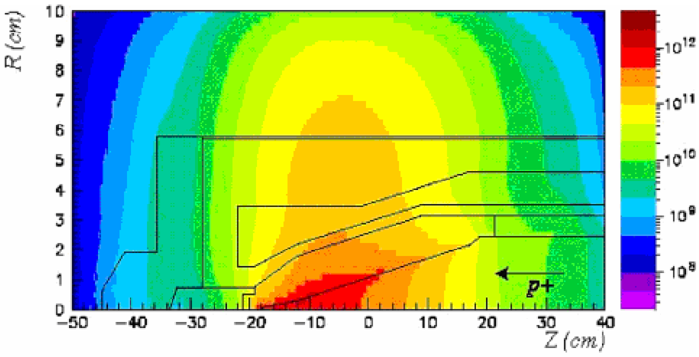
Table 3. Operating conditions



Parameter	Value
Power deposited in the target	38.7 kW (0.2857 mA)
Mass flow rate	2.24 Kg/s
Inlet mean velocity	0.728 m/s
Inlet mean temperature	25 °C
Outlet mean velocity	2.78 m/s
Outlet mean temperature	29 °C
Mass-averaged h×mfr i/o diff.	39.1 kW
Total-pressure loss	0.08 bar
Static-pressure loss	0.12 bar

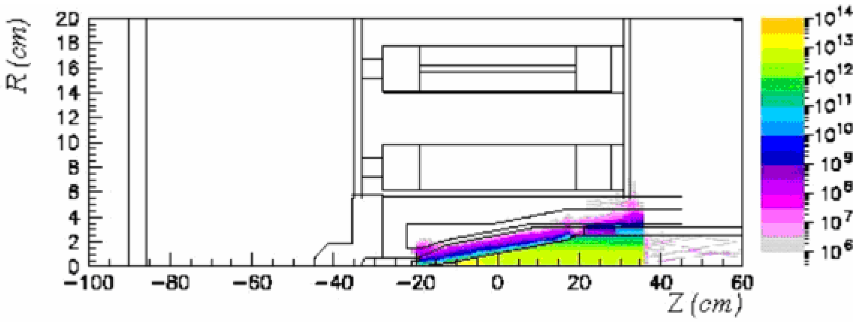
The neutron flux distribution outside the target is reported in Figure 5. Since the region of maximum production lies below the median plane of the core, in order to achieve a greater efficiency in the use of the source neutrons it is necessary to axially shift, by about 4 cm, the target body in the upward direction.

Figure 5. Neutron flux distribution in (n/cm^2/s) per kW of beam



Finally, the primary proton flux distribution for the target is reported in Figure 6. The fraction of protons escaping the target vessel is almost negligible apart from the upper part of the target (direct connection to the beam transport line) where the tails of the Gaussian profile are truncated. In any case the majority of the protons escaping the spallation target are either stopped in the cooling channel (riser) surrounding the target or inside the thick flow guide, none reach the core internal structures and only a few are backscattered into the vacuum beam pipe.

Figure 6. Primary proton flux distribution in (p/cm^2/s) per kW of beam



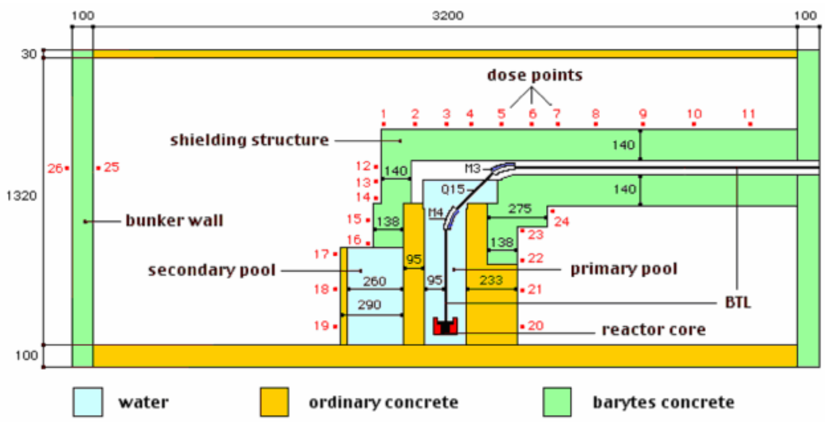
Radioprotection

The design of an ADS experiment in an existing critical facility such as TRADE presents some unusual shielding problems:

- A beam tube line entering from above the reactor that implies the requirement for shielding to be supported at a height in the facility hall.
- A vacuum pipe penetrating to the centre of the subcritical configuration and the subsequent radiation streaming back along this pipe from the core.
- The presence of both fission and spallation radiation components with quite different penetrative characteristics, with the existing shielding dimensioned for the fission component.

In designing the conversion of the TRIGA reactor to a subcritical configuration driven by a spallation source, preliminary solutions have been proposed to these problems. In order to support the shielding design, several Monte Carlo calculations have been performed by both the FLUKA and MCNPX transport codes [6]. These simulations have lead to the definition of the reference design of the BTL shielding and of the cover above the reactor well as well as to the need for two bending magnets in the final section of the beam transport line and an external full box around the reactor building. The reference configuration design has been modelled as shown in Figure 7, where the beam transport line, the core, the primary and the secondary pool and the shielding are shown (ordinary concrete at 2.3 g/cm^3 and barytic concrete at 3.2 g/cm^3).

Figure 7. Vertical section of a schematisation of the reactor building adopted in the Monte Carlo shielding and dose calculations



In order to reach dose rates below the limit of 0.5 mSv/h for the population, thicknesses of at least 170 cm barytic concrete would be needed around the BTL; on the other hand such weights might not be supported by the current foundations of the reactor hall. It has therefore been decided to limit the local shielding around the BTL to 140 cm barytic concrete and to introduce shields around the reactor hall (100 cm barytic concrete). Such a configuration produces maximum dose rates of 0.06 mSv/h outside the walls of the reactor building. This value has been evaluated by means of a 3-D mapping of the dose rates. Thus the dose limit to the population (0.5 mSv/h) is respected with a safety coefficient of 8. At the moment this should be adequate, and would possibly allow greater beam losses than those hypothesised (1 nA/m along the BTL and 30 nA for the quadrupole).

Concerning the dose limits inside the reactor hall, the calculational results show a maximum dose rate of 20 mSv/h, well below the allowable limit of 50 mSv/h inside the reactor hall.

The doses due to the streaming along the vertical part of the beam pipe have been calculated outside the shielding in the reactor hall and outside the bunker. Compared with the doses from the hypothesised beam losses, these doses are almost negligible.

Finally, the contribution to the dose rate in the reactor hall due to the spallation neutrons in the target and from the fission neutrons in the core has been evaluated. As the present reactor shielding has been designed for a critical 1 MW core, as expected the fission contribution from the 200 kW subcritical core is already well shielded. Instead the spallation component is far more penetrating, and it turns out that dose levels in the reactor hall are more than 2 orders of magnitude above the current limits of 50 mSv/h, with the fission contribution being negligible with respect to the spallation contribution. Solutions involving extra shielding around the core are currently being examined to reduce these doses.

The experimental programme

TRADE has begun the first phase of its experimental programme, and preliminary results have been described in past papers [7,8]. As discussed, TRADE will ultimately lead to the coupling of a high-energy spallation source to a TRIGA reactor. To ensure a meaningful transition from other preliminary ADS experiments, notably MUSE at Cadarache, an experimental programme has been developed consisting of three phases. In Phase IA, scheduled to extend from May 2003 to June 2004, a number of measurements in a mock-up of the TRADE core will be made, using a californium source. These include precise reactivity determinations, kinetic parameters such as b/L, and certain transient responses important to the safety case. In Phase IB, from June to December of 2004, the measures will be repeated with DD and DT sources, allowing direct comparison to the MUSE programme. Phase II deals with the start-up of the accelerator, and is scheduled for the 2007 time frame, while Phase III, the final TRADE experiments, will begin after.

Conclusions

The general set-up of the TRADE facility is now firmly established. The cyclotron building is separated from the TRIGA building. The geometry of the facility calls for a heavily shielded enclosure for the cyclotron and for the validation tests of the beam transport line and of the full target in water. After validation, the full unit is transferred to the TRIGA building. The beam is sent to the subcritical assembly through a shielded channel. A large external additional shielding externally surrounds the reactor building in order to ensure an adequate radiation protection of the radiation due to the production and injection of the particle beam. The structure of the shielding walls is well separated from the TRIGA building.

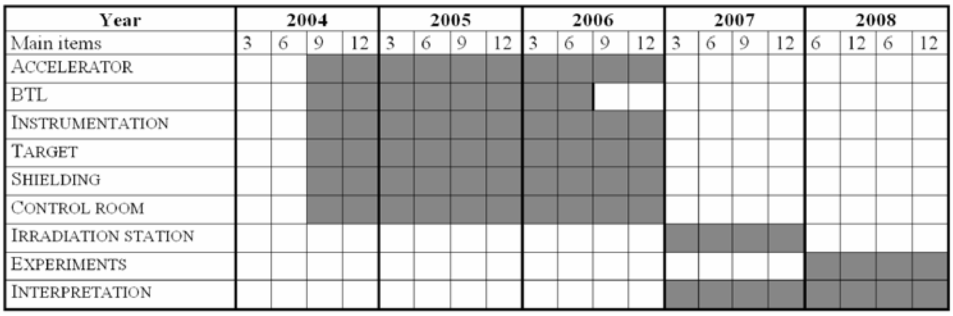
In summary, the main conclusions are the following:

- The accelerator is a compact H^- cyclotron of nominal current of approximately 300 mA, preceded by a HV set and an external source.
- The proton beam extraction from the H^- is based on an appropriate target stripper. Two independent extraction lines are foreseen, at about 180 radially from each other. The first line is used to validate the overall performance of the full acceleration system in the cyclotron building. After full certification, the subcritical TRIGA is activated in the final configuration.
- The beam transport line (BTL) has two main purposes: (1) to rotate the beam direction from horizontal to vertical (90), (2) to match the beam emittance from the cyclotron to the precisely circular shape of the size required by the subsequent target.
- An original “zoom” focusing geometry has been introduced in order to ensure with precision the required spot of the beam at the target position, independent of the actual emittances of the produced beam.
- All active components of the accelerator and of the beam transport must ensure the utmost reliability during operation.
- A comprehensive beam diagnostic will permit monitoring of the beam at all times, the main task being that of the observation of the beam shape immediately in front of the spallation target. A fast trip (microseconds) can switch off the cyclotron beam in case of emergency.

- The full subcritical source (spallation) will be evaluated in the test station, including the evaluation of the expected lifetime of individual components; one year operation at representative conditions (e.g. the same number of thermal cycles and same proton fluence); irradiation tests in order to evaluate and eventually optimise their mechanical characterisation and radiotoxicity; experimental determination of the beam losses and spectral measurements in order to optimise the shielding configuration in the final position.

Table 4 shows the relevant activities and milestones for TRADE design, construction and operation.

Table 4. Tentative schedule for the realisation of TRADE



Year	2004				2005				2006				2007				2008			
Main items	3	6	9	12	3	6	9	12	3	6	9	12	3	6	9	12	6	12	6	12
ACCELERATOR			■	■	■	■	■	■	■	■	■	■								
BTL			■	■	■	■	■	■	■	■										
INSTRUMENTATION			■	■	■	■	■	■	■	■	■	■								
TARGET			■	■	■	■	■	■	■	■	■	■								
SHIELDING			■	■	■	■	■	■	■	■	■	■								
CONTROL ROOM			■	■	■	■	■	■	■	■	■	■								
IRRADIATION STATION													■	■	■	■				
EXPERIMENTS																	■	■	■	■
INTERPRETATION													■	■	■	■	■	■	■	■

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THE EUROPEAN PROJECT PDS-XADS
"PRELIMINARY DESIGN STUDIES OF AN EXPERIMENTAL ACCELERATOR-DRIVEN SYSTEM"

Pierre D'hondt[1], Bernard Carluec[2]
[1]SCK•CEN, MOL, Belgium (Co-ordinator of ADOPT network)
[2]FRAMATOME ANP, Lyon, France (Co-ordinator of PDS-XADS project)

Abstract

During the 1990s, in different European countries, the idea of using accelerator-driven systems as efficient tools for transmutation of radioactive wastes came to the forefront. At the national level, various concepts of accelerator-driven system have also been suggested. In 1998, a Technical Working Group was mandated by the Research Ministers of France, Italy and Spain, to identify the critical technical issues and to prepare a "Roadmap" for a demonstration programme.

The Roadmap, issued in April 2001, defines the main requirements of an experimental accelerator-driven system commonly accepted by the European countries.

Subsequently, certain European research centres, universities and nuclear industry companies decided to merge their efforts on this topic so as to propose a common European experimental accelerator-driven system. One of the first steps towards attaining this objective is to evaluate the different candidates previously developed in Europe in order to select the most appropriate concept. This led to the creation of the *P*reliminary *D*esign *S*tudies of an E*X*perimental *A*ccelerator-*D*riven *S*ystem (PDS-XADS) project performed within the Fifth Framework Programme and supported by the European Commission.

Introduction

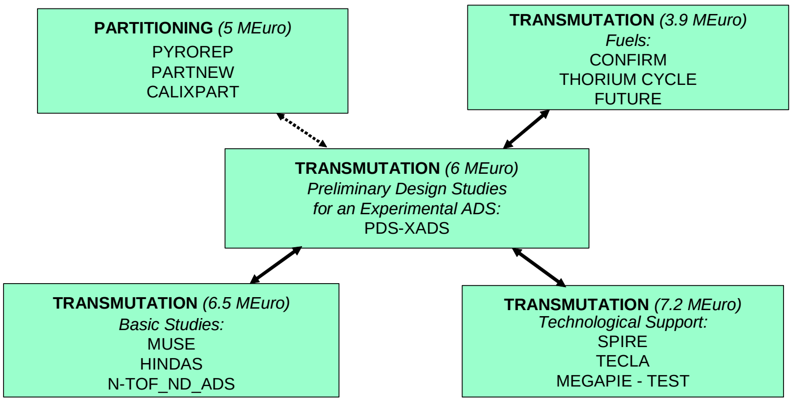
In 1998 the Research Ministers of France, Italy and Spain, set up a Ministers' Advisory Group on the use of accelerator-driven systems (ADS) for nuclear waste transmutation. This led to the creation of a Technical Working Group (TWG) consisting of representatives from Austria, Belgium, Finland, France, Germany, Italy, Portugal, Spain, Sweden and the European Joint Research Centres, whose task was to identify critical technical issues and to prepare a Roadmap [1] for a demonstration programme.

The goals of the Roadmap were to propose a technological route for the transmutation of nuclear waste in ADS; to prepare a technical programme which will lead to the realisation of an e*X*perimental *ADS* (XADS); to co-ordinate the human resources and experimental facilities in Europe and to identify the possible synergies in the scientific community.

In order to be able to define a consistent view of the programme needed for supporting the development of an XADS, it appeared necessary to establish a minimum detailed design of the XADS. The design activities initially performed in the European countries have been merged in a common European project named "Preliminary Design Studies of an XADS" (PDS-XADS), partially funded by the European Commission within the Fifth Framework Programme. The project rallies the main European organisations involved in partitioning and transmutation studies, both industrial companies and research institutes. The duration of the project is three years (2002-2004); its budget is 1 034 persons months.

The PDS-XADS project is consistent with various other activities performed within the framework of partitioning and transmutation studies supported by the European Commission (Figure 1).

Figure 1. Projects on *AD*vanced *O*ptions for *P*artitoning and *T*ransmutation (ADOPT)



In contrast to conventional nuclear reactors in which there are enough neutrons to sustain a chain reaction, subcritical systems used in ADS require an external source of neutrons to sustain the chain reaction. These external neutrons are provided by the spallation source in which high-energy protons produced by an accelerator interact with the spallation source.

ADS is considered for the transmutation of minor actinides (Np, Am and Cu). Because of their characteristics, cores loaded with high contents of minor actinides could not be burnt in critical reactors. These characteristics are especially a low fraction of delayed neutrons and a low Doppler effect. Under critical conditions, the control of such cores could not be safely maintained.

Previous studies have concluded that the most efficient transmutation of minor actinides requires a fast neutron spectrum, for which the ratio between fission and capture is the highest.

The mission of XADS is to demonstrate the safe and efficient operation of the XADS concept dedicated to the transmutation of long-life highly-radioactive wastes. The demonstration requests a significant neutronic power of several tens of megawatts.

Concerning the accelerator, the studies conclude that the demonstration might be achieved with a proton beam of several hundreds MeV, up to one GeV, and a few milliamps. The main requirement concerning the accelerator is its reliability, which must be very much higher than that observed for existing accelerators dedicated to physic experiments. The objective for the accelerator is a number of beam trips, the duration of which lead to the shutdown of the plant, lower than a few per year. Beam trips of short duration might be acceptable if the thermal loadings on the reactor structure, the fuel and the spallation target are not penalising. A duration lower than some hundreds milliseconds has been assessed acceptable *a priori*. Both cyclotron and linac concepts are assessed.

The efficiency of the spallation target in term of neutrons generated per proton is maximum if heavy metal is used. The reference solution is to use liquid metal (e.g. the lead-bismuth eutectic), which tolerates high-power density. The window separating the accelerator-end and the spallation target is a very highly loaded structure. Therefore a spallation concept without a physical window is also considered.

The XADS concepts investigated in the PDS-XADS project

Research and engineering activities have been performed in the European countries to integrate basic aspects of the ADS and to define conceptual XADS configurations. Several technological options have been considered. These options are oriented to the basic characteristics of the ADS concept dedicated to the transmutation of nuclear wastes:

- Fast spectrum subcritical core leading to use gas or liquid metal as coolant.
- No requirement concerning the conversion of the generated energy (no need for electrical production).
- The objective of demonstration of the operability of the ADS concept need not use cores having a high content of minor actinides, therefore in order to be consistent with the time schedule defined in the European Roadmap, the investigated fuels of XADS are classical MOX fuels (e.g. similar to the Superphénix fuel).
- Due to the innovative technological aspects of XADS, the operational criteria (temperature, pressure…) are selected as low as possible, but consistent with the objective of operability demonstration.

Three XADS concepts are studied:

- Two lead-bismuth eutectic (LBE)-cooled concepts:
    - An 80 MW concept.
    - A smaller concept (50 MW): MYRRHA.
- A gas-cooled concept (80 MW).

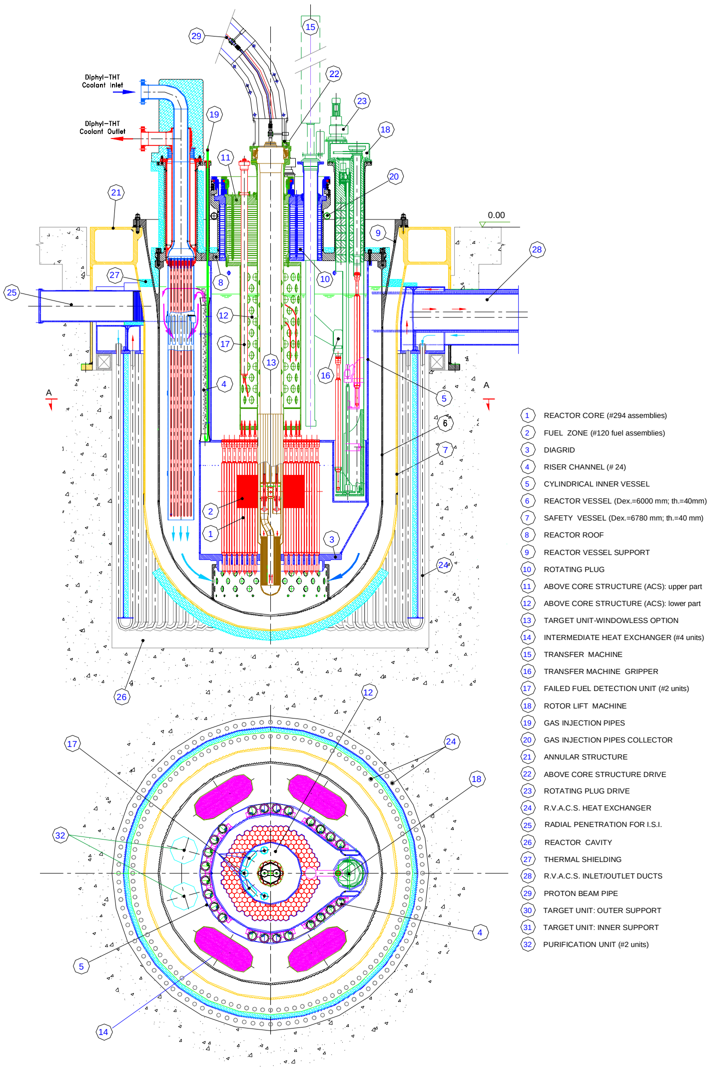
The main purpose of the PDS-XADS project is to develop the three concepts using common rules and objectives, to a level sufficient to precisely define the supporting R&D needs, to perform objective comparisons and eventually to recommend the solution to be engineered in detail and realised.

In the following sections we highlight the main characteristics of the different concepts studied as well as for the accelerator. More ample information on the XADS concept investigated in the PDS-XADS project can be found in the proceedings of the International Workshop on P&T and ADS Development (InWor), organised by SCK•CEN, Mol, Belgium on 6-8 October 2003 [2-5].

An 80-MW lead-bismuth-eutectic-cooled concept by Ansaldo

The primary system for this concept is a pool-type and the main characteristics can be found in Figure 2. A peculiarity in this concept is the argon gas lift system for primary coolant circulation to avoid rotating parts (mechanical pumps) immersed in Pb-Bi.

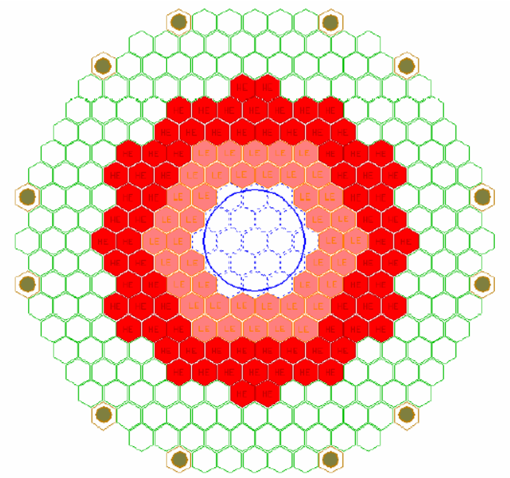
Figure 2. Primary system – main sections



The LBE target containing the spallation products is kept confined within the target unit in order to prevent the contamination of the primary LBE coolant. The target unit is a removable component of slim cylindrical form, positioned co-axially with the reactor vessel which also serves as an inner radial restraint of the core. Its component parts are the proton beam pipe, the heat exchanger and the LBE circulation system, that can be designed with forced or natural circulation, depending on the two design options currently under study: windowless or window.

The core (Figure 3) consists of 120 fuel assemblies arranged in an annular array of five rows. The inner row surrounds the target unit. The assemblies are all alike, each loaded with 90 fuel pins, which have the same cross-section and fuel MOX composition with two different enrichments. The 42 fuel assemblies of the two innermost rows are enriched as the standard Superphénix reload fuel, the remaining 78 fuel assemblies are higher enriched at 28.25% Pu, to set an operational $k_{eff} = 0.97$ at nominal power and BOL.

Figure 3. Core cross-section



For this concept it is concluded that:

- The LBE-cooled XADS concept has been developed at a sufficient level as to allow the identification of critical issues; for most of them, in any case, suitable solutions have already been identified.

- An operational $k_{eff} = 0.97$ at beginning of cycle and full power guarantees an adequate subcriticality margin under any operational and accident conditions (DBC and DEC) without the need for shutdown or control rods. Compensation of fuel burn-up would be achieved by increasing the 600-MeV proton beam current up to 6 mA max at EOL.

- In spite of the large mass of Pb-Bi of the primary system, the main and safety vessels can resist seismic loads because the reactor assembly rests on horizontal anti-seismic supports.

- The reactor can accommodate either a window or a windowless target unit, both designed as retrievable components. The final choice can be postponed even if the windowless option appears to present more merit in terms of less reactor roof activation, longer lifetime and reduced need of material qualification.

- The low LBE temperature and velocity allow the use of proven stainless or martensitic steels, even if qualification is still necessary.

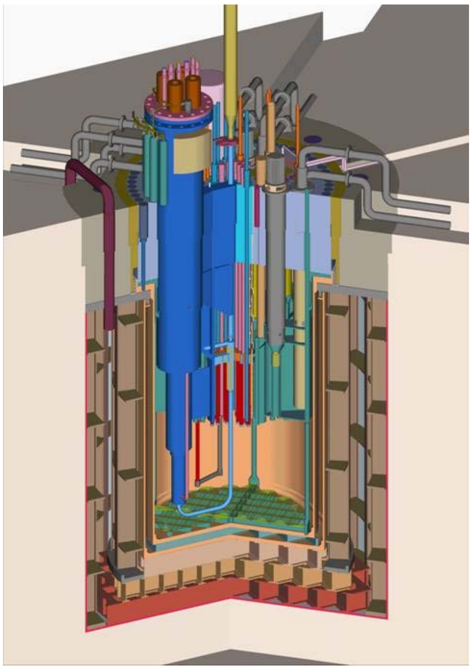
- Early results of the transient analyses indicate that the design exhibits a large safety margin on account of a combination of very favourable safety characteristics.

- The combination of good heat transfer properties, large thermal inertia and high boiling point of the primary coolant, with the design characteristics of the core, primary system, secondary system and reactor vessel air cooling system, all favourable for the promotion of natural circulation, prevents voiding within the core and fuel clad overheating even under the most severe transient conditions.

MYRRHA, a 50-MW lead-bismuth-eutectic-cooled concept by SCK•CEN

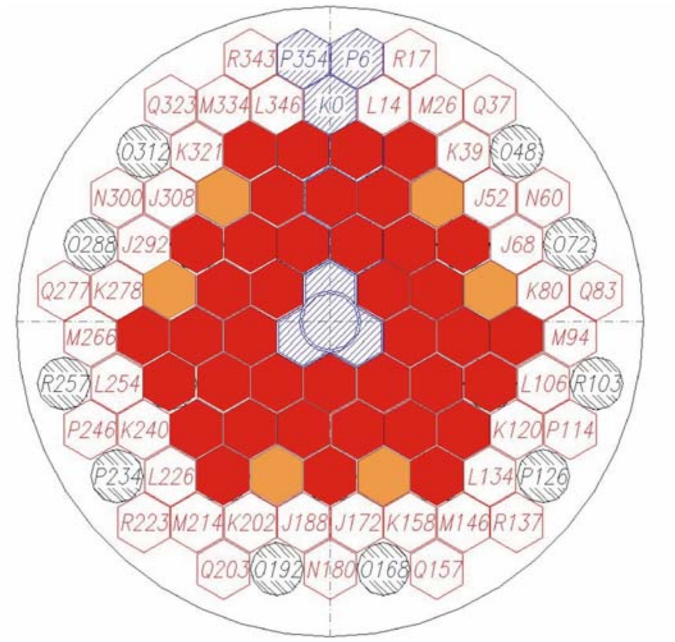
The MYRRHA project is based on the coupling of a proton accelerator with a liquid Pb-Bi windowless spallation target, surrounded by a Pb-Bi-cooled subcritical neutron multiplying medium in a pool-type configuration with a standing vessel (Figure 4). The spallation target circuit is fully immersed in the reactor pool and interlinked with the core but its liquid metal content is separated from the core coolant. This is a consequence of the windowless design presently favoured in order to use low-energy protons on a very compact target at high beam power density in order not to lose on core performance.

Figure 4. MYRRHA 3-D vertical view



The core pool contains a fast-spectrum subcritical core (Figure 5) cooled with Pb-Bi eutectic (LBE). The core is fuelled with typical fast reactor fuel pins with an active length of 600 mm arranged in hexagonal assemblies. The three central hexagons are left free for housing the spallation module. The core is made of fuel hexagonal assemblies of 85-mm flat-to-flat, composed of MOX typical fast reactor fuel (Superphénix-like fuel rods) with total Pu contents of 30% and 20%.

Figure 5. MYRRHA core layout



Since access from the top is very restricted and components introduced into the pool will be buoyant due to the high density of the LBE, the loading and unloading of fuel assemblies is foreseen to be carried out by force feedback-controlled robots in remote handling from underneath. The pool also contains the liquid metal primary pumps, the heat exchangers presently using water as a secondary fluid and the two fuel-handling robots based on the well-known rotating plug of fast reactors.

The spallation circuit connects directly to the beam line and ultimately to the accelerator vacuum. It contains a mechanical impeller pump and a LM/LM heat exchanger to the pool coolant (cold end). For regulation of the position of the free surface on which the proton beam impinges (whereby this defines the vacuum boundary of the spallation target), it comprises an auxiliary MHD pump. Further on, it contains services for the establishment of proper vacuum and corrosion-limiting conditions.

By mid-2002, the MYRRHA pre-design file had been submitted to an International Technical Guidance Committee for reviewing the pre-design phase as achieved for the MYRRHA project. This international panel consisted of experts from research reactor designers, reactor safety authorities and spallation target specialists. The conclusions and recommendations of this panel were as follows:

- No show-stoppers are identified in the project.
- More attention should be paid to safety case studies and iterate to the pre-design before entering the detailed engineering phase.
- Address some R&D topics that can lead to timing bottlenecks very soon, such as fuel pin and assembly development and qualification.
- Make a decision on the accelerator option (cyclotron vs. linac) and eventually revisit beam parameters.

MYRRHA responds to the objectives of the XADS facility in terms of demonstration and performance, and also responds by design to some key issues related to the LBE ADS such as:

- The LBE corrosion by leaving the majority of the system at "cold" conditions and limiting the LBE velocity below 2.5 m/s.
- Criticality control during core loading by leaving the spallation target in position and loading from underneath.
- Avoiding spallation target window break by choosing the windowless design.
- Addressing the ISI&R and the O&M from the conceptual design by means of robotics and ultrasonic visualisation.

A 80-MW gas-cooled concept by FRAMATOME ANP

The reference basic features have been fixed by the PDS-XADS project global coherency:

Reactor power	80 MWth
First subcritical core	Classical FBR fuel U-PuO_2 (Pu < 35%)
Accelerator	Linac type
Core and target unit	Designed for E = 600 MeV, I < 6 mA,
Target	Physically separated from the reactor

The main parameters for this gas-cooled design are:

Primary coolant fluid	Pressurised helium at about 6MPa
Primary helium containment	Metallic vessels
Power conversion system	Heat exchanger and circulator

The overall reactor architecture is shown in Figure 6.

The spallation target consists of a 460-mm diameter, 25-mm thick tube submitted to external helium pressure bolted on the roof slab and guided at the core centre. The thimble houses the target unit located at core centre and composed of a vacuum tube, an internal tube for flow arrangement and the liquid lead-bismuth eutectic (LBE) spallation material container. The proton beam enters the beam tube at the upper end of the target unit, penetrates the beam tube window, located just above core centre line and impinges on the upward flowing target LBE below the window (spallation zone). The target LBE is circulated by pumps and cooled by an external heat exchanger located in the target cooling room, outside the reactor vessel. The LBE external circuit option is favourable with respect to both neutronic efficiency and maintenance of target unit and components.

The XADS gas-cooled core is built up from a ring of 90 fuel subassemblies (SAs) surrounding the spallation target which take up the central locations (Figure 7). Surrounding the core are steel reflector SAs in turn surrounded by shield SAs containing boron carbide to limit damage to the RPV. Six absorber rods, located at the core fuel zone periphery, are to be used only during shutdown conditions to bring sufficient reactivity margins mainly with respect to fuel handling error and accidental water ingress in the core. The design of the core has been based largely upon previous fast reactor experience.

Figure 6. Gas-cooled XADS overall architecture

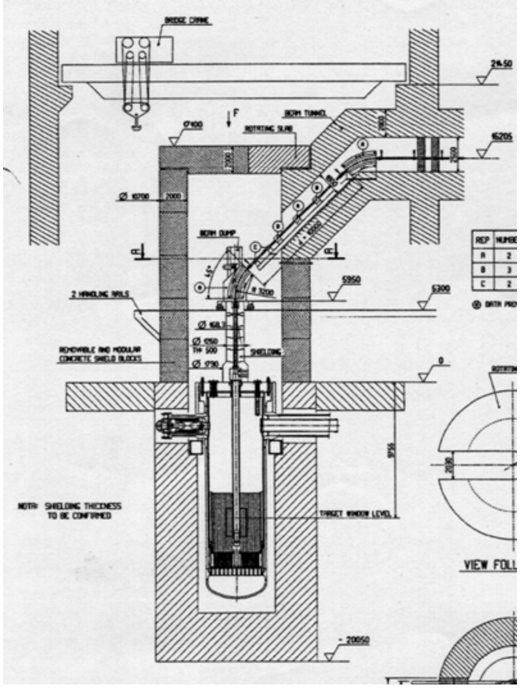
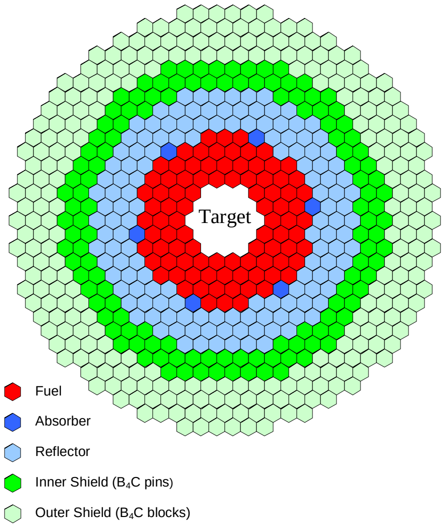


Figure 7. Gas-cooled XADS core layout



The XADS gas-cooled system has reached the end of the preliminary studies devoted to the definition and the justification of a reference and consistent reactor design. The basic options, sub-systems and components are described and ongoing analysis did not reveal major feasibility issues. Some important features are to be checked further such as:

- Selection of a core reference between single and multi-batch concepts and optimisation of core thermal-hydraulics.

- Confirmation of core subcriticality levels and associated measurement system.

- Reactor transient analysis (accelerator beam trip, transition between nominal and cold shutdown conditions, loss of flow and loss of coolant accidents) and consequences on structural mechanic analysis.

- Feedback on DHR system operating conditions and design.

- Evaluation of mechanical integrity and resulting residence time of beam tube and target unit.

- Confirmation and improvement of radiation dose rates outside and inside the reactor vessel, shielding design and definition of core instrumentation and ISI&R provisions.

- Reactor containment specification and design.

The PDS-XADS reference accelerator

The main technical specifications for the XADS accelerator are summarised in Table 1. These characteristics clearly show that this machine belongs to the category of the so-called high-power proton accelerators (HPPA). HPPA are presently very actively studied (or even under construction) for a rather broad use in fundamental or applied science. The overall performance of the subcritical system will be critically determined by a strict adherence of the XADS accelerator to its specifications. Compared to other HPPA, many requirements are similar, but it is to be noted that the reliability specification, i.e. the number of unwanted “beam trips”, is rather specific to the use as driver for an ADS. The reference design had to integrate this stringent requirement from the very beginning, taking into account that this issue could be a potential “show-stopper” for ADS technology in general.

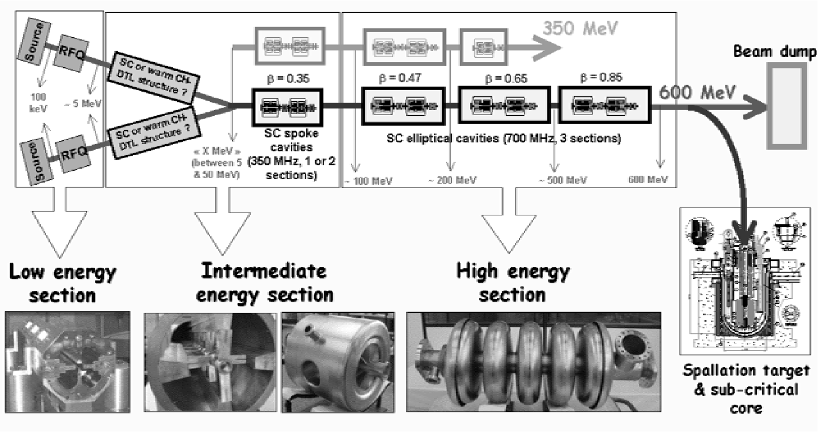
Table 1. XADS proton beam specifications

Max. beam intensity	6 mA CW on target (10 mA rated)
Proton energy	600 MeV (includes 800 MeV upgrade study)
Beam entry	Vertically from above preferred
Beam trip number	Less than five per year (exceeding 1 second)
Beam stability	Energy: –1%, Intensity: –2%, Size: –10%
Beam footprint on target	Gas-cooled XADS: Circular ˘ 160 LBE-cooled XADS: Rectangular 10 · 80 MYRRHA: Circular, “donut” ˘ 72
Intensity modulation	0.2 ms “holes” in CW beam for neutronics measurements, repetition frequency 0.01-1 Hz

The proposed reference design for the XADS accelerator, optimised for reliability, is shown in Figure 8. It is composed of a “classical” proton injector (ECR source + normal conducting RFQ structure). Additional warm IH-DTL or/and superconducting CH-DTL structures are used up to a transition energy. At this point a fully modular superconducting linac accelerates the beam up to the final energy.

Up to the transition energy, fault tolerance is guaranteed by means of a “hot standby” spare. Above this energy, “spoke” and, from 100 MeV on, “elliptical” cavities are used. Beam dynamic calculations for this part have shown that an individual cavity failure can be handled at all stages without loss of the beam. Besides this fault tolerance, another remarkable feature of the concept is its

Figure 8. XADS reference accelerator layout; a doubled injector accelerator is followed by a fully modular spoke and elliptical cavity superconducting linac



validity for a very different output energy range: 350 MeV for the smaller-scale XADS requires nine cryomodules of $b = 0.65$ elliptical cavities; in order to obtain 600 MeV, 10 more cryomodules simply have to be added (seven with $b = 0.65$ and three with $b = 0.85$) and 12 additional ($b = 0.85$) boost the energy to 1 GeV. Therefore, the small-scale XADS accelerator is already fully demonstrative not only of the 600-MeV XADS (and could be converted to it), but even for an industrial machine.

The chosen superconducting cavities are the subject of important R&D programmes presently underway. The performance of the prototypes has been measured to exceed the operational characteristics for the XADS by a very comfortable safety margin that ensures the "over-design" criteria imposed by the reliability strategy.

Within a period of less than two years, it has been possible to develop a generic and robust technical solution for the XADS accelerator and its associated beam line. This solution, based on a superconducting linear accelerator, can fulfil *a priori* the specifications for the XADS. This linac can be used for all different versions of XADS studied within the 5th FP, and it is also representative of an industrial machine.

The proposed machine is reliable through the rigorous implementation of a highly modular system with de-rated components operated in a fault-tolerant manner. The continuation of the vigorous R&D programme presently underway, with a focus on the reliability aspect within the 6th FP, places the XADS accelerator on a roadmap in line with the TWG recommendations.

Conclusion

Within the PDS-XADS project, supported by the European Commission, are performed design studies for the three XADS concepts. The accelerator study has shown that it is possible to develop a generic and robust technical solution for the XADS accelerator and its associated beam line. The PDS-XADS project will be finalised at the end of October 2004.

The first R&D needs resulting from the design studies have been identified and described on specific R&D questions sheets. These sheets have been issued and distributed to the organisations involved in the ADOPT network on P&T activities within the Fifth Framework Programme. The sheets constitute a valuable input for the preparation of the P&T-related projects for the Sixth Framework Programme.

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STATUS OF THE MEGAPIE PROJECT

F. Groeschel[1], **A. Cadiou**[2], **C. Fazio**[3], **T. Kirchner**[2], **G. Laffont**[4], **K. Thomsen**[1]
[1]Paul Scherrer Institut, Spallation Neutron Source, Villigen PSI
[2]École des Mines, Laboratoire SUBATECH, Nantes
[3]Forschungszentrum Karlsruhe GmbH, Nukleare Sicherheitsforschung, Eggenstein-Leopoldshafen
[4]CEA/Cadarache, DER/STR/LCET, St. Paul-lez-Durance

Abstract

The MEGAPIE project was started to design, build and operate a liquid metal spallation neutron target as a key experiment on the road to an experimental accelerator-driven system and to improve the neutron flux at the PSI spallation source. The design of the target system has now been completed and manufacturing has started. The target is designed for a beam power of 1 MW and 6 Ah of accumulated current. It will contain about 88 l of LBE serving as target material and primary heat removal fluid. The heat will be removed by forced convection using an in-line electromagnetic pump with a 4 l/sec capacity. The heat will be evacuated from the target through 12 mono-wall cooling pins via an intermediate oil and a water cooling loop. The beam window made of the martensitic steel T91 will be cooled by a jet of cold LBE extracted at the heat exchanger exit by a second EM pump from the LBE main stream.

A preliminary safety analysis has been performed considering normal, off-normal and accident conditions and a corresponding report has been submitted to authorities for licensing. The experience gained up to now shows that MEGAPIE may well be the first liquid metal target to be irradiated under high-power beam conditions.

Introduction

Based on an initiative of PSI, CEA and FZK, the MEGAPIE project was officially started in 2000 to design, build and operate a liquid metal spallation neutron target of 1-MW beam power as a key experiment on the road to an experimental accelerator-driven system [1]. The project is supported by an international group of nine research institutions (Figure 1) and is partially funded by the European Union within the Fifth Framework Programme.

Figure 1. The MEGAPIE partners

Objective of the project

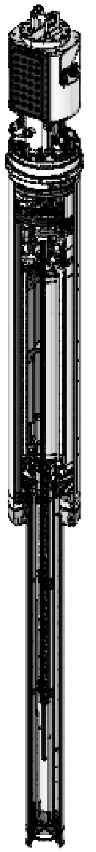
MEGAPIE is an experiment to be carried out in the SINQ target location at the Paul Scherrer Institute and aims at demonstrating the safe operation of a liquid metal spallation target at a beam power in the region of 1 MW. It will be equipped to provide the largest possible amount of scientific and technical information without jeopardising its safe operation. The minimum design service life will be 1 year (6 000 mAh).

Whereas the interest of the partner institutes is driven by the development needs of ADS, PSI is interested in the potential use of a LM target as a SINQ standard target providing a higher neutron flux than the current solid targets. Calculations of the undisturbed thermal neutron flux for the LBE target in comparison to the former zircaloy and current steel-clad solid lead target yield a gain of about 40% at the beam tube entrance positions (25 cm) [2].

Target system and performance

A sketch of the target and its main properties are shown in Figure 2. It is designed to accept a proton current of 1.74 mA, although the probable current in 2005 may not exceed 1.4 mA. The 65-kW thermal energy deposited in the LBE in the bottom part of the target is removed by forced circulation by the main in-line electromagnetic pump through a 12-pin heat exchanger (THX). The heat is evacuated from the THX via an intermediate diathermic oil and an intermediate water cooling loop to the PSI cooling system. The cooled LBE then flows down in the outer annulus. The beam entrance window is especially cooled by a cold LBE jet extracted at the THX outlet and pumped by a second EM pump through a small diameter pipe down to the beam window. The mass transport and temperature distribution is shown in Figure 3. The thermal-hydraulic system behaviour has been modelled with the RELAP5 code for normal and transient operations (beam trips and interrupts). The operating conditions were chosen in such a way to keep the LBE temperatures below 400°C and the maximum flow velocities

Figure 2. Model of the MEGAPIE target and its main characteristics



Dimensions

Length:	5.35 m	Weight:	1.5 t
LBE volume:	88 l	Gas volume:	2 l
Design pressure:	16/10 bar	Operating pressure:	0-3.2 bar
Design temperature:	400°C	Insulation gas:	0.5 bar He

Materials

Lower liquid metal container:	T91
Upper container	316L
Lower target enclosure:	AlMg3

Heat removal and beam window cooling

Deposited heat: 650 kW

Forced convection assisted by buoyancy

Main pump:	EM in-line pump (4 l/sec)
Bypass pump:	EM in-line pump (0.35 l/sec)

Liquid metal container

Upper container (316L, body of THX)

Lower container with beam entrance window (T91)

LBE flow control

Main flow and bypass flow guide tubes

EMPS with in-line main pump and bypass pump

Target heat exchanger

Temperature control

Central rod with 20 kW heater

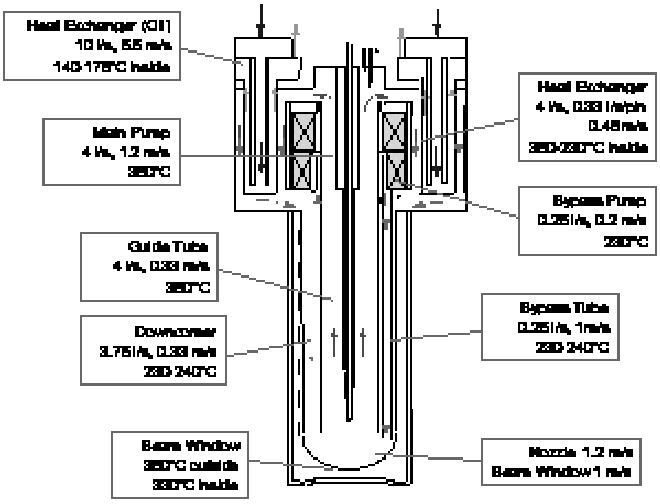
Outer enclosure (2nd barrier)

Target head

Upper target enclosure

Lower target enclosure with beam entrance window (AlMg3)

Figure 3. Mass transfer and temperature distribution in the target at normal operation



at about 1 m/s. Under these conditions, the corrosion rates in T91 and 316L steel remain low (<0.1 mm/year). This may, however, not be true for the beam entrance window, where interaction with the beam occurs. Specific investigations are therefore undertaken within the design support group to clarify this (LISOR and STIP) as well as the materials' susceptibility to liquid metal embrittlement [3-5].

The target itself is composed of nine subcomponents, which are manufactured separately and then assembled:

- Central rod inserted in the upward LBE flowpath carrying a 22-kW heater and a set of neutron detectors.

- Main flow guide tube separating the hot LBE upflow from the cold downflow in the outer annulus. The heat transfer across the tube wall raises the temperature of the downflowing LBE from 230 to 250°C. The guide tube is equipped with a number of thermocouples to monitor the temperature field in the spallation zone.

- Attached to the top of the tube is the electromagnetic pump system, consisting of the concentrically arranged bypass pump and the in-line main pump on top of it. Both pumps are equipped with electromagnetic, three-coil flow meters respectively. The Institute of Physics (IPUL) in Latvia designed the pumps and has built and tested a prototype of the main pump to demonstrate its proper functioning. While the pump performed according to predictions [6,7], the flow meter did not achieve the accuracy specified and failed during the test. Figure 4 shows a sketch of the pump system and the performance characteristics of the prototype pump.

- The pump system is surrounded by the target heat exchanger (THX), consisting of 12 pins concentrically arranged and 120 cm long. The pins' performance has been experimentally investigated [8] and numerically assessed [9]. Using the diathermic oil Diphyl THT as a cooling medium, it was necessary to implement a spiral in the oil path to increase the contact length. The main problem in the design of the THX was to comply with the complex thermal conditions and to limit the resulting thermo-mechanical stresses. This was accomplished by attaching the pins to the inlet and outlet oil distribution boxes by flexible bellows and inserting thin shrouds as heat shields. The heat is removed from the THX by an intermediate oil loop designed by Ansaldo. An intermediate water cooling loop designed and built by PSI then evacuates the heat from the oil loop. Using this concept, any interaction of LBE with cooling water is eliminated. The pressure in the oil loop is always kept higher than that of the water loop and that in the target. The oil is not significantly affected by interaction with LBE, except for the normal thermal and radioactive decomposition. The loops are also designed to serve during the target testing, which requires special operating conditions (see below). Table 1 provides the characteristic loop parameters. The heat exchanger also forms the upper enclosure of the LBE and the gas expansion tank. The lower enclosure of LBE is formed by the lower liquid metal container.

- The lower liquid metal container is made of the martensitic steel T91. The beam entrance window is hemispherical with a wall thickness tapered from 1.5 mm in the centre to 2 mm at the outer rim. The window is made of a forging and is EB-welded to the tube, which is 2 mm thick in the spallation zone and 4 mm in the upper part. Special attention is paid to the proper control of the temperatures and stresses in the beam window caused by the energy deposited by the proton beam. The current design relies entirely on CFD modelling and FEM calculations. Table 2 shows the amount of energy deposited in the different target components by a 1.74-mA current calculated with the CFX4 and FLUKA codes. The agreement is satisfactory. Different designs of beam window cooling have been investigated, finally leading to the reference design of a bypass jet flow along the long axis of the beam footprint and a 30° slanted guide tube. Figure 5 shows the reference design and the corresponding flow and temperature fields in the LBE as calculated by CFX-4. The design provides sufficiently low temperatures in all the components with respect to corrosion and thermal stresses as shown in Table 3.

Figure 4. Sketch of EMP system and prototype main pump characteristics

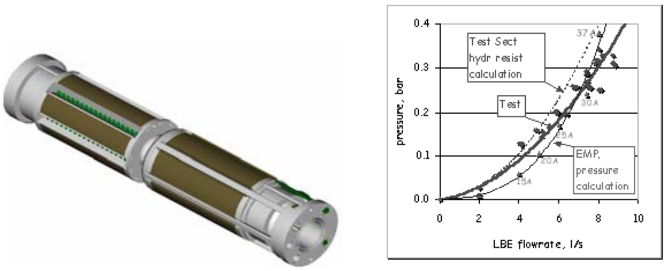


Table 1. Main parameters of the heat removal system

	LBE THX	Oil IHX	H_2O IHX
Inlet temp. [°C]	330	165	40
Outlet temp. [°C]	230	130	59
Oil loop			
Flow rate [kg/s]	9.28	Speed [m/s]	3.5
Pump head [m]	12	P drop [kPa]	626

Table 2. Energy deposited in the target components at 1.74-mA beam current

Material	**FLUKA [kW]**	**CFX-4.3 [kW]**
LBE	705.8	709.9
Window T91	5.56	5.28
T91 hull	2.68	1.21
Guide tube	5.55	6.03
Total	719.6	722.4

Figure 5. Temperature distribution in LBE in the spallation zone [11]

Table 3. Temperature in target components of the reference design as a function of beam current and bypass jet flow direction (parallel or perpendicular major axis of beam footprint)

Beam [mA]	**Maj. axis**	**Peak temperature [°C]**			
		LBE	**Guide tube**	**C. rod**	**Window**
1.74	= Bypass	422.7	368.2	386.6	370.2
	⊥ Bypass	424.1	363.1	389.5	360.3
1.4	= Bypass	384.4	339.4	355.7	342.5

Corresponding stress calculations using the above data as input yielded acceptable thermal and overall stresses in the beam window and the guide tube. For the optimum configuration, the maximum stresses in the beam window and the guide tube amount to 55 and 63 MPa, respectively, as shown in Table 4.

Table 4. Maximum temperatures and Mises stresses in the guide tube and beam window as a function of beam orientation to bypass jet flow for the reference design

Beam orient.	LBE weight	Peak temperature [°C]			
		Guide tube	Window	Guide tube	Window
0°	No	367	370	386.6	370.2
0°	Yes	367	370	389.5	360.3
90º	No	362	359	355.7	342.5

The lower liquid metal container, the flange of the guide tube and the heat exchanger constitute the boundary for the LBE, called the hot part. The second boundary is formed by three components, which are separated from the inner part by a gas space filled with either 0.5 bar He or Ar. The gas will stay enclosed during the experiment and only the pressure will be monitored. The components are the:

- Lower target enclosure, a double-walled, D_2O-cooled hull made of AlMg3. The containments of the current targets are made of the same material and experience on its radiation performance exists up to about 10 dpa. The enclosure is designed to contain the LBE in the case of a number of hypothetical accidents, which would lead to the breach of the inner container. Its proper functioning has been assessed by FEM calculations [12]. The enclosure is flanged to the upper target enclosure, formed by a stainless steel tube. This tube is welded to the target head.

- Target head, consisting of the main flange, which positions the target on the support flange of the central tube of the SINQ facility, and the crane hook. All supplies to the target and instrumentation lines are fed through the target head.

- Target top shielding, which connects the hot part to the target head. The LBE-containing part of the target is thus suspended from the target head and allowed to expand with the temperature. The component also contains tungsten to shield the target head area from the intense radiation of the LBE and the noble gases and volatiles collected in the gas expansion tank.

Ancillary systems

While the target is designed by CNRS-SUBATECH, the ancillary systems are designed and provided by PSI, ENEA and Ansaldo. The main components are the:

- Heat removal system already described above.

- Gas handling system for the cover and insulation gas. Although small in quantity (about 8 litres), the gases produced by the spallation process represent a high radioactive source term that must be properly handled to cope with the release limitations imposed under normal and accident conditions. The gases are collected in the target expansion tank and periodically evacuated via filters into a decay tank. The radioactive inventory accumulated in the target is so high that additional filters (active carbon) in the beam transport compartment and the TKE are required to retain all gases (except the noble gases) in case of a severe accident.

- LBE fill and drain (F&D) system. Draining of the active LBE had originally been envisaged and a corresponding engineering concept had been worked out. The installation of the complex and expensive equipment in the TKE (heavily shielded container permanently installed) turned out to be difficult and the operation was judged very risky with respect to radiation protection. Due to a better understanding of the LBE freezing process, it seems feasible to sufficiently control the LBE expansion (roughly 1.5% in the solid state with time) to avoid damage to the structural materials, which would jeopardise PIE. Freezing of the LBE in the target at the end of the experiment was therefore chosen as reference design and a F&D system to handle only un-irradiated LBE is now worked out. Its main purpose is to condition the LBE before filling, fill and drain the target during testing and fill the target in the TKE. The LBE expansion process has been modelled by FEM, showing that the stresses on the containers can be limited, if the LBE is solidified in a special procedure, which allows the LBE to creep [14].

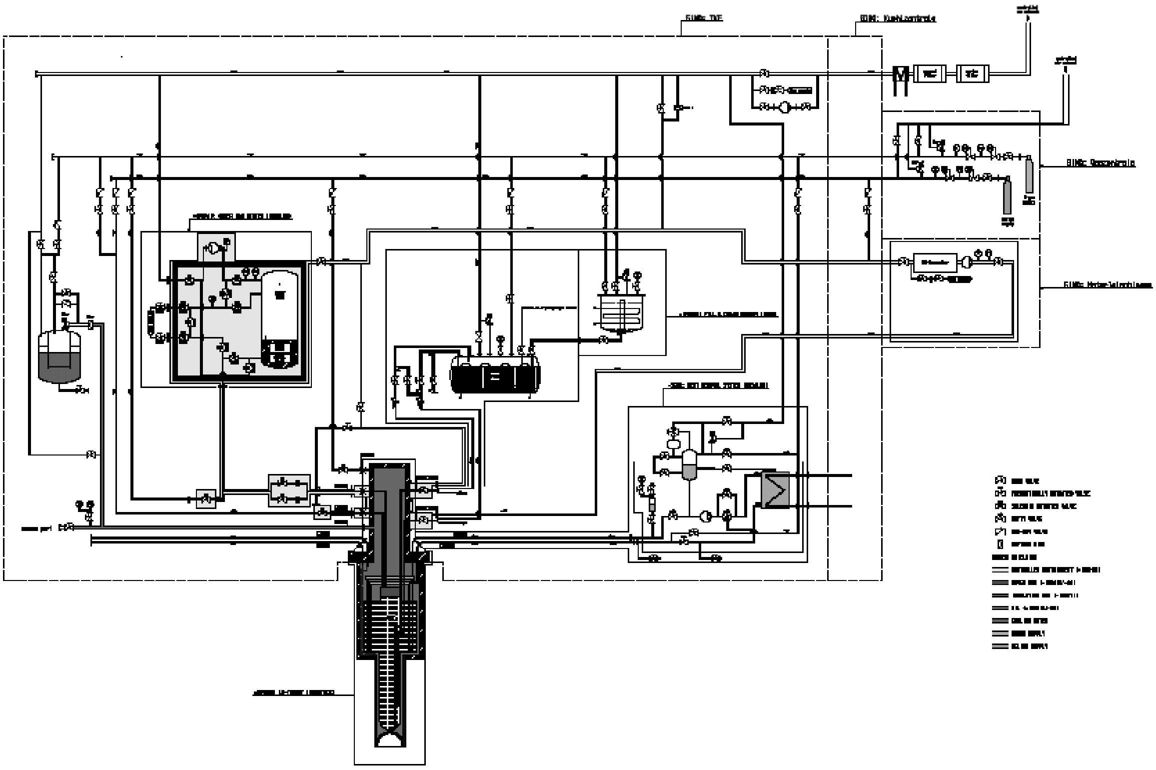
- Beamline adaptations including advanced beam monitoring.

- Handling devices for the target decommissioning, storage, dismantling and disposal.

- Control system with the adaptation of the SINQ infrastructure.

Figure 6 shows the layout of the main ancillary systems. All connections to the target have to pass by the target head. Components handling radioactive products under normal operation are placed in a second containment filled with He at a pressure below ambient. Activity is continuously monitored.

Figure 6. Layout of the ancillary systems with, from left to right: insulation gas system, cover gas system with double containment, fill & drain system and heat removal system



Manufacturing and quality assurance

The target system has been designed and is now manufactured at different sites in Europe. The assurance of the appropriate quality is therefore a key issue. The following modules are currently employed to assure proper quality:

- *Design validation*. Verification of the design and compliance with accepted standards by an independent, second member or group of the project team.

- *Manufacturing quality*. Establishment of a quality plan by the manufacturer, approval by the project QM, surveillance of the tests and assessment of the results by the manufacturer, the project quality manager or a certified body according to the Q-plan.

- *Materials*. Application of referenced materials with Q-certificate.

Safety analysis and licensing process

The safety concept is based on the defence-in-depth approach to contain the LBE, using four barriers for the liquid metal and three barriers for the gas phase. Accident scenarios have been established, analysed and countermeasures have been elaborated considering:

- Internal forces, such as beam focusing, LBE leak, LMC fracture, D_2O leak, gas leak.

- External forces, such as earthquake and airplane crash.

The safety concept must take the operability of the SINQ into account. In this case, we rely on the two inner barriers being part of the target system. The safety concept cannot rely on the integrity of the first barrier alone. The knowledge concerning the interaction of irradiation, LBE and mechanical loads with the structural materials is not sufficiently established (it is one of the goals of the experiment). The possible failure of the first barrier is detected by different sensors, which will trigger the stop of the beam and the transition of the target into a safe condition. The key element for LBE leaks is a sensor placed in the bottom of the target. A leak in the gas phase will be detected by monitoring the radioactivity in the He gas of the second containment. A breach of the first barrier and containment within the second barrier will cause no contamination of the SINQ environment. The target can be extracted and replaced without severe delay.

The two barriers may be breached due to malfunctioning of the proton beam. The target is hit by a fully or partially focused beam, if the target E fails or is bypassed. The peak current density is increased by more than 20-fold. Calculations show that the LMC beam entrance window can only withstand for less than a second [15]. Although the AlMg3 LTE itself supports the high local energy deposition, it will fail soon afterwards when contacted by LBE, if the beam is not switched off. Although devices exist to detect malfunctioning of the beam, two new monitoring devices are under development, given the high risk of such an incident. The beam slit is intended to block those protons bypassing the target E. These protons deviate from the normal path due to their slightly higher energy. The VIMOS device monitors the temperature distribution of the beam footprint on a tungsten grid just ahead of the target. Both devices were installed during the shutdown 2004 and shall prove their functionality before installation of the MEGAPIE target. The perforation of both beam entrance windows will send the LBE down the beam line. The LBE will be collected in a specially designed catcher, but the beam line will be heavily contaminated. The beam line will, however, withstand the pressure increase caused by the LBE/D_2O

interaction as shown in simulations with the MATTINA code [16]. Extraction of the target will require special measures and the operation of the SINQ is interrupted for several years. The reliable detection of beam malfunctioning is therefore a key requirement.

The protection of the public is a major concern. Source term and spreading calculations [15] show that the activity is sufficient to exceed the dose limit imposed by law. It is set at 1 mSv for the public. It had been reduced to this value from 100 mSv with the decision to release PSI from the emergency organisation. Whereas the target is designed to withstand a safety earthquake (probability of 10^{-4}/year) it must be assumed that the target and the beam line will fail during severest accidents. The inventory of the target will spread out in the beam transport channel compartment and the volatile components will be released. Calculations showed that the iodine isotopes, in particular ^{125}I, make the highest contribution to the dose outside PSI, which may reach 230 mSv. Upgrading of the ventilation system with earthquake resistant carbon filters and retention of the iodine brings the dose down to 66 μSv, which is acceptable. A similar upgrading is required for the target head compartment.

Licensing of the experiment by the authorities requires clearance for the following steps before the start of irradiation:

- Operation of the heat removal system.
- Operation of the gas system.
- Inactive operation of the target system.
- Dismantling, transport and waste disposal.
- Active operation of the target system.

Conclusions

The manufacturing of the target has started. Some details, like detectors, still have to be elaborated and the final design has to be validated. The progress on the ancillary systems is according to plan. PSI has managed to complete the installations in the beam line and the piping and cabling during the shutdown 2004. Assessment of the beam monitoring devices is now underway. The start of irradiation in May 2006 is still within reach.

Acknowledgements

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ADS ACCELERATOR RELIABILITY ACTIVITIES IN EUROPE

Paolo Pierini
Istituto Nazionale di Fisica Nucleare, LASA, Via Fratelli Cervi, 201 20090 Segrate (MI), Italy

Luciano Burgazzi
Ente Nazionale Energie Alternative, FIS-NUC, Via Martiri di Monte Sole, 4 40129 Bologna, Italy

Abstract

In this work we report the activities performed in Europe to assess the reliability characteristics for an ADS-class accelerator system. These activities are mainly carried in the context of Working Package 3 (“Accelerator”) of the EC programme PDS-XADS (funded by the Fifth Framework Programme, under contract FIKW-CT-2001-00179) aimed at the design of a highly reliable accelerator for an experimental ADS. We review the reliability-oriented guidelines followed to select the reference accelerator design, and present the methodologies used for highlighting the critical areas needing further work and R&D activities in future programmes. Furthermore, we describe the synergies with ongoing high-energy physics programmes aimed at the availability assessment of complex accelerator systems, which may facilitate the compilation of a much-needed reliability database of accelerator components. A rough exploratory “parts count” reliability analysis is then presented and briefly discussed to assess the needed work on the path to obtain more accurate reliability/availability predictions of the ADS accelerator operation.

Introduction

The reliability and availability requirements that an ADS design should fulfil have been mainly derived from the considerations expressed in a European Technical Working Group report [1]. The reference option for the PDS-XADS [2,3] accelerator is discussed in a separate contribution of these proceedings [4], in the internal deliverables issued by the programme [5,6] and in several other publications [7-9]. An important consideration was assumed in the above references concerning the duration of allowed beam trips from the accelerator. The order of magnitude of the allowable duration of the beam trips has been set to 1 second. Beam trips with duration much smaller than the threshold of 1 second lead to insignificant transients in the subcritical system, and no limits on the occurrence of such trips have been set. Regarding the damage to the reactor structures, the spallation target and the fuel, the allowable number of long beam interruptions (> 1 s) depends on the technological details of these equipments (window concept, materials, primary coolant). Nevertheless, in all cases this number is very limited. The order of magnitude is hundreds per year, depending on ADS type and design, assuming the plant is designed for a lifetime of 40-60 years. However, especially considering plant availability, the allowed number of even longer-term beam interruptions (the ones that lead to plant shutdown) is very limited. The PDS-XADS programme set as an objective for the accelerator design the value of few (five) unexpected beam interruptions per year with duration of the order of 1 s or longer.

The current operational experience at accelerator facilities world-wide surely exceeds by a great amount these requirements as regards allowed accelerator faults, but until now none of the existing accelerators has been designed with similarly demanding requirements. The design of an accelerator system can –and should – be devised using reliability-oriented criteria from its early conception stages (bearing in mind that extra costs would be needed for implementing the necessary redundancy and fault tolerance capabilities) and there is a considerable potential for improving the reliability, availability and fault rates from that demonstrated by present accelerators. It is also important to keep in mind that highly available accelerators do exist – the typical operation performance of third-generation light sources shows an overall beam availability well above 98%, but short (from few hours to a day) maintenance periods are scheduled on a frequent basis (typically weekly) and longer maintenance shutdowns are planned on a yearly basis. The impact of these maintenance periods is therefore not accounted for with regard to beam availability for user experiments. However, the accelerator maintenance policy highly influences the capability of reaching high ADS availability and low fault rates. The short maintenance periods scheduled in accelerator facilities are not compatible with the ADS, where the maintenance policy would be based on longer periods (from once every three months to once per year), in order to be compatible with the ADS fuel cycle. Hence, provisions need to be made to guarantee a high availability during the longer operation periods.

Reliability-oriented design considerations

Suitable strategies need to be followed early in the design in order to reach the extremely low fault rates expected from the ADS [6,10]. Compliance with these strategies is standard practice in reliability engineering [11], which is primarily a discipline aiming at the use of technical expertise to assist engineers in preventing or reducing the rates of failures in complex systems. Reliability engineering guidelines are followed for many industrial applications (from military systems and aerospace applications to consumer electronics and the automotive industry), where a precise definition of the reliability and availability goals is set early in the conception phase and reliability practices are used in all stages of the product life cycle, up to the production and service maintenance procedures.

As a starting point of any reliability-oriented design, it is necessary to identify the causes of all possible failures that might occur in the system. Where possible, these causes should be removed (either by a suitable design or operation of the components) and, for those that are impossible to avoid, strategies for dealing with the corresponding failures should be identified (e.g. by adding redundancies in the system or providing fault tolerance capabilities). The task of reliability engineering is to devise schemes for reliability estimations of new systems through the analysis of the reliability data of its components. The reliability design of a new system is generally an iterative process, which starts from a preliminary technical design (based on existing expertise for similar systems), evaluates its failure modes (with a list of possible causes), highlighting the critical areas, and derives first estimations of the overall reliability. The results of this analysis are then used for modifications in the technical design aimed at improvements in the system reliability and availability.

For most systems, due to the technical complexity of the design, it is not enough to specify and allocate the reliability of components in order to accurately predict the reliability of the system. Several formal mathematical and statistical methods can be applied to measure and assess reliability characteristics, but the associated uncertainties are high, leading to estimates with limited credibility. However, there exist design principles (and valuable tools for analysis) that can help to achieve a reliable system. First of all, since the failure rates of a component are usually strongly dependent on the stresses during its operation, components, where possible, should be operated at less severe stresses than those for which they are rated (part de-rating). Then, the formal mathematical and statistical methods teach us that not only the component specifications contribute to the reliability pattern of a complex system, but also, even more importantly, the logical and functional connections drive the overall system reliability (role of parallelism: different implementations of redundancies and spares, role of “strong design”, i.e. fault tolerance). In other words, proper planning of redundancies allows building reliable systems out of moderately reliable components.

The fact that existing accelerator facilities are not designed and optimised with respect to reliability considerations has a similarity in the historical evolution of other fields; see for instance the aerospace industry, where the reliability improvement has been attained via systematic application of reliability methods in design, and strict adherence to production, qualification tests and acceptance procedures. The same approach could and certainly should be applied to particle accelerators aiming at the ADS goals. A special effort can be dedicated to considerably improving availability by considering all the elements that influence repair times: the fault detection and diagnosis process, the preparation time needed to conduct the repair, the fault correction time itself, the post-repair verification strategies and finally the time to restart the system once the fault is corrected. Time needed to localise the exact cause of a failure can be reduced by proper installation of (redundant) diagnostic tools and the use of a dedicated control system. The time needed for repair also depends on policies concerning spare parts, redundant systems and fast access to failing components. Finally, the components’ mean time between failures can be increased by preventive maintenance, in addition to a strong design and de-rated operation.

The solution based on a superconducting linac represents the simplest solution for the accelerator design. It shows a very high degree of modularity – a repeated pattern of transversely focusing elements alternating with independently phased accelerating cavities – which allows a natural implementation of component de-rating, redundancy capabilities and (at least partially) fault tolerance with respect to radiofrequency failures.

One of the subsystems that will play a crucial role in maintaining a high reliability/availability and a low fault rate during the accelerator operation, and committed to guarantee the necessary fault tolerance, is the machine control system. It is clear that this support infrastructure needs to be based on an entirely new design philosophy with respect to existing accelerator facilities where, usually, the goal is to stop the beam as fast as possible when a component failure is detected, in order to start as soon as possible the procedures necessary for the repair. The control system will need to include strategies for dealing with faulty components, gracefully bringing them off-line while preserving the beam delivery within nominal target requirements. Given the redundancy intrinsically built into the design, and to avoid the abnormal intervention of the compensative actions due to a “spurious” fault detection, all the main signals should be redundant, and “voting schemes” need to be handled. The implementation of such a system will be strongly related to a number of requirements that still have to be precisely identified for the accelerator operation. For example, to handle the fault tolerance of RF cavities, the control system may intervene first by resetting the phases of adjacent cavities (with pre-defined tabular procedures) in order to guarantee beam transmission without losses, and then gracefully recover the nominal parameters. During this short time, which can be of the order of milliseconds to fractions of a second, the beam may fall outside the stability range set by the beam specifications, but only for this limited time. Presumably, the accelerator control system will also be driven by signals coming from reactivity measurements of the subcritical core, but at the present stage their role and consequences have not yet been addressed in the overall system design, and possibly the choice of different cores and target configurations (e.g. window or windowless for the LBE core design) will lead to different specific operating requirements and constraints. Moreover, there will be constraints provided by safety regulation, especially for what concerns radiation safety and associated interlocks.

Reliability figures of merit and goals: R, A or FR?

We have already introduced the concepts of reliability (R), availability (A) and fault rates (FR). These three quantities characterise different aspect of the operational behaviour of a system, and it is crucial to identify and set the proper requirements and assess relative weights to each one of the three.

The failure rate (FR) is the expected (average) number of failures per unit time of operation. Usually, the failure rate of any device will show a typical “bathtub curve”, with increased failure rates at the beginning and end of its lifetime (“childhood diseases” and “ageing”). Typically, a large region of the device lifetime is characterised by a slowly increasing or constant fault rate operation (for a given load condition). The MTBF is the inverse of the steady-state fault rate. The reliability $R(t)$ is the survival probability that the system (perfectly operational at $t = 0$) is still operating at time t. This parameter, evaluated at the duration of the mission time, is of paramount importance in mission-critical operations, for which it is crucial to minimise the occurrence of any system failure during the mission time (e.g. airplanes, satellite instrumentation, etc.). For a system with a uniform fault rate λ, reliability evolves in time according to the exponential law $R(t) = \exp(-\lambda t)$. Finally, availability is the portion of time that, on average, the system is up and functional. For an unrepairable system $A(t) = 1 - R(t)$, whereas in the repairable case one can define the steady-state availability as:

$$A_\infty = \frac{MTBF}{MTBF + MTTR}$$

where MTTR is the system mean time to recovery.

The reliability (R) of a series connection between components is merely the product of the reliability of the components. Therefore, complex systems for which many components are in series connection are typically characterised by a low reliability figure, approaching zero as more components are added, and, in order to increase it, parallelism must be provided. No matter how low R may evaluate to, the system availability can approach unity when MTTR << MTBF.

The ADS operation is not a mission-critical operation, where the presence of the beam needs to be guaranteed reliably at any particular instant during the operation time. On the contrary, the specifications ask that, for each operational year, the number of faults should be limited to a few (five), that is, a requirement of a fault rate of five faults per year. Assuming an operational cycle of three months accelerator operation, followed by a one-month-long stop, this translates to a FR requirement of approximately 8×10^{-4} h^{-1}, i.e. a system MTBF of 1 300 h. In this case the reliability at the end of each cycle would be R(2 190 h) = 0.19, even if the operational goal is achieved. Of course, the requirement for the ADS is really to limit the total number of faults while guaranteeing an overall high availability during its mission time. For the example above, a mission availability of approximately 98% can be reached if the MTTR is limited to a day. The precise values to require for the FR and mission availability depend on the assumption of the ADS operational cycle, strictly related to the fuel cycle issues. The above numbers are used to provide a simple, yet effective, numerical example.

In conclusion, *an ADS-class accelerator design is required to aim at a very low fault rate during its mission time* (due to the modest tolerance of the subcritical reactor to unexpected shutdowns), while meeting a mission availability goal that remains to be precisely set on the basis of the minimal transmutation rates assumed as a goal in the design. Too much importance cannot be given to obtaining a high mission reliability goal.

Reliability prediction and analysis methodologies

The reliability/availability estimations generally fall in two broad categories, depending on the approach to the system being analysed. They can be *deductive* if they follow a top-down analysis, starting from a precisely described system layout, considering the contribution of the individual components on the basis of their connection and location in the system, or *inductive* if they follow a bottom-up analysis, starting from the individual components and assessing their role in the system under consideration.

Deductive methods require the most detailed information about the different nature of connections between the system components, in addition to reliability figures for the components themselves (in terms of failure rates or MTBF and MTTR). The most common method is the set-up of reliability block diagrams (RBD), a visual arrangement of the component connections representing a given state of the system (under normal operation, fault conditions, etc.). From these diagrams, and using formal mathematical models, the reliability of the system in the given state can be assessed.

The inductive methods require a less detailed knowledge of the precise system configuration and component connection, and ranges from the “parts count” reliability assessment to the Failure Modes and Effects (Criticality) Analysis (FMEA/FMECA). The FMEA aim is to extensively list all possible component faults, identifying their causes, the possible preventive and corrective actions – and determining the consequences at various levels of the system (and, optionally, deriving a criticality ranking on the basis of expected occurrence or severity of the consequences). In the absence of precise technical information at the system/component level, it is possible to set up a FMEA analysis on the basis of subjective engineering expert judgment. This activity has been performed for the PDS-XADS linac [6,10]. The FMEA assumes a single component fault condition in order to assess its consequences on the system and can then complement with a fault tree analysis, a top-down (deductive) method that examines the “failure space”, where all the basic component and subsystem faults are arranged in a hierarchical tree according to the system event that they lead to. Conditional gate conditions (“AND”, “OR” …) are identified and shown in the fault tree hierarchy in order to assess the minimal conditions of component failures that lead to a system fault (cut-set analysis).

Although the possibility of giving precise estimates for the reliability of the accelerator system is limited both by the present stage of the design and by the uncertainties intrinsically associated to all the methods briefly discussed in the preceding subparagraph, nonetheless, a few guidelines can be followed early in the system design in order to aim at a high reliability/availability. These guidelines are mostly driven by the use of common sense in the system design stage, looking for simplicity and parallelism, and avoiding excessive stresses in the component operation (de-rating). Also, special effort needs to be directed toward the design of subcomponents, aiming at the design and qualification of objects with low failure rates and short repair times. It is also important to note that the mean time to repair (MTTR) of the system components needs to take into account not only the repair time itself, but also all the time needed for fault detection and identification, any time needed before accessing the component (e.g. radiation decay times), time to bring the spare part into position, and finally the time for system re-start and re-validation. All these times may be longer than the repair time and strongly depend on the whole system layout.

The PDS-XADS linear accelerator has been designed and analysed based on the considerations outlined above: the critical components have been de-rated with respect to the technological limitations (to avoid "load-strength" interferences), and the fault tolerance (resulting from detailed beam dynamics simulation) with respect to the main failures identified by a qualitative FMEA analysis has been assessed [12].

Fault tolerance assessment

A fault tolerant system has the ability to operate - possibly with reduced performances but within its requirements – in the presence of faulty components. Such a system needs to detect and diagnose the component fault, to isolate failing components and avoid fault propagation, and finally to compensate and recover from the fault, possibly with real time reconfiguration capabilities. Redundancy and parallelism are the key characteristics of fault tolerance, but they do not guarantee it automatically. For an ADS fault tolerance needs to be extended to the tight requirement of few beam interruptions per year (with durations of > 1 s). The accelerator must tolerate most components' faults without requiring a beam stop, since the beam start-up procedure would probably exceed this time limit. This is probably the most difficult point to assess in the accelerator design, because it is not only a technical problem, but also has deep interactions with the physics of high power beams and with the role of the accelerator control system. A preliminary assessment of the fault tolerance characteristics of an ADS-class superconducting linac, based on beam physics and modelling, is presented elsewhere in these proceedings [12].

(The need for an) Accelerator component database

The absence of a coherent, credible and validated component database with reliability figures for ADS accelerator components results in huge uncertainties in any reliability/availability assessments that could be performed with standard methodologies. Generally speaking, accelerator components are classified in two main broad categories. The first concerns the "industrial" components which are found mainly in the support systems as cooling systems, vacuum devices (pumps, valves), cryogenic components, or standard accelerator magnets and magnet power supplies, for which failure data are available from a large operating experience or other areas of applications as, for instance, fission and fusion field, medical accelerators, aerospace or cryogenic industry. The second category concerns major *ad hoc* accelerator components (HV sources, RF systems, cavities …) for which reliability parameters are inferred on the basis of either operational data of existing similar facilities (accelerator for high-energy physics or synchrotron radiation user facilities) or from vendors and the practice of "expert judgement". Clearly, many world-wide accelerator facilities have huge databases with many years of operating performances of components which are a useful source of information, but the data organisation in a coherent database has not yet been performed, mainly due to the great differences in data collection and log keeping between laboratories and to the lack of manpower required for such an effort [13].

The limits to the role of the component characteristics

However, it should be kept in mind that the connection (logical or functional) between components usually has a greater role in determining the system reliability/availability as opposed to the component characteristics. The failure of a single redundant component does not generate a failure of the system, and generally the system fails only when all (or most of) the redundant components fail. Obviously, while the parallel redundancy reduces the number of system failures, it increases the number of failing components, and the associated logistics. Furthermore, several options exist for parallel redundancy. The ideal situation, rarely met in reality, is “hot” parallelism, which assumes that the parallel components are statistically independent and the system is able to instantaneously detect the fault. Parallel components also exist in “warm” or “cold” configurations, depending on the failure rate of the standby component (in the warm case the failure rate of the standby component is lower than that of the operating, in the cold case it is zero). In these cases, switching devices triggered by fault detection diagnostics need to be included in the analysis. Moreover, time may be needed for the warm/cold component to provide the functions of the failing component.

As a last comment, when planning parallelism, special attention needs to be paid to common cause failures, which may have a probability of occurrence higher than the failure probability of an individual component, thus completely cancelling any possible reliability gain obtained by parallelism. Common cause failures may be associated with failure in the fault detection and switching systems, or with common support systems (e.g. power supplies, common control system, human errors, etc.). Also, failure of one component may determine an increase in the load conditions of other components, again causing a decrease in reliability due to “next-weakest link” failures. Other more complex arrangements are possible with highly reliable electronic equipments, like the “k out of n” redundancy, and may include voting mechanisms to assist in the detection of the failing component.

Design for high availability of future HEP accelerators

Future high-energy physics (HEP) programmes like the proposal to build a linear collider (LC) with a 500-GeV (extensible to 1 TeV) centre of mass collision energy have the ambitious goal of realising extremely complex and technologically challenging high beam power electron accelerators for fundamental subnuclear physics within the coming decades. The various designs proposed rely on two different and competing technologies: a high-frequency normal-conducting RF accelerator (NLC/GLC) and a moderate frequency RF linac, which pushes the limits of the technology of RF superconductivity with bulk niobium resonators (TESLA). In both cases the linear collider machine complex ranges in length more than 30 km. The successful operation of this technology at the TESLA Test Facility has been the driving motivation for the choice of the same technology for the much more moderate performance goals of the ADS accelerator.

A number of international panels and committees have been set to review and compare the designs, and assess the technical merits of the two proposed technologies. What has clearly emerged is that “if the typical reliability of HEP accelerators is scaled to the size of a 500-GeV c.m. linear collider, then the resulting uptime will be unacceptably low” [14]. This consideration stems from the fact that any reliability estimate starting from the “parts count” will lead to reliability and availability characteristics that would be too low for the realisation of the physics programme, and to huge logistics efforts for system maintenance. As an example, each of the two TESLA main SC linacs has approximately 10 000 cavities powered by slightly less than 300 high-power RF sources feeding 36 cavities each [15]. For all LC designs the main goal is to reach high beam availability at the interaction region to attain a 9-months-per-year operation cycle, measured in terms of total integrated luminosity for the experiments.

The linear collider designs have been reviewed by the ILC-TRC [14], identifying the necessary R&D activities that need to be undertaken to address areas of concern and ranking them in priority. Reliability considerations have been ranked in priority only after the actions needed to address the technical feasibility of the solution. In particular, for the TESLA design, no specific R&D items concerning the technical feasibility rank have been identified, whereas all LC designs have been asked to evaluate the reliability characteristics of critical subcomponents. A US-based panel was formed to prepare a technological comparison between the two competing technological options, and delivered a report in March 2004 [16] that includes a full section dedicated to a preliminary availability analysis of the two technologies. A Monte Carlo program was developed by an expert group in order to model the unavailability budget of the complex LC schemes and make predictions on the required MTBF of several key components of the main subsystems of the accelerator needed in order to guarantee a nominal availability of 85%. The results have been compared with the estimated nominal design MTBF, in order to determine the improvement factors needed and derive a model for costing the additional R&D efforts required to reach the high availability goals.

This excellent and rather sophisticated study, performed in a limited time, is still “a first crude step” [16] in order to determine a full availability model for such a complex machine and many important components have been treated by necessity as “lumped elements”, while the main linear accelerator and damping rings have been modelled to a large extent, including many beam dynamics based considerations in the Monte Carlo simulations. This choice is of course justified by the fact that the study was meant to make a relative comparison of the two different technologies, so the accelerators have been detailed in the areas where they differ most, leaving lumped elements where common technologies or subsystems were used in the two different proposals. Nonetheless, data of many years of operation of particle accelerators have been collected (mainly from SLAC and Fermilab) and reviewed in order to actually feed the simulation with starting values for component MTBF. The study represents a valid source with which to cross-check the component database for an ADS reliability study.

It should be noted, however, that these availability considerations were not raised in the mid-90s, when the first designs of the linear collider were first conceived, and were not even mentioned in the first ILC-TRC report in 1995. To some extent, the availability/reliability design revision is still in a “preliminary phase”, as the availability requirements were set after the first technological design. The proposed schemes for the ADS linear accelerator were outlined early in the conception stage using reliability-oriented design procedures and have much less ambitious technological goals.

An exploratory parts count reliability assessment for an ADS linac

Along the path to provide a better characterisation of the ADS linac, a rough “parts count” reliability estimation has been performed, assuming no fault tolerance is provided in the accelerator, which is modelled effectively as a series connection of all its components, besides a redundant injector. Thus, each component fault leads to a system fault. Obviously in this case, due to the considerations expressed in the preceding paragraphs, the reliability of such a system is practically zero for any practical mission time.

The model was fed with a preliminary set of MTBF data collected mainly from IFMIF or LANSCE experience and complemented with engineering judgement where data was missing. Given the subjectivity at this preliminary stage of the input data, especially in the MTTR data, that do not include logistic and waiting times, the results are only intended as a guideline for the identification of critical areas, and the study will be further iterated in the near future after a cross-check with other component sources, as the one described in the preceding paragraph.

Table 1. Main subsystems used for the "parts count" estimation

Subsystem	Main components	Redundancy	Comments
Ion source	1 lumped unit	2 systems in parallel	
RFQ	1 RF structure 2 RF systems		
Intermediate energy Beta = 0.15 spoke cavity	36 cavities 36 RF systems 36 magnets	None	18 focusing lattices
Intermediate energy Beta = 0.35 spoke cavity	60 cavities 60 RF systems 40 magnets	None	20 focusing lattices
High energy Beta = 0.47 elliptical cavity	28 cavities 28 RF systems 28 magnets	None	14 focusing lattices
High energy Beta = 0.65 elliptical cavity	51 cavities 51 RF sources 34 magnets	None	17 focusing lattices
High energy Beta = 0.85 elliptical cavity	12 cavities 12 RF sources 8 magnets	None	4 focusing lattices

Besides the warnings expressed above on the credibility of the results, this very rude parts count estimation performed for a three-month mission time led to a system MTBF of 28 h with a MTTR of 5 h, resulting in a 85% overall availability. An analysis of the percentage contribution to the overall failure rate is shown in Table 2.

Table 2. Percentage contribution to the overall failure rate from the subsystems

Subsystem	FR contribution (%)
Proton injector	0.6
Intermediate-energy section low beta	19.0
Intermediate-energy section high beta	31.7
High-energy section low beta	14.6
High-energy section intermediate beta	26.2
High-energy section high beta	6.7
High-energy beam transport system	0.1
Beam delivery system	0.1
Cryogenics	0.4
Water system	0.1
Compressed air	0.2
Electrical power	0.3
Total for accelerator	100

Clearly in this extremely oversimplified parts count estimation the critical points are found in the regions with a higher number of components (high beta spoke and intermediate beta elliptical). This is a simple artefact of placing all components in a series connection. Obviously the numerical values of such a simulation are reported only for illustrative purposes, both for the subjectivity of the input data and for the oversimplification of the model. However, based on the very modular nature of the superconducting linac, on the fact that fault tolerance with respect to many single failure events have been assessed [12], and on the possibility to include redundancies in many subsystems, it does not seem too optimistic to reach a 50 times improvement in the system MTBF in order to reach the goal of 1 400 h, with a more realistic system description and a careful evaluation and validation of the input data to the simulations.

Conclusions

In the practice of reliability engineering it is not enough to specify and allocate the reliability of components in order to accurately predict and control the system reliability, and strategies have to be implemented early in the system design to guarantee the necessary degree of redundancy and fault tolerance. The current work on ADS-class linear accelerators, with a modular design and a high degree of redundancy, suggests that a wide margin exists for the implementation of fault tolerance handling practices in several criticality areas.

The FMEA analysis has been a useful tool to identify the reliability critical areas in the ADS linear accelerator design, and to plan for the fault tolerance strategies. In the analysis of the reliability potential of the linac configuration, no fundamental showstoppers emerged, that could compromise the possibility of reaching the high reliability and availability goals. A preliminary exploratory study on a rough parts count model suggests that the design has the potentials for reaching the extremely low fault rate goal, but more work is needed in developing more realistic reliability models and in the set-up of a meaningful reliability component database. Finally, a large interest is growing in the HEP community for the availability predictions of linear colliders, which is greatly synergic with ADS reliability assessment activities.

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ADS NEUTRONICS

W. Gudowski
RIT, Sweden

No paper was available at the time of publication.

ADS SAFETY

P. Coddington
PSI, Switzerland

No paper was available at the time of publication.

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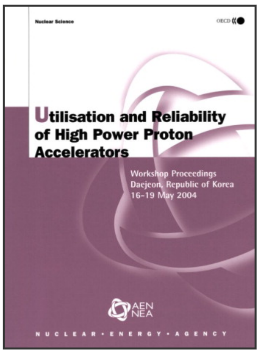

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