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PRELIMINARY DESIGN STUDY OF AN EXPERIMENTAL ACCELERATOR-DRIVEN SYSTEM

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FINAL SCIENTIFIC AND TECHNICAL REPORT

"General Synthesis Report of XADS preliminary design studies and needed R&D"

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Summary

The PDS-XADS contractual Deliverable 86, “General Synthesis report of XADS preliminary design studies and needed R&D” provides a general assessment of the concepts studied within the PDS-XADS Project with an evaluation of their potential to fulfil the XADS requirements with reasonable R&D difficulties or challenges.

After a brief description, the concepts are first evaluated for their potential to meet the XADS goals, and then with respect to the rules and criteria that are conventionally respected by a nuclear system and have to be also verified by the XADS.

In addition, the R&D needs are identified and assessed in order to determine the degree of difficulty in developing the systems to their estimated potential.

The document then provides preliminary recommendations for the Reference Options of the XADS to be further studied in the 6th FP in line with D77 "Recommendation Report for the Reference options of XADS".

This Deliverable is also issued as the Final Scientific and Technical Report of the project.

Contents

List of acronyms

AC : Alternative Current
ADS : Accelerator Driven System
ADT : Accelerator Driven Transmuter
ALARA : As Low As Reasonably Achievable
BOC : Beginning of Cycle
CFD : Computational Fluid Dynamics
CH-DTL : Cross Bar H Type - Drift Tube LINAC
CRDM: Control Rod Drive Mechanisms,
CW : Continuous Wave
CZP : Cold Zero Power
DBC : Design Basis Conditions
DEC : Design Extension Conditions
DHR : Decay Heat Removal
DHX: Decay Heat exchanger (immersed Na/Na heat exchanger for EFR)
DRC: Direct Reactor Cooling
DTL : Drift Tube LINAC
EDE: Effective Dose Equivalent
EC: European Commission
EFR: European Fast Reactor
EPR: European Pressurized Reactor
EOC : End of Cycle
FH : Fuel Handling
GT-MHR : Gas Turbine Modular High Temperature Reactor
HFP : Hot Full Power
HT : Hexagonal Tube (S/A wrapper)
HTR : High Temperature Reactor
IH-DTL : IH-DTL Interdigital H - Drift Tube LINAC
IHX : Intermediate Heat Exchanger
IP-EUROTRANS : Integrated Program - EUROpean research program for the TRANSmutaion of high-level nuclear watse in an ADS
LBE : Lead-Bismuth Eutectic
LINAC: Linear Accelerator
LLFP : Long Lived Fission Products
LOCA : Loss Of Coolant Accident

LOD :	Line Of Defence
LMFBR :	Liquid Metal Fast Breeder Reactor
LWR:	Light Water Reactor
MA :	Minor Actinide
MASURCA :	Maquette Surgénératrice à Cadarache : Zero Power Reactor
MEGAPIE :	Megawatt Pilot Experiment (at PSI)
MOX :	Mixed Oxide fuel
MSA :	Multiplied source (Approximated version)
MSM :	Multiplied source (Modified version)
MTBF :	Mean Time Between Failures
MUSE :	Multiplication with an external Source on MASURCA Reactor (at CEA)
MYRRHA :	Multi-purpose hYbrid Research Reactor for High-tech Applications (at Mol)
MWth :	Megawatt, thermal
NPP :	Nuclear Power Plant
ODF :	Diathermic fluid used in the 80 MWth LBE reactor
PCS :	Power Conversion System
PDS-XADS :	Preliminary Design Study of an Experimental Accelerator Driven System
PMT :	Project Management Team (of the PDS-XADS Project)
PND :	Prompt Neutron Decay
P&T :	Partitioning and Transmutation
RF :	Radio-Frequency
RCC-MR :	Design and Construction Rules for Mechanical components of FBR Nuclear Islands
RFQ :	Radio-Frequency Quadrupole
RPV:	Reactor Pressure Vessel
RV(A)CS :	Reactor Vault (Air) Cooling System
S/A :	Sub-Assembly
SCS :	Shut-down Cooling system
SPX :	Superphénix LMFBR reactor
TLOF:	Total Loss Of Flow
TLOH:	Total Loss Of Heat sink
TRADE :	TRIGA Accelerator Driven Experiment
WP :	Work Package
XADS:	eXperimental Accelerator Driven System
XADT:	eXperimental Accelerator Driven Transmuter

1. INTRODUCTION AND SCOPE

In the framework of PDS-XADS studies, Ref. [1], the general objective of Deliverable 86 “General Synthesis report of XADS preliminary design studies and needed R&D” is to assess and compare the concepts studied within the PDS-XADS Project.

After a brief description, the concepts are first evaluated for their potential to meet the XADS goals, and then with respect to the rules and criteria that are conventionally respected by a nuclear system and have to be also verified by the XADS (safety, economics and sustainability).

In addition, the R&D needs are identified and assessed in order to determine the degree of difficulty in developing the systems to their estimated potential.

The document then provides preliminary recommendations for the Reference Options of the XADS to be further studied in the 6th European Framework Programme in line with D77 "Recommendation Report for the Reference options of XADS".

Taking into account the relatively wide open range of alternatives in designing an ADS and according to the PDS-XADS Project description, three concepts are assessed , namely :

- The 80 MWth LBE-Cooled concept;
- The 80 MWth He-Cooled concept;
- The 50 MWth LBE-cooled small-scale concept (called MYRRHA);
- A Sodium-Cooled concept is only considered for economic comparison. Core and primary system are extrapolated from the EFR reduced size prototype, the interface with the accelerator/target are based on the 80 MWth LBE XADS design. This concept is dealt with in a specific section of chapter 2.

The main references used for this synthesis report are the following Deliverables of the PDS-XADS project:

- D40: Methodology and Criteria for concept comparison
- D61 & D62: Technical Option reports on the two LBE cooled XADS and Gas cooled XADS
- D63: Definition of XADS class reference accelerator concept and needed R&D
- D84: Cost evaluation and further scaling of the small-scale XADS
- D77: Recommendation report for the Reference options of XADS

The concepts comparison of chapters 3 and 4 is based on the evaluation grid proposed in D40. For any detailed explanation concerning the rationales of the criteria and the rating system, please refer to this Deliverable.

A detailed summary and the general conclusion of PDS-XADS project are provided at the end of this report in chapter 6.

2. DESCRIPTION OF THE XADS CONCEPTS

2.1 The XADS Accelerator

2.1.1 XADS accelerator specifications

The main technical specifications for the XADS accelerator are summarized in Table 2.1.1. These characteristics clearly show that this machine belongs to the category of the so-called HPPA (high-power proton accelerators) presently very actively studied or even under construction for a rather broad use in fundamental or applied science. The overall performance of the sub-critical system will be critically determined by a strict adherence of the XADS accelerator to these 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. Therefore, the WP3 studies for reference design had to integrate this stringent requirement from the very beginning, since this issue could be a potential "show-stopper" for ADS technology in general.

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 5 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*

Table 2.1.1 : XADS proton beam specifications

2.1.2 Choice of the basic accelerator concept

With the present state-of-the-art in accelerator technology, only two basic concepts of accelerators have shown to be able to deliver beam intensities in the mA range. These are sector-focused cyclotrons and linear accelerators (LINACs). Concerning cyclotrons, a final energy of 600 MeV is well established, mainly with the experience of the PSI machine, and from this, it is felt in the cyclotron community, that a maximum value of 5 mA should be considered as safely reachable. However, WP3 concluded that the cyclotron solution for an XADS presents a number of difficulties if not impossibilities: funneling, pulsing, beam trips, double-machine scheme, intrinsic current limitation, energy upgrading, that preclude this solution despite its advantages such as lower unit price. As a matter of fact, none of these limitations are present in a LINAC where intensities can reach above 100 mA without an intrinsic energy limit. Moreover, the strategy to implement reliability relies on over-design, redundancy and fault-tolerance, and requires a highly modular system where the individual components are operated substantially below their performance limit. A superconducting LINAC with its many repetitive accelerating sections grouped in "cryomodules" conceptually meets this reliability strategy.

Therefore, the reference solution is a superconducting LINAC, described in the next section.

2.1.3 The XADS accelerator reference layout

A reliable Linac

The proposed reference design for the XADS accelerator, optimized for reliability, is shown in Figure 2.1.1. It is composed of a "classical" proton injector (ECR source + normal conducting RFQ structure). Additional warm IH-DTL or/and superconducting CH-DTL are used up to a transition energy from where on a fully modular superconducting LINAC brings the beam up to the final energy. Up to the transition energy, fault-tolerance is guaranteed by means of a "hot stand-by" spare. Above this energy, spoke cavities 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 validity for a very different output energy range. Therefore, already the small-scale XADS accelerator is 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 subject of important R&D programmes presently underway e.g. at the laboratories of the collaborating institutions of WP3. 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.

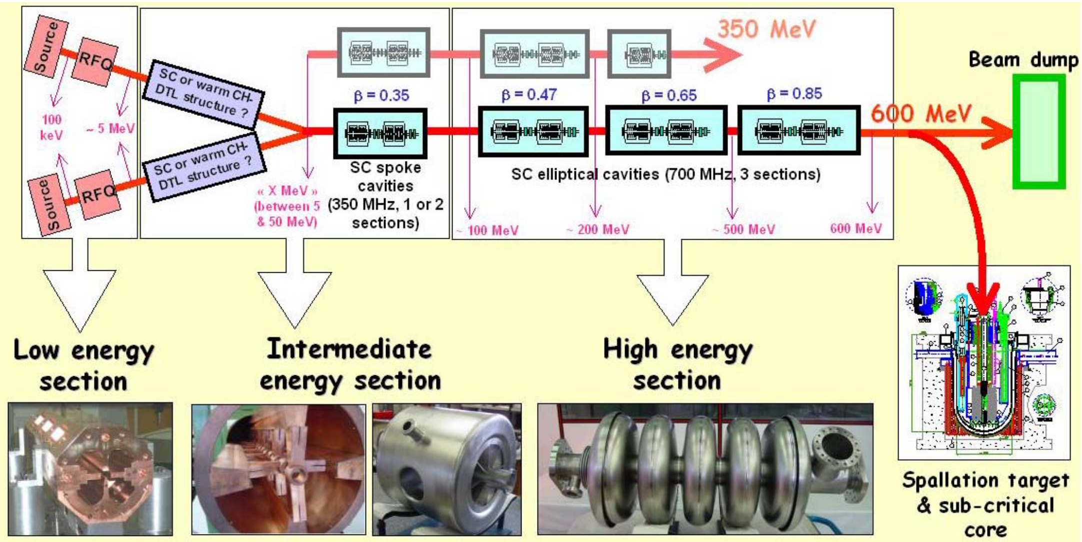


Figure 2.1.1 : XADS reference accelerator layout

A safe beam transport line

The objective of the final transport line is to safely inject vertically from above the 600 MeV (or 350 MeV) proton beam onto the spallation target with footprint of the required size and density distribution. To this end, a doubly achromatic module composed of two 45 degrees bending dipoles and three focusing quadrupoles has been designed and adopted for the two reference

XADS concepts. Such a system is non-dispersive: residual energy spread and central energy fluctuations from the accelerator will have no effect on the beam stability at the target. In addition, to expand the beam onto the target, the so-called raster scanning method has been adopted. It consists in deflecting a pencil-like beam with fast steering magnets acting in the two transverse directions in order to paint the target area.

A shielding for radiation protection

The goal of the shielding design of the XADS accelerator is therefore to guarantee that, under normal operational conditions, the added integrated dose to personnel around the XADS accelerator will be extremely small, i.e. comparable or smaller than the natural background. To obtain this goal, the shielding calculations are made using conservative (= pessimistic) normal beam loss assumptions, and assuming an “occupancy factor” of 1, that means that a person will be present during 2000 hours per year immediately behind the shield wall where maximum dose rates exist. Figure 2.1.2 shows for example the required earth profile in the case of an accelerator tunnel with 60 cm side walls and roof, buried underground (the top of the concrete roof corresponds to zero ground level). The profiles correspond to the minimum earth thickness required to reduce the residual dose levels outside the earth below 0.5 μSv/h for a 1 nA/m linear beam loss at 350 MeV (MYRRHA case). It is remarkable that the shielding profiles derived from the requirements for normal operation will provide sufficient shielding for the planned commissioning period as well as for planned periods of beam tuning and setup, by allowing beam loss rates 100 times higher than during normal operation during significant periods of time, and it will also protect correctly against several types of accident condition.

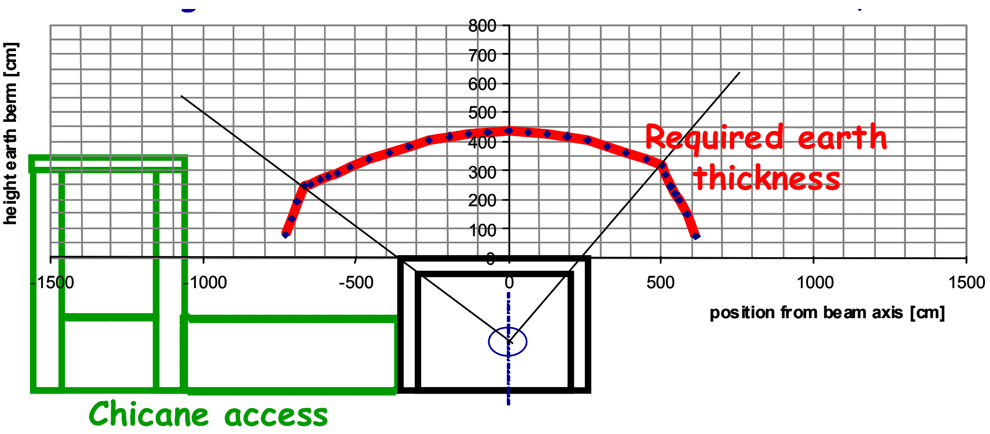


Figure 2.1.2 : Required earth profile above the 60 cm thick concrete linac tunnel
(for a 350 MeV proton energy and 1 nA/m linear beam losses)

A maintenance strategy

The foremost goal of the maintenance strategy for the XADS accelerator is to guarantee its reliability and availability goals for its operation, and that for its anticipated period of life, i.e. an order of magnitude of 30 years. These requirements request the development of an expert system able, while the accelerator is running and delivering nominal beam, to precisely identify and locate equipment that is showing degradation of rated performance, and/or that is out-of-order and to be replaced or repaired. Thus, the expert system provides the database that will be used during the scheduled maintenance periods for planning repair and/or replacement of deteriorated or faulty equipment.

2.2 The 80 MWth LBE-Cooled XADS

2.2.1 Nuclear Island

The Nuclear Island consists of four buildings, with a cylindrical reactor building and three outer structures contiguous with it, which are the Auxiliary/Control Building, the Fuel/Component Handling Building and the Air Coolers Building (Figure 2.2.1). The whole Nuclear Island rests on a single foundation consisting of an upper reinforced concrete basemat, quasi rectangular in shape, about 80 m x 40 m, and of a lower basement, separated by seismic support pads.

The NI Buildings are seismic category I and aircraft crash (ACC) protected (walls and roof 1.3 or 1.5 m thick), except the Air Cooler Building that is seismic category II and not designed against ACC.

The Reactor Building has a diameter of 33 m and is about 47.5 m high (from elevation -14.5 to elevation 33 m), with the Reactor Pit extending 14.5 m below grade. The overall volume of the Nuclear Island is about 120 000 m3.

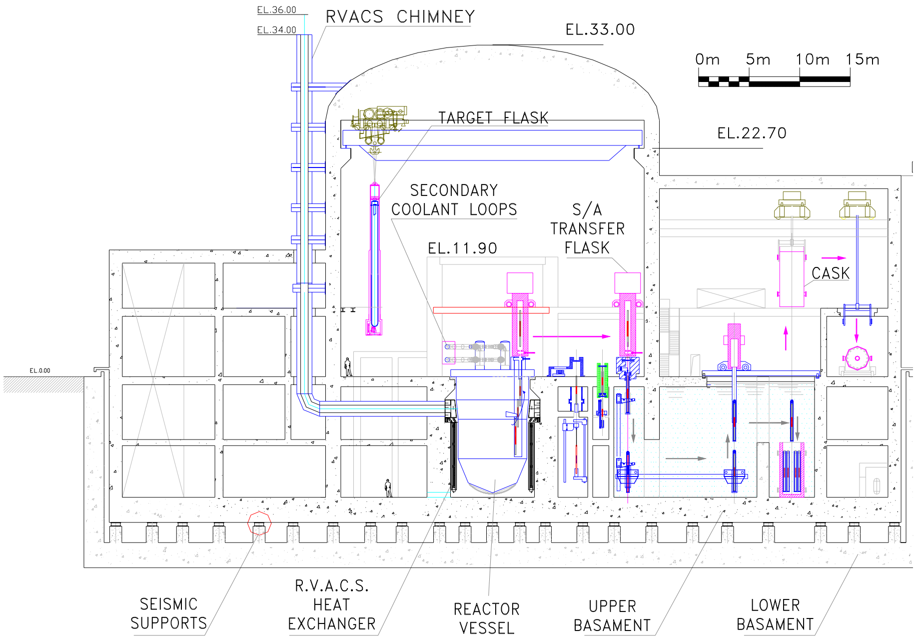


Figure 2.2.1 : Nuclear Island

2.2.2 Primary system

The primary coolant is molten lead-bismuth eutectic, which is characterized by good nuclear properties, operating temperatures lower than pure molten lead and compatibility with the low-pressure diathermic organic fluid used in the secondary system.

The configuration of the primary system (Table 2.2.1) is pool-type (Figure 2.2.2), similar to the design solution adopted for most sodium-cooled reactors, which has important beneficial features.

These include a simple boundary (the Reactor Vessel) containing all the LBE, thus eliminating all problems related to out-of-vessel primary coolant.

The Reactor Vessel is surrounded by the Safety Vessel to ensure containment of the primary coolant and its circulation through the core also in case of Reactor Vessel leakage.

The Reactor Vessel rests on the same boxed annular beam, anchored to the civil structure to which the Safety Vessel is suspended, and supports the Reactor Roof and the Internals.

The gap between the two vessels is sufficient to allow the access of a remote-controlled device, of the free rolling vehicle type, for ISI of the welds of the Reactor Vessel.

Both Reactor and Safety Vessel are made of a nozzle-free cylindrical shell with hemispherical bottom head. The upper side of the cylindrical shell of the Reactor Vessel ends with a Y piece, the inner branch of which supports the Reactor Roof.

The Cylindrical Inner Vessel, of asymmetrical cross section, hangs from the Reactor Roof. Its shape is determined by the need of including the in-vessel handling equipment and limiting the Reactor Vessel diameter, while leaving a large outer space to install the Heat Exchangers.

The Reactor Roof ensures the Reactor cover gas containment, the Biological protection of the Above-Roof Area and the support for Rotating Plug, Intermediate Heat Exchangers, Purification Units, Rotor Lift Machine and Gas Injection Pipes.

The Rotating Plug supports the Above-Core Structure, installed eccentrically inside a penetration, and the Transfer Machine with double gas seals to insure the integrity of the Reactor Boundary even in case of rotation for refuelling.

The Above-Core Structure, a crank-shaped structure that supports the Target Unit and the Core monitoring equipment, can rotate to allow refuelling.

The In-Vessel Fuel Handling System allows handling without opening the primary containment. It consists of a Transfer Machine that can reach all Diagrid positions, and of a Rotor Lift Machine that transfers the assemblies to/from a flask positioned on the Reactor Roof. There are two handling configurations, “Absorber handling” for which only assemblies located out of the ACS region can be reached and “Core handling” for which access to all core assemblies is possible.

To avoid rotating parts immersed in Pb-Bi, no mechanical pumps are used for primary coolant circulation which is obtained by an argon gas lift system.

The primary coolant leaves the core in radial direction about half a meter below the top of the fuel assemblies and enters the Riser channels arranged at the periphery of the Cylindrical Inner Vessel. Argon is injected at the bottom of Riser Channels to increase the density difference between the lead-bismuth in the Downcomer and the lead-bismuth-gas mixture in the Riser. The argon gas leaves the coolant at the free surface and escapes into the cover gas plenum.

This solution combines the high level of reliability of the natural circulation required by a safe Core cooling function, with Reactor compactness, operational flexibility, and lower thermal loading on the structures typical of the forced circulation.

Four bayonet-tube IHXs are freely immersed in the Downcomer, without membrane spanning the vessel to separate hot and cold plena (no Redan), to ensure coolant flow outside the IHXs, even in case of solidification of the LBE inside them.

The IHXs transfer heat from the LBE coolant to the secondary diathermic fluid during normal and DHR conditions. The LBE coolant enters radially the IHXs through a window provided in the upper part of the shell, leaves axially the IHXs and reaches the Core to start a new thermal cycle.

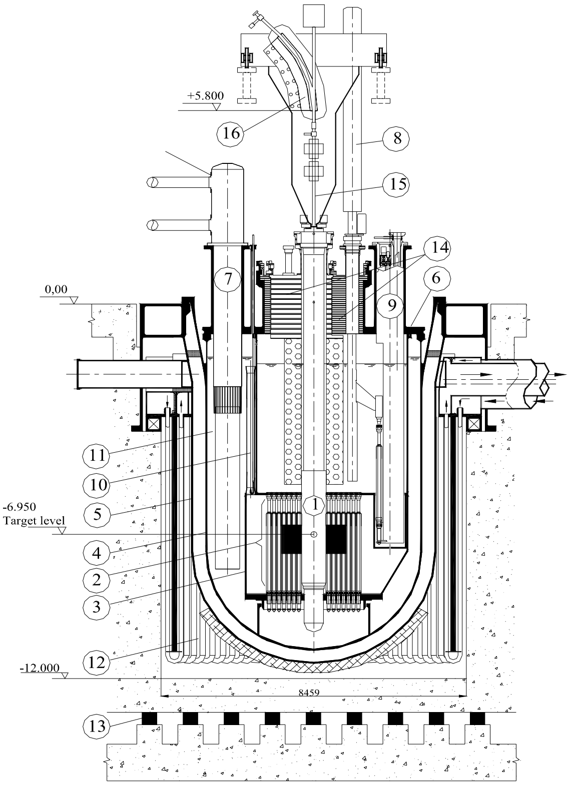
In the case of the Windowless Target Unit option, a small fraction of primary coolant (~ 5%) is bypassed through the Target Unit to remove the spallation power.

All primary system components are made of stainless steel (Z2 CND 17.12.Contr N RCC-MR for Main Vessel and Internals, and Z2 CN 18.10 RCC-MR for Safety Vessel) compatible with LBE at the XADS low operating temperature.

The mechanical analyses, performed so far, confirm the feasibility of the primary system components, thanks to the horizontal antiseismic supports that drastically reduce the most important load which is induced by the seismic excitation.

LBE cooled XADS		
Core Power	*MWth*	*80*
Primary Coolant	*LBE*	
Nominal Core Inlet Temperature	*°C*	*300*
Nominal Core Outlet Temperature	*°C*	*400*
Primary Coolant Flow rate	*kg/s*	*5961*
Total Primary System Pressure Loss	*MPa*	*0.029*
Argon Injection Flow Rate	*N-liters/s*	*120*
Argon Injection Pressure	*MPa*	*~ 0.5*
IHX secondary coolant	*Diphyl THT*	
Diphyl THT at IHX inlet	*°C*	*270*
Diphyl THT at IHX outlet	*C*	*312*

Table 2.2.1 – Main Primary System parameters



1 - Target unit

2 - Sub-critical core

3 - Inner Vessel

4 - Reactor Vessel

5 – Safety Vessel

6 – Reactor Roof

7 – Intermediate Heat Exchanger

8 – Transfer Machine

9 – Rotor Lift Machine

Figure 2.2.2 : Vertical section of the Primary System

2.2.3 Target Unit

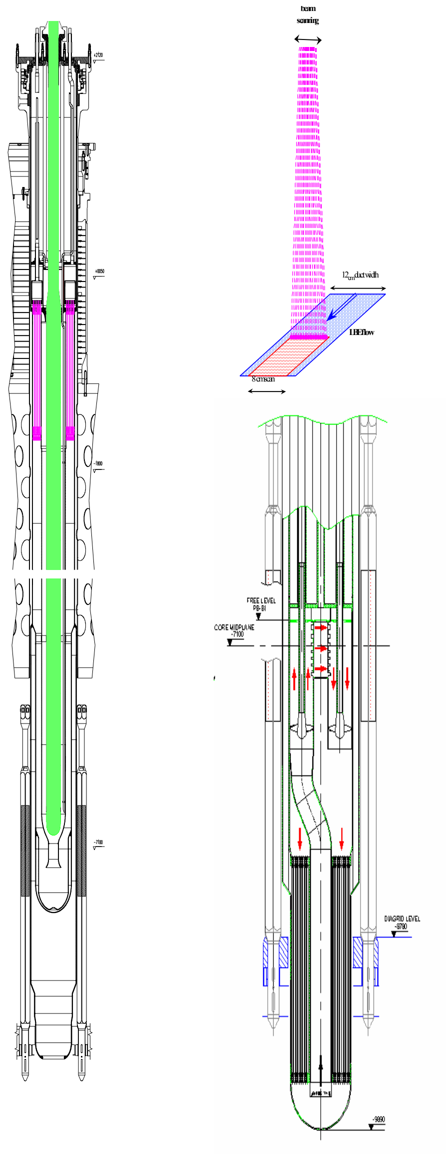
The Target Unit provides the physical and functional coupling between the Proton Beam Accelerator and the sub-critical Core.

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 serves also as 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 in forced or natural circulation, depending on the two design options which have been studied: window or windowless (Figure 2.2.3) Target Units.

The Hot-Window Target Unit features a thin metallic sheet, actually the end cap of the Beam Pipe, as a barrier between the LBE target and the Proton Beam Pipe. The Window and most of the Target Unit are made of ferritic-martensitic 9Cr1Mo.

The heat generated by the spallation reactions is removed by LBE in natural circulation. The LBE is cooled by the heat exchanger located at a higher level, an arrangement typical of natural-circulation cooling circuits.

The use of a diathermic fluid as secondary coolant gives high flexibility in the choice of the thermal cycle and in particular it allows limiting the temperature of the hottest spot of the window.



In the Windowless Target Unit the proton beam impinges directly on the free surface of the liquid LBE target. Natural circulation of the LBE is no longer possible, because the heat source is at the top of the loop. Thus the heated LBE must be driven downwards to the heat exchanger by some means, in this case two mechanical pumps in series.

A stream of primary LBE is bypassed from the cold plenum to the heat exchanger to serve as a cooling medium.

In the Windowless Target Unit no structural material is exposed to the direct proton irradiation. This option has the advantage of overcoming the material damage due to proton irradiation and hence allows lifetime and handling intervals similar to that of the fuel assemblies

A drawback of the ADS concept is neutron streaming from the Beam Pipe which makes difficult refueling and ISI&R, owing to the activation of structures and components above the Reactor Vessel Roof.

In the case of the Windowless Target Unit this problem is of less concern, owing to the smaller cross section of the beam pipe. This is possible because it is not necessary to open the beam spot, but it is sufficient to scan it perpendicularly to the horizontally flowing LBE (1D scanning, Figure 2.2.3, detail).

The smaller beam pipe of rectangular cross section of the new windowless Target Unit design (from 5 cm x 4 cm at the top to 12 cm x 5 cm at the bottom) reduces material activation, extending manned activities in the area (a few days after proton beam shutoff) to about one hundred hours without exceeding the yearly dose limit for professionals.

Figure 2.2.3 : Window and Windowless Target Units

2.2.4 Core

The Core (Figure 2.2.4) consists of 120 fuel assemblies arranged in an annular array of five rows. The inner row surrounds the target unit. The assemblies are identical, 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 keff = 0.97 at nominal power and BOC (Beginning Of Cycle). Only a single refuelling scheme has been considered and it appeared that with a limitation of the proton current of 5 mA, the target burnup of 22,300 MWd/Te has been reached. The fuel pin cluster is enclosed by an hexagonal wrapper; the lattice is about 40% larger than for Superphénix, while the active fuel length is slightly shorter (87 vs. 100 cm).

The fuel assemblies are surrounded by a buffer region of 174 dummy elements, the purpose of which is to keep the fixed structures away from the hard neutron region. LBE in the buffer region and adjacent downcomer provides a substantial neutron reflector for improving the overall neutron economy. Moreover, the core buffer allows a flexible management for irradiation testing of prototypical fuel assemblies containing different kinds of fuel or LLFP's and for positioning neutron absorbers closer to the core to lower the keff below 0.95 before refuelling.

The lower end of the assembly is terminated by a spike which plugs into the corresponding hole drilled in the forged diagrid plate. The spike cell contains the locking device that is actuated through a rod laid out along the centre line of the assembly. In the hold-down position, three pins, radially protuding from the spike, engage with the edge of the pintle and prevent the assembly from lifting up. Both core fuel and buffer assemblies, which otherwise would be thrust upwards by the buoyancy and flow momentum of the LBE, are thus secured down to the core diagrid and can be only disconnected through appropriate actions by the fuel handling machine when this is operated during core outage.

Because LBE is a highly diffusive and fairly transparent medium for neutrons, it has been possible to adopt a wide fuel pin lattice with associated reduced friction losses, that makes core cooling by natural convection possible even in the case of loss of the argon lift system.

The BOC and EOC subcriticality range, associated with the cycle length and core management, is a crucial parameter for defining the proton beam current.

The operational sub-criticality range is established in order to stay away from criticality (keff=1) with adequate margin under normal operational conditions so that postulated accidents which may lead to large temperature changes and positive reactivity insertions may also be taken into account without achieving criticality. For Design Basis Conditions (DBC), a safety margin of Vk = 1% and 0.6% allowance for measurement error are subtracted from the criticality state, so that the resulting upper limit for the multiplication factor becomes k = 0.984. Furthermore, consideration of Core cooling from operating down to assumed ambient temperature, beam pipe flooding by LBE or geometrical variations associated to earthquake or temperature variation and Doppler effect, cumulate to a predictable reactivity insertion of about 1.4%.

The core multiplication factor for normal operation at full power and BOC is thus set at k = 0.984-0.014 = 0.97, i.e. a sub-criticality margin of 3%.

Accidents like those involving large core compaction which may be worth about 0.5-0.6%, may be allocated to Design Extended Conditions (DEC). Also for these accidents the core remains subcritical, though with a reduced safety margin. As a conclusion the 0.97 core multiplication factor is sufficiently low to ensure the safe operation of the core without need of shutoff rods.

During operation, the core reactivity decreases at a rate of about 0.004%/day. Thus for the targeted 1000 days full power operation, the reactivity depletion would not exceed 4%, i.e. the operating multiplication factor reduces from 0.97 at BOC to 0.93 at EOC. The Core can be operated in these EOC conditions with a proton current of about 6 mA.

There are no absorber assemblies dispersed in the core during normal operation. There is, however, a set of 12 B_4C absorbers (worth ~ 5000 pcm), which are kept parked, during operation, at the periphery of the buffer region. At scheduled outages, these absorbers will be moved close to the core by means of the in-vessel handling machine, before extraction of the Target Unit. This allows to compensate for any reactivity insertion brought about by the extraction and to maintain the core at safe shutdown with the subcriticality required during refuelling (Keff ≤ 0.95).

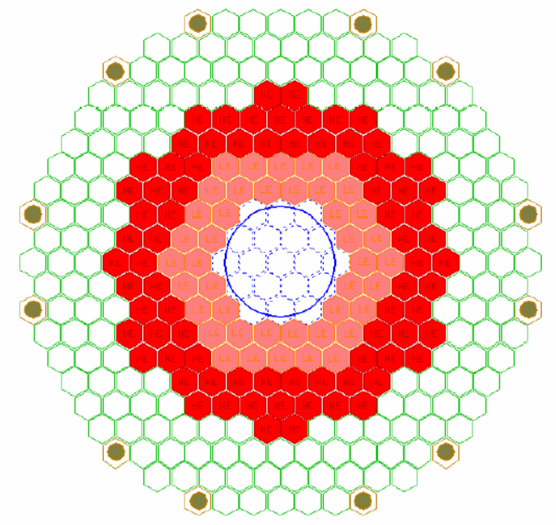


Figure 2.2.4 : Core horizontal section

2.2.5 Decay Heat Removal system

The normal decay heat removal is ensured by the Secondary Coolant System (SCS) that provides two functions:

• maintaining a sufficient primary coolant flow through the core in order to ensure that decay heat is transferred from the fuel to the primary coolant;

• ensuring that the decay heat is removed from the primary coolant and rejected to the ultimate heat sink.

The normal decay heat removal is ensured by one secondary loop only and in passive way, i.e. the primary and secondary coolants in natural circulation.

The RVACS provides for the passive removal of decay heat in case of a total unavailability of the SCS. This event is very unlikely because the SCS is made of two practically independent secondary loops. Multiple independent failures are required to cause the complete loss of both secondary loops; an aircraft crash only has the potential to breach both loops with the associated loss of the secondary coolant and the complete loss of heat removal capacity by the secondary system.

The RVACS consists of Air Cooler with annular U tube bundle arranged in the Reactor Pit with atmospheric air flowing pipe-side in natural circulation, so that the pipe legs connected to the air inlet manifold face the pit wall, whereas the return pipe legs face the Reactor Vessel.

Four equally-sized air intake ports and four chimney stacks are provided by design. This configuration ensures sufficient redundancy, and minimizes the effects of malfunction of an individual component.

The RVACS does not require valve alignment, it always operates because of natural draft: decay heat removal is through a combination of different heat transfer modes: conduction through the Reactor Vessel, natural convection and radiation into the gap between the Reactor Vessel and the Safety Vessel, conduction through the Safety Vessel and radiation from the Safety Vessel to the RVACS air pipes. In case of abnormal increase of the Safety Vessel temperature, heat dissipation by radiation increases with the 4th power of temperature and the atmospheric air circulation increases accordingly, driven by the natural draft.

During Normal Operation, the primary coolant temperature is controlled by the SCS, while the RVACS removes a power ranging from 364 to 439 kW, depending on the atmospheric air temperature.

In case of a total loss of the SCS, the accelerator will be shutdown and the RVACS will take over the removal of the decay heat.

2.3 The 80 MWth He-Cooled XADS

2.3.1 Nuclear Island

The overall architecture of the plant is derived and extrapolated from modular thermal High Temperature Reactor projects such as the GT-MHR. The Reactor Vessel is located within a concrete Reactor Vault and the whole system within the Reactor Building. Only the outline of the Reactor Building has been sketched. It has an external diameter of 30.7 m and is about 56 m high, of which 22 m below grade. The Reactor Vault is cooled by a specific circuit (water pipes embedded within the vault concrete).

The direction of entry of the proton beam and the target to the reactor has a large influence on the overall layout of the reactor building and, in case of the reference entry from the top, on the above roof area where the proton beam transfer line has to be accommodated.

For the mitigation of severe accidents, provision is made for an external core catcher located under the reactor vessel in the pit and cooled by a specific passive water cooling circuit.

An overall arrangement of the reactor building can be seen on Figure 2.3.1. The dimensions are only indicative as they may evolve significantly when more detailed assessment for instance on the shielding and concrete thickness are taken into account and when all the auxiliary equipments become available.

No detailed study of the reactor building and nuclear island layout has been performed as it was out of the scope of the PDS-XADS programme.

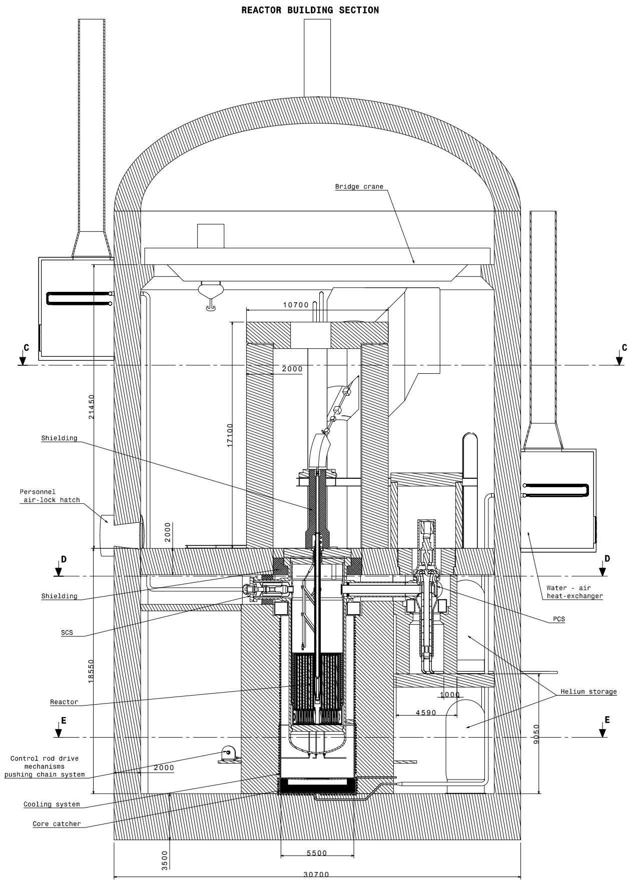


Figure 2.3.1 : Outline of the Reactor Building-Vertical section

2.3.2 Primary system

The reactor primary system (Figure 2.3.2) comprises a reactor vessel housing the core, a separate vessel that houses the Power Conversion System (PCS) and a cross vessel linking the two vessels. The primary vessel accommodates the Target Unit (TU), the sub-critical core and associated systems for fuel handling and the Shutdown Cooling System (SCS) for decay heat removal. The PCS vessel provides the coolant circulation, by a motor driven blower, and the heat exchanger transferring heat to an external cooling water circuit. Metallic vessels have been preferred to Pre-stressed Concrete Pressure Vessels for consistency with current HTR projects justified mainly by the extensive fabrication in existing NPP factory facilities which brings significant cost and schedule improvements.

The gas coolant medium is helium circulated with a motor driven blower and cooled by helium/water heat exchangers for normal power operation and transition to shutdown. The core cooling safety function for the rejection of decay heat is provided by the Shutdown Cooling System (SCS) complemented by the vault cooling system.

Main parameters of the primary circuit are listed in Table 2.3.1.

Gas-cooled XADS		
Core Power	*MWth*	*80*
Primary Coolant	*Helium at ~6 MPa*	
Core Inlet Temperature	*°C*	*200*
Core Outlet Temperature	*°C*	*450*
Coolant Flow Rate in the Core	*Kg/s*	*61,6*
Coolant Velocity in the Core	*m/s*	*~30*
Primary system target pressure drop	*MPa*	*0,1 **
Primary helium containment	*Metallic vessels*	
Power Conversion System	*Heat exchanger and circulator*	
Secondary Coolant	*Water*	
IHX Sec. Coolant Inlet Temperature	*°C*	*25*
IHX Sec. Coolant Outlet Temperature	*°C*	*65*

* : Parameter used for the blower design

Table 2.3.1 – Main Primary System parameters

The reactor pressure vessel (RPV) 15.5m high and 4.3m external diameter, is a conventional metallic pressure vessel including a bolted flat cover also known as the roof, a cylindrical section and an elliptical bottom head. The reactor thimble which houses the target unit is suspended from the reactor cover.

Basically, the RPV diameter is governed by the accommodation of a large number of reflector and shield assemblies around the core fissile zone whereas the height comes from S/A primary handling and natural circulation requirements.

The cross vessel and three SCS nozzles are housed evenly every 90° within a reinforced cylindrical shell located just under the reactor flanges. The RPV is supported by an annular box structure from the vault via the nozzles. The core is supported by a diagrid, which sits on a thick core support plate itself resting on a flange located at the bottom of the vessel cylindrical part. The core support line operates at cold temperature (200°C) and mainly under compressive stress.

Primary He is directed to the core via the annular gap between the hot duct and the cross vessel and downstream along the reactor vessel. It then flows into the diagrid where it is distributed to the fuel Sub-Assemblies (S/As) via the chandelles slots. Within the vessel, cold He (200°C) is separated from hot He (limited to 450°C for thermal creep exclusion) by the inner vessel. In the upper part, a calibrated by-pass flow is directed between the upper insulating plate and the roof slab. This plate also acts as a complementary shield plate (use of zirconium hydride with 1% boron) in order to limit the upper structures activation.

In compliance with the range of helium temperatures, Modified 9%Cr ferritic steel (T91) is selected for pressure containing vessels and type 316 L(N) austenitic stainless steel for reactor internals. Both grades are within the RCC-MR code, selected as project reference design code.

All reactor internals are designed as potentially removable structures and the gas coolant transparency brings significant advantages with respect to In-Service Inspection and Repair compared to liquid metals.

The reactor thimble, a specific feature within the primary helium containment, will be subjected to irradiation damage rate similar to this of a S/A wrapper. It will be hence conceived as a consumable component subject to periodic replacement.

The thermomechanical scoping verifications show acceptable structural margins at this stage of the project. The key issue is the irradiated thimble structural integrity involving both the adjustment of thimble temperature to avoid excessive embrittlement and creep and material selection (between T91 and 316 L(N)). This will deserve further studies and confirmation from R&D on materials. Concerning sensitivity to thermal cycles, the design seems very tolerant and fully compatible with a number of beam trips of 50/year. This is due to the relatively poor heat transfer coefficients of the helium coolant.

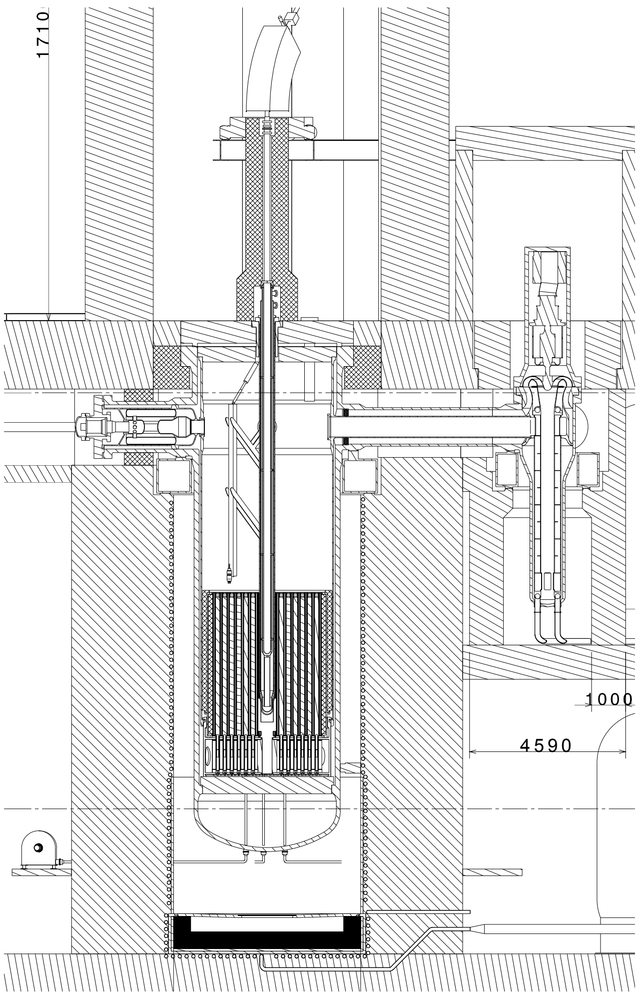


Figure 2.3.2 : Primary System vertical section

The option selected for Power Conversion System consists of motor driven blowers and helium/water heat exchanger. This exchanger is housed in the PCS vessel above which a circulator extrapolated from the existing AGR design is installed. The preliminary design studies show drastic size improvements, design simplifications and prospect for a significant capital cost saving compared to the Turbo-compressor option initially considered by similitude with the GT-MHR modular reactor.

The primary fuel handling system provides access to any core position by means of three locations for two pantograph machines able to withdraw and put down the S/As in two transfer positions or in the load unload position which is under the direct charge machine. The direct charge machine allows the sub-assemblies transfer from the reactor vessel to the fuel transfer cask.

Absorber Sub/Assemblies are set in the core lattice with the Fuel Handling system but the six absorber rods are lifted in the core active zone thanks to dedicated mechanisms prior to a Fuel Handling campaign.

2.3.3 Target Unit

The reactor thimble consists of a 460mm diameter, 25mm thick tube submitted to external helium pressure bolted on the roof slab and guided at the core centre. The thimble houses the target unit (Figure 2.3.3) located at core center 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 selection of T91 steel as reference material for the structures was made on basis of current knowledge resulting from R&D programme on corrosion and irradiation behaviour of materials in LBE cooled systems and very fast neutron spectra.

The target unit is conceived as a consumable component subject to periodic replacement. The proton beam tube including the highly irradiated window subject to frequent replacement can be mechanically disconnected from the target unit for independent removal.

The alternative option of a helium cooled solid target made of small tungsten rods and with a “cold window” outside of the reactor shows very appealing features for the Gas-Cooled XADS. This configuration would bring major improvements in terms of window lifetime (wide possibility of temperature adjustment and large number of candidate materials) and would drastically simplify the window replacement. In addition, the plant design is more consistent and simple (only one type of coolant : helium).

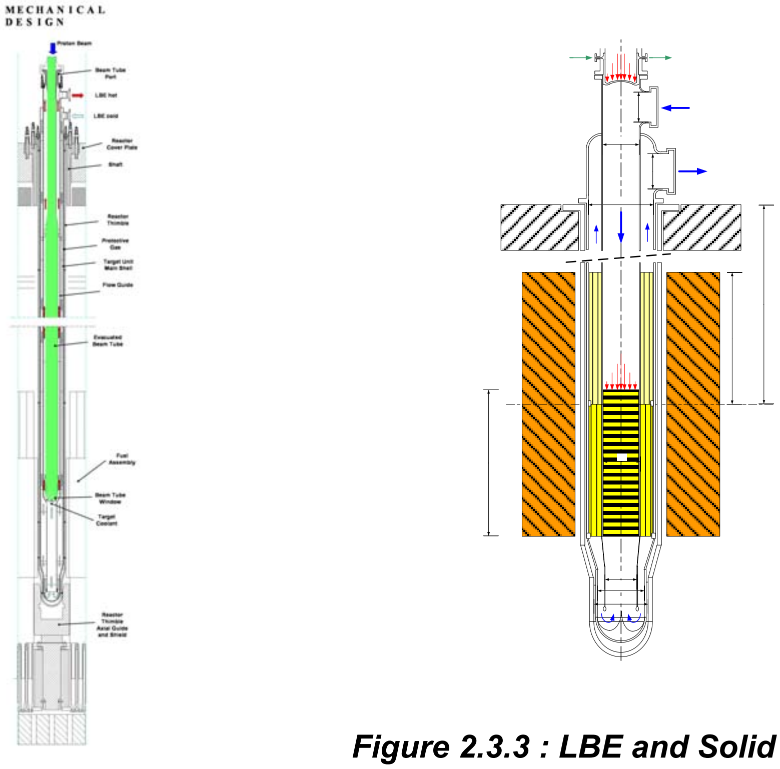


Figure 2.3.3 : LBE and Solid W Target Units

2.3.4 Core

The XADS gas-cooled core is built up from a ring of 90 Fuel Sub/Assemblies surrounding the spallation target which takes up the central locations (Figure 2.3.4). Surrounding the core are steel reflector S/As, themselves surrounded by shield S/As 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 reactivity increase at cold state, fuel handling error and accidental water ingress in the core. The design of the core has been based largely upon previous fast reactor experience.

Each fuelled sub-assembly contains 37 pins held in a triangular lattice by honeycomb grids. The fissile column length is 1.5 m and, like the LBE concept, the initial fuel loading will be MOX type fuel with the similar composition as the standard Superphénix reload fuel.

A key design feature is that the core should remain sub-critical under all plant conditions. An initial operating keff of 0.97 was chosen for the core and further justified by reactivity effects assessments for various fault conditions including core compaction. For refuelling, it is proposed to remain within an upper limit of Keff of 0.95 thanks to absorbers used only for this purpose.

At the start of the fuel cycle, a beam current of approximately 2.6 mA is required at a keff of 0.97. During operation, as burnup of the fuel progresses, the beam current is to be increased to compensate for the core reactivity drop. Both a single and a three-batch refuelling scheme have been considered and it appeared that with a limitation of the proton current of 5 mA, the target burnup of 40,000 MWd/Te can only be reached with a multi-batch concept.

Core calculation were combined with the results of thermal hydraulics calculations to determine a reference core cooling scheme. Preliminary studies show that with specific gags and clad roughening, the core can be operated at relatively low clad temperature (hot spot below 570°C). This provides comfortable margins for normal operating conditions with conventional fast reactor cladding material and also improves the behaviour in transient conditions (reduced fuel stored energy).

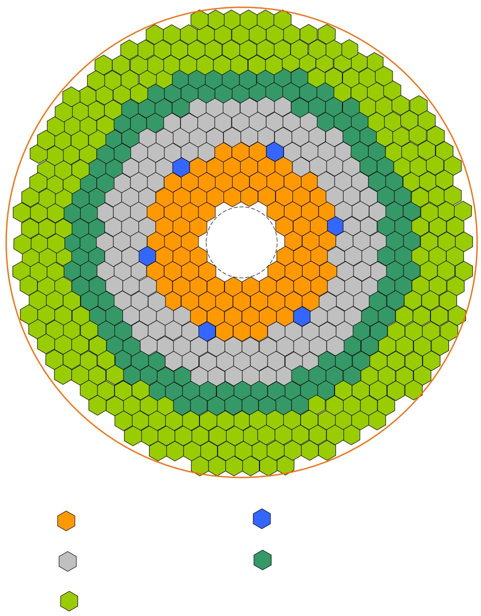


Figure 2.3.4 : Core horizontal section

2.3.5 Decay Heat Removal system

The Decay Heat Removal function is provided by the Shutdown Cooling System (SCS) complemented by the Reactor Vault cooling System also used to limit the temperature of the vault concrete during operation. The normal operational mode of the SCS is the forced circulation. In case of accidental loss of the forced circulation of primary helium, the decay heat can be removed in natural circulation using the helium/water heat exchangers and natural circulation on the secondary water side of the Shutdown Cooling System.

The three SCS units (each capable of 2MWth – i.e. 100% duty) are located into nozzles connected to the pressure vessel at the same elevation as the connection to the PCS. The elevation of the nozzles, about 7 m above the core mid-plane provides sufficient natural circulation draught. This compact arrangement of the SCS circuits is a big design simplification compared to external loops.

The SCS units are conceived as integral modules that can be removed and replaced by a spare unit. Each unit includes a check valve, a helium/water Heat Exchanger and a motor driven helium circulator complemented by an active flow shutter located in the Cross Vessel cold duct. The circulator motor and possibly the moving parts can be removed independently.

The ability to meet the reliability target of 10^{-7}/year for the loss of DHR is a key issue for the safety of the Gas–cooled XADS. It appears reachable with three SCS secured loops, partial depressurisation to about 10 bars at shutdown and a 2/3 diversity combined with a special SCS maintenance scheme.

2.4 The 50 MWth LBE-cooled XADS (MYRRHA)

2.4.1 Nuclear Island

The MYRRHA building is based on a fully remote handling system (fuel and components) scheme in view of the high activation on the top of the reactor and the Polonium contamination. The machine hall is maintained under oxygen-free atmosphere.

In the reference concept of the building (Figure 2.4.1), the accelerator and the main beam magnets are located at ground level in a separate building. The MYRRHA building is a long, high and relatively "thin" building (100 m length, 30 m width, and 40 m height). The beam line will then enter the reactor building from above what means that this building has to be (at least) partially sunk into the ground. The foundation invert lies at 30 m depth in this reference concept.

The reference concept may be improved by adding a 10 m-thick layer of sand, which is already available from the digging of the building, to cover the whole surface. Instead of adding a layer on top, the whole building may be lowered down.

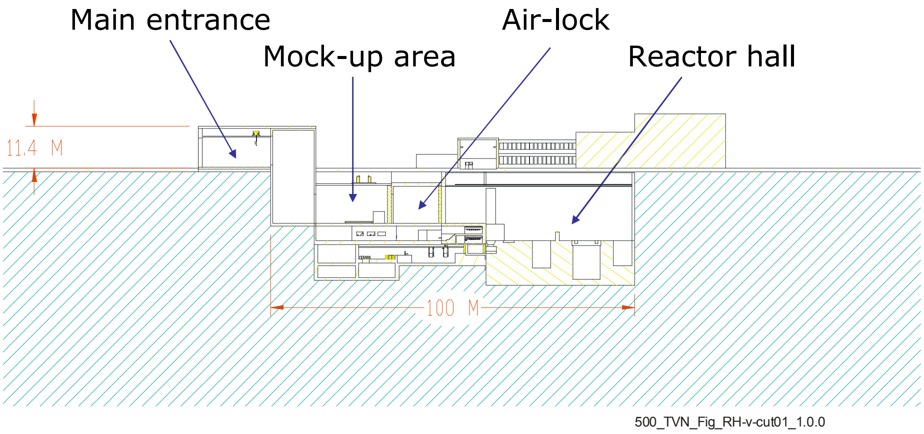


Figure 2.4.1 : MYRRHA reference building

2.4.2 Primary system

Because of the high fast flux and the high power density requirements of the MYRRHA machine, the primary coolant is a liquid metal coolant, Lead Bismuth Eutectic to operate at modest temperatures.

To take profit of the thermal inertia provided by a large coolant volume and of the feedback from Na cooled fast reactors, a pool-type system has been selected. The configuration selected is a standing vessel: due to the high mass of the coolant and the temperature distribution, it was found more convenient to design the supporting structures in such a way that the most stressed areas are not also the hottest – which would have been the case with a hanging vessel. The standing vessel is combined with a flat bottom which optimizes the volume of primary coolant.

The system is shown in Figure 2.4.2 with the double-wall pool Containment Vessel, surrounded by a biological shield to limit the activation of the soil as the reactor will be installed in an underground pit. This shield will be closed above the Reactor Lid to form a hot cell used as remote handling area for all operation and maintenance services to the reactor.

The Core is mounted on a central support column hung from the Reactor Lid and being stabilised by the Diaphragm, the separating shell between the cold and hot LBE coolant, which is fixed ultimately to the rim of the Double-Wall Vessel. The overall arrangement of the reactor roof and internals is highly influenced by the spallation target and its off-centered layout. Loading and unloading of fuel assemblies is foreseen to be carried out by classical in-vessel fuel handling, however from underneath. The pool also contains the liquid metal Primary Pumps, the Heat Exchangers using water as secondary fluid and the two fuel handling robots located on the typical Rotating Plug of fast reactors.

LBE cooled XADS		
Core Power	*MWth*	*50*
Primary Coolant	*LBE*	
Nominal Core Inlet Temperature	*°C*	*200*
Nominal Core Outlet Temperature	*°C*	*337*
Primary Coolant Flow rate	*kg/s*	*2500*
Total Primary System Pressure Loss	*MPa*	*0.5*
IHX secondary coolant	*Water or Steam*	
Water/Steam pressure	*MPa*	*2.5/0.7*
Water at IHX inlet	*°C*	*140*
Water at IHX outlet	*C*	*160*

Table 2.4.1 : MYRRHA Primary System parameters

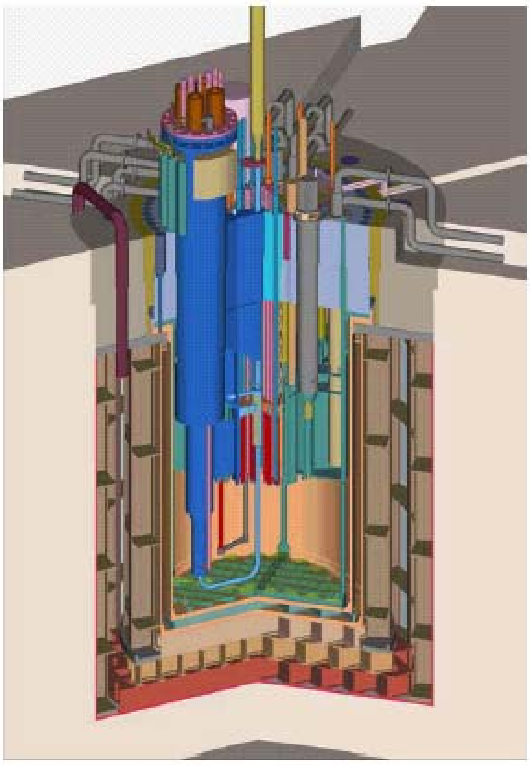


Figure 2.4.2 : MYRRHA primary system vertical cutaway

2.4.3 Target Unit

The MYRRHA machine should be a multi-purpose research facility of reasonable dimensions, but with high-level requirements, among others high flux levels ($\Phi tot > 5.10^{15}$ n/cm²s and Φ>0.75 MeV = ~ 10^{15} n/cm²s) and high availability rate. As a direct consequence, the central hole in the core (which houses the spallation target) should be of limited dimensions in order to keep many locations available in the core (to install experiments) where the fluxes are sufficiently high. Considering the moderate value of 350 MeV of the proton beam energy, resulting in high current intensity (Maximum 5 mA) and density, the choice of a windowless target design became mandatory.

The MYRRHA spallation target unit forms an interlinking circuit with the core as the central hole housing the spallation target is very limited in diameter (100 mm). Therefore the spallation target services (pumps, HX, vacuum pumps) are put in a cylindrical housing aside at the core periphery as shown in Figure 2.4.3. Despite the interlinking design, the MYRRHA spallation unit is also removable component to be extracted from the core as is. One should also mention that the spallation target unit is in place when loading or unloading fuel assemblies.

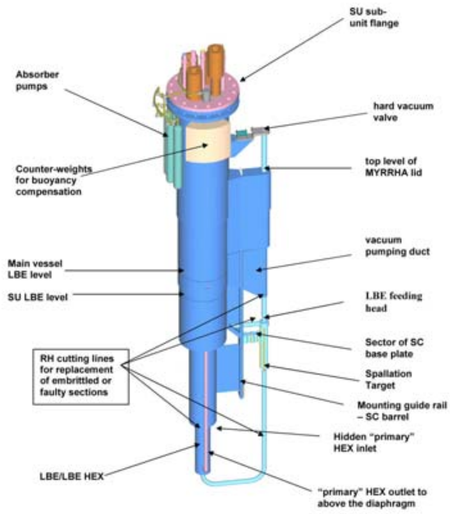


Figure 2.4.3 : MYRRHA spallation loop

2.4.4 Core

The core (Figure 2.4.4) of 50 MWth, is designed as a compact configuration with an active length of 600 mm and a maximum core radius of 1000 mm with 99 hexagonal positions, because the main objective of the facility is to obtain a very high fast neutron flux for experimental needs. Not all positions are occupied by fuel assemblies but could contain fast spectrum irradiation devices or moderating material to create thermal neutron flux regions. A typical configuration with BOC keff of 0.95, value used for fuel storage is achieved by using 45 to 50 fuel assemblies. There are 19 core positions accessible through the reactor lid capable of housing experimental devices with own ancillary equipment above the reactor lid. All remaining positions can house either fuel assemblies or off-line serviced experimental rigs. The Core is driven by a fixed proton current for the whole length of an irradiation cycle of 90 days with a keff swing due to burn up of 1%. After core re-shuffling, the keff will be brought back to the initial value of 0.95.

The operating scheme considered consists of two 90 operating days cycles followed each by 30 days light maintenance, plus a third 90 operating days cycle followed by 90 days heavy maintenance. This does not require current compensation for the keff swing, with an availability factor of 70%, reasonable for an experimental facility. This working scheme avoids overpower transients due to erroneous increase of beam current.

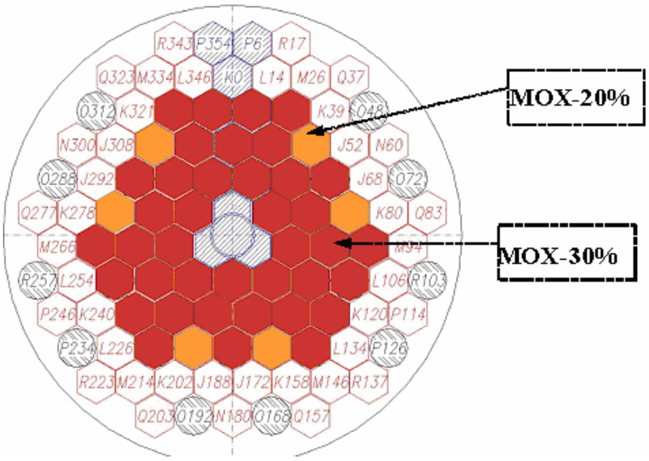


Figure 2.4.4 : MYRRHA core horizontal section

2.4.5 Decay Heat Removal system

The safety system for the Decay Heat Removal of the small-scale LBE-cooled XADS MYRRHA is the Emergency Cooling System (ECS). The ECS is based on a fully redundant and passive scheme with two independent systems, each capable of 100% duty. It also implies that the ECS is based on passive principles: no pumps or fans, no power-operated valves, no active pressurizer. Each ECS circuit is composed of a primary exchanger (EHX) providing the thermal contact between the primary LBE and the secondary loop fluid (water), a check valve at the bottom of the EHXs, and a closed circuit with water operating in natural convection and including a water/air cooler.

The check valve at the bottom of the emergency HXs is crucial for the good behaviour of the system. In emergency operation, i.e. when all primary pumps are lost, this check valve should be fully open in order to have a LBE flow through the ECS. In normal operation however, this check valve should in principle be closed to avoid a large LBE bypass of the core. This closing and opening of the check valve is a passive feature, triggered by the pressure head of the primary pumps.

2.5 Main Features of an Extrapolated 80 MWth Na-Cooled Concept

2.5.1 Introduction

For the PDS-XADS programme, studies of a sodium-cooled XADS are not included because it was considered that due to the considerable existing knowledge and validation of sodium technology, it was less urgent to launch design studies to assess the supporting R&D needs. Therefore, the Na cooled option was to be considered only for economic comparison purposes. The objective of this chapter is to review the main options and characteristics of a 80 MWth Na cooled XADS and then derive a cost from available cost data of Na-cooled reactor. This cost will not be considered as an absolute value but as a reference yardstick for comparison with other cost assessments performed in the course of the project.

2.5.2 Main plant features

A brief review of the main features of an extrapolated sodium cooled XADS is briefly discussed below :

- Power : 80 MWth

- Accelerator : XADS reference LINAC accelerator

- Core : The core can be derived from classical Fast Breeder Reactor sodium cooled cores. A compact core arrangement with a typical reduced pitch value (p/d ~ 1,15) can be conceived due to the sodium coolant heat transfer and heat transport properties. This would lead to high volumetric power in the range of 250 to 300 MW/m^3. The subcriticality level will be similar to the one of the 80 MWth LBE as some of reactivity insertions used for this core were derived from EFR even though this would require optimisation. The core ΔT can be optimized to reduce creep on hot structures from 150 °C down to 100°C such as for the LBE cooled XADS. However, even with a 150°C ΔT, the design of the primary system fixed structure should be compatible with a large number of accelerator beam trips as indicated in Ref. [2]. The core and sub-assembly technologies are already available.

- Primary system :

A conventional sodium cooled integrated concept can be used.

• The Secondary loops (3 a priori) can be extrapolated from EFR / Direct Reactor Cooling / loops (15 MWth) and upgraded to 23 MWth. In the case of EFR, the DRC loops were the Safety Classified system for Reactor Decay Heat removal. There were two different systems DRC1 and DRC2 to reach high level of reliability of the DHR function. DRC1 was only relying on natural circulation and DRC2 were active loops with a 2/3 capacity in natural circulation. Here for the main loops DRC2 active loops using Serpentine Sodium/Air Heat Exchangers and Compensated sodium/sodium dip coolers would be a most cost effective option and the natural circulation capacity will be high enough for the Decay Heat Removal. The complementary system for DHR will be the vault cooling.

• Reactor vessel can have a compact arrangement due to small core diameter and excellent HX properties. However this will be partly balanced by the room needed to accommodate the core feeding pipes and the redan (internal vessel separating cold and hot pool), see the sketch on Figure 2.5. It is likely that the sodium cooled XADS would result in dimensions fairly similar to the LBE-cooled XADS (i.e Reactor Vessel of 6 meter diameter and a total height of 10m).

• As far as technology is concerned, there is no significant need for significant developments. The technology including material/ISI/maintenance cleaning/decontamination of components is already fully available.

- Target :

A wide range of possibilities is offered to the designers. The three target concepts developed for the 80 MWth reactor can be adapted to the Na cooled XADS.

- LBE ANS windowless target
- LBE ANS window target
- LBE FANP window target with external circuit

• Solid target cooled by Na (offers wider possibilities for window material selection and temperature adjustment thanks to high heat exchange coefficients)

It can be considered that the technological and R&D needs are very similar to that of the 80 MWth LBE concept.

- Safety

- Reactor shutdown/reactivity : no big difference is expected compared to the LBE concept
- DHR : For EFR, in case of Category 2 and 3 operating conditions, the primary flow was insured in forced convection with Stand By Power System (STBP : Diesels). The natural convection was only considered for Category 4 events with a primary flow of more than 2% of nominal flow (core ΔP of 5 bars). However, it would have been possible to rely on natural circulation also for Category 2 events (taking into account inter-wrapper flow but this was not accepted by the safety advisors who asked for a STBP on the main pumps). It was considered that the combination of active and passive systems on the DHR loops would lead to the highest reliability of the DHR system. The same principles can be applied to the Na cooled XADS and no problem of Decay Heat removal in natural circulation if the secondary loops are extrapolated from EFR DRC2 loops.
- Radiation protection : slightly less favourable than LBE but very similar compensation with solid shielding
- Verification that interaction between LBE and Na in case of target leakage does not have safety consequences.
- Containment : No Polonium in the primary circuit but address secondary sodium fires (EFR).
- ISI & Repair : The technologies are already available and backed by a large feedback especially on Phénix and Superphénix and associated R&D programme. The design can be optimized to reduce the inspection needs (especially for a small size reactor) and improve the access to the critical areas as that was started in the course of the EFR project.

- The R&D needs

In case of sodium cooled XADS, the coolant technology, primary system, secondary system, Fuel and Component handling systems are already available. The R&D efforts could be concentrated on the specific issues of an ADS reactor i.e. Accelerator, Target and coupling issues. The sodium cooled option is therefore the natural fall-back option in case of difficulties or deadlocks revealed in the development of the LBE cooled reactor technology.

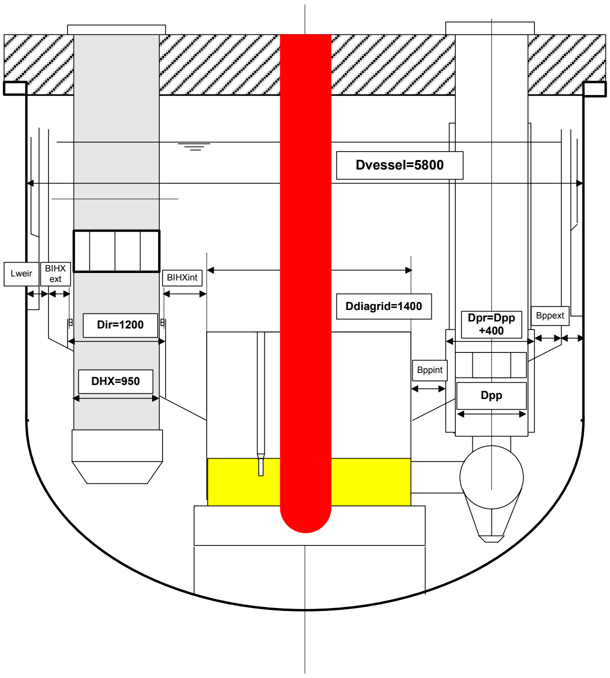


Figure 2.5 : Sketch of a Na cooled XADS

2.5.3 Cost trends of a Na cooled XADS

There are two practical routes for assessing a cost estimate in a pre-design phase i.e without detailed cost enquiries. The first and most reliable one is to derive cost estimate from physical quantities and unit power of various types of components vessels, heat exchangers, pumps, reactor building and to apply typical unit cost. Knowing that no design of a Na-cooled XADS is available, a more reliable route is probably to start from well known cost of larger size reactors and apply laws of economy of scale.

$$\frac{C1}{C0} = \left(\frac{P1}{P0}\right)^k$$

C0, P0: Plant construction cost (overnight) and power rating of a reference reactor

C1 Plant construction cost extrapolation for a P1 power rating reactor

Typical values of the scaling factor k (exponent of the scaling law) for each of the cost categories for nuclear and fossil-fired plants are given in Ref. [3]. For nuclear, these factors are derived from cost models based on LWR technology. There are two sets of factors : one for small size changes, and the other for the large transition implying discontinuities in cost size scaling. The first set results in a cost-weighted average factor of 0.5, compared to 0.64 for the second set.

The Reference Overnight Construction Cost is the EPR cost of 1283 €/KWe installed (2001 economical conditions), as described in Ref. [4].

The Unit cost for the Na cooled technology of similar Power Unit is derived from EFR (1500MWe/3600MWth) economical studies with a ratio EFR/EPR of 1.27.

The cost of a First Of A Kind (FOAK) is taken from EFR studies to 1.3 times the cost of a series reactor.

From this, the cost per KWth of an EFR FOAK of 3600 MWth, would be :

c_0 =1283 * 1.27 * 1.3 * 1500/3600 = 882,6 €/KWth

The reference overnight cost of EFR FOAK is therefore:

C0=c_0*3600 MWth = 3177 M€

Applying a k scaling law would lead to :

k	*0.5*	*0.6*	*0.64*	*0.7*
C1 (M€)	*474*	*324*	*278*	*221*

Considering a best estimate k factor in the range of 0.64 to 0.6, a 80 MWth Na cooled reactor would roughly cost between 280 MEuros and 330 M€ (2001 costs).

This figure is just to provide an order of magnitude for the comparison with a LBE cooled system ADS based on a pre-design. There will be considerable changes for the case of no electricity production which leads to plant simplification and economical savings. On the other hand the higher complexity and overall size of the building due to the presence of the accelerator (Beam transfer line) and associated shielding on top of the reactor should compensate this savings.

Sections 1 and 2 - List of references

[1] Preliminary Design Study of an Experimental Accelerator Driven System – E.C Contract FIKW-CT-2001-0179, Annex 1: Description of work - Rev. 3 – 29th June 2001

[2] Preliminary Engineering Requirements on Accelerators for ADS – B.Giraud et.al., Utilisation and Reliability of High Power Proton-Workshop Proceedings Aix-en-Provence, France 22-24 November 1999 – OECD/NEA (ISBN 92-64-18749-9) - Pages 279 to 292.

[3] Nuclear Energy Cost Data Base US-DOE report N° DOE/NE-0095 – September 1988

[4] “Les coûts de référence de la production d’électricité » Rapport du Ministère de l’Industrie Française – DGEMP/DIDEME – Décembre 2003

3. XADS CONCEPTS EVALUATION

The concept evaluation uses the set of criteria and ranking system established within Deliverable 40. For each criteria, a rating assessment is made, ranging from 1 to 3 points, 3 points implying the highest rating. After each assessment table of sections 3.1, 3.2 and 4, explanations are provided about the rationale of each criteria.

3.1 Review of the Concepts Consistency with the XADS Objectives

3.1.1 Recall of the XADS objectives

The missions, technical specifications and main characteristics assigned to the XADS were defined at the beginning of the Project in Deliverable 1, Ref. [1]. They were widely based on the ETWG Roadmap, Ref. [2] which defined, in 2001, the strategy to be pursued in Europe towards the demonstration of the feasibility of nuclear waste transmutation ; the construction of an XADS being one of the key steps of this demonstration. In this context, the main goal of the PDS-XADS Project was to progress towards the demonstration of the ADS feasibility.

Being now at the end of the PDS-XADS Project, it is of first importance to verify if the technical characteristics of the different XADS concepts designed during the three years period are consistent with the initial XADS objectives.

Those missions and objectives assigned to the XADS plants were divided into three main topics :

- The capability to demonstrate the feasibility of an ADS ;
- The capacity of the XADS to be converted into a XADT (eXperimental Accelerator Driven Transmuter) ;
- The reliability and availability of the plant.

In D40, Ref. [3], those missions and objectives have been translated in terms of technical characteristics. In the present section, the initial characteristics are recalled first and are then compared to the characteristics of the different proposed concepts. This comparison is based on the evaluation grid proposed in deliverable D40. Table 3.1 summarises the assessment.

3.1.1.1 Capability to demonstrate the ADS feasibility

Linked to the objective of ADS feasibility demonstration, technical characteristics were assigned to the XADS. Those technical characteristics are detailed hereafter for the three main components : accelerator, spallation target and sub-critical core.

Accelerator characteristics :

The main accelerator characteristics required in D1 were :

- Proton energy : 600 MeV[1]
- Beam intensity : 6 mA CW on Target (10 mA rated)

[1] feasibility of extrapolation to 800 MeV or 1 GeV should be easily achievable

Spallation module characteristics :

The main target characteristics required in D1 were :

- Power : in the range 2 – 5 MW
- Proton current density: 50 μA/cm² (for the window concept) and 750 μA/cm² (for the windowless concept)
- Target life time : -about one fuel cycle (3 years)
- Window life time : 3 to 6 months

Core characteristics :

The main core characteristics required in were :

- High fast flux level with a goal for the average neutron flux in the order of $1x10^{15}$ n/cm².s and a peak flux of about 2.5 to $3x10^{15}$ n/cm².s
- Minimal core volume : 500 litres
- Volumic power : in the range 80 – 200 W/cm^3
- Maximum plutonium content : 35 %
- Loading factor : 0.5

3.1.1.2 Flexibility/Convertibility

The XADS being a research tool, flexibility in the operating conditions is desirable. This flexibility should :

- allow to perform specific experiments aiming at a better understanding of the ADS physics ;
- take into account the possibility to load the core with fuel containing Minor Actinides (MAs) and demonstrate the capability to burn those MAs.

With those aims in view, variations of the following operating parameters should be taken into consideration for the sub-critical module :

- Capability to operate at different power levels ;
- Capability to operate at different sub-criticality levels ;
- Capability to accept fuel containing MAs (from both the core geometrical arrangement point of view and the safety point of view) and capability to burn those MAs.

3.1.1.3 Reliability and availability

Reliability and availability of the plant are to be considered from two points of view : economy and safety.

The XADS being an experimental reactor, from the economical point of view, the availability of the plant must essentially be sufficient to produce the required results in a reasonable time scale. The requirements in this field are certainly less demanding than for an industrial electricity production plant.

On the other hand, even if the XADS is an experimental reactor, its safety level must be consistent with the international safety standards. Consequently, the requirements that have been put on the XADS in terms of availability in Deliverable 1 are in the same order of magnitude as for critical reactors.

With the designs proposed for the three different XADS, the availability as well as the reliability of the plant are strongly dependent on the accelerator behaviour, particularly proton beam trips and periodic maintenance periods. Consequently, the reliability of the plant was essentially addressed form the accelerator point of view and a maximum number of shut-downs per year of 5 was assigned to the plant[2]. The reactor itself is to be designed for 50 beam-trips a year.

As far as availability is concerned, during the three years period of the PDS-XADS Project no detailed studies were carried out on this topic (only the LBE-cooled concept (80 MW_{th}) includes an annual availability target of at least 70% over plant lifetime).

3.1.2 Assement of the different concepts

3.1.2.1 LBE Cooled 80 MWth

3.1.2.1.1 Accelerator

First of all, it must be pointed out that the design of the proton accelerator was common to both the 80 MWth designs (gas-cooled, LBE-cooled). A LINAC (LInear ACcelerator) design has been chosen with a Continuous Wave (CW) operation mode. The main accelerator characteristics, summarized in Table 3.1.1, fit rather well with the requirements provided in section 3.1.1.

Max. beam intensity	6 mA CW on Target
Proton energy	600 MeV
Beam trip number per year[3]	< 5 for the accelerator design
Beam power stability	± 2%
Beam energy	± 1%
Beam intensity	± 2%,
Beam footprint size	± 10%
Beam footprint on target	- **Rectangular 80x-10 mm, for the LBE-Cooled concept** - **Circular 160 mm diameter, for the gas-cooled concept**

Table 3.1.1 : Accelerator characteristics

However, the technical solution proposed by WP3 still requires further investigations on several topics (Deliverables D61, D62, D63)). More particularly :

- The reliability requirement which has been put on the proton accelerator (less than 5 beam trips of duration higher than 1 second) is very stringent according to the current development of those machines (developments are planned within EUROTRANS on the reliability item : solution based on the fault tolerance principle) ;
- The beam intensity stability of ± 2 % is also rather stringent and is to be further investigated.

Moreover, it is worth mentioning that two other important topics were identified during the course of the Project :

[2] It is worth pointing out that the threshold which defines the limit between beam interruption (stop and re-start of the accelerator) and beam trip (full shut-down of the reactor without immediate restart) is not precisely defined at the present stage. A provisional value of 1 second has been chosen, but it may vary from a few hundreds of milliseconds to one second approximately. Further investigations are necessary to fix this value.

[3] exceeding 1 second

- Regarding the time structure of the proton beam, even if a CW operation mode has been chosen for the LINAC, the beam intensity must be shaped to allow for on-line sub-criticality measurements (beam interruptions of 200 µs approximately). The proposed beam time structure has to be translated in terms of technical solutions and cross assessments have to be done in order to check if the proposed duration of the beam interruption is compatible with a proper measurement of the core sub-criticality ;
- Finally, linked with the safety of the plant, the demonstration of the very high level of reliability of the accelerator has to be done (it is worth mentioning that, in ADS, the proton accelerator is comparable in terms of safety to the control/safety absorber rods of critical reactors).

On the basis of the above rationales and according to the definitions proposed in D40, i.e. to each criteria, a qualified, judgemental rating assessment (a rating ranging from 1 to 3 points: 1 point implying a relative low rating, 3 points implying a relatively high rating), it was decided to consider that *"The technical characteristics of the accelerator are fully coherent with the required values".* **But according to the needs for further R&D and the anticipated difficulty to fill the gap between the current "paper" design and the final one, a value of 2 has been put on the accelerator design of both the LBE- and gas-cooled XADS (80 MW_{th}).**

3.1.2.1.2 Spallation Module

The reference option of the spallation module is the windowless design ; the window design even if studied within the frame of the Project is considered as the back-up solution :

- Windowless option : protons impinge directly on the LBE fluid. Cooling is ensured by forced circulation ;
- Hot-Window option : there is a metallic separation between the vacuum pipe and the target. LBE is in natural circulation. There is a secondary cooling by an organic diathermic fluid.

The spallation module characteristics are summarised in Table 3.1.2. They fit rather well with the XADS requirements.

Proton energy	E = 600 MeV
Max. proton beam intensity	I = 6 mA
Max. target power / beam power	P = 2.6 / 3.6 MW
Target material	Liquid LBE
Max. proton current density (beam window concept)	$\leq$ 50 $\mu A/cm^2$
Average current density of the beam spot scanning (beam windowless concept)	$\approx$ 750 $\mu A/cm^2$
Target life time	About one fuel cycle (3 years)
Beam window life time	3 to 6 months
Max. window temperature	525 ^0C

Table 3.1.2 : Main Technical Characteristics for LBE Targets

However, it was found during the project that the window design is difficult and clearly constitutes a compromise between different phenomena : radiation damage, thermo-mechanics, thermal-hydraulics, material behaviour,… The consequence of this complexity is a rather large uncertainty on the window life time and consequently the frequency of replacement of the bottom part of the proton beam tube guide. The frequency of replacement of this component will strongly affect the XADS availability.

Because the target is one of the highest loaded components, accurate determination of the energy deposition in a XADS target is mandatory for a reliable thermal-hydraulic and thermo-mechanical design. Therefore numerous key issues are to be further investigated for the development of the target unit :

- Neutron generation (number and spectrum) ;
- LBE chemistry and corrosion control (limiting the operating temperature range, limiting the complexity of the circuits since it might enhance the corrosion, requiring a purification system) ;
- Corrosion of the structural materials (particularly the selected window material :T91) and mechanical characterization of materials under irradiation. High fluxes of protons and neutrons of different energies lead to material damage caused by displacements of atoms or by production of helium and hydrogen inside the structures thus leading to a considerable embrittlement of the materials ;
- Development of models and codes ;
- RCC-MR code was used as design rules for the sizing of the target components, but currently there are no irradiation effects included in this code for the reference material T91. Results of experimental investigations on irradiation behaviour of materials have to be evaluated with respect to an implementation in these design rules in order to provide a sound basis for mechanical design of target units;
- Radioactive product inventory (for purification systems and particularly for the windowless option) ;
- Shielding (a very sensitive issue since the proton channel offers an easy way for the particles to leak) ;
- For the windowless Target Unit : characterization and assessment of devices for removal of the spallation vapours released through the free surface; material characterization of a pump shaft in order to limit the energy deposit and to increase the cooling by radiation; free level stability.

Moreover :

- development of new turbulence models or qualification of the existing ones taking into account that the results of the analyses performed are very sensitive to these models;
- development of free surface model in the presence of vacuum space to be implemented in CFD codes and qualification of thermal-hydraulic correlations (heat transfer, pressure drop, etc).

On the basis of the above rationales and according to the definitions proposed in D40, it was decided to consider that *"The technical characteristics of the accelerator are fully coherent with the required values".* **But according to the needs for further R&D and the anticipated difficulty to fill the gap between the current "paper" design and the final one, a value of 1 has been put on the windowless spallation module of the LBE-cooled XADS (80 MW_{th}) and 1 on the window option.**

3.1.2.1.3 Sub-critical core

The sub-critical core of the LBE-XADS, as it has been designed, is fully coherent with the specifications. The ability of such core to meet the requirements is certainly maximized by making reference, where applicable, to the proven solutions of FBR's core and fuel designs.

The natural coolant circulation system which is, during normal operation, assisted by means of controlled gas injection in the riser channels offer however some innovative features which are out of the present knowledge. This circulation system is essential for doubling the flowrates limiting the coolant temperature increase to about 100 °C but offers limited flexibility in terms of power density and hence on transmutation rate capabilities. The wider spacing of the pin lattice helps sustaining natural circulation regimes due to the substantially reduced friction losses, which depend on larger hydraulic diameters.

The moderate fuel power density resulting from the core power choice and the assessed fuel mass has been considered reasonable for a first XADS core operation which is mainly entitled by the primary objective of testing the overall plant performance and, even more, of demonstrating and testing the coupling with the accelerator system, without any exigency of stressing the facility beyond these effective needs.

The duty cycle of the coolant has been set at moderate temperature levels, between 300-400°C. The lower operating temperatures and the higher boiling point of the LBE in comparison with the Sodium cooled FBR result in a higher margin to voiding and hence comparably higher availability for reactivity feedback during fast power/temperature surges occurring in abnormal transients or accidents which could be expected. This moderate temperature is also a prudent choice with respect to the risk of corrosion of structural materials.

The estimated LBE cooled 80MWth core power XADS reactivity variations in representative normal conditions as well as DBC's and DEC's has been analysed to avoid any reactivity excursion. The core multiplication factor for normal operation at full power and BOC is thus set at k=0.984-0.014=0.97, that is the subcriticality margin is -3%, while the required keff <0.95 during refueling implies the need to use neutron absorbing devices.

On the basis of the above rationales and according to the definitions proposed in D40, it was decided to consider that *"The technical characteristics of the sub-critical LBE core are fully coherent with the required values".*

Hence the needs for further R&D being limited, a value of 3 has been put on the sub-critical core of the LBE-cooled XADS (80 MW$_{th}$).

3.1.2.2 Gas-Cooled 80 MWth

3.1.2.2.1 Accelerator

As stated before, the design of the proton accelerator is common to both the LBE-cooled and the gas-cooled concept (80 MW$_{th}$). Thus, the assessment provided in section 3.1.2.1.1 remains valid.

3.1.2.2.2 Spallation Module

LBE was chosen as target material, and most of the work carried out in the XADS design was about LBE targets. Nevertheless, a totally different source was proposed for the gas-cooled XADS, based on a He-cooled solid tungsten target. This alternative has been only briefly described and studied in Deliverable D70, part 2, Ref. [4], but the solid target seems to be particularly well suited for the gas-cooled XADS.

Proton energy	E = 600 MeV
Max. proton beam intensity	I = 6 mA
Max. target power / beam power	P = 2.6 / 3.6 MW
Target material	Liquid LBE
Max. proton current density (beam window concept)	≤ 50 μA/cm^2
Target life time	About one fuel cycle (3 years)
Beam window life time	3 to 6 months
Max. window temperature	525 ^{0}C

Table 3.1.3 : Main Technical Characteristics for LBE Targets (80 MW$_{th}$)

The statement made in 3.1.2.1.2 for the LBE-cooled XADS remains valid : as anticipated at the beginning of the Project, the design of the target is one of the critical issues of the ADS development.

Particularly, the window design is rather difficult and clearly constitutes a compromise between different phenomena : radiation damage, thermo-mechanics, thermal-hydraulics, material behaviour,… The consequence of this complexity is a rather large uncertainty on the window life time and consequently the frequency of replacement of the final part of the proton beam tube guide. The frequency of replacement of this component will strongly affect the XADS availability. The solid target is likely to improve the availability but the design is still too preliminary to establish it.

As a consequence, several further developments were identified for the target module. They are the following :

- neutron generation (number and spectrum) ;
- radiation damage (for T91 and TZM alloys) ;
- radioactive product inventory (for purification systems and particularly for the windowless option) ;
- heat deposition and coolability (for the different windows) ;
- thermal and mechanical analysis (for T91 and TZM alloys) ;
- shielding (a very sensitive issue since the proton channel offers an easy way for the particles to leak) ;
- LBE chemistry and corrosion control : limiting the operating temperature range, limiting the complexity of the circuits since it might enhance the corrosion, requiring a purification system (an alternative to the oxygen control might be looked at in the windowless option).

On the basis of the above rationales and according to the definitions proposed in D40, it was decided to consider that *"The technical characteristics of the accelerator are fully coherent with the required values".* **But according to the needs for further R&D and the anticipated difficulty to fill the gap between the current "paper" design and the final one, a value of 1**

has been put on the liquid spallation module of the gas-cooled XADS (80 MW_{th}) and 1 on the solid spallation module.

3.1.2.2.3 Sub-critical core

The core is cooled by helium at a pressure of 60 bar. Helium has been chosen because it is inert and is consistent with the choice of this gas as a coolant for other advanced reactors such as HTR, which are also currently undergoing development. Technology can therefore be shared with these other projects. Because of the poorer thermal properties of gas when compared with liquid metal coolants a high pressure is required to give adequate cooling properties. The pressure has been limited to 60 bar to prevent operational difficulties that may arise from significantly higher pressures.

Since a primary objective of the XADS project is the demonstration of accelerator driven technology, conservative parameters have been chosen for burnup to ensure reliable fuel performance.

The core is provided with a radial reflector and boron carbide radial shields of two types, all based upon the EFR design. These reduce neutron damage to core components.

Shielding is also provided within the fuel sub-assembly, above and below the core. Above the core the shielding is in the form of steel and boron carbide pins to allow coolant flow through the shield whilst reducing neutron damage to structures above the core.

Compared with the LBE cooled core, there is only a limited amount of bismuth in the target. Consequently polonium production is much lower and there is no need for special means of special shielding to reduce its production.

An initial maximum operating k-eff of 0.97 was chosen for the core. Subsequently this has been reviewed on the basis of the more detailed information on the core performance obtained during the project.

For refuelling it is proposed to remain within an upper limit k-eff of 0.95, which is a level set for storage of fuel outside a reactor. For refuelling it is also necessary to allow for reactivity increases due to refuelling errors, in addition to those errors considered for normal operation. Absorber rods have therefore been implemented at the core periphery, to further reduce reactivity during refuelling, with three of their faces adjacent to fuel S/As in order to get a reasonable reactivity worth. Absorber rods, with a nominal worth of 3500 pcm, have been included in the core design to reduce reactivity whilst refuelling. To ensure that a refuelling k-eff of 0.95 is not exceeded it will be necessary to operate the core at a k-eff of 0.963 to 0.964, depending upon the uncertainties. To allow operation at k-eff = 0.97 a small increase to the worth of the absorber rods will be needed, and should be feasible. The assessment does show that a maximum operating k-eff of approximately 0.97 is realistic for this stage of the project, although further work will be required to fully substantiate this.

For the gas-cooled XADS the cooling of the clad is an important factor because of the relatively poor heat transfer from the clad into the coolant when compared with a liquid metal cooled core. To provide adequate cooling it is necessary to gag the sub-assemblies in four flow groups and to roughen the clad. A preliminary recommendation for the clad roughening is to use rectangular ribs with a height of 150 µm on a pitch of 1.0 to 1.5 mm, based upon experience with the UK Advanced Gas Reactor (AGR). With both gagging and roughening, a clad hot-spot temperature of approximately 570 ˚C is achieved, which shows some margin to the normally accepted clad hot-spot temperature of approximately 700 ˚C for fast reactor cladding material.

On the basis of the above rationales and according to the definitions proposed in D40, it was decided to consider that *"The technical characteristics of the sub-critical Helium core are fully coherent with the required values".*

Hence the needs for further R&D being limited, a value of 3 has been put on the sub-critical core of the Helium-cooled XADS (80 MW_{th}).

3.1.2.3 MYRRHA 50 MWth

3.1.2.3.1 Accelerator

The accelerator for MYRRHA is very similar to the LINAC proposed for the two other concepts. This is a remarkable feature of this accelerator concept : its validity for a very different output energy range: 350 MeV for the smaller-scale XADS require for example nine β = 0.65 elliptical cavities cryomodules; in order to obtain 600 MeV, simply ten more cryomodules have to be added (7 with β = 0.65 and 3 with β = 0.85) and 12 additional (β = 0.85) boost the energy to 1 GeV. The proton intensity for MYRRHA is slightly smaller (5mA) as for the two other concepts.

In consequence, if the principles for the assessment of the MYRRHA proton accelerator are the same than for the other concepts, the significantly lower characteristics associated to this component (350MeV, 5mA rather than 600MeV, 6mA as mentioned in the specifications) leads to a lower quotation **than for the two other concepts : 1 has been put on the MYRRHA LINAC because the design values of the accelerator are out of the range required for the XADS, even if the modularity of the design is very helpful to propose an extrapolated design of this component to higher proton energies.**

3.1.2.3.2 Spallation Module

The spallation module of the MYRRHA concept use a technology which is very similar to the one of the ANSALDO design : LBE used as both target and cooling material, windowless design. The biggest differences lays in two design options :

- Likewise for the accelerator characteristics, the design characteristics of the MYRRHA spallation module are out of the range of the XADS requirements (see Table 1.2.3) ;
- The target cooling loop implantation of the MYRRHA concept is forming a loop around the core within the primary system. Thus, MYRRHA has a very compact core design (158 mm in diameter) while the window or windowless X-ADS has a larger spallation target unit diameter (650 mm for the LBE-XADS and 550 mm for the Helium-XADS).

Proton energy	E = 350 MeV
Max. proton beam intensity	I = 5 mA
Max. target power / beam power	P = 1.4/1.65 MW
Target material	Liquid LBE
Average current density of the beam spot scanning (windowless)	≈ 150 µA/cm²
Target life time	About one fuel cycle (3 years)
Beam window life time	3 to 6 months

Table 3.1.4 : Main Technical Characteristics for the MYRRHA Target

Likewise for the ANSALDO design, the feasibility of the windowless design mainly depends on the practicability to maintain the vacuum in the accelerator tube and to properly confine the gaseous spallation products.

It can be seen in Table 3.1.4 that the MYRRHA spallation module presents characteristics which are significantly lower than the requirements. Moreover, the extrapolability of the current design to the industrial scale seems not obvious. Consequently, the proposed mark is 1.

3.1.2.3.3 Sub-critical core

Due to the objective of conceiving a fast spectrum core, and due to the fact that non-revolutionary options were considered, the neutronic design of the sub-critical core was based on MOX fast reactor fuel technology. Besides the smaller radial sizes, the solid (without central hole) fuel pellets were used in order to simplify fuel production. The initial request was to limit the Pu enrichment to maximum 30% in weight and the maximum linear power to 500 W/cm. Due to the low proton energy chosen (350 MeV), leading to a spallation neutron source length of ca 13 cm (penetration depth of protons), it was also decided to limit the core height to 60 cm. This height is compatible with the purpose of MYRRHA to be an irradiation facility for technological developments.

The triangular type grid has been used for the fuel rod bundle. The relative pitch (a ratio of the distance between the centres of the neighbour rods to a rod diameter) has been set up to 1.305 in order to assure the coolability of the hottest channel at the coolant velocity limited to 2 m/s and the coolant heat up limited to 200 °C.

The reference configuration of the MYRRHA core fulfilling beginning of live (BOL) conditions of a keff close to 0.95 and a thermal power ~50 MW.

This sub-critical core achieves a primary source neutron multiplication factor, ks, of 0.960 (the keff-eigenvalue being 0.9495) yielding, for a 5 mA proton beam, a thermal power of 51.5 MW. An additional 1.43 MW is deposited by the proton beam.

The peak linear power density in the hottest pin amounts to 361 W/cm at BOL, which does not show any overheating problem during some Design Basis Conditions (DBC).

A fast flux (F> 0.75 MeV) level of 10^{15} n/cm^{2}s is reached in the neighbourhood of the spallation target tube, in positions where irradiation devices for MA transmutation and structure material dpa studies can be inserted.

On the basis of the above rationales and according to the definitions proposed in D40, it was decided to consider that *“The technical characteristics of the sub-critical small LBE core are fully coherent with the required values”.*

Hence the needs for further R&D being limited, a value of 3 has been put on the sub-critical core of the MYRRHA (50 MW$_{th}$).

3.1.3 Flexibility of the XADS and its convertibility from XADS to XADT

Transmutation of both minor actinides (MA) and LLFP has been studied in the three cores (but in a non-consistent way) and show different results.

3.1.3.1 LBE-Cooled 80 MWth XADS

The capacity of the “XADS preliminary core” to irradiate radioactive waste in the form of three special dedicated elements with design proposed by Argonne National Laboratory, with quite different characteristics from a fuel element of the XADS core in terms of nuclides and their concentrations (metallic fuel with a significant amount of Minor Actinides and Tc-99 as LLFP, inserted in a zirconium matrix).

The impact of these fuel elements on the neighbouring pins and sub-assemblies has been found acceptable with a capability to demonstrate the technology of these fuels. However, due to the nature of the fuel being used, no transmutation capability can be verified with these experiments.

Other studies with a core fully loaded with MA (this time U-free fuel with MgO matrix) have demonstrated there is a good compromise between core and transmutation performances for a XADT core having a power ranging between 200 MWth and 400 MWth.

Core with lower power size allows to reach values of transmutation rate high enough and to meet the requirement to be subcritical by design without need of absorbers mechanisms to cope with reactivity increase.

Core with larger power size permits to reach values optimum for transmutation and neutronic performance, but it requires to carry out refuelling strategies (reshuffling or exploiting movable absorber assemblies strategies) to cope with K-eff increase during the cycle.

It is worth underlining that these analyses have preliminary investigated only the neutronic aspects of a core functioning as a transmuter.

An exhaustive study should take into account other aspects related to safety and economics as well as problems deriving from manufacturing and reprocessing processes of this kind of fuels.

On this basis, a precise assessment for those issues but given the present stage of the studies and according to the needs for further R&D, following decisions were taken:

- **the core is flexible in terms of power level since the accelerator is designed to operate at different power levels and a value of 3 has been set up for that,**
- **the core, with its absorbers, is flexible in terms of sub-criticality level and a value of 3 has been set up for that,**
- **the XADS is able to be loaded with MA fuel but with an Uranium support. Since the demonstration is not fully representative of what is planned in transmuter, and also the flux level is not suffiently high, a value of 1 has been put on the demonstration of the irradiation capability,**
- **The demonstration of the capability to burn a significant amount of MAs requires important system modifications and an increase of the power level. A value of 1 has been put on the demonstration of the capability to burn MAs, even if the 80 MWth XADS shows a good transmutation rate (about 44 kg/TWh$_{th}$ for the first cycle and ~30 kg/TWh$_{th}$ for the tenth cycle).**

3.1.3.2 Gas-Cooled 80 MWth XADS

Actinide transmutation can be demonstrated in the XADS core. However the masses capable of being transmuted in this facility are small but inserting special transmutation assemblies into the XADS may be valuable for technology demonstration.

For the technetium transmutation, it was found that the build-up in the driver fuel is larger than the transmutation in the special assemblies.

Large-scale transmutation will require dedicated cores with far higher density of nuclei in the fuel. In addition, neutron fluence should be significantly higher in order to achieve high transmutation efficiencies. The good compromise between transmutation and core performances of the Helium cooled ADT (pending further detailed studies) seems to be a core having a power between 200 MWth and 400 MWth.
Modifying the core for transmutation purposes will imply significant changes on the residual power which will increase by 50%.
Without system modification, a safe operation of the He-XADS will require a reduction of the specific power which will require an overall reduction of the power plant down to around 50 MWth from the 80 MWth initial value.
To remain at the same constant power of 80 MWth, an increase of the DHR loops capacity will be required. This will have consequences on the size of the components, heat exchangers and circulator for the forced circulation operation that should not lead to a big change in the design of the SCS (oversized components still integrated within larger/longer Reactor Vessel nozzles). Consequences for the natural circulation operation will deserve further assessments.

It appears that it is rather difficult to achieve a large heavy nuclide density when Minor Actinides are incorporated significantly in the fuel. Only a high MA fuel density could allow a small core with a net MA consumption and acceptable safety features. The current preliminary study has demonstrated that there is a good compromise between transmutation and core performance of the Helium cooled ADT (pending further detailed studies) for a core having a power between 200 MWth and 400 MWth.

At the present stage of the studies and according to the needs for further R&D, an approximate assessment for those issues can be given:

- **the core is flexible in terms of power level since the accelerator is designed to operate at different power level and a value of 3 has been set up for that,**
- **the core, with its absorbers, is flexible in terms of sub-criticality level and a value of 3 has been set up for that,**
- **the XADS is able to be loaded with U-free MA fuel.The demonstration is more representative than for the LBE-XADS but the flux level is not sufficiently high here also and hence a value of 1 has been put on the demonstration of the irradiation capability,**
- **the demonstration of the capability to burn a significant amount of MAs requires significant system modifications and an increase of the power level. A value of 1 has been put on the demonstration of the capability to burn MAs.**

3.1.3.3 MYRRHA 50 MWth

The MYRRHA small-scale core has been designed to have a much larger power density (peak linear power not exceeding 500 W/cm) in order to achieve the efficient transmutation capability even for limited number of MA pins or assemblies.

A fast flux (F> 0.75 MeV) level of 10^{15} n/cm^{2}s is reached in the neighbourhood of the spallation target tube, in positions where irradiation devices for MA transmutation and structure material dpa studies can be inserted. Hence, the MYRRHA performance assessment as partially MA loaded core, would lead to realistic technological feasibility demonstration of ADS as well as of MA transmutation at reasonable scale (~1 kg of MA burned/18 kg of Am-U_{free} fuel loaded).

The technical demonstration of the feasibility of burning large transmutation capabilities has not been studied for this system and remains an extrapolation to larger plant sizes of the plant . The fact that the MYRRHA system is smaller in size and exhibits features suitable only for small plants makes it less attractive for larger plant size.

On this basis, it is rather difficult to provide a precise assessment for those issues but at the present stage of the studies and according to the needs for further R&D, following status can be given:

- **the core is flexible in terms of power level since the accelerator is designed to operate at different power levels and a value of 3 has been set up for that,**
- **the core, without absorbers, is not so flexible in terms of sub-criticality level and a value of 1 has been set up for that,**
- **the XADS is able to be loaded with MA containing fuel with high flux locations. A value of 3 has been put on the demonstration of the irradiation capability,**
- **the demonstration of the capability to burn a significant amount of MAs requires significant system modifications and an increase of the power level. A value of 1 has been put on the demonstration of the capability to burn MAs.**

3.1.4 Relability and availability

The reliability of the XADS is strongly dependent on the accelerator reliability. That is the reason why a specific requirement has been put on the number of beam trips accepted for the accelerator (5 beam trips).

As far as the availability of the plant is concerned, it appears that it is dependent on the availability of two main components which require rather frequent maintenance periods : the accelerator and the spallation target.

However, during the three year period of the PDS-XADS Project no detailed studies were carried out on the reliability and availability topics (only the LBE-cooled concept (80 MW_{th}) includes an annual availability target of at least 70% over plant lifetime).

On this basis, it is rather difficult to provide a precise assessment for those issues. At the present stage of the ADS development, the proposed solutions are coherent with the required values. **However, according to the needs for further R&D and the anticipated difficulty to fill the gap between the current “paper” design and the final one, a value of 2 has been put on both reliability and availability topics of the three concepts.**

Table 3.-1 Concept Assessment Table of the consistency with XADS objectives

(Rationale given in the next pages - Data list corresponds to the averaged rating as judged by the two authors of this chapter and endorsed by the WP1 team).

Criteria		***Concept***		
		80 MW LBE-cooled XADS	**80 MW He-cooled XADS**	**50 MW LBE-cooled XADS (MYRRHA)**
Consistency with the XADS technical objectives				
Consistency with the XADS objectives for accelerator characteristics	***CXADS1***	***2***	***2***	***1***
Consistency with the XADS objectives for spallation module characteristics	***CXADS2***	***1 (windowless concept)*** ***1 (window concept)***	***1 (LBE target)*** ***1 (Solid target)***	***1***
Consistency with the XADS objectives for sub-critical module characteristics	***CXADS3***	***3***	***3***	***3***
Flexibility of the XADS– Convertibility from XADS to XADT				
Flexibility in terms of power level	***FC1***	***3***	***3***	***3***
Flexibility in terms of sub-criticality level	***FC2***	***3***	***3***	***1***
Capability to be loaded with MA containing fuel	***FC3***	***1***	***1***	***3***
Demonstration of the capability to burn MAs	***FC4***	***1***	***1***	***1***
Reliability and availability*				
Reliability** : Number of beam trips	***RA1***	***2***	***2***	***2***
Availability** : periodic maintenance	***RA2***	***2***	***2***	***2***
Total Points :		***18***	***18***	**17**
Max/Min/Delta Points		***27/9/18***	***27/9/18***	***27/9/18***
Relative Percentage	***(Mark-Min)/Delta***	***50 %***	***50 %***	***45 %***

* Ref. [3] (split in two criteria instead of a single criteria in D40)

** Does not includes the spallation module assessment.

RATIONALE OF RATING SYSTEM ON CONSISTENCY WITH XADS OBJECTIVES (from D40, Ref. [3]):

Consistency with the XADS technical objectives (CXADS) :

Principle: the XADS design must be consistent with the XADS technical objectives defined in the ETWG Roadmap and in Deliverable 1 in terms of :

- *Accelerator characteristics*
- *Spallation module characteristics (window/windowless)*
- *Sub-critical module characteristics*

Technical Qualitative Criteria	Rationale
Consistency with the XADS objectives for accelerator characteristics	The technical characteristics of the accelerator must be coherent with the required values, defined in DEL 1
Consistency with the XADS objectives for spallation module characteristics	The technical characteristics of the spallation module must be coherent with the required values, defined in DEL 1
Consistency with the XADS objectives for sub-critical module characteristics	The technical characteristics of the sub-critical core must be coherent with the required values, defined in DEL 1

Consistency with the XADS objectives for accelerator characteristics :	***CXADS1***
Some technical characteristics are not coherent with the required values and the gap is large	**1**
Some technical characteristics are not coherent with the required values but the gap is reasonable	**2**
The technical characteristics of the accelerator are fully coherent with the required values	**3**

Consistency with the XADS objectives for spallation module characteristics :	***CXADS2***
Some technical characteristics are not coherent with the required values and the gap is large	**1**
Some technical characteristics are not coherent with the required values but the gap is reasonable	**2**
The technical characteristics of the accelerator are fully coherent with the required values	**3**

Consistency with the XADS objectives for sub-critical module characteristics :	***CXADS3***
Some technical characteristics are not coherent with the required values and the gap is large	**1**
Some technical characteristics are not coherent with the required values but the gap is reasonable	**2**
The technical characteristics of the accelerator are fully coherent with the required values	**3**

<u>CONSISTENCY WITH XADS OBJECTIVES :</u>

Flexibility – Convertibility from XADS to XADT (FC) :

Principle: The XADS being a research tool, flexibility in the operating conditions is desirable. Moreover, it must show capabilities to move from technology demonstration (XADS) to transmutation demonstration (XADT). Thus, the XADS must have a certain level of flexibility in terms of sub-criticality level and fuel technology (with and without minor actinides). This flexibility should :

- *Allow to perform specific experiments aiming at a better understanding of the ADS physics ;*
- *Take into the consideration the possibility to load the core with fuel containing Minor Actinides (MAs) and to burn those MAs.*

Technical Qualitative Criteria	Rationale
Flexibility in terms of power level	From the scientific point of view as well as from the safety point of view, the XADS must be able to start operation at low power and to progressively increase the power level to its maximum
Flexibility in terms of sub-criticality level	The XADS must be able to operate at different sub-criticality levels in order to perform measurements of the physical characteristics and thus gain knowledge in the field of ADS behaviour
Capability to be loaded with MA containing fuel	The core must be preferably able to accept MAs. This criteria increases with the quantity of MAs that can be accepted by the core
Demonstration of the capability to burn MAs	The MAs loaded in the core must be burnt in the XADS. The number of MA isotopes which can be burnt is assessed (even for small quantities)

Flexibility in terms of power level :	***FC1***
The concept can only be operated at the nominal power level	**1**
The concept can be operated at intermediate power levels	**2**
The concept can be operated from very low power up to the nominal power level	**3**

Flexibility in terms of sub-criticality level :	***FC2***
The concept can only be operated at the nominal sub-criticality level	**1**
The concept can only be operated at sub-criticality levels slightly different to the nominal one	**2**
The concept can only be operated at sub-criticality levels significantly different to the nominal one	**3**

Capability to be loaded with MA loaded fuel :	***FC3***
No MAs can be loaded in the core	**1**
A maximum of one pin can be loaded with fuel containing MAs	**2**
A maximum of one sub-assembly can be loaded with fuel containing MAs	**3**
A large part of the core can be loaded with fuel containing MAs	**4**

Demonstration of the capability to burn MAs :	***FC4***
No MAs can be burnt in the core	**1**
A small number of MA isotopes can be burnt	**2**
A large number of MA isotopes can be burnt	**3**

CONSISTENCY WITH XADS OBJECTIVES :

Reliability/Availability (RA) :

Principle: The main technical characteristics assigned to the XADS deal with availability :even if the XADS is an experimental reactor, its safety level must be consistent with the international safety standards. Consequently, the requirement that has been put on the XADS for the maximum number of shut-downs per year is in the same order of magnitude as critical reactors: 5.

Technical Qualitative Criteria	Rationale
Availability	The maximum number of shut-downs per year allowed for the XADS is 5

Availability :	***RA1***
The number of beam trips anticipated is significantly higher than 5 and this value can not be reduced provided further developments	**1**
The number of beam trips anticipated is close to 5 or it is higher than 5 but this value can be reduced	**2**
The number of beam trips anticipated is smaller or equal to 5	**3**

Note: RA1 was renamed as reliability in the Table 3.1 and a more general plant availability criteria for periodic maintenance has been added (***RA2***).

Section 3.1 - List of References

[1] P.Richard and Al.: Deliverable 1 “PDS-XADS : Technical Specifications, Missions of XADS, Recommandations for the Main Characteristics” DEL02/001 rev.1 CEA

[2] ETWG “A European Roadmap for Developing ADS for Nuclear Waste Incineration”, The European Technical Working Group on ADS – ENEA April 2001

[3] P. Richard and Al.: Deliverable 40 “Definition of Methodology and Criteria for the XADS Concept Comparison”; DEL04/040 CEA

[4] D. Coors and Al.: Deliverable 70 “Target Unit Technical Evaluation and preliminary design”; DEL04/070 FANP-GmbH

3.2 Safety Evaluation

The safety objectives common to all the approaches for future nuclear plants are

- to protect individuals, society and the environment from harm by establishing and maintaining in nuclear installations effective defences against radiological hazards ;
- to ensure that in all operational states radiation exposure within the installation is kept below prescribed targets and as low as reasonably achievable (ALARA principle) ;
- to take all reasonably practicable measures to prevent accidents in nuclear installations and to mitigate their consequences should they occur.

The general safety approach adopted within the PDS-XADS Project is based on the European Utility Rules (EUR) and EFR defence-in-depth strategy approaches developed for LWR and LMFBR by European countries ensuring the safety of the public and for protecting the environment. It allows to achieve the same level of safety as for future critical plants.

Design aspects important for the safety evaluation of the different concepts considered in the PDS-XADS project were:

- Control of reactivity and power
- Decay heat removal
- Confinement of radioactive products
- Radiation protection of the personnel
- Transient response – Protected events
- Transient response – Unprotected events
- Safety design bases
- Reliability targets (safety systems)
- Inspectability and maintainability of safety equipment
- System qualification
- Severe accident management

Results of the evaluation of the various aspects for the different plant designs considered in the PDS-XADS project will be summarised hereafter and conclusions related to the XADS designs with different coolants will be drawn.

3.2.1 Control of reactivity and power of the 80 MW XADS

The control of the level of reactivity and control of the power level of sub-critical systems are two distinctly different functions that are not related to each other. The level of sub-criticality is a design specific characteristic of the reactor. Therefore, these two functions should be considered independently, since the associated functional requirements and involved systems are different.

It is known, that for a critical core, heavily loaded with minor actinides, a decrease in the effective delayed neutron fraction β_{eff} has the distinct disadvantage that relatively small reactivity increases can lead to prompt criticality situations. This concern is alleviated in sub-critical systems since the delayed neutron fraction β_{eff} (β_{eff} ~ 350 pcm in typical fast reactors) no longer determines the margin to prompt criticality. For sub-critical systems, the parameter of concern is the margin to criticality (i.e. ~ (k_eff - 1)), or indirectly the level of sub-criticality (i.e.; keff), which now provides a "reactivity safety margin" of ~ 3000 pcm, assuming a keff ~ 0.97.

Reactivity coefficients play a minor role during transient conditions in these systems since the core power level is largely determined by the external neutron source strength and the margin to criticality. Reactivity feedback effects themselves are only of major concern during plant conditions in which very large core temperature changes are to be encountered, namely during plant shut-down or plant start-up procedures.

For accelerator driven systems, whose cores are heavily loaded with minor actinides, the major safety concerns are thus the identification of events that could potentially lead to very large reactivity insertion taking the sub-critical systems close to criticality.

An additional feature particular to sub-critical systems is the response of the system to the insertion of control rods while the external neutron source is active. Exceedingly large negative reactivities would be required (> $ 30, i.e more than 10 000 pcm the dollar being defined by the ratio of reactivity to the proportion of delayed neutron equal to 1) to substantially decrease the power level of untripped (i.e. with the accelerator continuing to supply a proton current) sub-critical systems. Active control rods are therefore not considered effective means in controlling the power level of sub-critical systems. The thermal power generated in the core of sub-critical systems is solely controlled through the control of the accelerator operation.

Reactivity Control Function :

In a critical reactor system, the level of reactivity of the core is continuously maintained exactly at criticality by either moving control rods or changing the concentration of burnable poison dissolved in the coolant (i.e.; boronated water in PWRs).

In contrast, the level of reactivity of the core is continuously changing during the operation of sub-critical systems (due to the burnup of fuel). This fact necessitates continuous monitoring of the prevailing level of sub-criticality since the only method of direct control (intervention) is changing the source strength of the external neutron source (i.e.; beam intensity).

Other effects of reactivity insertions into the core (quickly or slowly) that significantly change the level of sub-criticality need to be carefully monitored and controlled in order to assure that the configuration will never approach or reach the level of criticality. Consideration must be thus given to those functions that minimise the possibility of events which involve the insertion of large reactivity into the core.

The following are the major functions to control the reactivity level:

- sufficient subcriticality margin,
- subcriticality measurement,
- prevention of large reactivity insertions (e.g.; core compaction, oil or water entering the primary system, etc.).

Sub-criticality margin:

Sub-criticality is directly related to the core design and not directly related to any safety system. Sub-criticality is an inherent characteristic of the core configuration and is independent of the external neutron source. The core is designed with sufficient subcriticality margin to ensure subcriticality under any operating mode, including incidental and accidental conditions. A larger subcriticality is advisable during refuelling.

To fix the nominal level of sub-criticality, all design basis operating conditions and design extension conditions leading to a reactivity increase (except hypothetical accidents which have been analysed independently) must be determined. The slow and the quick increases of reactivity must be distinguished and adequate means and procedures for intervention must be assessed.

More specifically, the following situations have to be taken into account:

- Reactivity change due to fuel burn-up,
- Reactivity change between the nominal power operating state and the cold shutdown state for refuelling,
- Reactivity effects related to the target (target removal, target flooding or leakage),
- Coolant Voiding,
- Moderator ingress for the gas cooled concept,
- Fuel assemblies loading error,
- Core compaction,
- Leakages of oil or water into the primary loops.

A larger subcriticality margin during refuelling leads to the use of dedicated absorber devices during the fuel handling mode, according to the nominal sub-criticality level. The design of the absorber devices are unlikely to be similar to those used in critical reactors. The following malfunction events have been taken into consideration:

- Absorber device withdrawal if feasible from a design point of view (for gas-cooled XADS).
- Replacement of an absorber device by a fuel subassembly (for LBE-cooled XADS).
- Core geometry modification, for example core compaction due to earthquake.
- Local core melting.

The chosen value of the nominal level of sub-criticality at hot full power (HFP) under BOC conditions, namely keff ~ 0.97, is actually determined for both the LBE-cooled and the He-cooled 80 MW XADS design by an appropriate weighting of each of the following seven issues:

1. the reactivity margin required to take the sub-critical system from the nominal plant state to ambient temperatures and pressures,
2. the additional reactivity margin required to take the sub-critical system to ambient temperatures and pressures following abnormal or accidental occurrences causing positive reactivity insertions,
3. the power decay characteristics of the sub-critical system after a beam trip,
4. the transient response of the sub-critical system to unprotected transients,
5. the subcriticality system response to potential accidental sudden reactivity insertions,
6. the proton beam intensity requirements at BOC and EOC nominal plant states,
7. the effect of the localized neutron source on the core power shape profile.

The first issue, namely reactivity margin required to take the sub-critical system from the nominal operating plant state (HFP: Hot Full Power) to ambient temperatures (CZP: Cold Zero Power), has been assessed to be < 1500 pcm that is added in reactivity due to decreasing core temperatures when taking the sub-critical system from the nominal BOC power state to ambient temperatures. The level of sub-criticality changes thus from keff = 0.97 to 0.985, i.e. ~ 1500 pcm away from criticality. This margin of 1500 pcm away from criticality was judged sufficient to allow the safe operation of the sub-critical LBE-cooled and He-cooled systems.

The second issue, namely the expectedly higher (than for first issue) reactivity margin required to take the sub-critical system from the nominal operating plant state (HFP) to ambient temperatures (CZP) following abnormal or accident occurrences with associated positive reactivity insertion other than from system cool-down (e.g. target flooding in the LBE cooled concept), has been assessed to be in the range from 1500 to 2000 pcm (most of which is due to decreasing core temperatures when taking the sub-critical system from the nominal BOC power state to ambient temperatures). The level of sub-criticality changes thus from keff = 0.97 to 0.99, i.e. ~ 1000 pcm away from criticality. This margin of 1000 pcm away from criticality was judged sufficient to allow the safe operation of the sub-critical LBE-cooled and He-cooled systems.

The third issue, power decay characteristics of the sub-critical system after beam trip, addresses the issue that the decay of power after beam trip is not as sudden in sub-critical, accelerator driven systems as in critical reactors after insertions of large amounts of negative reactivity in form of control rods. The time response of the decay of the power level of sub-critical system is relatively slow for low levels of sub-criticality (i.e., keff > 0.985). For systems with keff ~ 0.95 the drop in power level after a beam trip approaches the time response of critical systems. An operating level of sub-criticality of ~ 0.97 represents thus an appropriate compromise.

The fourth issue, the transient response of sub-critical systems during unprotected transients is known to be significantly different from the transient response of critical systems. A high level of sub-criticality (i.e. keff ~ 0.95) allows only a relatively small decrease from the nominal power level due to the negative reactivity feedback effects expected during most transient conditions, whereas a system with a low level of sub-criticality (i.e. keff ~ 0.99) leads to a much larger decrease in power level due to negative reactivity feedback effects.

For unprotected transient conditions during which negative reactivity feedback effects are normally counted on to decrease the power level as much as possible, a low level of sub-criticality (k-eff > 0.985) is clearly more advantageous than a high level (keff ~ 0.95).

Clearly a critical core configuration exhibits the optimal response under unprotected transient conditions since the decrease in power level is largest with negative reactivity feedbacks. The choice of keff ~ 0.97 seems an acceptable compromise, being aware that sub-critical systems in general are challenged much more severely during unprotected transient conditions than similar critical systems.

The fifth issue addresses large reactivity insertions that are conceivable even though they are considered of extremely low probability of occurrence, such as for example the sudden loss of core geometry (i.e. core compaction due to earthquake), ingress of large quantities of steam in the case of the He-cooled XADS, or vaporized oil into the primary system thereby voiding the core region in case of the 80 MW LBE-cooled XADS, target related reactivity effects, etc.. Each of these issues have been assessed in detail for each concept, and the largest, sudden reactivity insertion conceivable into either the 80 MW LBE-cooled or the He-cooled XADS concepts was judged not to exceed 2000 pcm, representing an upper bound. This assured that, with a margin away from criticality of ~ 3000 pcm, the sub-critical system would remain sub-critical by about 1000 pcm (i.e., keff = 0.97 + 0.2 ~ 0.99). The choice of keff ~ 0.97 seems therefore to be appropriate from the potential sudden reactivity insertion point of view.

The sixth issue, namely proton beam intensity requirements at BOC and allowance for compensation of reactivity changes due to burn-up (EOC) is indirectly proportional to keff. A high level of sub-criticality (low keff) requires a larger proton beam intensity which is economically disadvantageous. A relatively large keff close to unity is thus more desirable from this point of view.

Moreover the amount of energy deposited in the target is directly proportional to the proton beam intensity; so are the technical issues related to adequately remove it from the target itself. Again a relatively large keff is more desirable.

Current technological limitations on achievable proton beam intensity basically fix the sustainable level of sub-criticality under EOC condition. An upper limit of ~ 5.6 mA proton beam intensity limits the minimum sustainable keff to ~ 0.93 to 0.94 and accordingly the attainable EOC burnup for the 80 MW XADS design. The corresponding maximum power deposited in the target is ~ 3 MW. Since the burnup itself consumes ~ 4000 pcm of reactivity, this places keff under BOC conditions to around 0.97, quite consistent with the other consideration that need to be taken into account.

The seventh issue is associated with the influence of the external neutron source on the core power distribution. A high level of sub-criticality requires a high intensity neutron source which adversely affects the neutron flux distribution. A large source strength (or high beam intensity) leads to a more localized, peak shaped power distribution which can be compensated applying a multi-zone fuel enrichment scheme to minimize temperature hot spots. A lower level of sub-criticality with the correspondingly lower source strength would thus appear to be more favourable from the power profiling point of view. A keff ~ 0.97 seems to represent an appropriate compromise since the power profile in both LBE-cooled and He-cooled XADS designs are acceptable once a multi-zone fuel enrichment scheme has been adopted.

For refuelling it becomes necessary to establish smaller values of the criticality. For this purpose absorber devices are moved from the periphery into the active region of the core zone.

The chosen level of sub-criticality for the LBE-cooled 80 MW XADS of keff ~ 0.97 at HFP and BOC conditions is judged to be very close to the optimal operating reactivity level when appropriately weighting all of the above issues.

After deciding on the appropriate level of sub-criticality, the most important safety challenge is a reliable measurement of the sub-criticality level during the operation of the plant.

Reactivity Coefficient Issues:

The analyses performed showed that reactivity coefficients do not play a significant role in the dynamic response during protected or unprotected transients of the XADS system while the system is at hot full power (HFP). The reason for this is that the reactivity changes due to temperature feedbacks at HFP are small compared to the margin to criticality, (or the level of sub-criticality), especially for keff < 0.97.

Reactivity coefficients only gain in importance when keff > 0.98 since then the dynamic response of the sub-critical system approaches that of critical systems.

However, for ADS designs without active control rod systems, reactivity coefficients do play a very dominant role during the plant shut-down and the plant start-up procedure. The reactivity coefficients alone determine the decrease in the level of sub-criticality when the sub-critical assembly changes from the hot full power (HFP) operating condition to the cold zero power stand-by condition (CZP). All reactivity coefficients must then be known to a high degree of certainty in order to assure that the sub-critical system does not reach criticality during shut-down to ambient inadvertently, especially under BOC conditions when the level of sub-criticality is still relatively low, i.e. at the beginning of the cycle and hot full power, keff ~ 0.97. This issue is of particular concern when introducing minor actinide fuels (MA-fuels) in large quantities, since it is to be expected that the reactivity coefficients associated with these fuels are less well predictable (due to significant uncertainties in the nuclear cross-sections) than the reactivity coefficients associated with the well-known MOX fuels.

For both LBE-cooled and He-cooled MOX-fuelled XADS designs, about 1500 pcm of positive reactivity are expected to be added into the system when taking the plant from HFP conditions to ambient, allowing a margin of about 1500 pcm to criticality. Under EOC conditions when keff is relatively low, namely, at the end of the cycle and hot full power, keff_EOC_HFP ~ 0.94, a much larger margin to criticality is available when taking the plant to ambient temperatures.

Subcriticality Measurement:

The level of subcriticality, or margin to criticality, is a very important safety characteristic of sub-critical systems. The proposed measurement techniques, as developed and implemented in the MUSE experiments, seem to provide the capability that the level of sub-criticality and changes in reactivity can be reliably measured within acceptable uncertainty. Further experimental validation of the proposed measurement techniques under actual ADS conditions is however strongly recommended.

Ability to Shut Down the Reactor:

Shutdown of the reactor implies the reliable shut-down of the proton beam.

Reactor shutdown (beam trip) is clearly a critical function whose fulfilment must be ensured with the highest degree of reliability, and an appropriate design of the I&C system has to assure a high degree of redundancy and diversity for this function.

Proton beam shut-off is currently planned as consequence of the following initiating events:

- high reactor power (high neutron flux), for both reactor designs;
- high average outlet core temperature, for both reactor designs;
- high secondary system oil temperature (LBE-cooled design);
- low secondary system oil inventory (LBE-cooled design);
- low/high primary system coolant pressure (gas-cooled design);
- low primary coolant mass flow rate (gas-cooled design);
- pump rundown of primary coolant blower (gas-cooled system);
- target unit malfunctions (both LBE-cooled and gas-cooled design).

Other possible accelerator trip signals may be included in this list.

Alternative methods of stopping the proton beam from impinging on the target are conceivable, such as diverting the proton beam towards a barrier where the protons could be absorbed without causing any further effects.

3.2.1.1 Control of reactivity and power of the 80 MW LBE-cooled XADS

In the LBE-cooled 80 MW –ANSALDO XADS design, the level of subcriticality has been selected based primarily on the reactivity effects associated to normal, abnormal and accident conditions (issues no. 1 and 2 in section 3.2.1) and on accelerator performance/cost and target cooling related considerations (issue no. 6 in section 3.2.1). The selected keff value is obtained by acting on fuel enrichment and the number of fuel sub-assemblies loaded to the core configuration. During refuelling, absorber devices acting as safety rods in critical reactors are located at the periphery of the fissile core region assuring a level of sub-criticality below 0.95. The level of reactivity of the core will be monitored by appropriate instrumentation during all phases of plant operation, including the core loading procedure.

After moving the absorber devices from the core configuration to their operating position, the level of sub-criticality of the core configuration will increase but will not be higher than 0.986 under cold, zero power conditions.

As the primary system is heated to operating temperatures, and the power level of the core rises to the operating power level of 80 MW, the level of sub-criticality of the assembly will gradually increase from keff ~ 0.986 towards 0.97 because of negative temperature reactivity feedbacks. Under full power conditions, the final level of sub-criticality of 0.97 will be attained at the beginning of operating cycle conditions (BOC).

During normal operation of the plant the level of sub-criticality will gradually decrease from 0.97 to ~ 0.94 due to burn-up effects of the core. This decrease in core reactivity must be compensated by an increasing accelerator proton current to maintain the operating power level of 80 MW.

During transient conditions, changing core temperatures will impose various reactivity effects. The sum of these reactivity effects under most severe conditions are however limited to ~ +/- 1500 pcm, assuring that the core assembly will not reach levels of keff larger than 0.99. Extremely unlikely events of potentially sudden, large reactivity insertions (i.e. earthquake induced core compaction) will not induce core disruption in the sub-critical assembly as long as the LBE-cooled system remains sub-critical. Reactivity insertions not larger than 8$ (about 2900 pcm) will not challenge the integrity of the system. The detailed response of the LBE-cooled XADS system to various different plant transient initiators will be discussed in more details in subsequent sections.

Shutting down the plant from full-power, hot operating conditions to ambient temperatures will insert a maximum of + 1500 pcm into the core, assuring a keff < 0.99 under BOC conditions. As burn-up proceeds, the level of sub-criticality of the system will decrease, thereby increasing the margin to criticality should shut-down become necessary.

After shutdown to cold conditions (~ 200 °C) the absorber devices will be moved to the periphery of the fissile core region during maintenance and refuelling conditions. This will increase the level of sub-criticality when reactivity goes from 0.985 to less than 0.95.

The power level of the core will be controlled and maintained by the proton current supplied by the accelerator system. The sub-critical core power response to changes in proton current will be instantaneous. Shutting down the proton current will lead to a prompt shut-down of the sub-critical system, even though the power response of sub-critical cores to shut-down conditions are known to be somewhat delayed in time in comparison to the prompt shut-down characteristics of critical cores.

In the LBE-cooled XADS the capability of an insertion of ~1000 pcm of negative reactivity is foreseen by dropping few solid absorbers located inside the target down into the active core region on demand as a kind of accident management measure. This system provides an additional means of re-establishing a subcriticality margin of the system in case of unforeseen conditions.

3.2.1.2 Control of reactivity and power of the 80 MW He-cooled XADS

The control of reactivity and power of the He-cooled XADS system will be very similar in nature to the control of the LBE-cooled XADS system.

In the He-cooled 80 MW – FRAMATOME / NNC XADS design, the level of initial subcriticality will be limited by the level of fuel enrichment and the number of fuel sub-assemblies loaded to the core configuration. During refuelling procedures the absorber devices are located inside the core configuration assuring a level of sub-criticality below 0.95. The level of reactivity of the core will be monitored by appropriate instrumentation during all phases of plant operation, including the core loading procedure.

After moving the absorber devices from the core configuration to their operating position, the level of sub-criticality of the core configuration will increase but will not be higher than 0.986 under cold, zero power conditions.

As the primary system is heated to operating temperatures, and the power level of the core rises to the operating power level of 80 MW, the level of sub-criticality of the assembly will gradually decrease from 0.986 towards 0.97 because of negative temperature reactivity feedbacks. Under full power conditions, the final level of sub-criticality of 0.97 will be attained for the beginning of operating cycle conditions (BOC).

During normal operation of the plant the level of sub-criticality will gradually decrease from 0.97 to ~ 0.94 due to burn-up effects of the core. This decrease in core reactivity must be compensated by an increasing accelerator proton current to maintain the operating power level of 80 MW.

During transient conditions, changing core temperatures will impose various reactivity effects that are somewhat different from the reactivity effects in the LBE-cooled system. The sum of these reactivity effects under most severe conditions are however limited to ~ +/- 1600 pcm (very similar to the LBE-cooled system), assuring that the core assembly will not reach levels of sub-criticality larger than 0.99. Extremely unlikely events of potentially sudden, large reactivity insertions (i.e. earthquake induced core compaction) will not induce core disruption in the sub-critical He-cooled assembly as long as the system remains sub-critical. Reactivity insertions larger than 8$ (about 2900 pcm) will not challenge the integrity of the system.

Shutting down the plant from full-power, hot operating conditions to ambient temperatures will insert a maximum of + 1500 pcm into the core, assuring a keff < 0.99 under BOC conditions. As burn-up proceeds, the level of sub-criticality of the system will decrease, thereby increasing the margin to criticality should shut-down become necessary.

After shutdown to cold conditions (~ 200 °C) the absorber devices will be moved into the core region during maintenance and refuelling conditions. This will decrease the level of reactivity from 0.985 to less than 0.95.

The power level of the He-cooled core will be controlled and maintained by the proton current supplied by the accelerator system. The response of the power level of the sub-critical core to changes in proton current will be instantaneous. Shutting down the proton current will lead to a very effective shut-down of the sub-critical systems, even though the power response of sub-critical cores to shut-down conditions are known to be somewhat delayed in time in comparison to the prompt shut-down characteristics of critical core configuration.

Similar as in the LBE-cooled XADS, the capability of inserting negative reactivity during normal operating conditions is foreseen in the He-cooled system by dropping absorber rods into the active core region on demand as a kind of an accident management measure. This system could provide an additional means of safety assuring fast shut-down of the He-cooled system in case of unforeseen conditions.

3.2.2 Decay heat removal of the 80 MW XADS

The purpose of removing decay heat is to remove the heat which continues to be generated in the core following reactor trip. The function must ensure both the reliable heat removal from the core region and its transport to the ultimate heat sink.

The removal of decay heat in an ADS is very similar to the one in a conventional critical reactor.

Residual heat removal is achieved with the fulfilment of the following functions:

- Maintenance of the coolant inventory
- Coolant circulation
- Pressure control in the primary circuit
- Maintenance of a coolable geometry in the core
- Removal of heat from the primary coolant

The designs take into account that XADS with lead bismuth eutectic (LBE) cooling and gas cooling present different characteristics when it comes to performing each of these functions.

3.2.2.1 Decay heat removal of the 80 MW LBE-cooled XADS

The normal mode of decay heat removal of the 80 MW LBE-cooled XADS will be through the normal primary / secondary system heat trains. Sufficient redundancy in coolant loops (2) and heat exchangers is assured to allow failure of single components or failure of an entire heat removal train. An additional, totally independent emergency decay heat removal path is provided via the Reactor Vessel Air Cooling System (RVACS) exploiting radiation from main and safety vessel walls - and buoyancy-driven air natural convection. This system rejects about 260 KW of heat during normal operation; under abnormal conditions (elevated vessel temperatures), this system can remove up to 800 kW of heat.

The LBE-cooled 80 MW system features a very high in-vessel natural convection coolant flow rate in excess of 20% of the nominal flow rate in the decay heat mode due to the low pressure drop across the core (< 260 mbar) and the high elevation difference between the core and the ultimate heat sink. This high natural convection flow rate assures the even distribution of the decay heat from inside the active core region to all primary system components and potential primary system heat sinks / buffers.

In addition, the very large thermal heat capacity (thermal inertia) associated with the large mass of the LBE-coolant in the primary system provides a very large and extremely effective heat buffer assuring low core temperatures even under abnormal decay heat mode conditions.

Should both normal heat removal trains fail during the decay heat mode, then the natural convection driven RVACS system will remove sufficient decay heat to limit the primary system temperatures to well below 500 °C.

The decay heat removal during Design Basis Accident conditions is assured by the secondary coolant system functioning in forced or natural circulation [3.2-14]. Should both normal heat removal trains fail during the decay heat mode, then the irradiation and natural convection driven RVACS system will remove sufficient decay heat to limit the primary system temperatures to well below 500 °C.

It is the combination of these design features – namely, a high boiling point of the LBE-coolant (~ 1700 °C), high natural convection flow rate, and the very large thermal heat storage capacity of the primary coolant, and several redundant active and passive heat removal systems - that assure that all temperatures inside the primary system will be limited to well below < 500 °C even under the most unfavourable, abnormal decay heat mode conditions (i.e., failure of normal heat sink trains, failure of individual components).

3.2.2.2 Decay heat removal of the 80 MW He-cooled XADS

The normal mode of decay heat removal in the 80 MW He-cooled XADS will be through the Shutdown Cooling System (SCS) specifically designed to remove decay heat under various plant conditions. Sufficient redundancy in the SCS system and heat exchangers is foreseen (3 independent loops each of which can remove up to 2 MW of decay heat) to allow failure of single components or failure of an entire SCS heat removal train.

The SCS system is designed to operate under nominal pressure conditions (60 bar) as well as under depressurized conditions (also under ambient pressure conditions).

Under nominal pressure conditions (60 bar), the natural convection flow rate within the primary system will be sufficient to allow decay heat removal via the SCS system with the SCS in the passive mode (i.e., both primary helium and the secondary side of the SCS system (water cooled) in the passive mode).

Under depressurized conditions, the SCS will have to operate in the active mode to assure an adequate coolant mass flow rate in the primary system for decay heat removal.

The SCS consists of three sets of He-water heat exchangers, circulators and check valves housed in reactor vessel nozzles. Each set is designed for full thermal capacity. The heat exchanger secondary coolant is low pressure water in permanent natural circulation and secondary heat exchangers will be located at an elevation compatible with secondary coolant natural circulation. A flow restrictor will be located on the cold duct of the cross vessel.

Three design conditions have been identified for the SCS:

SCS passive mode: In case of loss of forced circulation of helium in the primary circuit, the decay heat can be removed in natural circulation using the SCS heat exchangers. The nozzles in the reactor vessel are located at about 7 m above the core mid-plane. This elevation will provide significant margins for natural circulation over the requirement of an estimated 3 m. The SCS contains a passive check valve designed to be naturally open, which remains open until a differential pressure of about 2000 Pa is reached.

SCS active mode: In case of a complete loss of pressure in the primary circuit, natural circulation capabilities are not sufficient and hence core cooling is achieved using the circulators (compressors) and heat exchangers of the SCS. This is also applicable during handling operations, where the primary circuit is partially depressurised.

In case of a large leakage on the PCS or cross-duct (linking the reactor vessel to the PCS vessel), an active redundant flow shutter is implemented on the cold duct to prevent the forced flow from the SCS escaping through the breach rather than through the core. It consists of a fixed annular plate with several windows and rotating discs with similar windows. During normal operating conditions the cold helium flows through the aligned windows. In case of fast pressure loss, the windows are rotated by either an electrical motor or a pneumatic system providing a large pressure drop.

A preliminary reliability analysis has been performed on the basis of the proposed design. From this analysis, which is to be further complemented, the objective of a failure rate of $\sim 10^{-7}$ / year for the loss of the DHR should be reached with a 2/3 SCS diversification (check-valve and Heat Exchanger), a special maintenance scheme and a partial depressurization (about 10 bars) during fuel handling operations.

3.2.3 Confinement of radioactive products of the XADS

The objective of the radioactive confinement function is to prevent radioactive releases from exceeding established, allowable limits. This function is assured by the integrity of the different fission product mobility barriers included in the design.

The following principal barriers are included in each XADS design to fulfil the defence in depth criterion:

- The fuel cladding
- The primary circuit boundary
- The reactor containment

These principal barriers are equivalent to those defined for a conventional fission reactor. However, the design of an XADS reactor has peculiar design aspects that must be considered on account of their impact on the confinement function, particularly the presence of the accelerator and the target; the accelerator in as much as it is a component that penetrates both the primary circuit boundaries and the containment boundaries, and the target inasmuch as it is a component in which radioactive activation and spallation products are generated that have to be controlled. From this point of view, it can be considered that target integrity is an additional barrier that can be considered a continuation of the primary coolant boundary for both the target solution (windowless and window). Its integrity must be maintained.

The confinement of fission and spallation products is achieved by providing physical barriers towards the external environment as well as safety systems dedicated to maintain the integrity of these barriers.

The barriers for the fission products are the same as for critical reactors : fuel clad, primary circuit boundary and containment, which is the ultimate barrier for preventing the release of radioactive materials into the environment in conformity with the defence-in-depth philosophy.

In both design options of the target (window and windowless), the confinement of the Spallation/activation products contained in the target LBE cooling loop constitutes one of the ADS peculiarities :

- for the windowless design, the spallation/activation products contained in the target coolant are not physically separated from the accelerator tube, but with a “dynamic” barrier provided by the vacuum system ;
- for the window design, the very specific operating conditions of the window (radiation, contact with LBE,…), leads to a higher risk of failure. The consequence would be the release of spallation products into the accelerator tube.

The consequence of this situation on the XADS design is that dedicated systems /devices are designed for the confinement function of spallation products: fast-acting isolation valves, “cold” window, etc…

Confinement of the spallation target has a singular position in the ADS layout because it is the component in which the accelerator tube (which is not a nuclear part) penetrates the nuclear island.

Containment isolation requirements ensure that fluid lines which penetrate the containment boundary are isolated in DBC or DEC events, so as to minimise the release of radioactivity to the environment.

A break in the target will open a path for LBE with radioactive secondary spallation products to get into the accelerator tube. These secondary radioactive products are likely to be distributed in the accelerator tube. In case of tube failure, either the containment atmosphere will be loaded with these products, or they might escape directly into the environment because the accelerator tube penetrates the containment boundary. In this regard, sufficient means are provided to isolate the accelerator tube from the target.

The following are the means that can be or are implemented to the containment function:

- A safety window which allows a small part of the accelerator tube to be continuously isolated from the rest of the tube.
- A system of fast-acting isolation valves which close with the same signals that trip the accelerator.
- A high vacuum system close to the target with a spallation product retention system.

Primary target system leakages could cause a limited pressure increase in the containment in the gas-cooled XADS design. This possible pressure increase is taken into account in the design of the containment structures.

For the active core region, the principal and most effective prevention against the release of fission product to the environment is the assurance that no likely single event, or sequence of events will lead to serious core failure, i.e., large-scale failure of the protective cladding of the fuel pins.

The principle of multiple barriers, namely retention of fission products inside the fuel matrix, the cladding of the fuel pins, the primary coolant acting as a matrix absorbing or retaining in suspended form a major fraction of the fission products in case of serious cladding failure, the boundaries of the primary vessel system, the active and passive containment systems preventing fission products from becoming air-borne, the boundaries of the containment system itself, and as a last resort, the active and passive filter systems extracting fission products from a vented containment system, all act in conjunction in case of demand to assure the prevention or minimization of the release of fission products to the environment.

The most important line of defence relies clearly in assuring prevention of core conditions which could lead to significant cladding failures of the fuel pins thereby releasing fission products from the fuel matrix into the coolant of the primary system.

3.2.3.1 Confinement of radioactive products of the LBE-cooled XADS

The safety analyses performed for the LBE-cooled XADS, as summarized in a subsequent section, clearly demonstrate that no likely or credible transient initiators could be identified which would lead to serious, massive fuel pin failures in the 80 MW LBE-cooled XADS.

Should fuel pin cladding failure be postulated nonetheless, then the non-volatile fission product will mostly be retained by the LBE-coolant matrix while the volatile fission gas products will accumulate in the cover gas. The non-volatile fission products will be retained by, or suspended in the LBE-medium, the coolant itself thus providing an effective retention matrix within the primary system boundary. No fission product release into the containment atmosphere is to be anticipated unless the primary system boundaries should be breached (i.e. vessel leakage).

In case of main vessel leakage there would be spillage of LBE-coolant into the annulus between main and safety vessel with no radioactivity release to the containment atmosphere. LBE coolant would spill into the reactor pit only in case of failure also of the safety vessel; in this scenario no serious chemical reactions with concrete or other material components are expected because of the near chemical inertness of the LBE-coolant.

Even under these degraded reactor cavity conditions natural convection of air within the RVACS system is still considered to provide a viable heat rejection path that prevents the reactor pit area from reaching excessive temperatures that could lead to the release of the fission products retained in the spilled LBE-matrix to load the containment atmosphere.

Most of the Polonium generated during normal operation is expected to remain in the LBE coolant. The volatile fraction escaping upwards to the inerted cover gas will be continuously filtered - and directed to bunkered storage. This assures that only a minor fraction of the active Polonium generated will be suspended in the primary coolant cover gas during normal operation. Vessel cover plate or gas system leakage as well as cover gas system piping failures will thus lead to no major release of Polonium into the containment atmosphere. Since the polonium storage tanks retain a large fraction of the generated polonium, all design safeguards are provided to assure the secure retention of these volatile activation products to those plant sites where dedicated storage tanks are located.

Should the containment atmosphere become loaded with radioactive products nonetheless, then sufficient filter systems must be foreseen in the containment design to assure that no excessive release of non-volatile radioactive products to the environment are encountered in case the containment system should have to be vented.

Since the LBE-coolant is not reacting with air, no significant source for over-pressurization of the containment system could be identified. All non-volatile fission products are thus expected to be securely retainable for the long term within the boundaries of the containment system.

Calculations performed for the 80 MW LBE-cooled XADS have shown that the radiological limits in term of Effective Dose Equivalent (EDE) varying from 0.1 mSv per year for DBC category 1 and 2 to 5 mSv per event for DBC category 4 at the site boundary can be met. For DEC the EDE shall not exceed 10 mSv at the site boundary, without credit to any protective measure.

The LBE-cooled 80 MW XADS as designed by ANSALDO is thus judged to be a very safe plant design.

3.2.3.2 Confinement of radioactive products of the He-cooled XADS

The primary assurance against the release of fission product to the environment is the assurance that no likely single event, or sequence of events will lead to serious core failure, or massive cladding failure of the fuel pins.

The principle of multiple barriers also applies to the He-cooled XADS. These barriers are the retention of fission products inside the fuel matrix itself, the cladding of the fuel pins, the boundaries of the primary vessel system, the active and passive containment systems preventing fission products from becoming air-borne, the boundaries of the containment system itself, and as a last resort, the active and passive filter systems extracting fission products from the vented containment system, all act in conjunction in case of demand to assure the prevention or minimization of the release of fission products to the environment.

The emphasis is clearly in assuring prevention of core conditions which could lead to failure of the cladding of the fuel pins.

The safety analyses performed for the He-cooled system, as briefly summarized in a subsequent section, demonstrated that no fuel pin cladding failure is expected if the accelerator shuts down on demand, and the decay heat removal system (SCS) functions as designed.

Should however in the extremely unlikely event: a loss of power under depressurized conditions occur (primary system depressurized due to a loss of coolant event with the beam un-tripped !), then the SCS would be only available in its passive mode. The coolant flow rate provided under these conditions would be insufficient to cool the core since the natural convection mass flow rate under ambient pressure conditions is too small. Cladding failure would be anticipated with the subsequent release of fission products into the primary system.

The safety analysis of the He-cooled system has also shown, that cladding failure of fuel pins must be anticipated in some transient events in which the accelerator does not shut down on demand. In these cases, fission products will be released into the primary system. These fission products can then be retained inside the primary vessel system as long as its boundary is not breached.

Since the coolant of the He-cooled XADS does not provide an effective material matrix that retains fission products (as is the case for the LBE-coolant XADS design) most fission products inside the primary system will be either suspended in the gas phase (volatiles and semi-volatiles) or retained in some form in the semi-molten fuel-structural material mixtures (non-volatiles).

In case the vessel boundaries should be breached due to molten fuel accumulation at the bottom of the vessel, the non-volatile fission products will enter the reactor cavity remaining mostly suspended in the fuel-cladding debris mixture while the volatiles will now load the containment atmosphere.

A core catcher located at the bottom of the reactor pit will assure cooling of the fuel-cladding debris leaving the primary vessel. The largest fraction of non-volatile fission products are thus expected to be retained by this fuel-structural material debris bed.

A fully functional containment system will now retain the volatile and most semi-volatile fission products that are to be expected to load the containment atmosphere in case the primary system should be breached.

High containment pressures are not to be expected in the He-cooled 80 MW XADS design since no significant sources of vapour generation could be identified due to the chemical inertness of the coolant. The only major source for containment pressurization is the possible flooding of the reactor cavity with SCS coolant. Since the coolant mass in the SCS loops is rather limited to a few hundred kilograms, relatively small masses of water are available for pressurizing the containment system.

The long-term retention and management of fission products inside the active containment system of the He-cooled XADS assures that no significant quantities of fission products will be released to the environment. All non-volatile fission products must be securely retainable for the long term within the boundaries of the containment system.

The He-cooled 80 MW XADS design thus incorporates a core catcher in the reactor cavity similar to other fast gas-cooled reactor designs to assure long-term cooling of the fuel debris should core melt-down occur, and the fission products loading the containment atmosphere will be retained inside the containment system that is to be specifically designed and engineered to mitigate this event.

For the 80 MW He-cooled XADS the dose limits for the public associated with normal and category 2 operating conditions will be “a minima” in compliance with those defined by ICRP60. The recommended dose limit is 1 mSv/year for normal operation. Releases from category 2 operating conditions will not cause the annual release criteria to be exceeded and, therefore, each category 2 operating conditions meets the annual release criteria.

For category 3 and 4 operating conditions, the criteria are based on two targets: no action beyond 800 m, and limited economic impact.

3.2.4 Radiation protection of the personal of the 80 MW XADS

The activation of materials of XADS affects the safety by exposure of workers during operation and maintenance.

The coolant activation and its effect on operational safety issues are similar for ADS and fast reactors. The He coolant is not activated by neutron irradiation, whereas the LBE coolant is activated producing a 138-day α-emitter (210Po). Thus, in case of leaks in the primary coolant system, LBE would release some 210Po into the containment atmosphere.

Spallation products, activated proton accelerator structures and beam pipes (both activated by beam losses during the operation of accelerator) are fully ADS specific features. Given the high quality design, monitoring and operation required by nuclear rules and the objectives fixed by radiation protection standards, direct and routine exposure should be minimal.

Routine and accidental exposure to radiation may come from two effects: the inherent in-design concept and the consequence of poor management and practices. In the present assessment, only the effect of design features are assessed valuating direct, routine, and accidental exposure to radiation or hazardous material. In this respect, the MYRRHA approach of a fully remote handling maintenance basically reduces the potential of exposure of personnel to radiation.

For the most part, the shielding requirements of ADS are common with gas-cooled fast reactors. The presence of the proton beam tube, however, presents several challenges which are unique to the ADS. They deal with the stream line effect of the proton beam tube in the core zone and the shielding of the proton beam line.

Proton beam streaming effects and proton beam shielding:

This issue has been addressed in the PDS-XADS Project performing activation calculations with MCNPX in which both the neutrons generated by spallation and in the core were considered. Initial results (without biological protection) showed high dose rates due to the activation above the target region at the reactor top closure level. Consequently, biological protections have been implemented in order to decrease the dose rates compatible with the handling of components above the reactor roof. In the windowless configuration preferred for the LBE reactors, the reduced beam tube cross section leads to a lower activation of the upper structures.

Combination of a constant linear beam loss rate under normal operation (3% beam loss in the RFQ, 10 nA/m in the intermediate energy part of the linac and 1 nA/m along the high energy part of the linac) and failures of certain accelerator subsystems (e.g. RF, power supplies, etc.) may cause unwanted beam trips. The probability that a single person will be exposed to radiation from a number of such beam trips per year has been estimated to be acceptable.

It is shown that for both scenarios, the risk is smaller than $1*10^{-6}$ per year (= trivial risk, in line with latest ICRP recommendations) and it was therefore concluded that the shielding defined for normal losses is also safe for accidental beam loss conditions.

Finally, it was also shown that the shielding profiles derived from the requirements for normal operation will provide sufficient shielding for the planned commissioning period as well as for planned periods of beam tuning and set-up. Indeed the proposed shielding will allow beam loss rates 100 times higher than during normal operation for significant periods of time.

3.2.5 Transient Response Analysis

The accident analyses are oriented to demonstrate the intrinsic safety characteristics of the sub-critical system and to verify the safety margin derived from the design choices of systems, such as the type of primary coolant, the configuration for the primary coolant system (pool type), and the natural-circulation flow rate, etc.

A comprehensive list of conceivable plant transients and their classification according to their frequency of occurrence has been identified for each of the XADS designs according to the following classification, Ref. [1] to [6]:

- design basis operating conditions (DBC)
- design extension conditions (DEC), i.e., limiting events, complex sequences and severe accidents,
- residual risk situations.

The design basis conditions (DBC) have been grouped in four categories on the basis of the expected occurrence frequency of the corresponding initiating fault.

- Category 1 – Normal operations
- Category 2 – Incidents
- Category 3 – Accidents (low frequency)
- Category 4 – Accidents (very low frequency)

Analyses results of the plant behaviour for groups of representative initiating events of the different design basis categories and of design extension conditions then have provided the basis for definition of containment design criteria Ref. [7]

Preventing failure of the cladding material during transient conditions was one of the primary safety criteria assuring fuel pin integrity, and thus ultimately safety of the plant. The maximum tolerable cladding temperature was somewhat arbitrarily set at ~1000 °C thus assuring a reasonable margin to the expected clad failure limit and the actual clad melting of ~ 1370 °C.

The various organizations involved in this safety study (ANSALDO, FRAMATOME, ENEA, CEA, NNC, PSI, JRC, FZK) used different computational tools. Due to the lack of an experimental data base regarding the operation of LBE-cooled and He-cooled sub-critical systems, this procedure of using different tools by different organisations allowed an independent cross-validation of employed procedures and calculated results, as well as an identification of the capabilities of each these tools.

3.2.5.1 Transient response – Protected events of the 80 MW LBE-cooled XADS

The detailed results of the extensive safety analysis performed of the 80 MW LBE-cooled XADS are reported in Ref. [8]. In this report, 11 protected transients (protected implying that the accelerator beam trips on demand) have been identified for detailed analysis by the various research organization involved in the LBE-cooled safety study (ANSALDO, ENEA, PSI, JRC, FZK) using different computational tools (RELAP, RELAP-PARCS, TRAC-AAA, STAR-CD and EAC2, SIMMER, SAS4A, and SIM-ADS).

The list of protected transients analysed included among others loss of flow (PLOF), loss of heat sink (PLOH), overpower transient (PTOP), loss of coolant (PLOCA), sub-assembly blockage, spurious accelerator beam trips, and heat exchanger tube ruptures.

Of the 11 protected transients identified for detailed analysis, none indicated that the 80 MW LBE-cooled system was challenged in any serious manner during these protected transients. No fuel, or pin cladding failure events could be identified among those transients analysed.

The 80 MW LBE-cooled system demonstrated a very benign behaviour to all types of protected transients due to its very large intrinsic thermal inertia and heat sink / heat buffer characteristics.

3.2.5.2 Transient response – Protected events of the 80 MW He-cooled XADS

The detailed results of the extensive safety analysis performed of the 80 MW He-cooled XADS are reported in Ref. [9]. In this report, 17 protected transients have been identified for detailed analysis by the various organizations involved in the He-cooled safety study (FRAMATOME, ENEA, PSI, JRC, FZK) using different computational tools (RELAP-PARCS, TRAC-AAA, STAR-CD and EAC2, and SIM-ADS).

The list of protected transients analysed included among others loss of flow (PLOF), loss of heat sink (PLOH), overpower transient (PTOP), system depressurization due to the loss of coolant (PLOCA) due to various leak sizes (3 cm^2, 30 cm^2, 100 cm^2, 500 cm^2) , sub-assembly blockage, spurious accelerator beam trips, and heat exchanger tube ruptures.

Of the 17 protected transients identified for detailed analysis, the protected loss of flow transient (PLOF) due to blower failure demonstrated the sensitivity of the He-cooled system to all coolant mass flow impairment related transients. The combination of a slow coast-down characteristics of the blower and the timely optimized switch-over from the main cooling train PCS to the SCS system assured that operational peak cladding temperature limits (~ 710 °C) would not be exceeded during this transient.

Another protected transient requiring the proper operation of active safety systems is the combination of primary system depressurization (PLOCA) and loss of off-site power. Removal of decay heat under depressurized conditions requires the SCS to provide a forced coolant mass flow through the core region. This can only be assured in case the SCS system remains in the active mode.

In some protected transients, the peak pin may exceed the operational clad limit temperature of 710 °C for a brief interval of time, however in all DBC identified transients the peak clad temperatures remain below 800 °C except for the very large break PLOCA transients.

In this study it has been demonstrated that the He-cooled XADS requires careful optimization of both the core and plant design in order to optimize the response of the plant to protected transients.

3.2.5.3 Transient response – Unprotected events of the 80 MW LBE-cooled XADS

An unprotected accident is characterized by the failure to trip the proton beam upon demand following the initiation of an abnormal event. As a consequence the LBE-cooled XADS continues to operate at a relatively high power level (close to nominal power) since the reactivity feedback mechanisms are insufficient to substantially decrease the power level of sub-critical systems operating at relatively low levels of sub-criticality (i.e keff ~ 0.95). This particular feature, specific to sub-critical systems, needs special attention during the design phase of both core and plant layout.

The list of unprotected transients analysed included loss of flow (ULOF), loss of heat sink (ULOH), overpower transient (UTOP), loss of coolant (ULOCA), sub-assembly blockage, spurious accelerator beam trips, and heat exchanger tube ruptures Ref. [8].

Of the 12 unprotected transients identified for detailed analysis, only two transients indicated that the 80 MW LBE-cooled system might be challenged, namely in the extremely unlikely event that an unprotected loss of heat sink occurs in combination with a loss of flow (ULOF + ULOH), or total blockage of a sub-assembly.

In the case of the combination (ULOH+ULOF) transient, core temperatures could exceed 1000 °C about 30 to 40 minutes into the transient. This assumes that the beam is not shut off during this transient, an event judged not credible. Even then, the 80 MW LBE-cooled system demonstrates a remarkably large grace time of more than 30 minutes for the operators to intervene manually by shutting of the accelerator.

The second, unprotected transient leading to cladding failure is the nearly complete blockage (97% of flow area) of a sub-assembly. Cladding temperatures in excess of 1000 °C will be reached within 20 seconds after transient initiation. To cope with this event shut-down of the accelerator within seconds after transient initiation and in-core instrumentation on the sub-assembly level is foreseen even if this event of 97% blockage is considered to be extremely unlikely, and the potential damage will be confined at most to the failure of a single sub-assembly.

3.2.5.4 Transient response – Unprotected events of the 80 MW He-cooled XADS

An unprotected accident is characterized by the failure to trip the proton beam upon demand following the initiation of an abnormal event. As a consequence the He-cooled XADS continues to operate at a relatively high power level (close to nominal power) since the reactivity feedback mechanisms are insufficient to substantially decrease the power level of sub-critical systems operating at relatively low levels of sub-criticality (i.e keff ~ 0.95). This sub-critical system specific feature amplifies the sensitivity of the He-cooled XADS to all mass flow related transients.

The list of unprotected transients analysed included among others loss of flow (UPLOF), loss of heat sink (ULOH), overpower transient (UTOP), system depressurization due to the loss of coolant (ULOCA) due to various leak sizes, sub-assembly blockage, spurious accelerator beam trips, and heat exchanger tube ruptures Ref. [9].

The safety analysis of the He-cooled XADS has shown that the sub-critical, gas-cooled XADS will tolerate some unprotected transients such as sudden reactivity insertion induced over-power transients (UTOP), beam overpower transients, and unprotected over-cooling transients.

For unprotected over-power transients (UTOP), only modest increases in fuel and cladding temperatures are expected, provided the reactivity insertion is less than the margin to criticality, namely of ~ 3000 pcm (~ 8 $) while the plant is under full power conditions.

Clad failure cannot be avoided in the He-cooled 80 MW XADS for all unprotected, mass flow degradation related transients such as loss of flow (ULOF) and system depressurization (ULOCA). This fact places an increased emphasis on the reliability of the beam shutdown mechanisms for the He-cooled XADS design in order to assure that this mechanism operates on demand to a very high degree of reliability. The required high reliability of the accelerator beam trip is such that the failure of beam trip places all unprotected, mass flow related transients into the DEC category. The diversity and redundancy of the beam trip will need to be automatic (to be addressed with appropriate Instrumentation and Control implementations) since the grace time frame is not sufficiently long to take advantage of manual operator intervention.

In case of DEC conditions leading to core melting, the consequences of these transients will be mitigated in the current plant design by the ex-vessel core catcher system in the reactor cavity.

3.2.5.5 Conclusions to the Transient Analysis of the LBE-cooled XADS

The 80 MW LBE-cooled XADS can be considered to be a very robust design against all types of unlikely transient event. This is due to the particular combination of design features incorporated into this reactor design, namely :

- a very high in-vessel natural convection coolant flow rate in excess of 30% of the nominal flow rate due to the low pressure drop across the core (< 260 mbar) and the high elevation difference between the core and the final heat sink. This high natural convection flow rate assures the even distribution of the decay heat from inside the active core region to all primary system components and potential primary system heat sinks / buffers,
- the very large thermal heat capacity (thermal inertia) associated with the large mass of the LBE-coolant in the primary system that provides a very large and extremely effective heat buffer assuring low core temperatures even under abnormal conditions.
- the very high boiling point of the LBE-coolant (T_boil ~ 1700 °C) that assures that no coolant vapour generation due to coolant boiling is to be expected in this concept,
- the low linear power rating of the fuel (average / peak power rating ~ 85 / 135 watts/cm).

It is the combination of these design features that makes this particular design very resistant to almost all transient initiators, protected or unprotected. Temperatures inside the primary system will be limited to well below < 1000 °C preventing failure of fuel pins and thus release of the radioactive inventory into the primary system.

Temperature cycling of structural components such as upper internal structures, grid plate, vessel, pipes etc. as consequence of frequent beam trips, appears to be small. However, impact of cyclic loadings on the structure integrity over the expected life time of the plant would need further in-depth analyses.

3.2.5.6 Conclusions of the He-cooled Transient Analyses

The He-cooled PDS-XADS concept can be characterized by the following combination of inherent features, namely:

- the coolant has a low thermal inertia in the active core region and in the primary system (in relation to the high core power rating) because of the low density associated with the coolant being in the gaseous phase.
- a relatively low natural convection coolant flow rate due to the low density of the gas,
- a linear power rating about twice as high as that of the LBE-cooled design.

The combination of these three features makes the He-cooled XADS design relatively sensitive to any perturbation in its nominal thermal-hydraulic steady state, in particular to any perturbation due to changes in the mass flow rate of the coolant as encountered during LOF and LOCA transients.

In this study it has been demonstrated that the He-cooled XADS requires careful optimization of both the core and plant design in order to optimize the response of the plant to protected transients.

In some protected transients, the peak pin may exceed the operational clad limit temperature of 710 °C for a brief interval of time.

For all DBC transients the peak clad temperatures remain below 800 °C except for the very large break PLOCA transients.

Clad failure is difficult to avoid for all unprotected, mass flow degradation related transients due to the sub-critical system specific feature that the power level does not decrease sufficiently during unprotected transients. This fact places an increased emphasis on the assured reliability of the beam shutdown mechanisms for the He-cooled XADS design to quickly trip the accelerator beam.

In case of DEC conditions leading to core melting, the consequences of these transients will be mitigated in the current plant design by the ex-vessel core catcher system in the reactor cavity.

3.2.5.7 Conclusions of the Transient Analysis of MYRRHA

The following conclusions can be made based on the transient analyses performed for the MYHRRA XADS concept Ref. [10].

- For the protected transients no serious consequences are expected.
- For unprotected transients (proton beam remains on), problems are created to the cladding in case of total loss of flow or total loss of heat sink. The safety criterion of 2500 °C for the fuel is not reached, but the cladding temperature strongly exceeds the safety limit of 700 °C. The grace times are about 20 seconds for the TLOF (Total Loss Of Flow) and about 10 minutes for the TLOH (Total Loss Of Heat sink). Those results highlight the imperative need to design a very reliable beam trip system for MYRRHA making the occurrence of unprotected situations very unlikely.
- The reactor shutdown does not avoid LBE freezing in the heat exchangers in case of overcooling, but the grace times are significantly increased with respect to the case with reactor shutdown.
- Fuel assembly blockage will lead to localized fuel pin failures in the protected as well as unprotected transient.

Finally, the fully passive emergency cooling system as proposed for MYRRHA has demonstrated its capability to face successfully all the protected transients. Further optimization of the design is however possible and recommended such as improvement of the elevation of the heat sink with respect to the core.

3.2.6 General basis for design of the 80 MW XADS

The general principles which support the reactor design must respect the following rules:

- All the structures, systems and components are carefully identified and classified on the basis of their function and significance with regard to safety to provide a basis for determining the appropriate codes, standards and other requirements to be applied in their design ;

- All the events of the XADS plant are classified into a limited number of categories according to their probabilities of occurrence and potential consequences ;
- Engineered safety systems are included in the plant design to protect or to mitigate the consequences of classes of accidents that would otherwise contribute significantly to risk. Moreover any engineered safety system must be designed to prevent or to mitigate a specific spectrum of accidents ;
- Realistic assumptions and best estimate analyses are used to assess additional multiple failures and severe core damage sequences considered in the design.
- Some safety performances or capabilities of various components, systems and safeguards as well as the design of severe accidents on best estimate basis are evaluated with the criteria related to protected and unprotected events (PE, UPE), confinement of radioactive products (CRP3, CRP5) and accident management (SAP and SAM).
- Availability of design rules and criteria: needs for checking the applicability of the current practices, strongly linked to the implemented materials and technologies.

For the large size concepts, the RCC-MR has been selected as reference Design and Construction code for the studies. Adaptations of the codes together with dedicated design rules for specific components are used and they require supporting R&D programs to be evaluated. Key issues are the exclusion of corrosion and LM interaction for the LBE-cooled system and irradiation aspects for the spallation target and surrounding structures.

Moreover the effect of random and systematic uncertainties on simulation of load conditions and the capability of codes to model particular phenomena, as stratification, seismic sloshing effect, etc., have been assessed.
For critical reactors, the fundamental safety functions are:

- Control of reactivity,
- Removal of the decay heat,
- Containment of the dangerous materials and fission products,
- Protection of the operators against the radiation exposure.

For an accelerator driven system the following additional functions must be added:

- control of the power, and
- control of the level of sub-criticality .

Besides, other safety related generic issues have to be taken into account:

- Minimise by design possible chemical reactions,
- Minimise production of wastes and effluents,
- Prevent by design possible types of human malevolence.

The general basis for the design of the 80 MW XADS systems is the “Defence in Depth” principle based on the following five different levels of defence:

- Level 1 is the prevention of situations that deviate from normal operating conditions,
- Level 2 is the provision of means to detect these deviations and of means to compensate and prevent them from leading to accident conditions,

- Level 3 is the provision of means to control the consequences of accident conditions within the design basis,
- Level 4 is the control of severe plant conditions including prevention of accident progression and mitigation of the consequences of severe accidents,
- Level 5 includes the mitigation of radiological consequences of significant releases of radioactive materials.

The prevention of deviations from normal operating conditions is related to the main design characteristics in which the requirement for a high level of safety and reliability in continuous normal operation expressed in Deliverable 1, Ref. [11] is taken into account, as well as high quality in construction and operation.

The detection of deviations and the means for compensating them requires the definition of the different possible normal operating conditions as well as the acceptable parameter ranges defining each of those conditions. This definition is detailed in Deliverables 43 and 44, Ref. [12] and [13].

Taking this scheme into consideration, safety systems comprise engineered safety features designed to control and mitigate the consequences of accident conditions. Deliverable 22, Ref. [14] focuses on the definition of design criteria for these engineered safety features.

Safety systems are designed to actuate in the event that a Design Basis Condition occurs. Their objective is to take the plant to safe shutdown conditions. The Design Basis Conditions in the design of both LBE- and gas-cooled XADS are defined in Deliverables 19 and 20 Ref. [3] and. [4].

The initiating events associated with the Design Basis Conditions assume some kind of failure associated with plant systems which are in operation. The specific conditions imposed by the most significant events identified for LBE- and gas-cooled XADS designs are addressed in the following sections.

Specific accelerator and target issues:

- In case of abnormal increase of fuel, structure or coolant temperatures, it is necessary to shut down the accelerator quickly and reliably relying on redundant and diversified core instrumentation.
- Inadvertent beam power increases lead to overpower conditions.
- The accelerator is an additional source of activation of the structures, which are taken into account in the radiological protection of the workers.
- The radioactive elements generated by the spallation reactions in the target are kept confined.

3.2.6.1 General basis for design of the 80 MW LBE-cooled XADS

The Design Basis Conditions in the design of LBE-cooled XADS are discussed in Deliverable 19, Ref. [3]. They are summarized in the following manner:

The main difficulties associated with using LBE as a coolant are related to:

- corrosion issues,
- in-service inspection issues,
- decommissioning issues (i.e., elimination of a contaminated and chemically toxic substance),

- generation of significant quantities of polonium 210 due to the activation of bismuth under irradiation,
- potential freezing of the LBE-coolant in overcooled section of the primary system,
- the volumetric expansion of LBE subsequent to solidification, and
- oxide formation, which can potentially creates flow blockages in the primary system, in particular in flow-stagnant areas.

Related to the corrosion issue, monitoring of in-vessel structures for cracks is definitely a very major issue of concern since it requires the use of complicated remote handling equipment under non-translucent conditions.

A leak-before-break methodology must be established for the primary vessel system. The objective is double: first, to demonstrate by a crack propagation analysis that the credible flaws of the main vessel do not propagate up to through-wall-cracks, and second, to show that if a through-wall-crack occurs it can be detected before it becomes critical. This necessitates implementation of a system that is able to detect small LBE leaks.

3.2.6.2 General basis for design of the 80 MW He – cooled XADS

The gas-cooled design of the XADS is generally motivated by several unique advantages associated with gas as a coolant. The main features can be summarized as follows:

- simple in-service inspection of the primary system and internal vessel components because of the transparent nature of the coolant,
- gas (especially helium) is chemically inert and accumulation of corrosion products in the primary system is not to be expected,
- the gas coolant does not become activated by irradiation,
- no change in phase of the gas coolant,
- no decommissioning issues associated with the coolant (i.e., no radioactive or chemically toxic substances need to be disposed of).

Several issues however require close attention, namely :

- Residual grit and impurities content in the primary gas (other gases, steam, etc…) could lead to chemical interactions with internal structures (corrosion…). The coolant must thus be continuously purified to minimize this issue.
- Loss of pressure can induce positive reactivity effects that are however relatively minor (+ 140 pcm for the He-cooled 80 MW XADS due to complete coolant voiding),
- water/steam ingress into the primary circuit from heat exchanger tubes failure could potentially have significant reactivity consequences in addition to chemical water attack effect on the structures.
- for helium as coolant, lack of oxygen leads to a tribology related phenomena, the removal of the natural oxide layer of the structure materials. As a result, risk of seizure of moving parts without oxide layer (lubricant) might occur,
- helium embrittlement of the cladding surface due to helium penetration induced by a high fast neutron fluence,

- the poor properties of gas as coolant are not a major issue at nominal operating conditions due to the elevated system pressure (increase of density),
- the main issue of gas cooling is the lack of thermal inertia associated with the coolant in comparison with liquid metal coolant (coolant thermal inertia) requiring the highly reliable trip of the accelerator immediately after accident initiation, and
- due to the low gas density, natural circulation of gas is not efficient at low pressure, especially with helium as coolant gas.

The gas-cooled XADS is designed assuring coolability of the core under all plant conditions.

If the primary system gas pressure is maintained at a sufficient level, removal of decay heat can be accomplished by natural convection.

In case the primary system should be fully depressurized, either due to a LOCA transient or during the fuel handling mode, cooling by forced convection will be required.

3.2.7 Reliability targets (safety systems) of the 80 MW XADS

During the design process, it is necessary to ensure that safety systems and functions can meet the assigned reliability targets.

Reliability targets are assigned to safety systems or functions. The targets are established on the basis of the safety objectives and are consistent with the roles of the systems and functions in different accident sequences. Provision is made for testing and inspection of components and systems for which reliability targets have been set:

- ensure that safety systems and functions can meet the assigned reliability targets during the design and the plant life,
- provide systems that are testable in service and to develop system model to demonstrate that reliability targets are met during the design and the system life

Detailed probabilistic methods are available and are used for assessing the reliability required to safety systems and functions that rely on active features to perform their missions. However, if the system or function relies on passive features, their possible failure modes are different from the more familiar active systems and probabilistic methods are not efficient. In this case, the so-called Lines-Of-Defence (LOD) method can be used.

The designs of the safety systems of the LBE-cooled and He-cooled XADS designs are all based on the same reliability targets.

The probabilistic approach is a method that allows verification that the measures employed for preventing a risk (i.e. core melt) are adequate. This method is adapted to well defined designs where significant feedbacks exist. Uncertainties associated to probabilistic studies of unique designs such as the XADS are relatively large (uncertainties related to both the definition of the accidental sequences and the quantitative data concerning the frequencies of initiating events and the failure probabilities of equipment). Therefore, the values used as probabilistic objectives are considered as guidelines for orientation, rather than stringent criteria. The probabilistic evaluations are performed in best estimated conditions (mean probabilistic values).

In accordance with the safety philosophy, quantitative probabilistic design targets can be defined. In the European Utilities Requirements (EUR) approach, consistent with IAEA recommendations, the probabilistic targets are:

- The core damage cumulative mean frequency shall be lower than 10^{-5} per reactor year.
- The cumulative mean frequency of exceeding the criteria for limited impact shall be lower than 10^{-6} per reactor year.
- The sequences involving very large releases shall have a cumulative mean frequency well below the previous target of 10^{-6} per reactor year. This requirement refers to the avoidance of the so called "cliff edge effect" and the cumulative mean frequency for these sequences should be at least one order of magnitude below this for the one criteria for limited impact.

The definition of core damage might depend on the concept; generally it refers to core melt. For European Fast Reactor (EFR), it is taken advantage of the high level of protection against core damage that can be achieved with Liquid metal fast reactors (LMFR), and the quantitative probabilistic targets are:

- The mean value of the cumulative frequency of core damage shall be lower than 10^{-6} per year.
- The sequences involving very large releases (larger than the criteria for limited impact) shall have a mean value of the cumulative frequency well below 10^{-6} per year.

To be consistent with the cumulative frequency target of 10^{-6} per year (mean value), a target of 10^{-7} per year (mean value) is assigned to the individual sequences leading to core damage.

For the XADS concept, the quantitative probabilistic targets of EFR are used because of the higher potential for criticality in case of core damage (compared to LWRs).

3.2.8 Inspectability and maintainability of safety equipment of the 80 MW XADS

All safety related components, systems and structures are designed and constructed so that they can be inspected throughout their operating lifetimes to assure their continued acceptability for service with an adequate safety margin.

All safety related components, systems and structures are the subject of regular preventive and predictive maintenance, inspection, testing and servicing when needed, to ensure they remain capable of meeting their design requirements throughout their operating lifetimes:

- Special attention is placed to the radiological protection of operators, their accessibility, available technology and drawback on plant availability and safety.
- Expected needs for inspectability and maintainability.
- Capability to directly monitor the inspectability /maintainability activities.
- R&D needs.

In designing for the in-service inspection and maintenance of safety related components, structures and systems, special attention is placed to the radiological protection of operators, their accessibility, available technology and drawback on plant availability and safety.

Having the radiological protection of workers already considered, the items which have been identified as criteria are the expected needs for inspectability (i.e., maintainability and accessibility for maintenance and repair) and R&D needs.

LBE freezing :

A concern to the designer of liquid metal cooled reactor is the risk of coolant freezing. This is the main obstacle, due to its higher melting point, for the selection of the pure lead as the coolant, in spite of several advantages.

In a pool-type reactor freezing is less probable to occur than in a loop type reactor (a loop filled with lead is in any case not advisable for the predictable poor resistance against seismic loads).

Although freezing of a large pool of lead has not been enough investigated so far, it can be thought that it is possible to design a primary system configuration that ensures core cooling for all transients leading to frozen lead inside the in-vessel IHXs or SGs.

Further investigations are necessary to verify the present capability and the need of development of codes to easily move from convective to conductive models to simulate coolant circulation/freezing inside complicate structures with heat generation and dissipation.

3.2.9 System qualification of the 80 MW XADS

The technologies incorporated into design of safety systems have been proven by experience and testing. Significant new design features are introduced only after thorough research and prototype testing at component, system or plant level, as appropriate.

All systems, components and structures are conservatively designed, and will be manufactured, constructed and tested to quality standards commensurate with the safety objectives.

The use of proven technologies allows that the simultaneous objectives of reliability and safety are achieved.

If a new design feature is introduced, the safety of the feature will have to be demonstrated to be adequately conservative by appropriate supporting research programs or by operational experience from other relevant applications. Moreover, it shall be adequately tested before being brought into service and monitored during service. System qualification is assessed evaluating the availability of system and material technology.

3.2.10 Severe accident management of the 80 MW XADS

The principal emphasis is placed on the primary means of achieving safety by the prevention of accidents, particularly those which could cause severe core damage.

In-plant and off-site mitigation measures are implemented into the design that will substantially reduce the effects of an accidental release of radioactive material.

The accident management is a set of actions performed by operators and/or systems involved during the evolution of a very low probability accident sequence that could lead to core degradation in order to achieve a controlled safe state and to mitigate any consequences. It includes actions that could be taken to protect the confinement function (prevention) or otherwise to limit any potential releases of radioactive material to environment (mitigation).

Prevention is improved:

- by increasing the level of redundancy, separation and diversity of the safety systems, the testability of the systems, the qualification of the systems, components and structures for specific environmental conditions that may result from an accident or external hazards, the plant automation for reducing vulnerability to human failure;

- by using inherent and passive means where this is more efficient, and
- by reducing common failure due to design, manufacturing, construction, internal or external hazards.

Despite the high prevention of severe situations achieved by application of the three first levels of the defence in depth strategy, mitigation of these hypothetical situations is required: fission and spallation product barriers and/or additional mitigation features, independent of fuel robustness, should provide effective retention of any aerosols formed from volatile fission and spallation products and should greatly delay and control any residual release of gaseous products.

The containment systems of the various XADS designs are designed with robust independent mitigation features and high resistance to damage, and without by-pass in order to reduce any release to the environment following core damage.

Criteria related to potential to criticality and for direct containment heating, in-vessel and ex-vessel retention and coolability, and corium release from vessel allow to assess the accident mitigation capability of the plants.

First of all, it is worth pointing out that the severe accident studies were rather different depending on the concept. This situation was essentially governed by the difference of development of the different designs:

- For the 80 MW LBE-cooled concept (most detailed design), preliminary studies of the core disruptive behaviour have been performed by means of SIMMER calculations. Results are discussed hereafter ;
- For the 80 MW gas-cooled concept, no calculations were performed, but severe accident situations were preliminarily addressed by the implementation of a core-catcher in the reactor pit ;
- For MYRRHA, severe accidents were not considered.

For the 80 MW LBE-cooled XADS extensive safety calculations for Design Basis (DBC) and Design Extension Conditions (DEC) have been performed which are documented in Ref. [8]. These analyses demonstrated that the LBE design is very resistant to severe transient initiators. Only some of the unprotected accidents analyzed with a very large mismatch between generated and removed power could lead to loss of cladding integrity and core damage. Grace times are large and these transients should be successfully managed by operator intervention. The consequences of these transients have therefore not been further analyzed with mechanistic codes. A complete picture on transients and accidents could therefore not be achieved within the PDS-XADS project, as especially severe accident behavior and analyses have played a minor role.

From mechanical point of view, a peculiarity of the LBE-XADS primary system is the relevant weight to which the structures are submitted. In fact the Reactor Vessel itself is filled with about 2000 tons of LBE that have to be transferred through the annular structure to the reactor building foundations. For this reason, the Reactor Vessel and annular support are the most critical components. In particular the effect of this mass is amplified during seismic conditions (LBE sloshing effects) so that horizontal anti-seismic supports were foreseen in the frame of previous dynamic analysis to drastically reduce the horizontal loads. Use of codes able to study this should be encouraged in order to identify and validate the best design.

To recall, in a more complete safety approach, which has been originally developed in the EUR Ref. [15], two kinds of design extension conditions are considered : (1) the situations for which the consequences have to be demonstrated to be limited, and (2) the severe accidents.

Complex sequences and limiting events:

Complex sequences are unlikely sequences which go beyond those in the deterministic design basis in terms of failure of equipment or operator errors and have the potential to lead to significant releases but do not involve core melt. In the EFR safety approach, the complex sequences are complemented by limiting events defined for licensing purposes. They are bounding cases not associated with an occurrence frequency resulting from risks specific to the design or the process.

Severe accidents:

Severe accidents are certain unlikely event sequences involving significant core damage which have the potential to lead to significant releases. The severe accidents to consider are not defined on a probabilistic basis. The goal of the analysis of severe accidents is to prove the efficiency of the containment measures for limiting the consequences of core damage accidents. In the EFR safety approach, despite the very low occurrence frequency of a whole core accident, a number of beyond design plant states forms the basis for judgment of what mitigating measures should be provided by the containment design. The objective of this analysis is to provide a robust and homogeneous containment without any weak point in order to reject as far as reasonably possible any cliff edge effects.

The performed safety analysis shows that only some of the unprotected accidents could lead to loss of cladding integrity and core damage. When the temperature of the cladding reaches its melting point, molten-steel and even fuel particles will be released into the coolant channel and driven upwards by buoyancy. The simulations show that fuel dispersion dominates over fuel compaction, preventing severe recriticality accidents and that the behavior is very different as regard to sodium-cooled reactors.

The simulation should be pursued forwards to investigate molten steel and released fuel redistribution inside the primary system. The behavior will be certainly different from that of sodium or water cooled reactors for which the idea of the core catcher has been developed. The designer will have to design provisions for removal of decay heat from the reactor upper plena.

As mentioned above, only two of the unprotected accidents could lead to loss of cladding integrity and core damage. Clad failure on a local scale might then take place first, leading to plenum gas leakage through cracks and/or even massive gas blow-down with local voiding. When the temperature of the cladding reaches its melting point, more gas and molten-steel droplets will be released into the coolant channel and are driven upwards by buoyancy. After the disruption of cladding, the unclad fuel stubs might disintegrate and fuel particles will also be released. Finally, disruptions might spread and propagate and could lead to fuel sweep-out or fuel accumulations downstream with the potential of re-criticalities.

To cover some core melt situations and investigate the potential for re-criticalities, so called snap-shot analyses with ad hoc postulated conditions have been performed. The idea was to investigate some severe accident scenarios, by starting from unfavorable disrupted core conditions. The resistance of the XADS design against severe recriticality scenarios should thereby be tested. The analyses have been performed in 2 steps, starting first from static neutronic calculations of various disrupted core conditions and then proceeding to the analysis of transients, triggered by the already partially disrupted core geometry. The outcome of these scoping analyses showed that, after pin disruption, fuel relocation can transiently lead to an increase in reactivity and thus a mild power surge. No severe recriticality with release of mechanical energy has however been observed. In conclusion, the simulations starting from postulated severe core disruptive accident conditions suggest that the fuel sweep-out and the dispersion effects are the dominating processes when compared to the potential of fuel compaction and severe recriticalities potentially leading to with accident energetics.

After such a mild power surge, material is usually redistributed and dispersed into the upward direction. No special investigations have been performed how the molten steel and released fuel will redistribute within the vessel and where they will be deposited. These are however important issues to be studied in the framework of post accident heat removal (PAHR), which might have some influence on the overall design

3.2.11 Safety assessment concluding remarks:

The PDS-XADS project has studied the technical feasibility and design of an experimental Accelerator Driven System, that could be built in the European Union in order to advance in harnessing the technology of this new kind of systems. Different XADS designs and coolant options have been studied and an assessment of the safety related issues associated with each design is attempted in this summary.

The goal of the safety analysis of any design is to show that any release from the plant under all plant conditions is limited, below intolerable values regarding the environment, the health of public living near the plant site, and the health of the operational staff.

The set of safety related criteria upon which the comparison is made has been established and discussed in detail in Deliverable 40, Ref. [16]. To each of the individual safety topics discussed in this chapter, a set of criteria judged to be of importance have been established, and are listed in Table 3.2 and detailed at the end of this section. To each criteria, a qualified, judgemental rating assessment (a rating ranging from 1 to 3 points: 1 point implying a relative low rating, 3 points implying a relatively high rating) has been recommended.

In Table 3.2, the averaged subjective rating of several authors of this report is provided as regards the safety related issues of the various XADS systems.

The following, concluding observations can be made when analyzing the data supplied in Table 3.2:

All 3 concept obtained essentially the same number of total points (a variance of + / - a few points among the 3 concepts must be judged as absolutely meaningless in such a judgmental exercise) which corresponds to a percentage rating ranging between 55 % to 62 %. Thus all 3 concepts are judged to provide a very similar level of safety, based upon the list of criteria as established in Table 3.2.

On the safety issue of control of reactivity, all 3 systems are considered very similar, each obtaining 5 out of 9 points.

On the safety issue of decay heat removal, all 3 systems are considered comparably effective; each system assigned 6 points out of 6 points.

On the safety issue of confinement of radioactive products, the LBE-cooled systems are considered to be somewhat more effective in the retention of these products on account of the LBE providing an effective material matrix which binds a significant fraction of non-volatile and semi-volatile fission products. The He-cooled concept does not offer an equivalent material matrix which can function as a retention buffer to radio-nuclides.

On the issue of radiation protection of personnel, all 3 systems are judged to provide a similar level of safety. All 3 concepts rely on accelerator tubes directing the proton beam to the core. These beam tubes require shielding. Personnel are thus basically exposed to a similar source of potential radiation. Nevertheless, the LBE concept with the windowless target design presents some advantages in terms of reduced activation of reactor upper structures. Moreover, the fully remote maintenance of the MYRRHA concept is again a favorable feature.

On the issue of transient response of the 3 systems, the LBE-cooled systems are judged to provide a somewhat higher level of safety because of the large thermal inertia associated with the large mass of LBE-coolant in their primary systems. The LBE systems obtained a rating of 12, or 11 points out of a total of 12 in contrast to the He-cooled system with 7 points.

On the issue of general design base, the He-cooled system obtained 5 out of 6 points, the LBE-cooled 4 points each. The He-technology is considered to rely on a larger, more readily available experimental data base obtained during the operation of gas-cooled reactor systems in various European countries during the last 40 years (i.e., Dragon project in United Kingdom, HTR experience in Germany).

On the issue of meeting reliability targets, a similar line of reasoning applies in that the European reactor experience using gas-technology is significantly larger than in the use of LBE-technology. The He-cooled concept was rates 5 points out of 6 whereas each LBE-concept was rated 3 points each.

On the issue of inspectability and maintenance of safety systems, the He-cooled system was judged clearly superior to the LBE-cooled system since the He-coolant allows in-vessel and safety component inspection under transparent conditions and at colder temperatures. It was provided a rating of 8 out of 9 points, whereas the LBE systems were assessed with 3 points each because of the difficulties associated with the in-vessel inspection under non-transparent conditions requiring difficult, still to be developed remote access technology.

As regards system qualifications, all systems were considered to be rather similar, being rated 4, 5, or 4 points out of 6. He-technology is again judged more readily available than LBE-technology, and the MYRRHA design incorporates more innovative features compared to the 80 MW LBE design.

As regards severe accident management, the LBE systems were considered to have a slight advantage because of 1) the large in-vessel retention capability of these systems ascribable to the large LBE-mass in the primary system, and 2) their relative insensitivity to transients. The LBE-systems were rated 12, or 11 points out of a total of 12 whereas the He-cooled system was rated 8 points.

In total, the 3 systems were rated a total of 65, 61, and 63 points out of 87 total points (29 points being minimum points assignable), implying essentially an equivalent level of safety. Expressing the same information in terms of relative percentages, the systems range from 62% to 55%.

The above summary illustrates that the LBE-cooled concepts clearly exhibit an advantage as regards the level of operational safety due the large inherent safety characteristics associated with the LBE-coolant. In contrast, difficult maintenance and lack of available technological data base provide the counterbalance.

In contrast, the He-cooled XADS exhibits very clear advantages as regards operational maintenance and a readily available technological data base. These positive aspects are however counteracted by the operational safety features that rely on the assured availability of active safety systems. By proper optimization of both the core and the design of the plant, these features can be however largely compensated.

Table 3.2 - Concept Assessment Table of the Safety of the various XADS

(Rationale given in the next pages - Data list corresponds to the averaged rating as judged by the authors of the safety chapter and including the comments from WP1 partners).

Safety - Control of the reactivity and the power		**80 MW LBE-cooled XADS**	**80 MW He-cooled XADS**	**50 MW LBE-cooled XADS (MYRRHA)**
Sub-criticality control	***CR1***	1	1	1
Sub-criticality measurement	***CR2***	2	2	2
Power control: simplicity and robustness of Power control system	***CR3***	2	2	2
System Points :		5 / 9	5 / 9	5 / 9
Safety – Decay Heat removal				
Robustness and reliability of normal decay heat removal	***DHR1***	3	3	3
Emergency heat removal effectiveness	***DHR2***	3	3	3
System Points		6 / 6	6 / 6	6 / 6
Safety - Confinement of radioactive products				
Confinement of fission products : source term assessment	***CRP1***	2	2	2
Confinement of spallation products : source term assessment	***CRP2***	3	1	3
Uncertainties assessment	***CRP3***	1	2	1
Long-term constants for all potential core damage mechanisms	***CRP4***	3	1	3
Assessment of confinement structures and safeguard systems capabilities	***CRP5***	3	3	3
System Points		12 / 15	9 / 15	12 / 15

Safety - Radiation protection of personal		**80 MW LBE-cooled XADS**	**80 MW He-cooled XADS**	**50 MW LBE-cooled XADS (MYRRHA)**
Direct and routine exposure to radiation or hazardous material	***RPP1***	2	2	3
Accidental exposure to radiation or hazardous material	***RPP2***	2	2	2
System Points		4 / 6	4 / 6	5 / 6
Safety - Transient response to Protected events				
Potential to fuel damage	***PE1***	3	2	3
Potential to radioactive products release into containment	***PE2***	3	2	3
System Points		6 / 6	4 / 6	6 / 6
Safety - Transient response to Unprotected events				
Grace time	***UPE1***	3	1	2
Potential to criticality	***UPE2***	3	2	3
System Points		6 / 6	3 / 6	5 / 6
Safety - General design basis				
Availability of design rules and criteria	***GDB1***	2	3	2
Uncertainties of models	***GDB2***	2	2	2
System Points		4 / 6	5 / 6	4 / 6
Safety - Reliability targets				
Suitability of systems and functions to safety objectives	***RT1***	2	3	2
Capability of data to assess the concept reliability	***RT2***	1	2	1
System Points		3 / 6	5 / 6	3 / 6

Safety - Inspectability and maintainability of safety equipments		**80 MW LBE-cooled XADS**	**80 MW He-cooled XADS**	**50 MW LBE-cooled XADS (MYRRHA)**
Expected needs for inspectability, maintainability and accessibility for maintenance and repair	***IM1***	1	2	1
Capability to directly look over the inspectability/ maintainability activities	***IM2***	1	3	1
R&D Needs	***IM3***	1	3	1
System Points		3 / 9	8 / 9	3 / 9
Safety - System qualification				
System technology availability	***SQ1***	1	2	1
Materials technology availability	***SQ2***	3	3	2
System Points		4 / 6	5 / 6	3 / 6
Severe accidents – Management				
Sensitivity to accident sequences	***SAM1***	3	1	2
In-vessel corium retention and coolability	***SAM2***	3	1	3
Potential for direct containment heating	***SAM3***	3	3	3
Ex- vessel corium retention and coolability	***SAM4***	3	3	3
System Points		12 / 12	8 / 12	11 / 12
Total Points : Safety		65	61	63
Max/Min/delta Points		87/29/58	87/29/58	87/29/58
Relative Percentage [%]		(65-29)/58= **62**	(61-29)/58 **= 55**	(63-29)/58 = **59**

RATIONALE OF RATING SYSTEM ON SAFETY (from D40, Ref. [16])

Control of reactivity and power (CR) :

Principle: The XADS design shall ensure that the core remains subcritical under all plant conditions (Design Basis Conditions and Design Extensions Conditions). Suitable subcriticality margins shall be set up in order to guarantee that effective multiplication factor is always maintained below one under normal operating conditions and DBC and DEC.

For this purpose, the subcriticality level shall be measured and controlled by adequate systems.

The power produced in the core shall be controlled to avoid situations that lead to the loss of the integrity of the first barriers.

Technical Qualitative Criteria	Rationale
Sub-criticality control	XADS plants must be designed to be subcritical in any plant conditions (DBC and DEC). The reactivity level changes are only due to reactivity insertion, such as water or air ingress, target flooding, etc.. They can be offset with inherent and/or engineered features. Systems with inherent features and passive engineered safety systems should be preferred
Sub-criticality measurement	The uncertainty margins on the reactivity measurement, which depends on the number, localization and type of reactivity detectors, should be small enough to guarantee a correct operation in sub-criticality. Systems where measurement uncertainties are small and have been characterized experimentally must have highest ranking.
Power control : simplicity and robustness of power control system	In the XADS plant, the power generated in the core depends almost linearly on the proton beam current. Thus the power anomalies can be associated to anomalies of the proton beam current and reactivity insertion effects (water ingress, air ingress, target flooding, core compaction, etc.). Generally the former contribution is more important than the latter one. Features that can counteract power anomalies are : inherent features, such as Doppler coefficient, etc., and/or engineered features, as absorber element, control rods, etc.. Systems that react to power excursion with inherent feautures have to be preferred.

Sub-criticality control :	***CR1***
Inherent features + active engineered safety features	**1**
Inherent features	**2**
Inherent features + passive engineered safety features	**3**

Sub-criticality measurement :	***CR2***
High	**1**
Medium	**2**
Small	**3**

Power control :	***CR3***
Engineered safety features	**1**
Inherent features + engineered safety features	**2**
Inherent features	**3**

SAFETY :

Decay heat removal (DHR) :

Principle: The residual heat generated in the core has to be removed by dedicated systems in normal operation, when the reactor is shut-down, or during anticipated operational transient situations and during most types of accidents.

Provision has to be taken for alternative means to restore and maintain fuel under accident conditions, even if normal heat removal fails or the integrity of the primary cooling system boundary is lost.

Technical Qualitative Criteria	Rationale
Robustness and reliability of normal decay heat removal	Systems receive higher ranking when the normal decay heat removal is based on simple design and on passive and active features
Emergency heat removal effectiveness	If the normal decay heat removal is unavailable or the integrity of primary circuit boundary is lost, systems based on passive and active features for transferring decay heat to ultimate heat sink must receive higher score.

Robustness and reliability of normal decay heat removal :	***DHR1***
Active features	***1***
Passive features	***2***
Passive & active features	***3***

Emergency heat removal effectiveness:	***DHR2***
Active features	***1***
Passive features	***2***
Passive & active features	***3***

SAFETY :

Confinement of radioactive products (CRP) :

Principle: The plant has to be designed to retain the bulk of the radioactive materials that might be released from the fuel and target as a result of an accident. Effects of hypothetical severe accidents has to be considered for assessing the capabilities of confinement structure and safeguard systems.

Technical Qualitative Criteria	Rationale
Confinement of fission products : source term assessment	Fuels characterized by high resistance to damage reduce the amount of fission products released in the coolant in case of clad failure should be preferred for meeting the off-site dose goals. During the first step of the Project, fuel will be “classical” (use of proven technologies coming from Na-cooled FRs). Thus, the XADS source term may be compared with the one of FRs.
Confinement of activation and spallation products : source term assessment	Spallation products are a typical feature of ADS. They may give a non negligible contribution to the rise of the Source Term due to fission products. System characterized by a lower increase of source term (IST), defined as the ratio between the total activity due to activation and spallation products and the total activity due to fission products, should be preferred.
Uncertainties assessment	Evaluation of release resulting from each category 3 and 4, and DEC should be performed using “best estimate” approach together with a quantification of uncertainties to determine, for representative scenarios, a spectrum of the possible outcomes. Systems where all dominant phenomena can be accurately characterized and studied experimentally in order to reduce modelling uncertainties receive highest ranking; whereas systems where it is difficult to characterize and bound them are ranked lower.
Long term constants for all potential core damage mechanisms	Systems where long time constants exist for the occurrence of all potential severe fuel damage events, including thermal, chemical and mechanical damage, should be preferred because they allow substantial periods of time to diagnose and correct failures and should make the magnitude of any release sufficiently small to meet off-site risk goals.

Assessment of confinement structures and safeguard systems capabilities	The confinement structures and safeguard systems can be subjected to a range of energy releases with the potential to damage the structures capabilities to hold up radioactive materials. Systems where the timing and magnitude for potential release of all internal stored energy sources, and external energy sources, can be predicted and bounded with high confidence should be preferred. The number of significant energy release mechanism (N_{erm}) is used as surrogate for the probability of containment damage and bypass given a core damage event.

Confinement of fission products : source term assessment :	***CRP1***
Worse than FR	***1***
Similar to FR	***2***
Better than FR	***3***

Confinement of spallation products : source term assessment :	***CRP2***
IST $>$ 0,1	***1***
0,01 $<$ IST $\leq$ 0,1	***2***
IST $\leq$ 0,01	***3***

Uncertainties assessment :	***CRP3***
Dificult	***1***
Medium	***2***
Easy	***3***

Long term constants for all potential core damage mechanisms :	***CRP4***
Intrinsic features lead to severe accident core damage directly following initiating event	***1***
Intrinsic features delay severe accident core damage one hour after initiating event	***2***
Intrinsic features delay severe accident core damage by over 24 hours following initiating event	***3***

Assessment of confinement structures and safeguard systems capabilities :	***CRP5***
$N_{erm} \geq 4$	***1***
$2 < N_{erm} < 4$	***2***
$N_{erm} \leq 2$	***3***

SAFETY :

Radiation Protection of personnel (RPP) :

Principle: To ensure that in all operational states radiation exposure within the installation is kept below prescribed targets and low as reasonably achievable.

Technical Qualitative Criteria	Rationale
Direct and routine exposure to radiation or hazardous material	Attention should be focused on measures (remote handling, predictive maintenance, etc.) implemented in the design to reduce the risk of personnel exposure to radiation or hazardous material.
Accidental exposure to radiation or hazardous material	During an accident, the hazards may be physical (e.g. high temperature or pressure), radioactive and chemically active or toxic taking into account the chemical species produced by spallation reactions. Once hazards are identified, the analysis should be followed up with a screening of safeguards[4] to verify in a qualitative way that workers are protected at a level commensurate with potential for harm. Systems with low risk receive highest ranking. If it is difficult to evaluate the risk without performing calculations, an alternative method is to verify that the type (intrinsic or extrinsic) of protection(s) are used in design to cope with hazards. As an intrinsic ("designed in") protection is more convincing and may be more reliable, low risk has to be assigned to systems with intrinsic protections, medium risk to systems that use both intrinsic and extrinsic protections and high risk to systems with extrinsic protections.

Direct and routine exposure to radiation or hazardous material :	***RPP1***
High risk of personnel exposure	***1***
Medium risk of personnel exposure	***2***
Low risk of personnel exposure	***3***

Accidental exposure to radiation or hazardous material :	***RPP2***
High risk of personnel exposure	***1***
Medium risk of personnel exposure	***2***
Low risk of personnel exposure	***3***

[4] Protection against the hazards

SAFETY :

Transient response – Protected events (PE) :

Principle: The plant is designed so that during any protected incidental and accidental sequences limitation of core geometrical modification and maintaining of core coolability are assured in order to reduce fuel damage and radiological release.

Technical Qualitative Criteria	Rationale
Potential to fuel damage	No systematic clad melting is allowable, because cladding failure represents a basic loss of defence in depth and the fission products are the major contributor to Source Term. The amount of fission products released into primary coolant depends on the number of fuel pins that have lost their integrity and the capability of fuel to reduce the fraction of fission products released into the gap between clad and fuel during normal operation and postulated accident sequences. The number (N_{pe1}) of the protected events reported in the tables 1 and 2 that can be a challenge to the first barrier can be used as a surrogate for the potential to fuel damage.
Potential to radioactive products release into containment	Likewise to the previous point, the number (N_{pe2}) of the protected events that can be a challenge to the second barrier can be used as a surrogate for the potential to release of radioactive products into containment. Systems characterized by a small number of these events must be preferred.

Potential to fuel damage :	***PE1***
Large ($30\% \le N_{pe1}$)	***1***
Medium ($10\% \le N_{pe1} < 30\%$)	***2***
Small ($N_{pe1} < 10\%$)	***3***

Potential to radioactive products release into containment :	***PE2***
Large ($30\% \le N_{pe2}$)	***1***
Medium ($10\% \le N_{pe2} < 30\%$)	***2***
Small ($N_{pe2} < 10\%$)	***3***

SAFETY :

Transient response – Unprotected events (UPE) :

Principle: The plant is designed so that during any unprotected accidental sequences extended core melting is prevented otherwise the coolability of the damaged core is assured.

Technical Qualitative Criteria	Rationale
Grace time	System characterized by large grace times with reference to the unprotected transients listed in the tables 1 and 2 of Appendix 2 must be assigned the greatest score
Potential to criticality	Attention must be given to those severe accident sequences for which significant core damage occur and risk of secondary power excursions due to relocation and compaction of fuel is very high. System characterized by small potential to criticality must be assigned the greatest score.

Grace time :	***UPE1***
Small	***1***
Medium	***2***
Large	***3***

Potential to criticality :	***UPE2***
Large	***1***
Medium	***2***
Small	***3***

SAFETY :

General design basis (GDB) :

Principle: Conservative rules and criteria incorporating safety margins are used to establish design requirements. Comprehensive analyses are carried out to evaluate the safety performance or capability of the various components and systems in the plant.

In addition prevention and mitigation of addressed severe accidents are explicitly taken into account in the design, consistent with overall design and safety objectives. However, best estimate, as opposed to conservative rules and criteria, are used in the evaluation process.

Technical Qualitative Criteria	Rationale
Availability of design rules and criteria	The XADSs are prototype plants with innovative features. Therefore, there is the need to check the applicability of current rules, standards, criteria and properties data of innovative materials to the design of structures, components and systems. Systems that require limited R&D program to make up for the lack of rules, standards and criteria must receive highest score.
System models have small and well-characterized uncertainties	The analysis of design basis operating conditions for the current critical plants with system codes includes the effect of random and systematic uncertainties. For an innovative reactor such as the XADS, the uncertainty level is not well known. It depends on the way to nodalize the system into discrete control volumes and to evaluate the transient processes using finite time step sizes, which introduce numerical errors uncertainties on constitutive relationships and the capability of the system codes to model the phenomena governing the transient response. For the design extension conditions, which have very low mean occurrence frequency, the analyses will be performed without uncertainties, using physically-based assumptions and best-estimate data. Some analysis including uncertainties could be performed in order to identify possible cliff edge effects and in order to verify that the plant design is homogeneous and consistent, without weak Systems that require limited R&D program to validate system codes must receive highest score.

Availability of design rules and criteria :	***GDB1***
Poor	***1***
Medium	***2***
Good	***3***

System models have small and well-characterized uncertainties :	***GDB2***
High	***1***
Medium	***2***
Small	***3***

SAFETY :

Reliability targets (RT) :

Principle: Reliability targets are assigned to safety functions. The targets are established on the basis of the safety objectives and are consistent with the roles of the systems and functions in different accident sequences. Provision is made for testing and inspection of components and systems for which reliability targets have been set.

Technical Qualitative Criteria	Rationale
Suitability of systems and functions to safety objective	The verification of adequacy of systems and functions to achieve their reliability targets is indirectly performed evaluating their classification in terms of LOD. Systems or functions that can be considered as “strong line” must receive the highest score.
Assessment of the capability of systems and functions to maintain their reliability targets	The level of inspectability and testability of a system and function is assumed as parameter to evaluate their capability to maintain and to achieve the reliability target. Systems that can be entirely inspected and tested should be preferred and receive the highest score.

Suitability of systems and functions to safety objective :	***RT1***
Medium	***1***
Medium & Strong	***2***
Strong	***3***

Availability of data to assess the concept reliability :	***RT2***
For nothing	***1***
Partially	***2***
Wholly	***3***

SAFETY :

Inspectability and maintainability of safety equipments (IM):

Principle: Safety related components, systems and structures are designed and constructed so that they can be inspected throughout their operating lifetimes to assure their continued acceptability for service with an adequate safety margin.

Safety related components, systems and structures are the subject of regular preventive and predictive maintenance, inspection, testing and servicing when needed, to ensure they remain capable of meeting their design requirements throughout their operating lifetimes.

Technical Qualitative Criteria	Rationale
Expected needs for inspectability, maintainability and accessibility for maintenance and repair	The needs for inspectability, maintainability and degree of accessibility must be assessed to identify the potential for interaction with the normal plant operations (e.g. drawback on plant availability). Systems with reduced needs compared with the current nuclear plants should be preferred
Capability to directly look over the inspectability /maintainability activities	The visibility through the coolant simplifies the maintenance, testing and inspection activities foreseen by procedures as well as refuelling operation, reducing the personnel's errors. Systems characterized by a high visibility should be preferred.
R&D needs	Systems that require a limited R&D program to assure that they are able to meet design requirements during their lifetime must be preferred. The expenses of R&D needs related to the innovation of systems are accounted in the economic TQC.

Expected needs for inspectability, maintainability and accessibility for maintenance and repair :	***IM1***
Higher than current nuclear plants	***1***
Similar to current nuclear plants	***2***
Lower than current nuclear plants	***3***

Capability to directly look over the inspectability /maintainability activities	***IM2***
Low	***1***
Medium	***2***
High	***3***

Needs for R&D :	***IM3***
High	***1***
Medium	***2***
Low	***3***

SAFETY :

System qualification (SQ) :

Principle: Technologies incorporated into the design of safety systems have been proven by experiences and testings. Significant new design features are introduced only after thorough research and prototype testing at component, system or plant level, as appropriate.

Technical Qualitative Criteria	Rationale
System technology availability	Degree of availability of the implemented technology, operation modes and procedures should be evaluated. Systems that are designed basing as far as possible on experience from earlier operating plants or on the results of R&D program and operation of prototypes should be preferred.
Materials technology availability	Degree of availability of the implemented technology should be evaluated. Systems that use existing technology should be preferred.

System technology availability:	***SQ1***
Low	***1***
Medium	***2***
High	***3***

Materials technology availability:	***SQ2***
To be developed	***1***
Available outside the range of the expected operating conditions	***2***
Available for the expected operating conditions	***3***

SAFETY :

Severe Accident Management (SAM) :

Principle: Principal emphasis is placed on the primary means of achieving safety by prevention of accidents, particularly those which could cause severe core damage.

In-plant and off-site mitigation measures are available and are prepared in order to substantially reduce the effects of an accidental release of radioactive material.

Technical Qualitative Criteria	Rationale
Sensitivity to accident sequences	Systems that have low sensitivity to accident sequences belonging to DECs should be preferred.
In-vessel corium retention and coolability	Systems characterized by high capability to confine and cool corium inside the vessel without any risk of rupture should be preferred.
Potential for direct containment heating	If a vessel rupture happens following a severe accident sequence, the containment may be damaged depending on the type of release and spreading: at high, medium or low pressure. Systems characterized by low pressure release should be preferred.
Ex-vessel corium retention and coolability	For avoiding the containment damage, ex-vessel retention and coolability has to be assured. Systems provided of core catcher and means for assuring the corium coolability have to receive higher score.

Sensitivity to accident sequences	***SAM1***
Following a DEC, the plant is rendered safe by specified procedural actions	***1***
Following a DEC, the plant is rendered safe by passive systems or/and the action of safety systems that are continuously operating or need to brought in service	***2***
Following a DEC, the plant is rendered safe by inherent characteristics	***3***

In-vessel corium retention and coolability	***SAM2***
Small	***1***
Medium	***2***
High	***3***

Potential for direct containment heating	***SAM3***
High pressure	***1***
Medium pressure	***2***
Low pressure	***3***

Ex-vessel corium retention and coolability	***SAM4***
Limited capability of corium retention and coolability	***1***
Medium capability of corium retention and coolability	***2***
High capability of corium retention and coolability	***3***

Section 3.2 - List of References

[1] S. Ehster: “Integrated Safety Approach – Goals, Principles, Rules for Assessment, Safety Design and Criteria” DEL03/006 Framatome ANP SAS

[2] G. Bandini: “Accident Control Mechanisms/Safety Limits” DEL03/034 ENEA

[3] R. Monti: “Design Basis Conditions for Lead Bismuth Eutectic Cooled XADS”; DEL02/019 ANSALDO

[4] K. Peers: “Design Basis Condition (DBC) Scenarios for the Gas Cooled XADS Design”; DEL03/020 NNC

[5] F. Bianchi: “Identification and Probabilities of Design Extension Conditions for Lead-Bismuth Eutectic Cooled XADS – DOC04/031 ENEA

[6] K. Peers: “Identification of Design Extension Condition (DEC) Scenarios for the Gas Cooled XADS Design” DEL04/033 NNC

[7] P. Fernandez: “Containment Design Requirements” DEL04/030 EA

[8] M. Schikorr, et.al. : “Safety Analysis of the 80 MW LBE-cooled Experimental Accelerator-Driven System” –Deliverable 45”, DEL. 04/045

[9] M. Schikorr et.al. : “Transient Analysis of the 80 MW He-cooled Experimental Accelerator-Driven System” –Deliverable 46”, DEL. 04/046

[10] J. Pirson et.al.: “Safety systems and analysis of the small-scale XADS:Sizing, Drawings and Analysis report”, Tractebel Engineering and SCK*CEN, Deliverable 66, DEL/04/066

[11] P.Richard and Al.: “PDS-XADS: Technical Specifications, Missions of XADS, Recommandations for the Main Characteristics” DEL02/001 rev.1 CEA

[12] R.Monti “PDS-XADS – Normal operation for the LBE-cooled XADS” –Deliverable 43”, DEL. 04/043 ANSALDO

[13] G.Francois “PDS-XADS – Normal operation for the He-cooled Experimental Accelerator-Driven System” –Deliverable 44”, DEL. 04/044 FANP-SAS

[14] P.Richard “PDS-XADS –Main specific safety phenomena of the Gas-cooled XADS” –Deliverable 42”, DEL. 05/042

[15] "European Utilities Requirements for LWR Nuclear Power Plants", Revision B, November 1995

[16] P. Richard et.al.: “Definition of Methodology and Criteria for the XADS Concept Comparison”; DEL04/040 CEA

3.3 Structural Integrity/Robustness

3.3.1 Introduction

For the three concepts the most critical issue is the structural integrity of the target components facing very high irradiation damages. This is particularly true for the concepts using a beam window for which a sound value of the lifetime cannot be assessed on the basis of existing data. With this respect, the LBE cooled XADS relies on a windowless target for which “reasonable” lifetimes should be attainable. For the Gas-Cooled XADS the solid target option with a cold window should be developed to improve lifetime and window replacement aspects.

This chapter was initially devoted to review the structural integrity and design margins of each reactor type. In the course of the studies, as far as the primary system is concerned, this was not revealed as a major critical issue. Only the main trends are dealt with. On a generic standpoint for the LBE systems, the key issue is the compatibility of the LBE coolant with the reactor structure materials. It must be adequately demonstrated that thanks to engineering measures such as controlled oxidation protection layer, severe corrosion damages can be totally excluded.

3.3.2 Structural integrity of the 80 MWth LBE-Cooled XADS

The design shows comfortable margins provided that horizontal anti-seismic supports are used. The small core ΔT considerably reduces the magnitude of the potential thermal stresses on reactor structures. The pending issue is the evaluation and qualification of the sloshing effect evaluation at coolant free surface and loading impact on the structures.

3.3.3 Structural integrity of 80 MWth He-cooled XADS

The design is still at a very preliminary stage and only key issues have been dealt with mainly on the basis of engineering judgement and Design by Formula approach. The main issue is the structural integrity of the reactor thimble facing significant irradiation damages. The lifetime of this thimble and the material selection requires further considerations and needs to be backed by representative testing before assessing the lifetime of this component. It seems however that a higher operating temperature should be a prudent choice at least for the reference T91 ferritic material.

3.3.4 Structural integrity of the 50 MWth LBE-cooled XADS (MYRRHA)

The mechanical and thermomechanical assessments of the MYRRHA concept were developed separately within the WP 5.3. From the documentation, the design is showing acceptable margins. However two issues specific of the MYRRHA design will deserve further assessments :

• The shell “diaphragm” separating the hot and cold plenum is facing both significant primary stresses (ΔP between the two collectors of about 5 bars) and secondary stresses (ΔT of about 140°C). The detailed design of this complex component involving a lot of penetrations/welds will deserve further assessments. Moreover, this component has to be almost leak tight to avoid leakage and associated problems (erosion/corrosion/thermal fluctuations/..). Piston rings can be used for axisymmetric penetrations but the leak tightness at the level of the radial core support plate integral with the spallation module seems difficult to achieve.

•The lower part of the vessel is a flat bottom submitted to a relatively high pressure (hydrostatic + core ΔP of about 12 bars) which is commonly not the case in conventional Fast Reactor vessels.

• The reactor vessel is supporting the reactor cover (lid) and the components. This allows to avoid the complex expansion bellows generally considered for rested vessels. However, verifications of the vessel structural behaviour in case of seismic loadings is still to be done.

3.4 Economics

3.4.1 Accelerator economics

The cost of the Reference XADS LINAC (600 MeV, 6mA) is assessed in Deliverable 63, Ref. [1] from EISS project. The construction cost of the facility amounts to 303 M€ at 2003 economic conditions. This figure includes capital investment and engineering during construction as well as infrastructure investment of 30 M€. This estimate would be considerably reduced for a lower energy and if a single injector line was considered (in case of relaxed reliability requirements). As concerning operation cost, the concept of using superconducting technology from a very low energy range is cost effective. The construction phase for the accelerator and its infrastructures would typically last 7 years.

A breakdown of the reference construction cost is given in Tables 3.4.1 and 3.4.2 :

Major sub-systems	Costs (M€)
Low Energy *	46
Intermediate Energy	18
High Energy	57
RF Power System	45
HEBT + Beam dump (500 kW)	21
Diagnostics + Vacuum + Control System	54
Cryogenic plant	20
Production assembly Hall of cavities	12
Total Estimated Costs (M€)	**273**

* including 2 Injector lines

Table 3.4.2 : Cost estimates of Linac associated building (in k€)

Buildings	Civil Engineering	Electricity & HVAC distrib.	Total
Front - End	7 000	3 000	10 000
Linac tunnel	4 500	1 500	6 000
Klystron Hall	3 000	7 000	10 000
Central Liquifier	600	900	1 500
Production assembly Hall	1 250	1 250	2 500
Total (k€)	16 350	13 650	30 000

Table 3.4.2 : Cost estimates of Linac associated building (in k€)

In addition, preliminary figures were provided during a topical day in SCK-CEN (Mol) “ From MYRRHA towards XT-ADS” about the extrapolation of this cost to the MYRRHA accelerator and associated electrical power consumption. Figures are listed in the Table 3.4.3.

Accelerator Characteristics		**600 MeV XADS Linac**	**350 MeV MYRRHA Linac**
Linac main characteristics	Beam power	3.6 MW	1,75 MW
	Linac total length	~ 280 m	~ 200 m
Electrical Power consumption	**Total AC power consumption**	**~ 21,5 MW**	~ 9,5 MW to 15,9 MW depending on injector philosophy and extent of SC
Construction cost estimates (incl. Investment and Manpower from design up to commissioning)	Major sub-systems	273 M€	Rough extrapolation 170 to 210 M€
	Associated buildings	30 M€	Rough extrapolation 15 to 25 M€
	Total construction cost	**303 M€**	**185 to 235 M€**

Table 3.4.3 : Comparison of the costs of the XADS and MYRRHA accelerators

3.4.2 Reactor economics

The stage of development of the three concepts being very different, a detailed cost comparison would be unfair and impracticable. For instance the stage of development of the Gas Cooled XADS is not sufficient to derive sound cost estimates on both reactor primary system and components and reactor building. The components are still in a very early development stage and the reactor vessel and internals are significantly oversized in terms of dimensions and weight balance. This chapter will be just devoted to the comparison of dimensions and physical quantities of the three reactor concepts which are reported in Table 3.4.4:

Reactor concept	**80 MWth LBE**	**80 MWth Gas**	**50 MWth LBE (MYRRHA)**	**80 MWth Na**
Power (MWth)	*80*	*80*	*50*	*80*
Core External Diameter, shielding included (m)	*1,3*	*1,62*	*1*	*1,3*
Assembly height, spike included (m)	*3,6*	*4,8*	*2*	*3,6*
Overall Core volume (m^3)	*19*	*40*	*6*	*19*
Reactor Vessel Diameter (m)	*6*	*4,3*	*4,4*	*5,6*
Reactor Vessel Height (m)	*10,6*	*15*	*9*	*11,6*
Reactor Vessel Volume (m^3)	*300*	*218*	*137*	*286*
Reactor Main Vessel weight estimate (Tons)	*72*	*310*	*51*	*54*
Reactor Main Vessel material	*SS 316 L(N)*	*Ferritic Steel Mod 9%Cr*	*SS 316 L(N)*	*SS 316 L(N)*
Reactor Building Footprint (m^2)	*855*	*740*	*1500*	*not assessed*
Reactor Building/Hall Height (m)	*47,5*	*56*	*30*	*not assessed*
Reactor Building Volume (m^3)	*40627*	*41453*	*45000*	*not assessed*
Total Reactor Building Height (m)	*47,5*	*56*	*40*	*not assessed*
Estimate of N.I building Volume (m^3)	*120000*	*not assessed*	*120000*	*not assessed*

Table 3.4.4 : Reactor Concepts comparison

Some parameters of the Gas-Cooled XADS seem less favourable than the LBE-Cooled XADS like, extent and weight balance of the primary system, height of the reactor building, additional shielding, three safety graded SCS loops, core catcher. On the other hand, the unit cost of primary system structures will be much less (ferritic steel and PWR technology compared to Stainless Steel FBR technology in case of the LBE systems) and the cost of the coolant itself will be very significant compared to the cost of primary system.

From the comparison of the dimensions of the three liquid metal cooled reactors the cost should remain of the same order of magnitude. A comparison point in the range of 300 M€ is given for a 80 MWth sodium cooled Reactor (without accelerator) (see Section 2.5.3).

The development (R&D cost) is likely to be higher for the LBE reactors compared to the gas which can take benefit of parallel developments on GCFR and HTR.

It must be pointed out that the extent/volume of the Reactor building is rather large for such small Power Units reactors. This can be mainly explained by the penalty on the overall height of the Reactor to accommodate the Accelerator Beam Transfer line and also the Target Handling Flask in the case of the Gas-cooled XADS.

Further comparisons with other projects of Experimental Reactors would be interesting.

3.4.3 MYRRHA cost assessment

Within the work package 5.3 of the PDS-XADS project, devoted to the small-scale LBE-cooled XADS (MYRRHA), a first cost estimate of the construction of such a machine in Mol has been provided in Deliverable 84, Ref. [2].

This cost estimate is made on the so-called "Draft-2" evolution of the MYRRHA design, with a nominal power of 50 MWth, as described in the other deliverables of this WP 5.3. This cost evaluation is based on 2004 economical conditions without taking into account financial charges during construction.

An estimated total of 440 M€ is obtained and taking into account the possible contingencies on the different items, a global "high total" of around 560 M€ is also be estimated.

This cost includes the MYRRHA accelerator cost of 185 M€ consistently with Section 3.4.1. The reactor cost is therefore in the range of 255 M€ to 355 M€, rather consistent with the estimate derived from sodium cooled reactors.

This estimate does not include the cost of engineering during construction, which typically amounts to 20% of the construction cost of such a prototypical machine.

The R&D cost, commissioning & operational costs, dismantling costs at the end of cycle (which however may be estimated to range between 15 and 20% of the construction costs) are not included either.

Section 3.4 - List of References

[1] J.L Biarotte and Al.: PDS-XADS Deliverable 63 “Definition of the XADS-Class Reference accelerator Concept and needed R&D”, DEL04/063 rev.1 CNRS

[2] D.De.Bruyn: PDS-XADS Deliverable 84 “Small-Scale XADS: Cost evaluation and further scaling”, DEL05/084 SCK-CEN

4. OPTION VALIDATION STATUS (R&D Needs)

R&D needs have been specified for the different components and concepts of an XADS as a result of the work performed during PDS-XADS project and documented in the deliverables of the associated working packages. 37 "R&D Question Sheets" have been issued within ADOPT network. This section summarises the requested R&D needs. More detailed information can be gained from the quoted deliverables or "Question sheets".

The R&D needs, which the Gas-cooled and LBE-cooled XADS have in common (both 80 MW^{th} and 50 MW^{th} for MYRRHA) are discussed at the beginning of this section which is divided into the following sub-sections:

- Reactor Physics
- Fuel Development
- Main Components / System qualification
  - Target/Window
  - Proton Accelerator

The R&D needs specific to each of the two systems are discussed later using the following categories:

- Thermal-hydraulics
- Materials Research
- Main Components / System qualification
- Safety

4.1 Gas and LBE-cooled Systems

4.1.1 Reactor Physics

4.1.1.1 Uncertainties associated to the ADS core characteristics and the spallation source /1/, /2/ (Ref. 1 and 2 at the end of Section 4)

The importance of having an accurate knowledge of the prevailing level of sub-criticality is very much associated to the safety approach of the ADS as the core should remain sub-critical under all foreseeable plant conditions. This should include calculation uncertainties. Other characteristics are not directly associated to safety issues but large uncertainties affect the optimisation of the design and therefore a reduction in these uncertainties is highly desirable. Core characteristics to be considered are: criticality and sub criticality levels, reactivity coefficients, importance of the source, power peak in pins located at the periphery of the core, power distribution including core, reflector and spallation module regions, and dynamic constants. The following actions and results should be taken and are proposed as objectives in the FP6 EUROTRANS/NUDATRA programme:

- Nuclear data evaluation for: Lead, Bismuth and MA isotopes
  - i.e. for improved accuracy of radiation damage and circuit activation calculations /3/
- Improvement of experimental database /2/
  - Energy deposition
  - Spallation product yields
  - Reduction of uncertainties associated to spallation source (CEM vs. Bertini model /4/; Neutron yields, neutron spectra and reaction rates)
- Definition of uncertainties on XADS characteristics with nuclear data covariances associated to evaluation used for the design
- Verify adequacy of uncertainties with integral experiments and try to reduce uncertainties

- Improvement and qualification of simulation tools (codes and libraries)

4.1.1.2 Control and instrumentation of an ADS /5/

Variations in the total power level for an XADS/XADT can be eventually considered as arising from two independent contributions which are directly proportional to the sub-criticality level and to the source strength. The dynamic decoupling between the sub-critical core and the spallation source requires, that in order to maintain the XADS/XADT at a fixed power level, reactivity changes occurring during operation, are compensated by a corresponding change in the source strength. The actions for maintaining the pre-set power level shall be necessarily based on instrumentation readings from the core and the core cooling system. The signals shall be conveyed and displayed to the plant operator console for undertaking the appropriate source strength adjustments through the accelerator control system as needed.

The core instrumentation is therefore deeply associated to the safety philosophy of an ADS (and furthermore to the experimental aspect of the XADS) and particular attention should be given to its design.

According to a preliminary list of devices and systems envisaged for the monitoring of the core in /5/ the experimental verification in particular of:

- in core fission chambers (positions and responses within the sub assemblies, within the reflector or within the spallation module) behaviour with temperature and irradiation,
- in line reactivity (SPJ) measurements and accuracy attainable,
- monitoring of source via neutron detectors and accuracy reached

should be requested for future R&D programs that could start from the experience gained in MUSE and is planned for the EUROTRANS FP6 coupling experiment programme.

The list is not exhaustive but an over-sizing of the control systems might lead to new incident initiators while a too few sets of measurements might lead to insufficient control and safety characteristics.

As no-one can judge definitively on results of these R&D works, a reference approach should be taken based on the limited R&D risk and other expert systems envisaged as back up solutions.

4.1.2 Fuel Development

As summarised in /6/ two different stages are considered in the XADS fuel development:

1. The use of conventional fuel (evoked as phase 1)
2. Advanced fuel options (phase 2)

For the first stage, two approaches can be followed:

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

assembled into assemblies of a new design, or, eventually, the fuel pins can be re-fabricated into new fuel pins ;
- The fabrication of new MOX fuel elements. This has the advantage that the design can be adapted to the core design of the XADS. There doesn't seems to be technical problem for the fabrication of new MOX fuel elements. It can be done in existing industrial facilities although their future availability cannot be guaranteed.

Regarding the first approach it has been shown in /7/ for the gas-cooled version of the XADS that on account of the large number of SPX sub-assemblies required (378) to generate 80 MWth, as well as on account of the thermal-hydraulic limitations encountered by the current SPX sub-assembly and fuel pin design, it was decided not to pursue the SPX fuel element option for the gas-cooled XADS design any further. From the thermal-hydraulic point of view, the use of existing SNR300 sub-assemblies in the gas-cooled version of the 80 MWth represents however a feasible option.

Both fuel types are suitable for LBE-cooled version of XADS but the SPX-R2 high-enrichment U-Pu MOX fuel, which contains a fissile concentration of about 20% HM Pu, has been selected for constituting the basis both for composition and diametric dimensions of the fuel pin for the XADS reference fuel rod /8/. Most R&D issues for oxide fuel are related to the cladding materials. These problems are discussed in more detail in sections 4.2 and 4.3.

4.1.2.1 Minor actinide loaded advanced fuels, safety behaviour and integration in the core /9/,/10/,/11/12/13

The choice for the advanced fuel is not obvious at present. Oxides and nitrides are considered the most promising fuel materials (but metal fuel also is being studied), oxides (either as mixed transuranium oxide or as inert matrix oxide) being the primary candidates for the XADS /14/. Whatever the choice will be the following problems have to be addressed:
- Fission gas and He behaviour
- Curium management which requires simple, compact and robust fabrication process to deal with the high decay heat and neutron sources. Other fuel forms than pellets form, e.g. VIPAC fuel, may be considered.
- Design and fabrication of advanced fuels considering:
  - Thermal stability of envisaged fuel
  - Thermal conductivity of fuel and of fuel with cladding in case of pin fuels
  - Mechanical resistance of CERCER and CERMET blocks (gas core)
  - MA density, maximum MA over Pu ratio
- Safety behaviour:
  - Stability of envisaged fuel compounds (homogeneous and composite fuels) at high temperature and under melting conditions
  - Dispersiveness of fuel configurations
  - Behaviour of un-clad pin stubs
  - Fuel/coolant interaction/redistribution
  - Fuel pin failure modes
  - Small scale out-of-pile experiments to increase basic phenomenological understanding
- Development and realisation of experimental programme for irradiating those fuels.

4.1.3 Main Components / Systems Qualification - General

4.1.3.1 System Allocation /15/

The objective of the project "Preliminary Design Studies of an XADS" is to address the critical points of the whole design, the coupling of the three elements of the ADS (accelerator, spallation target and sub-critical reactor), the safety and licensing issues, and the road mapping for the XADS. Within this objective main elements and systems required for plant operation have been identified. Also from the safety point of view criteria for system classification and design criteria for safety system have been developed. Accordingly with the preliminary status of design development those criteria mainly apply to the design of what can be called front line systems. It is therefore required to further develop safety systems design taking into account the support systems required for each safety system to perform their required function as well as the interfaces between systems. It is also necessary to adapt design requirements in accordance with the findings reached in other R&D projects.

The objective of the required R&D activities is to provide a complete picture of the systems required performing safety function advancing in the identification of:

- Safety system required
- Support system required for each front line system
- Design requirements for each support system
- New or modified requirements deduced from new findings from other R&D projects
- Develop more detailed design requirements based on simplified reliability and availability models.

4.1.4 Main Components / Systems Qualification – Target

Lead-bismuth eutectic (LBE) will be used as a coolant not only for the primary core system of the LBE-XADS but also the spallation target. Therefore most of LBE related R&D issues do apply to LBE-cooled and gas-cooled XADS and are discussed in this section.

4.1.4.1 LBE chemistry/corrosion control and monitoring /2/,/16/,/17/,/18/,/19/

The main objective is to ensure that the LBE remains liquid in all operating conditions (avoid lead oxide build-up at any temperature, avoid other oxides built-up or/and mass transfer within the system, ...) and that the mechanical structures are protected against corrosion.

The first objective has to be ensured by chemistry control and monitoring the second one by corrosion protection. Prevention of corrosion-erosion of the structural steels in contact with the Lead- Bismuth Eutectic (LBE) melt is made, for the reference XADS design, by maintaining a continuous, compact metal oxide film adherent to the metal substrate of the structures. This implies the presence of dissolved oxygen in the molten LBE.

Both issues, chemistry and corrosion control, are closely linked to each other as for instance, in situ oxide layer is linked to the oxygen monitoring and control processes to a specified concentration that favour the oxide film formation. As a second example, the purification requirements are based on the corrosion rate relationships, that would give the impurities pollution sources in normal operating conditions.

A third topic is related to the contamination issue, as the corrosion products are partly activated due to the neutron flux, and as some fission products and mainly spallation and other activation products will be generated during normal operating conditions. In addition, several comments were raised concerning motivations and requests for target purification from toxic nuclides, especially Po, from a safety point of view in case of loss of confinement.

Strong links exist also between these topics, as all impurities behaviour in the LBE is due to their chemistry with dissolved oxygen, in particular, so that all of these impurities (corrosion, spallation and activation) could be addressed at the same time. Thus, it should be divided into four main sub-topics:

- Oxygen monitoring system:
  - Confirmation of the feasibility of reliable sensors for oxygen activity measurement
  - Improve reliability for nuclear use
  - Improve predictability by calibration procedure, including recovery procedure and cross calibration
  - Recommendations for nuclear design
  - Accurate data for solubility (O, Fe, Ni, Cr, etc.) and diffusivities (O, Fe, Ni, Cr, etc.) for calibration on the field and sensor design
- Oxygen control processes:
  - For the H2O/H2 equilibration process, validate mass transfer across the gas-liquid interface and scaling-up, by establishing the relationship across the interface
  - For the separate H2/O2 addition process, further validation for intermediate oxygen concentration control is required
  - For the PbO dissolution process, acquisition of process data for dissolution rate (temperature, flow rate), as well as the pelletising process for the lead oxide pellet fabrication
  - Recommendations for design (process and operation), especially as regard the issue of the homogeneous or not distribution of the dissolved oxygen within the spallation target
  - Other related data such as the oxygen solubility and diffusivity, the oxygen distribution within a system, as well as the various pollution and consumption rates for a given system
  - Confirmation of the possibility of oxygen control in large plena of LBE
- Solid impurities control and management:
  - Monitoring of impurities by determining operating conditions for liquid metal sampling
  - Determine efficiency of different processes available that could be applied:
    - Simple free surface settling filter unit to remove oxide particles as well as the efficiency of purification by decantation
    - Purification by filtration (Development of a Russian type filter unit in case of non-adequacy of free surface filter and large scale test if needed)
    - Activation and spallation impurities analysis from viewpoint of chemical or radioactive toxicity in order to define processes that can deal with these impurities
- Gaseous impurities control and management (compare to section on spallation vapours/Polonium):
  - Define adequate strategy to manage gaseous products: confine or remove
  - If chosen strategy is to remove, define corresponding removal techniques

4.1.4.2 Verification of corrosion protection layers /20/

In the lead-bismuth eutectic (LBE) cooled XADS, the T91 steel has been selected both for the structural fuel assembly components not involved in heat transfer processes (e.g. the central tie-rod, the spacer grids and the wrapper) and for the fuel cladding. While the operating conditions (primarily temperature) of the former are such that no significant mechanical property degradation is anticipated during the expected lifetime, potential problems may be experienced by the fuel rod cladding. Aluminization of its outer surface may be required to limit corrosion at the expected operating temperatures.

Although this measure is up to now envisaged for the LBE cooled XADS only it might be attractive also for spallation target materials. The goals of the required, mostly experimental R&D are:

- to demonstrate the feasibility to aluminise large areas with small aluminium layer (order of 20 µm) with no significant reduction of its mechanical properties
- confirm that protective Al-layer does not undergo degradation in flowing LBE environment, including in regions subject to fretting corrosion
- verify that aluminization does not cause material embrittlement under neutron irradiation
- extend the available information on irradiation induced embrittlement to lower temperatures

4.1.4.3 Characterisation and assessment of means for removal of spallation vapours /21/,/22/

The spallation target LBE is generally kept separated from that of the primary system, in order to limit the pollution by spallation products. The hydraulic separation is in any case required for the windowless target, where a free surface of flowing LBE is directly exposed to the ultra-vacuum tube, with the proton beam impinging. About one kilogram of spallation products can be estimated to form for one year operation at the maximum beam power (3.6 MW for the PDS-XADS).

A fair quantity of the spallation products is released in the gaseous state, mainly composed of ordinary gases (hydrogen and noble gases) and of elements which could be fully vaporised at the target operating temperatures (such as Hg, Br, I, etc) or have significant vapour pressures (Cs, Se, As, Po, etc). Vapours of these elements which, together with some Pb-Bi, stream into the beam tube above the spallation zone, must be removed in order to both maintain vacuum at the required level and avoid propagation through the beam line, with potential pollution up to the accelerating cavities. Moreover these gases represent a potential contamination source for the beam line and accelerator parts, with added safety issues.

The definition and design of a spallation gas removing system or other safety measures require R&D on:

- Characterisation of spallation nuclides (vapours or gaseous)
- Pb-Bi evaporation rate in vacuum
- Development & validation of the conditioning and outgassing procedures of LBE to minimise outgassing
- Characterisation end test of propagation of vapours and gasses along evacuated pipes
- Test of spallation product formation in LBE target (MEGAPIE Tests)
- Test of evaporation of:
  - Pb-Bi
  - Spallation products contained in Pb-Bi (or their similarities)
  - activation products contained in Pb-Bi (or their similarities)
- confirmatory tests of trapping system of volatiles (cryopumps, turbopumps, getter pumps)

4.1.4.4 Polonium /23/,/11/

Although this topic is strongly related to the one discussed above it has to be considered as a special item due to the large radiotoxicity of Po210. In the lead-bismuth eutectic (LBE), radioactive Po210is generated as a consequence of neutron absorption by Bi. Po210 generation takes place in the target, the core and also in the primary LBE outside the core region (in case of LBE-cooled XADS). A fraction of it then escapes from the LBE, moving either into the proton beam guide pipe (in a windowless target configuration) or into the primary system cover gas plenum and connected piping and components (such as those belonging to the cover gas circulation and purification system). Both in the cover gas and the proton beam guide pipe it therefore contributes to the total radioactive contamination, in addition to gaseous and/or volatile fission products due to failed fuel rods as well as gaseous and/or volatile spallation and activation products generated in the LBE. To design the vacuum system in the beam pipe and the cover gas purification system on the one hand and, on the other hand, to estimate radioactivity releases under accident conditions following R&D is required:

- reliable prediction of Polonium release rates:
  - LBE free surface (windowless target)
  - LBE free surface with argon cover gas, LBE flowing in natural convection
  - LBE free surface with argon cover gas, LBE flowing in natural convection enhanced by argon gas injection
- Construction of algorithms describing Polonium release rates
- Polonium propagation along pipes and deposition mechanisms and rates on metal structures
- Small and large scale experiments with Polonium-simulates
- Small scale experiments with Polonium

4.1.4.5 Verification of the windowless LBE target /22/,/24/

The proton beam produces heat as by-product of the spallation into a restricted zone of flowing liquid LBE. In order to skip the interposition of a structural wall between the impinging protons and the LBE, that may put at risk the target life, a circulation pattern is produced locally so that a liquid LBE free surface is directly exposed to the impinging protons. The accelerator cavities that require an inner Ultra High Vacuum UHV are in connection, without any structural barrier (windowless), with the ambient on top or the free surface in the spallation zone that collect vapours of the heated LBE and other elements generated by spallation. The novelty of the UHV techniques applied in the presence of hot LBE with various added elements requires R&D:

- Validation with small scale experiments the techniques for the UHV in presence of hot LBE with different contaminants representing the spallation products
- Vacuum interface (see also section 4.1.4.3):
  - Develop and validate the conditioning and degassing procedures of LBE to reduce/minimise degassing to an acceptable level
  - Establish the dynamical behaviour of vapour/spallation products from the target taking into account absorption and desorption processes on beam line walls
  - Modelling of plasma formation in presence of proton beam to validate the envisaged pressure range
  - Validate vacuum pumping system taking into account:
    - Pumping capacity
    - High temperature – high radiation level environment
    - Minimal maintenance
    - reliability
- Validate collection procedure of radioactive spallation products at end of vacuum system
- Validate with partial mock-up experiments the hydraulic pattern and shape of the LBE free surface in vacuum presence and the circulation propeller capability
- One-to-one scale experiments under vacuum conditions:
  - Using water as simulating fluid
  - Using LBE
- Evaluation of alternative LBE pumps:
  - Helix pumps
  - Electromagnetic pumps

For the validation of flow control following issues have to be addressed:
- Development of a CFD system and benchmarking by experiments in order to have a tool for heat transfer calculations
- CFD simulations of proton beam heating
- One-to-one scale experiments of the full windowless spallation loop (and in presence of beam heating)
- validate with an integral test the windowless target primary loop circulation with internal heat source and heat removal by the intermediate exchanger

4.1.4.6 Verification of LBE target natural convection /25/

In the window spallation target, the structural material, especially the beam window, is exposed to a high irradiation and thermal loads. A safe heat removal from the spallation target is one of the key issues in designing the target. Heat is removed from the spallation target via natural convection. The heat exchanger is inserted into the target module.

A large deficiency exists in the basic understanding of the heat transfer behaviour (also section 4.3.1.1) and in tools for the target design. For the final design of the target, transient behaviour under start-up and beam trip conditions is required. The reliability of the numerical tools, which have been applied during the PDS-XADS project, needs to be validated by experimental studies.

Oxygen control systems are required to prevent corrosion of the structural material. Although, in FP5, separate studies have been performed to develop oxygen control systems, the applicability and the performance of such systems to the target module configuration needs to be verified, and if necessary, to be improved

The goal of the R&D activity is to experimentally demonstrate the integral performance of the heat removal system and the oxygen control system in the spallation target module. There is a need to establish a large scale experimental system to simulate the complete interaction between various components and to enable a design optimisation of the target module. The items to be studied are:
- Local heat transfer under natural or forced convection condition
- Hydraulic behaviour of the components in the heat removal chain
- Heat transfer performance and optimisation of the heat exchanger
- Cooling capability of the beam window at steady and transient conditions
- Heat removal capability from the target module under steady state and natural convection conditions
- Transient flow and temperature distribution in the target module under natural convection conditions
- Assessment and optimisation of oxygen control systems for the target module
- Optimisation of geometric parameters of various components in the heat removal chain

4.1.4.7 Thermal hydraulics /2/

Two kinds of computer codes, i.e. computational fluid dynamics (CFD) codes and system codes, are necessary for thermal hydraulic design of the spallation target unit. R&D is necessary on:
- CFD codes:
  - Assessment of Turbulence models
    - Recirculating Flows
    - Stagnation heat transfer

  - Study for turbulent Prandtl number
  - Study for Free Surface Modelling
- System Codes:
  - Assessment of fundamental correlations
  - Enhancing basic knowledge under specific transients

4.1.4.8 Material irradiation and testing /2/

Radiation damage in structure materials of a target unit is a key issue for all target options considered and is, to a certain extent, independent of the option. In order to assure the envisaged window lifetime of 3 to 6 months the current experience with irradiation damage at temperatures from 400 °C to 500°C has to be improved significantly. For other structure materials of a target like guide tube, main shell and baffles, reliable experimental data for the required boundary conditions are needed to assure material integrity after the irradiation.

Components for ADS have to be designed according to design rules established for nuclear power plants, for XADS the RCC-MR has been agreed. Currently there are no irradiation effects included in the RCC-MR for the reference material T91. Therefore results of experimental investigations on irradiation behaviour of materials have to be evaluated with respect to an implementation in these design rules in order to provide a sound basis for the mechanical design of target units.

4.1.4.9 Large scale integral experiment on prototypical window target unit /2/

Design of a target unit in an accelerator driven system relies on a large number of basic information available from various experimental and theoretical investigations performed world-wide in the frame of programs supported by the EC.

Experimental investigations on selected technical effects and physical characteristics and their results can depend on boundary conditions relevant for these experiments. Therefore they often cannot consider the wide range of influence for all requested operating conditions and cannot give answers to all questions of interest.

Megapie as an integral experiment of a spallation target module with the same structural material (T91) as XADS target unit, an operating proton beam and a forced convection LBE heat removal system via an internal heat exchanger is expected to give answers to several items also interesting for a XADS target unit. R&D should be done to evaluate the

- experience from operation of Megapie:
  - behaviour of components
  - measurement of evaporation of spallation products contained in LBE
  - applicability and reliability of instrumentation
  - comparison of calculated and measured target temperatures, neutron fluxes and power densities
  - activation and decay heat of LBE and structure material
  - experience with beam trips and consequences on target

  - experience with target handling
  - long term behavior of spent targets in the target repository
- experience from post irradiation:
  - radiation damage of structure materials at different positions, correlation with neutron irradiation and helium production
  - mechanical properties of structure materials as function of radiation damage, helium and hydrogen production for implementation in design rules (RCC MR)
  - corrosion behavior of structure materials under neutron and proton irradiation
  - analysis of target LBE with respect to spallation and corrosion products

4.1.5 Main Components / Systems Qualification – Proton Accelerator

One of the major requirements for a transmuter demonstrator is the reliability of the driver accelerator, i.e. a very low number of so-called beam-trips (unwanted interruptions of the beam that last longer than a certain time: typically the order-of-magnitude is a second). A reliable accelerator should not exceed a number of a few trips per year.

The strategy to implement the required reliability relies on over-design, redundancy and fault-tolerance. This approach requires a highly modular system where the individual components are operated substantially below their performance limit. A superconducting LINAC, with its many repetitive accelerating sections grouped in "cryomodules", conceptually meets this reliability strategy. It further allows keeping the activation of the structures rather low, important for radioprotection and maintenance issues, in turn strongly influencing the capital cost of the machine.

During the last years, and related to the foreseen projects for high-intensity proton accelerators, several R&D programs have been started in different laboratories around the world. An overview of the status of this work is given in /26/. The main focus of a R&D program for FP6 taking into account the results of PDS-XADS and other international projects will thus be an experimental evaluation of the reliability performances of the main components of the reference accelerator configuration that has been elaborated within the PDS-XADS study. Five essential tasks have been identified and discussed in detail in /26/:
- Experimental evaluation of the proton injector reliability
- Assessment of the reliability performance of the intermediate energy accelerating components
- Qualification of the reliability performance of a high-energy cryomodule at full power and nominal temperature
- Design and test of a prototypical RF control system for fault tolerance operation of the linear accelerator
- Overall coherence of the accelerator design, final reliability analysis, and cost estimation of XT-ADS

4.2 Gas-cooled Systems

4.2.1 Thermal-hydraulics

It has been shown in /27/ that for gas-cooled XADS the limiting clad temperature of app. 700 °C will be reached for smooth pins even in steady state. Therefore clad temperatures have to be minimised by sub-assembly gagging and clad surface roughening. There exist considerable uncertainties due to different heat transfer and friction correlations between coolant and clad.

That leads to the following conclusions for future R&D /27/:

- The suggested geometry for clad surface roughening is based on previous work. Nevertheless more detailed studies, including investigation of other optimised geometries have to be carried out.
- The effect of sub-assembly gagging and clad surface roughening on the transient behaviour has to be analysed.
- Working close to material limits the minimisation of uncertainties due to different heat transfer correlations is a very important issue. That should be done as soon as possible by an experimental program. This could cover also studies on the influence of clad roughening on thermal-hydraulics. Some of the questions which have to be answered in this context are included in /28/:
  - What are suitable heat transfer and friction correlation for tube bundle configurations with roughened clad? (from turbulent to laminar flow region)
  - What parameters determine the heat transfer and friction factor correlation?
  - What uncertainties exist for the heat transfer and the friction with roughened clad?
  - What effects will normal manufacturing tolerances and pin support grids have on heat transfer and friction correlation?
  - What is the experience of wear and erosion of rib profiles during operation?
- Additional studies are required about effects of fuel rod, fuel element and possible core vibration induced by flow regimes and flow pathways /29/.

It can be concluded that the existing thermal-hydraulic analysis is a good basis for further development of a gas-cooled XADS. But more detailed R&D is required to answer open questions. Since a gas-cooled system works quite close to material limits further R&D should also include the investigation of effects of manufacture tolerances on thermal-hydraulics and how they develop during operation.

4.2.2 Materials Research

The material selection is based on experience gained in European fast reactor development. The current material choice, which does not exclude other materials that might be more appropriate for gas-cooled XADS, is described in chapter 8 of /27/.

4.2.2.1 Choice of pin clad material

The most important tasks of future R&D for the choice of a suitable fuel pin cladding have been identified in /30/:

- AIM1 is based on 15/15Ti and so its material data were derived from 15/15Ti. That has to be proven.
- The descriptive equation for neutron induced voidage swelling of AIM1 needs to be confirmed against irradiation data.
- The equations for irradiation creep should be validated.
- The equations for mechanical properties of irradiated clad materials are based upon a small database. Additional data should be used to validate the equations.
- Some data like total elongation or rupture data are lacking.
- The temperature range of the validated data has to be extended to encompass also XADS transient operating conditions.

- Internal corrosion was assessed by a simple design rule. A comprehensive analysis of all available corrosion data should be performed to determine the factors influencing corrosion depth and its spatial distribution.
- The effect of external corrosion/erosion of cladding due to helium flowing at high velocity and helium containing contaminants (e.g. steam) have to be assessed by experiments.

Another issue, the effects of creep strain on fuel pin cladding, which requires future R&D has been addressed in /31/. In the gas-cooled XADS the coolant is at a mean pressure of around 60 bar leading to a compressive stress on the fuel pins. The effects of compressive strain on the integrity of the cladding material at high temperatures and under irradiation are not well known. An experimental and theoretical program is needed to answer at least the questions:

- Is compressive strain damaging?
- If compressive strain is damaging, what is the maximum compressive strain allowed?

4.2.2.2 Material qualification for the gas-cooled XADS

The helium cooled primary system of the XADS basically consists in a GT-MHR style reactor. Modified 9% Cr ferritic steel has been selected for the reactor pressure vessel and the reactor thimble which houses the target unit. The operating temperature of the vessel should remain rather low (200°C normal operating conditions). The thickness is in the range of 150mm for the shells up to 600mm for the flat roof slab. The operating temperature of the reactor thimble, about 25mm thick is up to 450-500°C for normal operating conditions and up to 600-650°C in accidental conditions. In addition, this structure is submitted to high damage coming from the core and the target and might be also submitted to significant thermal creep conditions. Welds cannot be excluded at least in less irradiated regions. The following R&D needs have been identified /32/:

- reactor thimble:
  - Confirmation of material selection (Mod 9%Cr, alternative material: 316 LN).
  - Lifetime prediction and material characterisation for highly damaged reactor thimble in Mod. 9%Cr steel (about 70 dpa after 3 years of irradiation at full power).
  - Lifetime prediction for welds located in less irradiated regions
- Vessel material
  - Base material characterisation up to 600 mm thickness
  - Developments of welded joints up to 200 mm thick (common with HTR material development)

4.2.3 Main Components / Systems qualification

4.2.3.1 Design code for the Gas-cooled XADS system

The RCC-MR has been selected as reference Design and Construction code for the PDS-XADS studies. However, it does not cover neither the helium chemistry aspects, nor the high irradiation damage and gas components design aspects. Adaptations of the code together with specific design rules for specific components are to be proposed /32/.

4.2.3.2 He-technology /33/

In the XADS Gas-cooled system there are several areas and components subject to friction and jamming hazards. These components are:

- the internal structures such as the core support located in quasi-isothermal conditions and therefore submitted to very small cumulative displacements.
- the inner vessel and the thermal sleeves submitted to differential thermal expansion between cold and hot legs (static friction conditions and cumulative displacement of the order of 40mm per cycle)
- the check valve and flow shutter, safety components for which the risk of jamming has to be prevented
- the moving parts such as the SCS compressor and main blower bearings (dynamic and high cumulative displacement).

Basically the components are 316 LN stainless steel for the reactor internals and Modified 9%Cr steel for the reactor vessel and also the reactor thimble. The normal operating temperature is 450°C for the reactor internals of the hot plenum and a maximum accidental temperature in the range of 600-650°C, the operating temperature of the vessels remaining close to 200°C. The concept of the Gas-cooled XADS being in progress, the detailed design of these mechanical parts and the selection of the materials is not yet fully defined.

The goal of the R&D activity is to assess, from the specific operating conditions of the XADS helium cooled primary system, the:

- definition of helium chemical environment (oxygen control)
- recommendation on materials/coatings
- definition of R&D needs (specific to XADS/common with HTR).

This assessment will be performed considering available data on friction under helium coming from the feedback from HTR operation together with HTR developments currently in progress.

4.2.3.3 Development of several specific components /34/

The Gas-cooled XADS requires the development of several specific components which are to be qualified. These components are :

- Pantograph machine, working in helium at 200°C in shutdown conditions
- ISI&Repair components if activation conditions call for remote handling operation
- SCS components and especially SCS compressor due to lack of industrial experience with He at 450°C and PCS blower (will take benefit of parallel developments for HTR)
- Passive check-valve, some parts working in transient conditions at temperatures up to 800°C
- Active flow restrictor located in cold duct of cross-vessel

4.2.3.4 ISI&R

In /35/ R&D needs regarding In-Service Inspection & Repair have been expressed, considering:

- protection and corresponding dose rate are to be established around proton beam thimble in roof slab region and roof closure level
- definition of temperature instrumentation required at sub-assembly outlet as regards the safety criteria linked to plugging risk
- requirements for the water ingress detection in primary circuit

- threshold and overall strategy for helium leak detection outside primary circuit and toward water circuits
- conditions and requirements for hydraulic tests for primary circuit and for reactor building
- confirmation that temperature of reactor and PCS vessels remain in non significant creep area
- assessment of reactor thimble and target component lifetime and maintenance scheme
- studies for conception of removal of internal parts of RPV (proton beam thimble, SCS) and PCS (heat exchangers, flow shutters, cross duct disconnection,...)

4.2.4 Safety

4.2.4.1 Stabilisation of the Severe Accident for the Gas-cooled Subcritical XADS /36/,/37/

In the gas-cooled XADS, design provisions may be implemented for mitigating the consequences of severe accident. The design approach for that is to implement below the reactor vessel a debris tray, the function of which is to cool and maintain sub-critical the core debris after the failure of the reactor vessel induced by the severe core accident. On the basis of previous studies performed for the former projects of gas-cooled fast breeder reactors, sacrificial material (e.g. lead) is implemented in the debris tray, allowing to achieve stabilisation by transferring the stored and decay heat to the cooling circuit implemented below the debris tray. The spreading of core debris maintains sub-criticality and the cooling circuit protects the debris tray structures. This is complemented by the containment boundary which limits the releases of the radioactive materials to the environment. It is necessary to perform R&D for supporting this option. This requires to investigate:

- the behaviour of the core in the vessel after the accident, taking into account that the accident is characterised by the loss of any cooling capability in the vessel,
- the risks of criticality, and its consequences if this occurs,
- the consequences on the reactor vessel of any mechanical energy releases occurring when the core debris is in the vessel,
- the failure of the reactor vessel and the drop down of the core debris in the debris tray,
- the coolability of the core debris mixed with the sacrificial material in the debris tray.

The investigations should include:

- Study of applicability of information developed for accident stabilisation schemes of:
  - EPR-Project
  - Russian Core Catcher design for Tian Wan VVER-1000
  - GFCR-Project
- small scale simulant material experiments,
- development of a feasible design for stabilisation structure,
- real material experiments at appropriate scale,
- design refinement for melt stabilisation structure,
- open material issues (appropriate sacrificial materials),
- effects of PuO_2 and fission products on corium viscosity,
- corium pool thermal-hydraulics for low Height/Diameter ratios,
- development estimates for additional costs.

4.2.4.2 Safety and Plant performance of Gas-cooled XADS /38/

Due to the poor heat capacity of helium and the need for relatively high power densities of Fast Reactors, the Decay Heat Removal is one of the key issues of the Gas-cooled XADS. At this stage of the studies scoping calculations of accidental core cooling are performed with CFD code. However due to model size and computational time limitations, the behaviour in transient conditions can hardly be modelled without simplified or over pessimistic assumptions. To better assess the transient behaviour of the Gas-cooled primary system it is mandatory:

- Development of a system code for helium cooled XADS primary system starting from HTR code under development
- Modelling of core post accidental (after core melting) sequences with a SIMMER3 type code including thermal-hydraulic, mechanical energy release, risk of criticality, impact of a core with minor actinides
- Development of optical measurements of the core outlet temperature (and more generally core instrumentation) in the neutron flux conditions of the Gas-cooled XADS

4.3 LBE-cooled Systems

4.3.1 Thermal-hydraulics

4.3.1.1 Heat Transfer Coefficients in LBE Environment /39/

When using lead-bismuth eutectic (LBE) as a coolant, heat transfer coefficients are expected to be lower than in sodium; consequently larger temperature differences are anticipated to affect components involved in heat transfer (primarily the fuel rod cladding) even if the power density is low. Heat transfer correlations are available from the literature but adequate information on the range of their applicability and on their uncertainty needs resolution. In order to support the thermal-hydraulic design of an LBE cooled ADS it is necessary to reliably know the heat transfer coefficients for the anticipated hydraulic operating conditions and, in general, all the anticipated operating conditions (normal, transient and accident conditions). Experimental tests on a single heated rod and heated test section with a representative scale of one XADS fuel assemblies should be envisaged.

4.3.1.2 LBE-cooled XADS design aspects /40/

Throughout the analysis of the thermal-hydraulics of the LBE-cooled XADS design aspects have been identified which need further R&D effort, such as:

- Experimental qualification of the measurements in water by measurements in LBE
- Experimental qualification of the core by-pass flow characteristics (core to target interface with appropriate simulation of the insert configuration into grid plate)
- Experimental qualification of the pressure drop characteristics and especially the inlet flow gagging of the reflector and absorber elements /40/,/41/

4.3.1.3 LBE enhanced circulation by means of gas injection /42/

The primary coolant of the XADS circulates in enhanced natural circulation as described in /42/. That solution combines the high level of reliability required by the core cooling safety-related function with the advantages of Reactor compactness, operational flexibility, and the lower thermal loading on the structures typical of the forced circulation. Nevertheless this solution is not without uncertainties and inconveniences that must be kept under control. The main verifications to be performed are:

- Performance verification
- Instabilities evaluation

- Exclusion/limitation of structural material erosion
- Gas carry-under verification
- Gas injection system optimisation
- Acquisition of T/H data for codes validation
- Evaluation of the amount of produced aerosol and Polonium stripping

4.3.1.4 Need for improvement of T/H codes and models /11/

Existing thermal hydraulic models have to be adapted in order to consider:

- the effect of molten LBE sloshing during earthquake /43/:

The very high density of lead alloys (e.g. the Pb-Bi eutectic) brings about not negligible loads upon the internals in case of sloshing. Horizontal anti-seismic supports drastically reduce both the reactor building own frequencies and the seismic horizontal loads on the reactor structures. The beneficial effect on the sloshing loads is less important because, the frequency is lowered to a value, which is near the natural frequencies of the sloshing motion. The existing codes are not easy to use to address these phenomena. R&D actions have to aim on implementation of adequate models to simulate the molten heavy metal sloshing and the mechanical loads applied to main vessel and internal structures of the primary system in the existing codes. In particular comparison could be made between existing Finite Element Structural Codes method of approach (based on seismic spectral analysis) and CFD numerical approach using direct time history simulation.

- heavy metal coolant stratification in the primary system
- dispersion of molten fuel in lead
- core cooling inside a skull of frozen lead
- damping of pressure waves from SG tube rupture
- Intermediate Heat Exchanger Tube rupture:

  The LBE of the 80 MW XADS is cooled by means of four IHX with tube-side low vapour pressure diathermic oil to attenuate the consequences of a tube rupture. This solution does not require significant R&D, but the need to install a SG inside the vessel in the future industrial reactors makes necessary to analyse the effect of mixing a secondary coolant (water) with hot lead in term of steam generation and solid particles formation, pressure increase and shock waves and effects on the integrity of the system. R&D is requested to verify the physical effects of this kind of interaction and to provide data for the verification of the capabilities of the existing mathematical model and codes.

4.3.2 Materials Research

4.3.2.1 Fuel pin mechanics issues /40/

The following fuel pin mechanics issues have been identified throughout the analysis of the thermal-hydraulics of the LBE-cooled XADS for further R&D:

- Clad swelling law dependent on dose and temperature
- Outer corrosion rate of the clad material dependent on temperature and oxygen content of the coolant
- Inner corrosion rate of the actual clad material dependent on O/M ratio of the fuel
- Clad yield strength, ultimate tensile stress and failure strain dependent on temperature and strain rate
- Creep fatigue failure data of the clad material

- corrosion and erosion effects of LBE in tubes

4.3.2.2 Fuel Rod Fluid Induced Vibrations /44/

Since in a Lead-Bismuth Eutectic (LBE) environment and in the proposed primary system configuration (reactor building supported by seismic isolators) the loads originated on the fuel rods by the design basis earthquake have been estimated to be small, the number of fuel assembly spacer grids is determined by the loads derived from the fluid induced vibrations. The objective of R&D actions should be:

- Development of computer models suitable to analyse the fluid induced vibrations on fuel rods in an LBE environment
- Experimental verification and validation of the computer models for the conditions typical of the LBE cooled XADS concept

4.3.2.3 Establishment of database for CR9 martensitic steel specific to the design /45/

In the MYRRHA design the structural material in the vicinity of the subcritical core is intended to be a martensitic steel of the sort either T91/T92 or F82H (of the fusion development). The steel of choice is also foreseen for the cladding of the fuel pins. Although the database of these steels is being established in many European associated laboratories for both these classes, for non-irradiated as well as irradiated material it is also clear that the scarce availability of these materials and the fact that very limited amounts of the material are needed for testing and finally construction pose a real problem so that there is a real danger that neither the particular base form nor the end form of the material is available, nor that the general database can be used for the specific licensing of an early ADS like MYRRHA. It is therefore of utmost importance that the manufacturability of the end product from the base form of the material by non-mass production means is being managed. Likewise it is the final form of the material which needs to be characterised in testing and certified in licensing. This is especially mandatory for the cladding as the first confinement barrier of the nuclear fuel, but is valid also for the structural material.

4.3.2.4 Stainless steel 316L-SPH in contact with Pb-Bi /46/

The well known material 316L seems adequate for use up to 450°C in flowing lead-bismuth with a speed below 2m/s and oxygen activity control. These operating domain is compatible with the operating condition of those primary system structures which in normal condition are below 420°C. The maximum speed of the Pb-Bi is about 1 m/s in the riser pipes (/47/ which addresses the specific phenomenon of erosion in two- phase conditions). The currently available information is of a preliminary nature and in addition no results are available on of the adequacy for welded joints and on the corrosion behaviour under stress. Therefore R&D is needed:

- Confirmation of the use of the Stainless Steel 316L-SPH for long term operation in Pb-Bi below 450°C and short-term operation (few days) between 450°C and 500°C for base material and for welded joints.
- Verification of the behaviour in case of accidental condition with loss of oxygen control.

4.3.2.5 Materials for mechanical equipment operating in LBE /47/

In addition to AISI 316L steel, used for Vessels and Internal Structures, other materials are planned to be used both for high strength pieces (gears, bolts, etc.) and for cinematic links (roller/ring, etc.) of mechanical equipment working under LBE coolant. To avoid bad operation or even seizure of the cinematic links investigation is needed:

- of compatibility between LBE and special mechanical materials
- about friction coefficients
- about evolution of functional clearance between roller and ring due to deposit of impurities or surface corrosion.

4.3.2.6 MOX fuel development and qualification for XADS driver /48/

In order to accelerate the fuel pin design fabrication procedure and licensing for the small XADS (called below MYRRHA), the existing MOX fuel designs for fast reactor cores, such as Superphénix (SPX), are used as basis, except that a low-swelling martensitic stainless steel (T91 or another) was chosen as the cladding material, which has good mechanic parameters and corrosion resistance in Pb-Bi environment. Despite the fact that MOX fuel was very detailed qualified and a large experience exists in its production and operation, the use of the T91 martensitic steel in Pb-Bi environment, in presence of the high energy (> 10 MeV) spallation neutrons and protons, and expected frequent trips of proton beam, requires supplementary research. A major problem for the driver fuel is its irradiation tests and qualification under representative irradiation conditions. Moreover, extensive modelling of the fuel long term and accidental behaviour must be performed before the final design and fabrication of the fuel elements. Significant (R&D) efforts will be required to optimise the current fuel design and to demonstrate its robustness under all expected operation conditions.

4.3.3 Main components / Systems qualification

4.3.3.1 Technologies for Visualisation and Instrumentation in LBE 49/50/51/52/

During In Vessel Fuel Handling in Sodium Cooled FR, a VISUS (VISualization Under Sodium) is used as sweep-arm ultrasonic probe for the detection of obstacles in the interspace between core assemblies heads and bottom of the above core structure. Important R&D activities were performed in Sodium Cooled FR for investigations under sodium. Also in the LBE cooled XADS, an ultrasonic sweep-arm probe is necessary to ensure that no obstacles prevent fuel handling operations. More generally the availability of a scoping device would be advisable to improve plant operation. R&D actions in short term should assess the possibility to apply technologies validated for investigation under sodium, modified for use in LBE, also for investigation under LBE or, if necessary, to identify alternative methods. The long term aim has to be the development of the inspection in service (ISI) technology under Heavy Liquid Metals, according to a program similar to the one established for under-sodium inspection including development of:

- high temperature, radiation resistant UT (Ultrasonic Testing) transducers, operated by remote electronics and turn out these finally into phased array systems.
- the acoustic properties of liquid Pb-Bi over a wide temperature range and with an accuracy sufficient for UT sensing
- inductive elements for eddy current detection of cracks in steel through a boundary layer of LBE
- inductive feed-back sensors for direct monitoring of robotic movements under LBE
- a true visualisation system, capable of recognising objects or large cracks, based on phased array visualisation techniques in a similar way to US ocean floor and ship wreck monitoring.
- a highly reliable and redundant spallation source level sensor on the basis of the LIDAR principle.
- of robotic elements for remote manipulation under liquid LBE

4.3.4 Safety

4.3.4.1 Severe Accident Progression /53/

The postulated extension conditions for a LBE-cooled subcritical reactor of the type considered in the PDS-XADS design project can lead to the melting of the fuel bundles in the core. The progression of such a severe accident will be very different from that for a light water cooled reactor and the information database to evaluate the consequences of such a severe accident is almost non-existent. Thus, either the consideration of such accidents is excluded through arguments made about the extremely low probability of the severe accidents or a focused research program has to be initiated to develop information, which would determine, albeit with acceptable uncertainty, the consequences and the risk associated with the progression of a severe accident in the lead-bismuth subcritical reactor. The consequences and risks of prime concern are those associated with the release of radioactivity to the environment. Such a release can occur only if the barriers of clad, vessel and containment are destroyed during the severe accident.

The objectives of the research in the severe accident progression are:

- to prevent the occurrence of the severe accident and to make the core damage frequency (CDF) as low as possible, and
- to mitigate and manage the consequences of a severe accident if it occurs.

R&D to support these objectives have to include:

- Performing small scale tests:
  - with melt simulants for studying corium interactions with Pb-Bi ,
  - with representation of loadings on the vessel,
  - on the ex-vessel interactions of simulant corium with containment materials and structures,
  - to identify the compounds formed on the mixing of the simulant fission products and the lead bismuth.
- Development of models:
  - for representing the melt interaction phenomena,
  - to represent the in-vessel accident progression and its consequences, e.g. vessel failure ,
  - to represent the ex-vessel accident progression and its consequences, e.g. containment failure,
  - employ real corium melts and the fission products for confirmatory experiments. Use information from these experiments for correcting and improving the analysis models developed above.

4.3.4.2 Safety experiments /19/

Experimental study is a very basic and important method in the innovation of any nuclear installation. Since the safety assessment is based on a complicated modelling system that needs the input of experimental finding and validation, experiment is always necessary for safety study. So far, no data exist for safety issues. For fundamental understanding and model development, following aspects of the XADS under abnormal conditions have to be investigated:

- coolability potential of the natural circulation (compare also section 4.1.4.6): in order to confirm that the decay heat can be sufficiently dissipated by intrinsic natural convection,
- behaviour of the impurities due to corrosion: the formation and deposition of corrosion products may deteriorate the flow and heat transfer condition and raise safety issues,
- thermal and mechanical properties of material concerned with dedicated fuel (compare section 4.1.2.1),

- interaction of LBE with other coolants (oil/water): to investigate the behaviour of the LBE-cooled XADS in the event of oil/water injection into the secondary side of the heat exchanger containing a large body of LBE at temperature up to 500°C. The consequence will be investigated in term of:
- the access of steam formed to the core region which could lead to RIA,
- the pressure rise/shock and its effects on the heat exchanger integrity,
- the formation of particulate lead bismuth which could form blockage in the core if transported there,
- the effect of a pressure wave travelling through the LBE coolant system,
- interaction of LBE with molten structure,
- interaction of LBE with representative binary oxide melts to determine the accident. Issue is whether corium will accumulate at the bottom of the tank to pose a vessel melt through hazard and later a recriticality hazard,
- interaction of inactive Cs, Iodine, Te, Ba, La with Pb-Bi at different temperatures to understand what fission product compounds can be formed.

4.3.4.3 Containment design requirements

The LBE-cooled XADS with its mass of the coolant in the vessel and its heat capacity has a good chance of containing any core damage accident within the vessel. This, however, is predicted under condition of no recriticality event and continuous removal of heat decay. In case of recriticality or heat removal malfunction, the vessel failure is potentially possible. R&D is required since there is currently no study which has ever considered the possibility of vessel failure and ex-vessel propagation and containment loads.

4.4 R&D Needs Synthesis

R&D needs have been specified for the different components and concepts of XADS in the course of the PDS-XADS project and in particular through 37 Question Sheets addressed to the ADOPT network.

The R&D needs are classified into five main domains :

- Reactor physics,
- Fuel development,
- Thermal-hydraulics,
- Main component development,
- Materials.

Within Deliverable 40 /6/, a set of criteria have been established for the comparison of the R&D needs of the three concepts. In Table 4.1, an attempt of ranking of the three designs with respect to these criteria is provided.

On the Reactor Physics, the R&D needs are mostly generic and common to the three concepts and each concept still requires extensive uncertainty assessments on Sub-criticality levels and Transition to Transmutation Core strategy.

The situation is the same for fuel development. As far as cladding is concerned, it is considered that the development needs for both concepts are similar (Corrosion protection/ aluminization for LBE concepts and rough cladding for gas).

Concerning thermalhydraulics, larger R&D needs can be expected for the LBE systems including test on fuel pin bundles and behaviour of the large LBE collectors and low flow velocity or stagnant regions but this is not a critical issue for this concept which shows high design margins. For the gas, past experiments are already available but additional confirmations are highly recommended because maximum clad temperature is a key issue, here. Therefore more emphasis is to be put on R&D on the gas.

On the materials issue, the LBE concepts are facing a lower ranking on corrosion (the mark retained is 1 which does not strictly follow the rating criteria from Deliverable 40, where mark 1 corresponds to “Very bad knowledge from the corrosion point of view”). It is however considered that a large R&D effort (testing in non-isothermal pool configurations, potential need for aluminization on cladding, oxygen control process and monitoring, control/ISI of metal oxide film for corrosion inhibition) is necessary to fully qualify the materials and exclude corrosion.

On components and system qualification, the accelerator is a common issue for all concepts and the R&D needs are well established and covered by existing programmes. Windowless targets are requiring larger R&D programmes and an integral test which is not scheduled today but the R&D effort and prospect for successful outcome is judged at the same low level from today (no proof of phenomena) for both window/windowless options. The solid target could drastically reduce the R&D needs but the level of knowledge of this option for the XADS is not sufficient to improve the rating. Components of the primary system and in particular, visualisation and inspection means and associated carriers require large developments for the LBE concepts. The MYRRHA reactor and its more innovative design of the primary systems will call for a larger technological development programme. Concerning other components and systems, there are more extended needs for the Gas components in terms of qualification of the reliability but it is considered that these needs will be balanced by technological needs for the LBE concepts (fuel and components handling /washing/decontamination,…).

The comparison shows a slightly smaller extent of R&D needs for the Gas-cooled XADS compared to the LBE concepts. The difference is however not very significant. More important is the fact that most of the R&D needs are common with other helium cooled reactors (Gas Cooled Fast Reactors for core and DHR issues and High Temperature Reactors for the technology) as illustrated on Table 4.2, extracted from Deliverable 83 /54/. This is likely to drastically reduce the specific development costs (technology, CFD and system codes, use of the same Helium loops, large synergy on core/cladding issues,…).

Table 4.1 Concepts Assessment on R&D Needs

(Rationale given in the next pages - Data list corresponds to the averaged rating as judged by the author and the comments made by the WP1 team).

R&D needs – Reactor physics		**80 MW LBE-cooled XADS**	**80 MW He-cooled XADS**	**50 MW LBE-cooled XADS (MYRRHA)**
Sub-criticality levels in normal and accidental conditions	***RP1***	1	1	1
Control and instrumentation	***RP2***	2	2	2
Transition to transmutation core demonstrator	***RP3***	1 (means Extensive uncertainty assessment)	1	1
System Points :	***RP***	4 / 9	4 / 9	4 / 9
R&D needs – Fuel Development				
Need for conventional fuel development	***FD1***	3	3	3
Need for innovative fuel development	***FD2***	1	1	1
System Points	***FD***	4 / 6	4 / 6	4 / 6
R&D needs – Thermalhydraulics				
Heat transfer coefficient	***TH1***	3	2	3
Flow distribution	***TH2***	2	2	2
Other specific phenomena	***TH3***	2	2	2
System Points	***TH***	7 / 9	6 / 9	7 / 9
R&D needs – Material research				
Thermal behaviour	***MR1***	2	2	2
Corrosion	***MR2***	1*	3	1*
Irradiation effects	***MR3***	2	2	2
Capacity to be manufactured	***MR4***	3	3	3
System Points	***MR***	8 / 12	10 / 12	8 / 12

R&D needs – Components and system qualification		**80 MW LBE-cooled XADS**	**80 MW He-cooled XADS**	**50 MW LBE-cooled XADS (MYRRHA)**
Accelerator qualification	***CSQ1***	4	4	4
Target module qualification	***CSQ2***	2	2	2
Main components of the primary system	***CSQ3***	3	4	2
Main components of the PCS and auxiliaries (SCS, Fuel Handling, component handling/cleaning/decontamination…)	***CSQ4***	3	3	2
System Points	***CSQ***	12 / 20	13 / 20	10 / 20
Total Points : R&D needs		35 / 56	37/ 56	33 / 56
Max/Min/delta Points		56/16/40	56/16/40	56/16/40
Percentage R&D State of Completion	***%***	(36-16)/40= **48**	(37-16)/40 = **53**	(34-16)/40 = **43**

RATIONALE OF RATING SYSTEM ON R&D NEEDS (from D40 /6/):

Reactor physics (RP) :

Principle: The use of different materials for the core associated to the unconventional arrangements (spallation module in the centre part) induces uncertainties on the neutronic characterisation of the core. These uncertainties can be coming either from the bad knowledge of nuclear data or from method problems. For instance, the use of He induces little nuclear data uncertainties while lead and bismuth are not as well known. Consequences on the characteristics of the design under consideration must be looked at and the needed R&D evaluated.

Technical Qualitative Criteria	Rationale
Sub-criticality levels in normal and accident conditions	*Uncertainties on the reactivity effects to be considered when assessing the maximum reactivity levels under DBC, DEC and refuelling conditions (with or without absorbers)*
Control and Instrumentation	*Uncertainty associated to the determination of the reactivity level (consideration should be given to the position of the fission chambers, their response over time under different signals)*
Transition to Transmutation Core demonstrator – XADS/XADT Strategy	*Uncertainties on the XADS characteristics associated to the use of MA (with much larger nuclear data uncertainties).*

Sub-criticality levels in normal and accident conditions:	***RP1***
No further uncertainty assessment required	**1**
Limited uncertainty assessment required	**2**
Extensive uncertainty assessment required	**3**

Control and Instrumentation:	***RP2***
No further uncertainty assessment required	**1**
Limited uncertainty assessment required	**2**
Extensive uncertainty assessment required	**3**

Transition to Transmutation Core demonstrator – XADS/XADT Strategy:	***RP3***
No further uncertainty assessment required	**1**
Limited uncertainty assessment required	**2**
Extensive uncertainty assessment required	**3**

R&D NEEDS :

Fuel Development (FD) :

Principle: The fuel to be used in the XADS can be conventional or innovative. In a first stage, the use of conventional fuel is recommended. The R&D required for this fuel and the potential adverse effects are considered.

In a second stage, more innovative fuels could be used, particularly to include minor actinides in the fuel composition.

Technical Qualitative Criteria	Rationale
Need for conventional fuel development	The need for fuel development (to be used in the first stage) must be assessed in terms of amount of R&D to be carried-out.
Need for innovative fuel development	The development of MAs containing fuel must be assessed in terms of amount of R&D to be carried-out.

Need for conventional fuel development :	***FD1***
The fuel used in the concept (during the first stage) is very different from the conventional fuel and a large amount of R&D is needed either for the fuel fabrication or for the fuel qualification in the XADS environment	**1**
The fuel used in the concept (during the first stage) requires a limited amount of R&D either for the fuel fabrication or for the fuel qualification in the XADS environment	**2**
The fuel used in the concept (during the first stage) is conventional and no (or very limited) R&D is needed either for the fuel fabrication or for the fuel qualification in the XADS environment	**3**

Need for innovative fuel development :	***FD2***
The fuel containing MAs is very innovative and a large amount of R&D is needed either for the fuel fabrication or for the fuel qualification in the XADS environment	**1**
The fuel containing MAs is rather innovative and requires a limited amount of R&D either for the fuel fabrication or for the fuel qualification in the XADS environment	**2**
The fuel containing MAs is conventional and no (or very limited) R&D is needed either for the fuel fabrication or for the fuel qualification in the XADS environment	**3**

R&D NEEDS :

Thermal-hydraulics (TH) :

Principle: The choice of the coolant induces strong consequences on the thermal-hydraulic behaviour of the concept and, hence, on the temperature in the different parts of the plant. The level of knowledge available in this field must be addressed from different points of view :

- *Heat transfer coefficients ;*
- *Physico-chemical characteristics (viscosity mainly) and its consequences on the flow distribution ;*
- *Specific phenomena*

The corresponding information must be available in the XADS operating conditions (pressure, temperature, coolant velocity, geometry,…).

Technical Qualitative Criteria	Rationale
Heat transfer coefficients	The heat transfer coefficients are only defined by dedicated T/H experiments. Depending on the coolant choice, one must verify the availability of data in the XADS operating conditions range.
Flow distribution	The physico-chemical characteristics (particularly the viscosity) of the coolant may have significant consequences on the flow distribution and the subsequent temperature distribution. The availability of this information must be checked.
Other Specific phenomena	If advantage is taken from specific phenomena in the thermal-hydraulics (e. g. the flow enhancement by bubbles in the LBE), the availability of the knowledge on these phenomena must be assessed.

Heat transfer coefficients:	***TH1***
Heat transfer coefficients are poorly known from past experiences	**1**
Heat transfer coefficients are partly known from past experiences	**2**
Heat transfer coefficients are well known from past experiences	**3**

Flow distribution :	***TH2***
The flow distribution has not been studied in past experiments	**1**
The flow distribution has not been extensively studied in past experiments and further R&D is required	**2**
The flow distribution has already been observed in past experiments	**3**

Other Specific phenomena :	***TH3***
The specific phenomena anticipated in the XADS have never been observed and quantified in past experiments	**1**
The specific phenomena anticipated in the XADS have partly been observed and quantified in past experiments	**2**
The specific phenomena anticipated in the XADS have already been observed and quantified in past experiments	**3**

R&D NEEDS :

Material research (MR) :

Principle: The materials used in the design of the XADS components must be assessed in terms of available knowledge and from different aspects :

- *Thermal behaviour ;*
- *Corrosion in the XADS environment ;*
- *Irradiation effects ;*
- *Capacity to be manufactured*

Technical Qualitative Criteria	Rationale
Thermal behaviour	The mechanical behaviour of the chosen materials must be assessed in the XADS conditions.
Corrosion	The corrosion behaviour of the chosen materials must be assessed in the XADS conditions.
Irradiation effects	The irradiation behaviour of the chosen materials must be assessed in the XADS conditions.
Capacity to be manufactured	The capacity to manufacture the XADS main components must be addressed.

Thermal behaviour :	***MR1***
The materials used in the concept are very badly known from the thermal point of view, in the XADS conditions	**1**
The materials used in the concept are partly known from the thermal point of view, in the XADS conditions	**2**
The materials used in the concept are well known from the thermal point of view, in the XADS conditions	**3**

Corrosion :	***MR2***
The materials used in the concept are very badly known from the corrosion point of view in the XADS environment	**1**
The materials used in the concept are partly known from the corrosion point of view in the XADS environment	**2**
The materials used in the concept are well known from the corrosion point of view with in the XADS environment	**3**

Irradiation effects :	***MR3***
The irradiation effects on the materials used in the concept are very badly known	**1**
The irradiation effects on the materials used in the concept are partly known	**2**
The irradiation effects on the materials used in the concept are well known	**3**

Capacity to be manufactured :	***MR4***
The materials used in the concept are under development and cannot be used at a short time-scale to manufacture XADS components	**1**
The materials used in the concept need further developments to manufacture XADS components	**2**
The materials used in the concept are well known and can easily be used to manufacture XADS components	**3**

R&D NEEDS :

Components and systems qualification (CSQ) :

Principle: The development of a new component/system follows different stages from the basic research to the proof of concept. The degree of development of the components and systems can be expressed in terms of technology readiness level.

Technical Qualitative Criteria	Rationale
Components and systems qualification	Each main component of the XADS is assessed in terms of further R&D needed. This qualification process must be applied for the main subsystems of the ADS : - Accelerator - Neutron source - Sub-critical assembly (primary system/PCS, auxiliary systems)

Accelerator qualification :	***CSQ 1***
Basis research in new technologies : Scientific research begins to be translated into applied R&D	**1**
Proof of phenomena : Analytical and experimental demonstration of critical function(s) and/or characteristic proof of concept	**2**
Technology development : Small-scale (laboratory) demonstration in a relevant environment	**3**
Proof of practicality : Sub-system or separate effects test completed in representative conditions	**4**
Proof of concept : Large-scale (integral facilities) tests in representative conditions	**5**

Target qualification :	***CSQ 2***
Basis research in new technologies : Scientific research begins to be translated into applied R&D	**1**
Proof of phenomena : Analytical and experimental demonstration of critical function(s) and/or characteristic proof of concept	**2**
Technology development : Small-scale (laboratory) demonstration in a relevant environment	**3**
Proof of practicality : Sub-system or separate effects test completed in representative conditions	**4**
Proof of concept : Large-scale (integral facilities) tests in representative conditions	**5**

Main components of the primary system :	***CSQ 3***
Basis research in new technologies : Scientific research begins to be translated into applied R&D	**1**
Proof of phenomena : Analytical and experimental demonstration of critical function(s) and/or characteristic proof of concept	**2**
Technology development : Small-scale (laboratory) demonstration in a relevant environment	**3**
Proof of practicality : Sub-system or separate effects test completed in representative conditions	**4**
Proof of concept : Large-scale (integral facilities) tests in representative conditions	**5**

Main components of the PCS and auxiliary systems :	***CSQ 4***
Basis research in new technologies : Scientific research begins to be translated into applied R&D	**1**
Proof of phenomena : Analytical and experimental demonstration of critical function(s) and/or characteristic proof of concept	**2**
Technology development : Small-scale (laboratory) demonstration in a relevant environment	**3**
Proof of practicality : Sub-system or separate effects test completed in representative conditions	**4**
Proof of concept : Large-scale (integral facilities) tests in representative conditions	**5**

Table 4.2 - R&D Gas Cooled XADS

Designation	Reference solution	R&D objectives	Specific GCXADS	GCFR	General HTR
Materials Reactor vessel, hot duct, Power Conversion System Internals Thimble and beam and target tubes	 9%Cr 316 9%Cr	Validation of material choice (thermal mechanical database and code) and welding characterization No specific concerns Specific concern due to the high irradiation level (50-70dpa) and cold part	 RDQ 02/193 x	 x x	 x x
Core and subassemblies Fuel clad temperature Core and S/A I&C Specific issues of a subcritical syst. Instrumentation	 Fuel pins	High T° melting for fuel cladding is an interesting way to increase the acceptable delay for beam trip T° & reactivity monitoring Uncertainties, core monitoring	RDQ 02/188 02/204 x x	 x x	 *	
Systems Decay Heat Removal Helium Service System Transients analysis Instrumentation & Control	3 SCS integrated in nozzles Helium quality regulation	Efficiency of conception in natural convection is to be validated & qualified Tribology, chemical, mechanical, aspects Purification methods development and qualification of operating calculation detailed codes taking into account the GC XADS specific features Reliability for short time beam trip	RDQ 02/192 450°C RDQ 02/191 RDQ 02/192 x	x x x x	 x x
Internals structures Core inlet / outlet plenum Hot duct insulation	 Diagrid inside	 Flow pattern Thermal performances vibration, erosion,..	 x RDQ 02/194	 o x	 o x
Target Thimble & cooling circuit Thimble LBE cooling circuit	LBE cooling circuit	Material R&D: . forT91 due to high irradiation level (70 dpa). - embrittlement for low temperature . for stain less steel (316L) swelling is to be verified Corrosion & activation aspects associated to LBE	RDQ 02/193 RDQ 02/180 02/198		
Shutdown Cooling System	Integrated in 3 reactor vessel nozzles	Validation of compressor, heat exchanger and check valve operation (natural circulation under pressure) on representative large scale loop Clarification of water ingress consequences	RDQ 02/194 RDQ 02/192	x x	x x

Designation	Reference solution	R&D objectives	Specific GCXADS	GCFR	General HTR
Power Conversion System	Circulator Helium water heat exchanger	Validation of the preliminary design (helium loop) Clarification of water ingress consequences	RDQ 02/194 RDQ 02/192	x x	x x
ISI – R and maintenance	NDT from outside	Definitions: . intervention conditions (dose rate) . pneumatic tests, . Helium leakage detection, . NDT requirements for tools development . full core unloading possibilities for contingency inspection	RDQ 02/194 x x x x x	 x x x x x	 x x x x x
Fuel handling Machines	Direct lift machine and pantograph	Tribological aspects qualification (including instrumentation)	RDQ 02 191 RDQ 02/194	x x	x x
CRDM	6 independent mechanisms from the bottom	Technological validation & qualification of the pushing chain system Anti-reactivity inserted to be calculated and compared to the target (-3500pcm)	RDQ 02/194 x		
Shielding	Under roof plate and core radial protection	Confirmation of latest results, optimization and complete the data for the over primary circuit	x	x	
Core catcher & vault pit integration	Core catcher outside the RV and design for subcritical core melting	Determine the amount of melted product from a realistic scenario (time duration between core melting and arrival in the core catcher).	x	x	

Alternative options for the GC XADS

Designation	R&D objectives	Specific GC XADS	GCFR	General HTR
Beam penetration from bellow	No specific R&D in needs for this option. R&D concern is more the biological protection required for the proton beam (see also solid target option)	x		
Solid target	Neutronic characterization, studies of accidental conditions (loss of cooling water ingress) need of calculations tools; comply with beam penetration from below (no LBE ingress in the beam line)	x		
Pre-stressed concrete vessel	Development for reactor vessel pre-stressed concrete vessel.	x	x	
Absorbers introduced with the fuel handling system	Fuel handling error to be analyzed in details	x		
Conclusion	Cost comparison / reference options and combination of pre-stressed concrete vessel + beam penetration from below + solid target might be interesting for large power reactor			

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5. RECOMMENDATIONS FOR THE REFERENCE OPTIONS TO BE STUDIED IN THE 6th FP

At this stage of the developments of the XADS, for such a complex plant the guiding parameter should not be economics but feasibility. This is why only trends are provided for economics with a reference point for Na-cooled reactor and a cost assessment of the 50 MWth reactor (MYRRHA) construction at Mol.
As far as technical evaluation is concerned the comparison and the assessment of the reference options to be studied for the 6 FP have been made in Deliverable 77. Only the general conclusions are recalled in Italics :

The PDS-XADS project has been the first one to start a rather detailed ADS design, making a full use of European expertise of different research organizations, industries and universities.

Elaborated designs are sufficiently advanced to confirm the good prospects in the feasibility of such ADS plants. Weak points have been identified and it is not a surprise that the open issues appear in the most unusual parts of reactor design that is in the spallation module. Six different drawings of the spallation module have been elaborated and each of them has advantages and weaknesses, weaknesses which could be overcome only by appropriate R&D programmes.

For what concerns the accelerator, the high reliability/availability requirements remain a pending problem. The strategy to overcome these difficulties is a standard practice in reliability engineering, a technical discipline for risk estimation and management that is followed for many industrial applications or products in various fields. A “Failure Mode and Effect Analysis” activity performed on the reference LINAC design has been performed, and a critical overlook at the reliability studies of existing accelerator facilities has allowed the possibilities of setting up a database of accelerator components in order to collect component data for more quantitative reliability predictions in further studies. An appropriate sizing of the components, a redundancy of the weakest components and the use of corrective actions based on appropriate diagnostics should allow to meet the requirements.

The LBE technology, if it brings some appropriate margins in the conception, brings with it potential problems of corrosion and oxidation. Promising solutions to overcome these problems exist. Nevertheless, their demonstration needs to be performed at adequate scale and in representative working conditions (temperature, LBE flow & speed, ...). The large core as developed by ANSALDO has a robust behaviour as designed but the somehow low specific powers used (47 MW/m3) reduces its cost efficiency for its transmutation objective. The use of a higher specific power as envisaged in the EUROTRANS integrated project will increase the plant efficiency as a waste transmuter. The safety issues of these higher power systems need to be reanalysed. The use of Pb as a coolant rather than LBE will allow higher operating temperatures which will increase the overall plant thermodynamic efficiency. This will allow also a reduction of the source term coming from Polonium as a radioactive product of Bismuth activation.

On the other hand, the small-scale core developed by SCK•CEN in the MYRRHA system, even developed for a lower power (50 instead of 80 MWth), was intended to have a much larger power density (peak linear power not exceeding 500 W/cm) in order to achieve the efficient transmutation capability even though for limited number of MA pins or assemblies. Consequently, several iterations were necessary to meet the safety requirements. The final design parameters (361 W/cm peak, 282 W/cm average linear power in the hottest pin) lead to an efficient transmutation system and, at the same time, respecting pre-established safety requirements.

Furthermore, MYRRHA possesses several innovative features like the multi-batch capacity, the fully remote components handling and the small proton beam diameter, what makes it attractive as a multi-purpose R&D machine.

The design of the Helium-XADS is less advanced than the large LBE which has taken large advantage of the extrapolation of the Na-cooled liquid metal technology. However, the gas technology exhibits clear interests in terms of coolant chemical inertness, overall simplicity of the reactor (internals, components) that can be based on proven Helium cooled reactor experience and take benefit of parallel developments which drastically reduces the material/technological R&D needs, large ISI & repair capabilities, and convenient fuel and components handling due to the transparent *nature of the coolant. Moreover, if the solid target option can be demonstrated, the need for the development of a new liquid metal technology can be totally avoided. On the other hand, the key issue is the poor Helium thermal properties versus the Fast Reactors power density requirements and hence the high sensitivity of the core cooling to any fast loss of mass flow transient. The chosen volumic power 56 MW/m*^{3} *for this concept represents an upper limit due to constraints to the mechanical behaviour of the steel of the cladding. The use of refractory cladding (made of SiC for example) would allow both an increase in the volumetric power density and in plant efficiency hence making the overall scenario of an introduction of ADS in the nuclear park more attractive. On the hand, the removal of the decay heat is very much associated to the use of active systems even under protected transient conditions, i.e. with proton beam trip.* The reliability target of the DHR system should be attainable if three decay heat removal systems are used with an appropriate diversification and maintenance scheme.

Preliminary studies of the transmutation of the PDS-XADS project have demonstrated that on the long run only plant sizes in the range of several hundreds MWth can reach satisfactory transmutation rates suitable for Industrial Scale Transmuter, the optimum being 45kg/ TWhth of actinides coming from a PWR park. The technical demonstration of the feasibility of this remains an extrapolation of the plants being studied up to now. It is one of the purpose of the EUROTRANS integrated project to demonstrate that an ADS designed to transmute nuclear waste is feasible at the lowest cost, the feasibility assessment being set up on a best-estimate approach. On the other hand, the MYRRHA performance assessment as partially MA loaded core, would lead to realistic technological feasibility demonstration of ADS as well as of MA transmutation at reasonable scale (~1 kg of MA burned/18 kg of Am-Ufree fuel loaded).

6. SUMMARY AND GENERAL CONCLUSIONS

6.1 Introduction

The strategy related to the closure of the fuel cycle depends on nuclear policies adopted by each European Union member country. In any case, the transmutation of most of the long-lived radioactive wastes is a promising solution, which could play a substantial role in the closure and safety of the fuel cycle.

Previous studies have shown that a fast neutron spectrum allows maximising the transmutation of minor actinides (MA), because of both the better fission efficiency compared to the neutron capturing rate, and the potentially high level of neutron flux. A core dedicated to the fission of the MA should be designed in order to minimise its self-production of actinides. Such a core has a very small delayed neutron fraction and a small Doppler coefficient making its control in a critical core configuration more complex and difficult to achieve; this difficulty can be resolved by using the core in a sub-critical mode; controlled by an external neutron source, namely a spallation source.

The demonstration of the practicability of transmutation on an industrial scale requires a cooperation at the European level, for the construction of an Experimental ADS (XADS) at a scale large enough, which will demonstrate the safe coupling of the accelerator, the neutron spallation target and the sub-critical core.

Complementary to the demonstration of the basic phenomena involved in the ADS technologies, the objectives of the design-oriented PDS-XADS programme within the 5th Framework Programme (FP) were :

1. to select the most promising technical concepts,
2. to address the critical points of the whole system,
3. to identify the Research and Development (R&D) in support,
4. to define the safety and licensing issues,
5. to preliminary assess the cost of the installation,
6. to consolidate the road mapping of the XADS development.

The project has evaluated different XADS design candidates in order to select the most appropriate one to be further developed. Three designs, two based on heavy liquid metal (Lead-Bismuth eutectic) cooling and one on gas cooling have been studied according to a common basis (General Specifications, Safety Rules).

The project has been organized into Work Packages to address conceptual design and feasibility of the main sub-systems (accelerator, spallation target unit, sub-critical core, primary system).

All the designs have reached a level of definition and justification sufficient to address the six objectives of the Project. The Technical feasibility and synthesis of the activities performed in each of the WP is reported in detail into the WP synthesis.

Within the WP1 "Global Coherency", "Technical Option reports", D61 for the LBE systems and D62 for the Gas are giving an overall synthesis of each of the three concepts.

D77 "Recommendation Report for the Reference Options of XADS" is providing recommendations on the main options of the XADS and the projection toward the 6^{th} FP.

The assessment and comparison of the three concepts is completed by D86. The main findings with respect to each of the main comparison criteria are summarized below.

6.2 Concepts Comparison

6.2.1 Consistency with XADS objectives

The missions, technical specifications and main characteristics assigned to the XADS were defined at the beginning of the Project. They were widely based on the ETWG Roadmap which defined, in 2001, the strategy to be pursued in Europe towards the demonstration of the feasibility of nuclear waste transmutation ; the construction of an XADS being one of the key steps of this demonstration. In this context, the main goal of the PDS-XADS Project was to progress towards the demonstration of the ADS feasibility.

Those missions and objectives assigned to the XADS plants were divided into three main topics :

- The capability to demonstrate the feasibility of an ADS,
- The capacity of the XADS to be converted into a XADT (eXperimental Accelerator Driven Transmuter),
- The reliability and availability of the plant.

The three concepts show a similar overall rating for the consistency with the project objectives close to 50 %.

The weakest points are :

- the feasibility status of the spallation targets (window/windowless/solid) where the gap in R&D needs and anticipated uncertainties in a proven design are currently judged to be still relatively large,

- the demonstration of the capability to burn Minor Actinides at rate suitable for an Industrial Scale Transmuter which requires important system modifications and an appropriate increase of the power level (in the range of 200 to 400 MWth),

The irradiation capability of the MYRRHA concept (in a few high flux locations) is better than the one achievable in the 80 MWth concepts.

6.2.2 Safety evaluation

The goal of the safety analysis of any design is to show that radiological release hazards from the plant under all service conditions are limited, below intolerable values regarding the environment, the health of public living near the plant site, and the health of the operational staff.

A common safety approach, based on the feedback from European Utility Requirements (defined for modern PWR) and the European Fast Reactor project (recent sodium cooled Fast Reactor project) has been applied to the three concepts. The safety strategy is the same as applied to EFR : the objective being to provide a very high level of prevention of severe core damage.

A set of safety related criteria and a rating system has been proposed within Deliverable 40 to make an overall safety evaluation of the three concepts.

Applying this methodology, all three concepts obtained essentially the same number of total points (a variance of + / - 2 points among the 3 concepts must be judged as absolutely meaningless in such an exercise) which corresponds to a percentage rating ranging between 57 % to 62 %. Thus all 3 concepts are judged to provide a very similar level of safety.

On the safety issue of control and reactivity, all 3 systems are considered very similar.

On the safety issue of decay heat removal, all 3 systems are basically considered comparably effective.

On the safety issue confinement of radioactive products, the LBE-cooled systems are considered to be somewhat more effective in the retention of these products on account of the LBE providing an effective material matrix which binds a significant fraction of non-volatile and semi-volatile fission products. The He-cooled concept does not offer an equivalent material matrix which can function as a retention buffer to radio-nuclides.

On the issue of radiation protection of personnel, all 3 systems are judged to provide a similar level of safety. All 3 concepts rely on accelerator tubes directing the proton beam to the core. These beam tubes require shielding. Personnel are thus basically exposed to a similar source of potential radiation. Nevertheless, the fully remote maintenance of the MYRRHA concept is a more favourable feature.

On the issue of transient response of the 3 systems, the LBE-cooled systems are judged to provide a somewhat higher level of safety because of the large thermal inertia associated with the large mass of LBE-coolant in their primary systems.

On the issue of general design base, the He-technology is considered to rely on a larger, more readily available experimental data base obtained during the operation of gas-cooled reactor systems in various European countries during the last 40 years (i.e., Dragon project in Great Britan, HTR experience in Germany) and current HTR and GFR projects.

On the issue of meeting reliability targets, a similar line of reasoning applies in that the European reactor experience using gas-technology is significantly larger than in the use of LBE-technology.

On the issue of inspectability and maintenance of safety systems, the He-cooled system is judged clearly superior to the LBE-cooled systems since the He-coolant allows in-vessel and safety component inspection under transparent conditions and at colder temperatures. Moreover, the ISI needs on internal structures are more important for the LBE-cooled systems due to potential corrosion damages.

As regards system qualifications, all systems were considered to be rather similar. The He-technology is again judged more readily available than the LBE-technology, and the MYRRHA design incorporates more innovative features compared to the 80 MW LBE design.

As regards severe accident management, the LBE systems were considered to have a slight advantage because of the large in-vessel retention capability of these systems ascribable to the large LBE-mass in the primary system, and their relative insensitivity to transients.

The above summary illustrates that the LBE-cooled concepts clearly exhibit an advantage as regards the level of operational safety due the large inherent safety characteristics associated with the LBE-coolant. In contrast, difficult maintenance (larger ISI needs with respect to the risk of corrosion, and difficulty to practically inspect the internal structures) and lack of available technological database provide the counterbalance on operational safety.

In contrast, the He-cooled XADS exhibits very clear advantages as regards operational maintenance and a readily available technological database. These positive aspects are however balanced by the operational safety features that rely on the assured availability and performance of the accelerator beam trip and on active DHR systems in depressurized conditions. By proper optimization of both the core and the design of the plant, these features can be however largely compensated.

6.2.3 Structural integrity issues

For the three concepts the most critical issue is the structural integrity of the target components facing very high irradiation damages. This is particularly true for the concepts using a beam window for which a sound value of the lifetime cannot be assessed on the basis of existing data. With this respect, the LBE cooled XADS rely on a windowless target for which “reasonable” lifetimes should be attainable. For the Gas-Cooled XADS the Solid target option with a cold window should be developed to improve lifetime and window replacement aspects.

On a generic standpoint for the LBE systems, the key issue is the compatibility of the LBE coolant with the reactor structures materials. It must be adequately demonstrated that corrosion can be controlled when relying on engineering measures such as oxidation protection layers. The seismic behaviour of the very heavy pool reactor (80 MWth LBE system) seems adequate if the building is rested on horizontal anti-seismic supports. The MYRRHA reactor includes more innovative options for the reactor internals and vessel that will however require further thermo-mechanical assessments.

For the Gas-cooled XADS primary system, the main issue is the structural integrity of the reactor thimble facing significant irradiation damages. The lifetime of this thimble and the material selection requires further considerations and needs to be backed by representative testing before assessing the lifetime of this component. It seems however that a higher operating temperature should be a prudent choice at least for the reference T91 ferritic material.

6.2.4 Economic trends

The stage of development of the three concepts being very different, a detailed cost comparison would be meaningless. For instance the stage of development of the Gas Cooled XADS is not sufficient to derive sound cost estimates of both reactor primary system and components and reactor building. The components are still in a very early development stage and the reactor vessel and internals are significantly oversized in terms of dimensions and weight balance. Only a comparison of dimensions and physical quantities of the three reactor concepts has been performed which shows that the extent of the Reactor Buildings are quite similar and rather large compared to critical facilities due to the extra height of the building to accommodate Accelerator Beam Transfer line and Target handling operations. For what concerns the liquid metal systems, the primary system of the LBE reactors compares quite well with an extrapolated sodium cooled reactor which can indicate an order of magnitude of the cost.

The cost exercise was then focused on the accelerator part and on the MYRRHA construction at MOL.

The cost of the Reference XADS LINAC (600 MeV, 6mA) has been assessed from EISS project to 303 M€ at 2003 economic conditions. It was then extrapolated to the MYRRHA characteristics (350 MeV, 5 mA), single injector, site specifics radiation protection to reach a “minimum cost” of 170 M€.

For the 50 MWth MYRRHA construction, an estimated total of 440 M€ is obtained and taking into account the possible contingencies on the different items, a global "high total" of around 560 M€ is also estimated.

The reactor part cost is therefore in the range of 255 M€ to 355 M€, rather consistent with the estimate derived from sodium cooled reactors.

This estimate does not include the cost of the Engineering During Construction which typically amounts to 20% of the construction cost of such a prototypical machine.

The R&D cost, commissioning & operational costs, dismantling costs at the end of life (which however may be estimated to range between 15 and 20% of the construction costs) are not included.

6.2.5 Option validation status

R&D needs have been specified for the different components and concepts of XADS in the course of the PDS-XADS project and in particular through 37 Question Sheets addressed to the ADOPT network.

The R&D needs are classified into five main domains :

- Reactor physics,
- Fuel development,
- Thermal-hydraulics,
- Main component development,
- Materials.

Using the set of criteria defined by the project, the comparison of the R&D needs of the three concepts can be summarized as follows:

On the Reactor Physics, the R&D needs are mostly generic and common to the three concepts and each concept still requires extensive uncertainty assessments on Sub-criticality levels and Transition to Transmutation Core strategy.

The situation is the same for fuel development. As far as cladding is concerned, it is considered that the development needs for both concepts are similar (Corrosion protection/ aluminization for LBE concepts and rough cladding for gas).

Concerning thermalhydraulics, significant R&D needs can be expected for the LBE systems including test on fuel pin bundles and behaviour of the large LBE collectors and low flow velocity or stagnant regions but this is not a critical issue for this concept which shows high design margins. For the gas, past experiments are already available but additional confirmations are highly recommended because maximum clad temperature is here a key issue. Therefore more emphasis is to be put on R&D on the gas.

On the materials issue, the LBE concepts are facing a lower ranking due to corrosion related issues. Significant R&D efforts (testing in non-isothermal pool configurations, potential need for aluminization on cladding, oxygen control process and monitoring, control/ISI of metal oxide film for corrosion inhibition) are necessary to fully qualify the materials to exclude corrosion damage.

On components and system qualification, the accelerator is a common issue for all concepts and the R&D needs are well established and covered by existing programmes. Windowless targets are requiring larger R&D programmes and an integral test which is not scheduled today but the R&D effort and prospect for successful outcome is judged at the same low level from today (no proof of phenomena) for both window/windowless options. The solid target could drastically reduce the R&D needs but the level of knowledge of this option for the XADS is not sufficient to improve the rating. Components of the primary system and in particular, remote and indirect visualisation and inspection require large developments for both LBE concepts. The MYRRHA reactor and its more innovative design of the primary systems will call for a larger technological development programme. Concerning other components and systems, there are further R&D needs for the Gas components in terms of qualification of their reliability.

The comparison shows a slightly smaller extent of R&D needs for the Gas-cooled XADS compared to the LBE concepts. The difference is however not very significant. More important is the fact that most of the R&D needs are common with other helium cooled reactors (Gas Cooled Fast Reactors for core and DHR issues and High Temperature Reactors for the technology). This is likely to significantly reduce the specific development costs (technology, CFD and system codes, use of the same Helium loops, large synergy on core/cladding issues,…).

6.3 General Conclusions

The XADS main objective is to proceed with a global demonstration of the safe operation of an ADS, coupling an accelerator, a spallation target and a sub-critical core, at a scale large enough to be the precursor of an industrial transmuter.

The PDS-XADS project has developed three XADS concepts, two based on LBE-cooling and one on Helium-cooling, in sufficient detail that allows definition of the critical issues as regards design, safety and associated technological and basic R&D needs.

The three designs fit rather well with the technical objectives fixed at the beginning of the project, consistent with the European Roadmap on ADS development .

The designs are sufficiently consistent and advanced to :

- confirm the overall complexity and extent of the plant compared to a critical system (Accelerator, Interface between spallation target and primary system, accommodation of accelerator beam transfer line above the reactor and within the reactor building, radiation protection/shielding, containment issues),

- confirm the good prospect for the feasibility of the XADS apart from the target itself, which is currently considered the weakest point of the system, and

- compare the three concepts and provide recommendations on the best options to be pursued in the 6th Framework Programme.

For what concerns the accelerator, the superconducting LINAC has been clearly assessed as the most suitable concept for the three reactors in particular with respect to the stringent requirements on reliability. Associated R&D needs have been identified and will be focused on critical components (injector, cryomodule) long term testing.

The comparison between the three XADS is rather balanced with no clear advantage of any of them. Each system exhibits advantages in one area which are somehow counterbalanced by other less favourable design features.

This is particularly clear when comparing the 80 MWth LBE-XADS and the 50MWth MYRRHA both using LBE coolant. Both designs appear attractive and fit with the overall objectives of the PDS-XADS project with an emphasis on passive features for the 80 MWth LBE-XADS and some attractive features on the irradiation capabilities for the 50 MWth MYRRHA. This clearly demonstrates the necessity to identify the pro and cons of each system but also to enlarge the objectives associated to the plant to transmutation capability and economical aspects

The design of the Gas-cooled XADS, which did not benefit from an available large base of prior system analyses (compared to the 80 MW LBE-XADS), still has the potential for further optimization The main issues associated with an Helium cooled XADS needing further improvement have been clearly identified and are being currently addressed. The concept design based on conventional steel cladding of the fuel, compatible with the ASAP objective of the XADS, imposes stringent constraints on the maximum power rating which is today close to the limit of about 50 MW/m^3. Besides, the demonstration of prevention of severe core damage strongly relies on the reliable proton beam trip and on an active DHR system in depressurized conditions. Such a conclusion could be revised significantly if more innovative fuel or plant designs such as the ones envisaged for GFR are used (SiC used as cladding material).

The LBE-cooled systems do not have such constraints, and clearly exhibit an advantage as regards the level of operational safety due to the large inherent safety characteristics associated with the LBE-coolant. In contrast, important demonstration, mainly in the field of technology, is needed to establish the prevention of corrosion damage and the requirements and feasibility of inspection of reactor internal structures.

Integration of the liquid LBE spallation target is more straightforward in the LBE systems than in the Gas system and offers a wider range of possibilities (compatibility with window and windowless targets). The lifetime of the window target is expected to limit the availability of the plant. Emphasis is thus to be placed in the development of the windowless target which requires significant R&D efforts on the interface between vacuum and LBE free surface. The two designs of windowless target for 80 MWth and 50 MWth (MYRRHA) are significantly different and would require an in-depth evaluation and comparison.

It is recognised that an Experimental ADS facility is required to acquire knowledge and practicable experience in coupling an accelerator to a sub-critical core, on one hand, and on the other hand to accumulate some experience in the irradiation behaviour of advanced U-free fuel. For that purpose, LBE-coolant seems the preferable option because of its lower operating temperatures. The existing MYRRHA design includes features which make it attractive for a multi-purpose R&D facility (high flux level, high power density, small diameter target, multi-batch core, remote handling) while the 80 MWth LBE-XADS exhibits very positive features as regards its safety behaviour, its expected reliability and its overall economic performance.

Preliminary studies on the transmutation capabilities have demonstrated that only plant sizes in the order of several hundreds of MWth can reach satisfactory transmutation rates, the optimum being 45kg/TWhth of actinides coming from a PWR park. The technical demonstration of the feasibility of this remains an extrapolation of the plants being studied up to now.

It should be pointed out that in case of difficulty in the demonstration of the LBE technology (R&D support on corrosion, inspection, maintenance), the currently existing (and validated) technology of the sodium cooled Fast Reactors provides a “natural Fall-back option”. It would allow concentration of the R&D efforts on ADS specific issues such as coupling of the Accelerator and Target. It would also provide some guarantee on the feasibility of constructing a Demonstration Facility in the short term.

As a final statement, the PDS-XADS project has been the first project to start a rather detailed ADS design, making full use of European expertise of different research organizations, industries and universities.

The three designs are sufficiently advanced to confirm the practicable prospects for the successful feasibility of such ADS plants. The detailed engineering drawings (blue prints) of the three XADS concepts are of sufficient detail to provide reasonable assurance and confirmation of this feasibility . It appears that each ADS concept has advantages and weaknesses, weaknesses that should be overcome by additional studies. Pending questions associated to technology gaps have been identified and appropriate R&D programmes should be activated to overcome them.

In the next future, one of the purposes of the EUROTRANS integrated project will be to demonstrate that an ADS, designed to transmute nuclear waste, is feasible at reasonable cost, the assessment being set up on a best-estimate approach. These studies will concentrate on the Lead-cooled system preferred in the long run to LBE (reduction in the generation of Polonium, high cost of Bismuth, higher efficiency of the plant). A gas-cooled ADS with a high temperature cladding material will also be considered as an alternative as this type of design might offer advantages for larger size plants.

A second objective will be to go further in the design studies of the intermediate step Experimental ADS (XT-ADS), with a MOX-fuelled core cooled by LBE, to demonstrate the main features of an Industrial Transmuter.

These design activities will be complemented and supported by activities on accelerator sub-critical core coupling experiments, on U-free dedicated fuels, on LBE technology and materials and on nuclear data uncertainty evaluation and improvement within the EUROTRANS Integrated Project.

This work is intended to provide an overall assessment of the feasibility and cost for an ADS based transmutation so that a decision can be taken to launch a detailed design and construction of the intermediate step Experimental ADS.