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The experimental accelerator driven system (XADS) designs in the EURATOM 5th framework programme

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Abstract

The Accelerator-Driven System has the potential to safely fission Minor Actinides and transmute, on industrial scale, selected long-lived fission products into isotopes of lesser concern. European leading nuclear Industrial Companies and Research Centers,within the EURATOM 5th Framework Programme, have studied three solutions of eXperimental Accelerator Driven Systems (XADS), different for the power (80 and 50 MW) or the primary coolant (Lead Bismuth Eutectic and Gas). Two main concepts of Target Unit are envisaged: the Window Target Unit which features a thin metallic sheet as a barrier between the LBE target and the Proton Beam Pipe and the Windowless Target Unit in which the proton beam impinges directly on the free surface of the liquid LBE target. These designs are under study in order to assess and compare them on a common basis, and to outline the main R&D needs.

1. Introduction

Further to a conceptual design of the Energy Amplifier made by CERN [1], in 1998, the Research Ministers of France, Italy and Spain have established a Technical Working Group (TWG) which has indicated the need to design and operate an eXperimental Accelerator-Driven System (XADS) facility at a sufficiently large scale to become the precursor of the industrial, practical-scale transmuter. This objective has been recognised by the European Atomic Energy Community in the frame of the 5th Framework Programme of EU for research and training in the key action of nuclear fission.

The XADS is a facility designed for demonstrating basic aspects of the ADS power prototype, such as the viability of the system made of a sub-critical reactor driven by an accelerator via a spallation Target Unit.

Three designs have been studied:

Design A – 80 MW LBE-Cooled XADS.
Design B – 80 MW Gas-Cooled XADS.
Design C – 50 MW LBE-Cooled MYRRHA.

Some of the main features of the XADS are common to the three designs: a Proton Accelerator feeding a Target Unit placed inside an hollow Core and spallation power dissipated via an intermediate loop. Designs A and C feature solutions known from the technology of

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the large pool-type Liquid Metal Fast Reactors, whereas a few are peculiar to the different designs (e.g. gas injection instead of mechanical pumps for Design A, blowers for Design B and refueling from the bottom of the Core for Design C).

The paper describes the three Designs, with emphasis for Design A that is more progressed, along with the R&D programme that would be needed to support their further development.

2. Primary system

2.1. Design A, the LBE-cooled XADS

The primary coolant is molten LBE, which is characterised 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 (Table 1).

The configuration of the primary system is pool-type [2,3], similar to that of most sodium-cooled reactors, which has important beneficial features. These include the Reactor Vessel (Fig. 1) containing all the Lead Bismuth Eutectic (LBE), thus eliminating all problems related to out-of-vessel primary coolant.

The Reactor Vessel ④ is surrounded by the Safety Vessel ⑤ to ensure containment of the LBE and core cooling also in case of Reactor Vessel leakage. The gap between the two vessels is sufficient to allow the access of a remote-controlled vehicle, for In-Service Inspection (ISI) 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 ends with an Y-piece, the inner branch of which supports the Reactor Roof ⑥. The cylindrical Inner Vessel ③, of asymmetrical cross section, hangs from the Reactor Roof. Its shape is determined by the need of including the in-vessel fuel handling system and limiting the Reactor Vessel diameter, while leaving a large outer space to install the Intermediate Heat Exchangers (IHXs) ⑦.

The Reactor Roof ensures component support, reactor cover gas containment, and the biological protection. The In-Vessel Fuel Handling System operates without opening the primary containment. It consists of a Transfer Machine ⑧, and of a Rotor Lift Machine ⑨ that transfers the assemblies to/from a flask positioned on the Reactor Roof. To avoid rotating parts immersed in LBE, no mechanical pumps are used for primary coolant circulation which is obtained by an argon gas lift system.

The primary coolant leaves the Core ② in radial direction below the top of the fuel assemblies and enters the Riser Channels ⑩ arranged at the periphery of the Inner Vessel. Argon is injected at the bottom of Riser Channels to increase the density difference between the cold LBE in the Downcomer ⑪ and the hot LBE-gas mixture in the Riser. The argon gas leaves the coolant at the free surface and escapes into the cover gas plenum.

Four bayonet-tube IHXs are freely immersed in the Downcomer, without membrane (Redan in French), spanning the vessel to separate hot and cold plena, to ensure coolant flow outside the IHXs in case of solidification of the LBE inside them. In the Reactor Vessel Cavity, the large U-tube heat exchanger of the Reactor Vessel Air Cooling System ⑫ keeps cooled the concrete walls of the Vessel Cavity and is always available to remove decay heat via two concentric headers and four stacks that constitute redundant inlet and outlet air paths.

The whole Nuclear Island lies on a foundation consisting of an upper and a lower basement separated by seismic support pads ⑬ made of alternate layers of high-damping rubber and steel. As a result of these choices, the seismic loads are drastically reduced and the mechanical analyses, performed so far, confirm the feasibility of the primary system.

2.2. Design B, the Gas-cooled XADS

The primary coolant is helium at about 6 MPa.

Table 1
Design data (nominal) of the three XADS design

	Design A	Design B	Design C
Core Power (MW)	80	80	50
Primary Coolant	LBE	Helium at ~6 MPa	LBE
Core Inlet Temperature (°C)	300	200	200
Core Outlet Temperature (°C)	400	450	350
Coolant Flow Rate in the Core (Kg/s)	5471	61,6	2500
Coolant Velocity in the Core (m/s)	~0.42	~30	<2
Secondary Coolant	Diphyl-THT[a]	Water	Water
IHX Sec. Coolant Inlet Temperature (°C)	270	25	140
IHX Sec. Coolant Outlet Temperature (°C)	312	65	170

[a] Trade name of a mixture of synthetic, partially hydrogenated terphenyls.

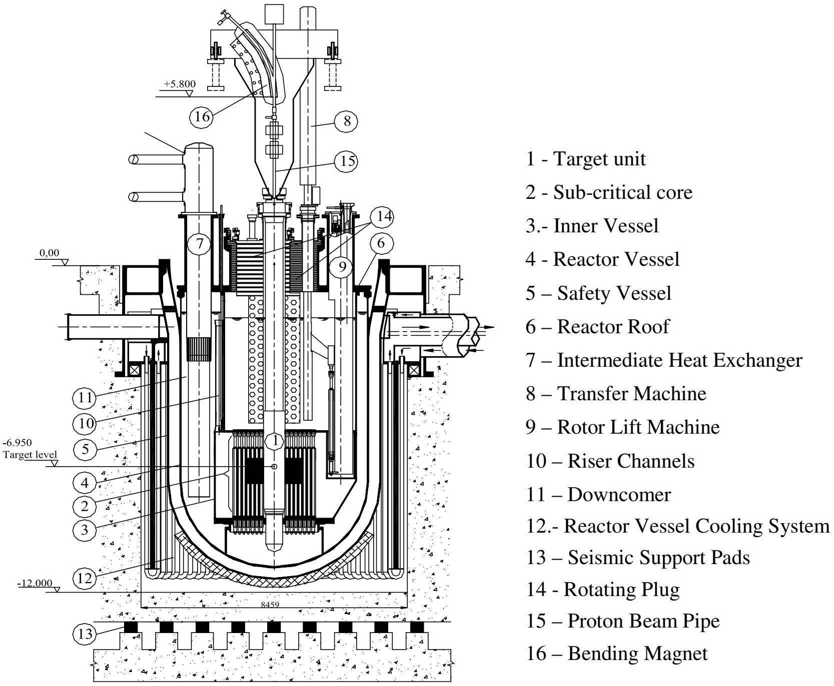

Fig. 1. Design A, the LBE-cooled XADS.

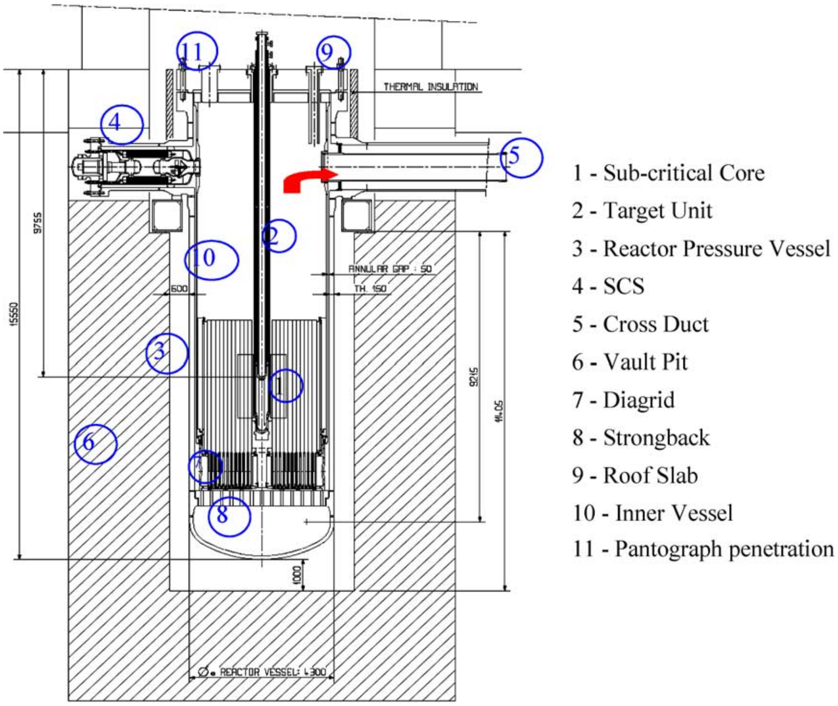

Fig. 2. Design B, the Gas-cooled XADS.

The reactor primary system [4], extrapolated from modular thermal reactor projects such as the Gas Turbine-Modular Helium Reactor (GT-MHR), comprises a Reactor Vessel (Fig. 2) housing the Core ①, a separate

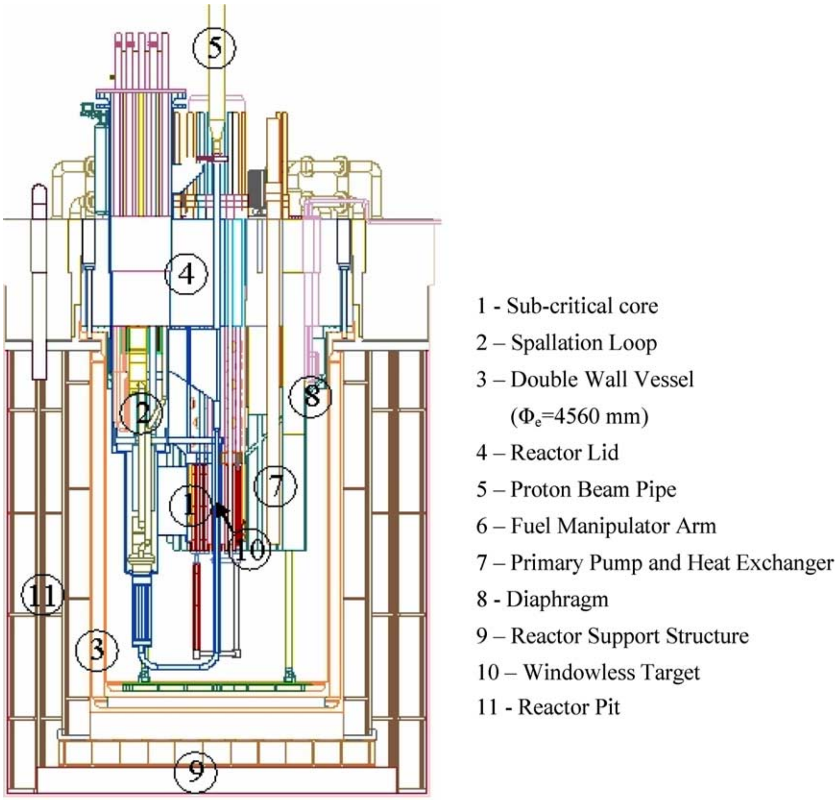

Fig. 3. Design C, the LBE-cooled Myrrha.

vessel that houses the Power Conversion System (PCS) and a Cross Duct ⑤ linking the two vessels.

The Reactor Vessel ③ accommodates the Target Unit ②, the sub-critical Core and associated systems for fuel handling and the Shutdown Cooling System (SCS) for decay heat removal. The PCS vessel (not shown in the figure) provides the coolant circulation by a motor driven blower, and the heat exchanger transferring heat to an external cooling water circuit. The Reactor Vessel is located within a concrete Reactor Vault and the whole system within the Reactor Building. The Reactor Vault is cooled with air in natural circulation in a specific circuit.

The primary coolant is in forced circulation during power operation. In case of accidental loss of the forced circulation, decay heat can be removed using the helium/water heat exchangers and natural circulation on the water side of the SCS. A circulator is provided as part of the SCS for the normal decay heat removal and the accidental depressurised state.

2.3. Design C, the LBE-cooled MYRRHA

The system is shown in Fig. 3 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 [5].

This shield will be closed above the Reactor Lid ④ to form a hot cell used as remote handling area for all operation and maintenance services to the reactor.

The Core ① is mounted on a central support column hung from the Reactor Lid and being stabilised by the Diaphragm ⑧, the separating septum between the cold and hot LBE coolant, which is fixed ultimately to the rim of the Double-Wall Vessel ③. Since space for access from the top is scarce and components introduced into the pool will be buoyant due to the high density of the LBE, 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 ⑦, the Heat Exchangers using water as secondary fluid and the two fuel handling robots located on the characteristic Rotating Plug of fast reactors.

3. Target unit

The Target Unit provides the physical and functional coupling between the Proton Beam Accelerator and the

Table 2
Target Units of the three XADS design

	Proton energy (MeV)	Max. beam current (mA)	Window	Windowless	Solid
Design A – 80 MW LBE	600	6	S1, Fig. 4	S2, Fig. 5	
Design B – 80 MW Gas	600	6	S3		S4
Design C – MYRRHA	350	5		S5, Fig. 6	

Sub-critical Core. The three designs can accommodate five different solutions according to Table 2.

The LBE, containing the spallation products, is kept confined within the Target Unit in order to prevent the contamination of the primary coolant. Solutions S1, S2, S3, S4 are removable components of slim cylindrical form, co-axial with the Reactor Vessel, which serves also as inner radial restraint of the core. Solution 5 [8] is a loop interlinked with the core with service equipment (pumps, HX, vacuum pumps) put aside at the Core periphery because the central hole diameter of the Core is very narrow (100 mm). Despite the interlinked design, the Solution S5 is also a component removable from the core, maintained in place when loading or unloading fuel assemblies (Figs. 4–6).

The Window Target Unit (S1, S3) features a thin metallic sheet (the Window) as a barrier between the LBE target and the Beam Pipe. The Window and most of the Target Unit are made of ferritic-martensitic 9Cr1Mo steel. The Proton Beam Pipe including the high irradiated Window can be mechanically disconnected from the Target Unit and removed independently.

In S1 heat is removed by LBE in natural circulation cooled by the integrated heat exchanger located at a higher level. The use of a diathermic fluid as secondary coolant gives flexibility in the choice of the thermal cycle and in particular it allows to limit the temperature of the hottest spot of the window.

S3 is cooled in forced circulation via a pump and a heat exchanger located outside the vessel [7]. This arrangement minimizes the Target Unit diameter and simplifies both design and maintenance of the components. The Target Unit is housed in a thimble made of ferritic-martensitic 9Cr1Mo steel that is part of the pressure boundary of the primary circuit.

In S2, S5 the proton beam impinges directly on the free surface of the liquid LBE. No structural material is exposed to direct proton irradiation, avoiding the associated severe material damage and hence extending the Target Unit lifetime to that of the fuel assemblies. No additional scheduled outages will be necessary for the replacement of this component.

An issue of the ADS concept is neutron streaming from the Beam Pipe which makes difficult refueling and In-Service Inspection and Repair, owing to the activation of structures and components above the Vessel Roof. In the case of the Windowless Target Unit, however, this problem is attenuated because it is not necessary to scan the proton beam through a large area and the Beam Pipe can be of reduced cross section (60 cm^2 in S2 and 41 cm^2 in S5 against 314 cm^2 of the Window Target Units).

In S2 [6] the heated LBE is driven downwards to the heat exchanger by two mechanical pumps in series. A stream of primary LBE is bypassed from the cold plenum to the heat exchanger to serve as the cooling medium.

The back up solution of the Gas-cooled XADS is a Solid Target (S4), cooled by helium, consistently with its primary system gas technology.

3.1. Core of Design A

The core consists of 120 hexagonal fuel assemblies arranged in an annular array of five rows. The assemblies have 90 fuel pins loaded with MOX fuel with a lattice about 40% larger and active fuel length slightly shorter (87 vs 100 cm) than for SPX. 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.

The fuel assemblies are surrounded by a buffer region of 174 dummy elements, which protect the fixed structures from the hard neutron spectrum, while LBE acts as a neutron reflector for improved neutron economy. The dummies can be replaced by prototypical fuel assemblies for irradiation testing or by neutron absorbers in order to decrease keff below 0.95 before refueling.

The large fuel pin lattice allows for core cooling by natural convection in the case of loss of the forced circulation.

The chosen initial subcriticality, cycle length and core management, ensure core sub-criticality over lifetime also in case of postulated accidents, which may lead to large temperature changes and positive reactivity insertion. For Design Basis Conditions (DBC), a safety margin of $\Delta k = 1\%$ and 0.6% allowance for measurement error lead to keff = 0.984 as the upper limit. Core cooling from full power down to (conservatively assumed) ambient temperature, Beam Pipe flooding by LBE and displacements associated to earthquake cumulate a reactivity insertion of about 1.4%. For normal operation at full power and BOC keff is set accordingly at 0.97, which is sufficiently low to ensure safe operation without need of shutdown rods. For the targeted 1000 days full

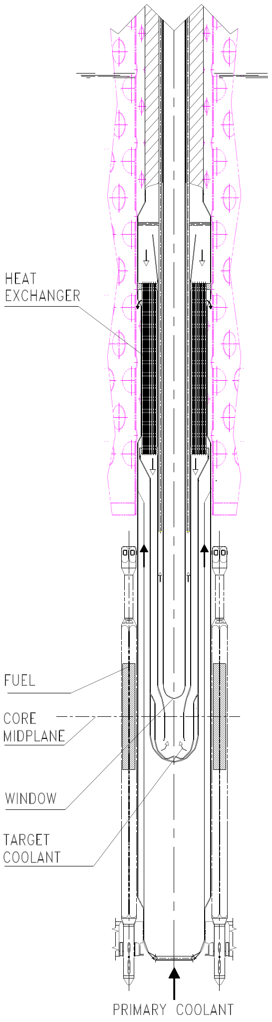

Fig. 4. Design A Window Target Unit.

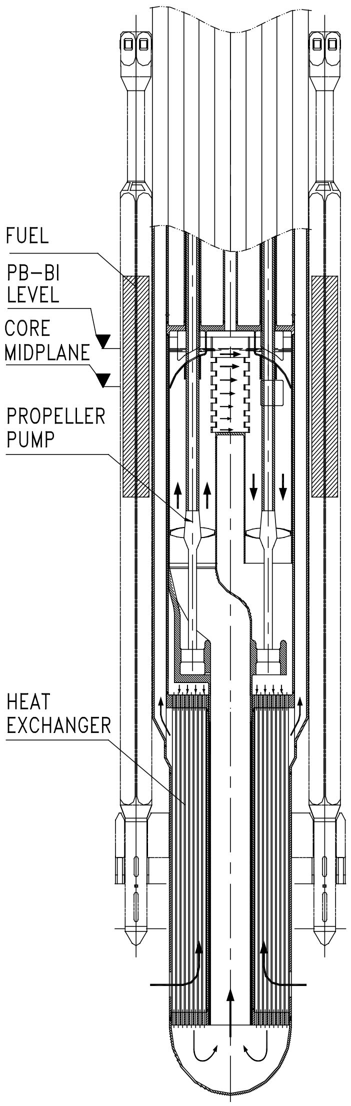

Fig. 5. Design A Windowless Target Unit.

power operation, the reactivity swing would not exceed 4%, reducing keff to 0.93 and increasing the needed proton current to about 6 mA.

3.2. Core of Design B

The core [4] is made of an annular array of 90 fuel assemblies arranged around the Target Unit. Surrounding the core are steel reflector assemblies in turn surrounded by assemblies containing boron carbide as shield to limit damage to the Reactor Vessel. Six absorber rods, located at the active core periphery, are used only at shutdown to provide reactivity margin, mainly for compensation of fuel handling error and accidental water ingress in the Core. The design of the Core is largely based upon fast reactor experience.

For the Core to remain subcritical, a strategy is assumed similar to that of Design A, apart from the fact that an alternative option of refueling scheme is proposed with three fuel batches, to increase burn-up without excessive requirement on the proton beam power.

3.3. Core of Design C

The core is designed as a much more 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

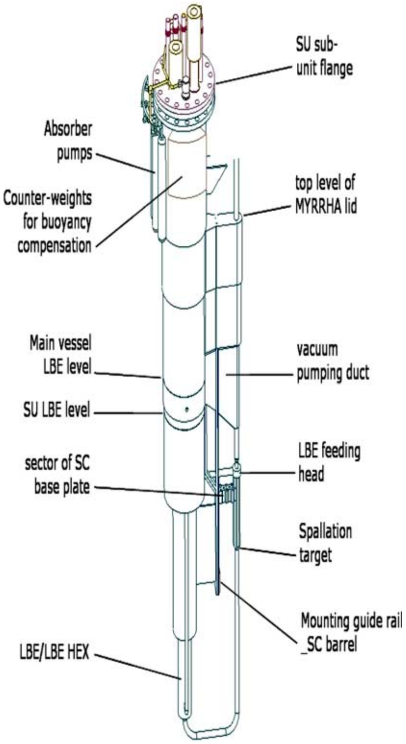

Fig. 6. Design C Windowless Target Unit.

configuration with BOC keff of 0.95 can be 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.

4. Safety analysis

Extensive transient analyses of Design A [9] have been done by the different Organizations (ANSALDO, ENEA, FZK, PSI, JRC, NNC, KTH), using different codes to provide confidence in the assessment of these innovative reactors. The codes used are RELAP5/PARCS, TRAC-M/PARCS, SIMADS, SIMMER, SAS4ADS, EAC2, and STAR-CD.

The purpose has been to study the dynamic characteristics of the sub-critical cores and the system response to different transient initiators. A total of 26 transient initiators [10] (e.g., spurious beam trip, protected/unprotected loss of flow, loss of heat sink, fuel assembly blockage) have been considered and classified into Operational Transients (3), Protected Transients (11), and Unprotected Transients (12).

The results indicate that Design A exhibits a large safety margin, owing to very favorable safety features, the combination of which makes it very unlikely overheating the fuel clad and the risk of release of fission products. Similar analyses are ongoing for the Designs B and C.

5. The complementary R&D programme

Despite extensive use of proven technology, there are a number of features of the three designs, which need confirmation/development through an ambitious research programme.

The XADS design team has identified critical technological areas and development needs, described in about 40 Question Sheets, that require supporting R&D activities. Among the main R&D topics, there are LBE technology, thermal-hydraulics and qualification of materials for Primary System, Fuel Cladding, Target Unit and Window, and particularly:

- Minimum coolant temperature to avoid fuel cladding embrittlement in fast spectrum.
- Maximum fuel cladding temperature in LBE with oxygen control.
- Maximum LBE velocity to prevent excessive corrosion and erosion of structural material.
- Structural material damage under neutron and proton irradiation for the target window.
- Data base of the structural materials (T91 for fuel cladding, core structure and Target Unit; AISI 316 L for the Reactor Vessel).
- Al-coating of the fuel cladding.
- Oxygen control in the LBE melt in a pool configuration.
- LBE flow pattern in a Windowless Target Unit.
- Beam line vacuum and free level stability in a Windowless Target Unit.
- Remote handling.

6. Conclusions

Three XADS concepts have been developed at a sufficient level to allow the identification of critical issues and suitable solutions.

The operational keff chosen at BOC guarantees sufficient subcriticality margin under any operational and accident conditions (DBC and DEC) without need of shutdown or control rods. Compensation of fuel burnup would be achieved by increasing the proton beam current when needed.

In spite of the large mass of LBE of the primary system, Reactor and Safety Vessel of the LBE-cooled XADS can resist seismic loads, because the Reactor Building rests on antiseismic supports.

For the LBE-cooled XADS and MYRRHA, the Windowless Target Unit option appears to present more merits in term of less Reactor Roof activation, longer lifetime and reduced need of material qualification. The Gas-cooled XADS has a Window Target Unit, with a solid target as back up solution.

The design of the three XADS concepts, carried out in the European 5th FP, has produced an impressive amount of technical solutions and documents that constitute a sound basis for designing an ambitious reference solution in the next European FP.

Early results of transient analyses of the LBE-cooled XADS indicate that it exhibits a large safety margin owing to very favorable safety characteristics, namely good heat transfer properties, large thermal inertia and high boiling point of the primary coolant. These characteristics combined with core, primary system, secondary system and Reactor Vessel Air Cooling System, all favorable to promote the natural circulation, prevent voiding within the core and fuel clad overheating even under the most severe transient conditions.

The XADS design team has identified critical technological areas that need development and supporting R&D activities such as LBE technology, thermal hydraulics and qualification of materials for Primary System, Fuel Cladding, Target Unit and Window.

References

[1] C. Rubbia et al., Conceptual Design of a Fast Operated High Power Energy Amplifier, CERN/AT/95-44(ET), September 1995.

[2] L. Cinotti et al., XADS Pb-Bi Cooled Experimental Accelerator Driven System – Reference Configuration – Summary Report, ANSALDO ADS1SIFX0500, Rev 0, June 2001.

[3] L. Cinotti et al., Status of the Studies performed by the European Industry on the LBE cooled XADS, International Workshop on P&T and ADS Development – Mol, Belgium, 6–8 October 2003.

[4] B. Giraud et al., Preliminary Design Study of an accelerator driven system. Description of the gas cooled primary system, International Workshop on P&T and ADS Development – Mol, Belgium, 6–8 October 2003.

[5] H. Aït Abderrahim et al., MYRRHA, a Multipurpose Accelerator Driven System for R&D. State-of-the-art of the project at mid-2003, International Workshop on P&T and ADS Development – Mol, Belgium, 6–8 October 2003.

[6] L. Cinotti et al., Design of a Windowless Target Unit for the XADS Lead–Bismuth Cooled System, International Workshop on P&T and ADS Development – Mol, Belgium, 6–8 October 2003.

[7] D. Coors et al., Window Target Unit for the XADS-Gas Cooled Primary System, International Workshop on P&T and ADS Development – Mol, Belgium, 6–8 October 2003.

[8] P. Kupschus et al., Myrrha Spallation Loop Design, International Workshop on P&T and ADS Development – Mol, Belgium, 6–8 October 2003.

[9] M. Schikorr et al., Transient Analysis of the LBE-Cooled XADS design, International Workshop on P&T and ADS Development – Mol, Belgium, 6–8 October 2003.

[10] B.R. Sehgal et al., Assessment of the safety of PDS-XADS designs, International Workshop on P&T and ADS Development – Mol, Belgium, 6–8 October 2003.