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The Pb-Bi cooled XADS status of development

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1. Summary

On 1998, the Research Ministers of France, Italy and Spain have established a Technical Working Group (TWG) including R&D organisations and industrial companies in charge of reactor and accelerator studies, in order to identify the crucial technical issues for which R&D is needed. The recommendations of the TWG indicate the needs to design and operate an eXperimental ADS (XADS) facility at a sufficiently large scale to become the precursor of the industrial, practical-scale transmuter.

This interest is confirmed by the two-years program which has recently started, sponsored by MURST (the Ministry of the University, Scientific and Technological Research), under the leadership of INFN for the Accelerator and of ENEA for the subcritical Reactor. This program is considered of particular relevance for the creation of a well mixed group of competencies, and it will provide important results in support to any related industrial program.

Since early 1998, the Italian ENEA, INFN, CRS4 and Ansaldo have set up a team, led by Ansaldo, to design an 80 MWth XADS, a key-step towards the assessment of the feasibility and operability of an ADS prototype. The results obtained so far, allow to outline a consistent XADS configuration. The main issues investigated and the associated solutions adopted are concisely described in the paper.

2. XADS plant description

The main features and associated working principles of the the Reference Configuration of the XADS are the following:

The Nuclear Island consists of four main elements, viz. a cylindrical reactor building, two outer buildings contiguous with the reactor building, which are the main room and service building and the building housing the fuel and active component handling facilities, and the outer air coolers building. The composite plan outline of the three outer buildings is rectangular in shape, except for the annular outline contiguous to the reactor building. The whole of the Nuclear Island rests on a single foundation consisting of upper reinforced concrete basemat and lower basement separated by seismic support pads.

The Reactor assembly presents a simple flow path of the primary coolant with a Riser and a Downcomer. The heat source (the Core), located below the Riser, and the heat sink (the

Intermediate Heat Exchangers) at the top of the Downcomer, allow an efficient natural circulation of the coolant. The additional means provided to enhance the primary coolant flowrate is not a mechanical pump, but bases on the principle of gas lifting: Argon of the cover gas plenum is injected into the bottom of the Riser and generates the gas-coolant mixture that, being lighter than coolant alone in the Downcomer, keeps the coolant circulating at a higher flowrate, the level of which can be controlled by the amount of gas injected.

Consequent to the elimination of the mechanical pump and to the natural circulation configuration of the primary circuit, there is assurance of no high speed of the coolant, not even across the smallest cross sectional areas of the flow path. This technological option helps to reduce the erosion/corrosion of the structural material brought about by flowing Lead-Bismuth Eutectic (LBE), and creates a large gas bubbles to primary coolant interface area for faster reaching the equilibrium dissolution of atomic Oxygen in the LBE.

All primary coolant remains inside the Reactor Vessel, including the coolant that circulates through the LBE purification unit, that is immersed in the Reactor pool.
The use of LBE as the primary coolant allows a relatively low operating temperature, in order to eliminate risks of creep damage of the Reactor structures and to reduce their corrosion rate.

The organic diathermic fluid used as the secondary coolant has a low vapor pressure and is chemically inert against the primary coolant.

The accelerator design is compatible with the XADS construction timescale.

This Reference Configuration of the XADS embodies features that cope with its demonstration duties and is flexible enough to cope with requirements that cannot be precisely specified at present, but are predicted to be focused at a later stage.

Among these duties there is the capability to accommodate different cores, minor actinides and long-lived fission product sub-assemblies at locations where neutrons have the required intensity and the appropriate energy level. This capability is ensured by the long, absorber-free path in the LBE, that has been provided in the reactor vessel for the scattering neutrons, which thus offer a continuous, isolethargic energy spectrum on their way to gradual thermalisation. The first core will be U and Pu MOX of the proven SPX1 isotopic composition or slightly more enriched in Pu, in order not to unnecessarily delay the operational availability of the XADS, because the development of new fuel is a long-lasting task.

As a second example of flexibility, the primary coolant control system can operate at different flowrates and pressure losses, in order to cool different-configuration Cores.

The requirement of large operational flexibility can be better achieved if no constraints from electric energy generation are superimposed to the XADS, and hence the reactor power will be dissipated to the external atmosphere by means of air coolers.

Table 1-1 summarizes the main engineering choices by plant area, and Figure 1-1 shows the reactor assembly of the Reference Configuration of the XADS

TABLE 1-1

XADS Main Options by Plant Area

Plant Area	Reference Solution	Rationale for Selection
Power	80 MWth	• 80 MWth is a power consistent with a representative core characterized by an annular configuration • The Accelerator requires a moderate power upscaling factor with respect to the existing machines • The decay heat can be removed by a Reactor Vessel Air Cooling System in natural circulation, with negligible creep damage (according to the RCC-MR French mechanical design rules)
Accelerator	Two-stage Cyclotron scheme based on the PSI configuration: • One source pre-injector Linac of 3÷6 MeV, 2÷6 mA • One intermediate, separate-sectors injector cyclotron (100 MeV) • One booster, separate-sectors Cyclotron (600 MeV)	• The Cyclotron is a compact solution in comparison to a Linac • The selected solution is based on existing machines. The required, moderate 2 to 4 power upscaling factor is possible on the basis of already identified modifications (e.g., increased number of cavities from 4 to 6)
Target Unit	Pb-Bi eutectic separated from primary coolant as the target material Two optional concepts of Target Units: Hot-Window : metallic separation between vacuum pipe and target LBE in natural circulation. Cooling by organic diathermic fluid (back-cooled by water) Windowless : protons impinge directly on the LBE target. Forced circulation. Cooling by primary coolant.	• A liquid target is necessary because a solid target cannot dissipate high-density thermal power without risk of melting and hence loss of its capability to be cooled • Pb and Bi have good nuclear properties • Pb and Bi have a good spallation neutron yield • The Pb-Bi eutectic has a low melting point (125 °C) No selection. Both Target Unit concepts remain candidate. Nota: Outline dimensions of the Target Units defined. The Reactor configuration can accommodate either Target Unit without major modifications. The selection of the Target Unit will be possible as soon as the results of the experimental campaign will be available.

TABLE 1-1

XADS Main Options by Plant Area (continued)

Plant Area	Reference Solution	Rationale for Selection
Core	sub-critical over lifetime with Keff ~ 0,97 at BOL decreasing to 0,94 at EOL, at full power	• The Keff at BOL is sufficiently low to ensure safety without control and shutdown rods.
Fuel	U and Pu MOX The proposed Core is based on a fuel having the isotopic composition of the fuel at the higher enrichment of the second SPX Core or slightly more enriched in Pu The fuel pellets have been assumed of the same geometry as for SPX.	• Proven technology • Potential use of fuel belonging to the 2nd SPX1 Core
Primary Coolant System	• Lead-Bismuth Eutectic as primary coolant. • Thermal cycle: 300 °C at core inlet, 400 °C at core outlet • Natural-circulation flowrate enhanced by cover gas injection, fed by a compressor, into the bottom part of the Riser, made of pipes arranged at the outside periphery if the Inner Vessel. The bi-phase, eutectic-gas mixture in the Riser, being lighter than the eutectic alone in the Downcomer by the amount corresponding to the mean void fraction in the Riser, creates the additional driving force. The lift gas separates at the interface with the cover gas plenum, thereby closing the gas loop. • Free-flow pattern in the Downcomer with flowrate distribution dictated by convection within the IHX. Stable eutectic thermal stratification outside the IHX. • The quasi stagnant LBE plenum inside the Inner Vessel and the LBE plena outside are hydraulically connected by high-friction flow paths in order to improve the stability of the primary coolant flowrate.	• The hot plenum remains below the creep temperature of the structural steel • The cold plenum remains far from the freezing point • The thermal cycle is consistent with the selection of an organic diathermic fluid as secondary coolant • This solution is justified by the high pressure head brought about even by a modest void fraction in the Riser, owing to the high density of the lead eutectic • The solution cumulates most of the advantages of a natural-circulation reactor configuration: -The Primary System layout is made simpler -Easier ISI of the Primary System components -In case of unavailability of the gas injection the low pressure loss of the primary circuit allows decay heat removal through natural circulation to cope with the safety requirements of a full-passive plant • The solution cumulates most of the advantages of a forced-circulation reactor configuration: - Plant flexibility through control of the primary coolant flowrate, -Reduced Vessel height.

TABLE 1-1

XADS Main Options by Plant Area (continued)

Plant Area	Reference Solution	Rationale for Selection
Secondary Coolant System	• The secondary coolant is a low-vapor pressure, synthetic organic Diathermic Fluid. • The thermal cycle is 280÷320 °C at full power. The Secondary Coolant System is made of two independent loops. Each loop consists of two IHX's immersed in the primary coolant, of three Air Coolers arranged in series, of a mechanical pump and interconnecting piping. Each loop is capable to remove the decay heat in natural circulation, with only one Air Cooler in operation. This latter configuration is safety-related.	• Low pyrolysis at high temperature (up to 340 °C) in continuous operation • Low radiolysis because of the low radiation level at the IHX bottom • Vapour pressure lower than atmospheric pressure over the selected operating temperature range • No chemical reaction with LBE • Self-ignition point far above the operating temperature • No activation (sodium traces below one ppm) • Low toxicity to humans • High thermal capacity (about 2 times that of Na and about 15 times that of Pb-Bi) • Large experience in the chemical industry • Low cost • Air coolers once constructed for the Na-filled secondary loops of the PEC reactor and made available for the XADS. The six Air Coolers in loops filled with diathermic fluid, have a capability that copes with the design requirements of the XADS. Their mechanical design is adequate for the new mechanical and thermal loads: - the operating temperature is lower than in the case of PEC , - in operation, the Diathermic Fluid has about the same density as the Na density.
Normal and safety-related Decay Heat Removal	Both functions performed by the Secondary Coolant System	• The cumulation of but functions is possible because of the two-loops arrangement and the natural circulation capability. One loop in natural circulation with one air cooler is sufficient to remove the decay heat.

TABLE 1-1

XADS Main Options by Plant Area (continued)

Plant Area	Reference Solution	Rationale for Selection
RVACS (Reactor Vessel Air Cooling System)	Circular U-pipe bundle arranged in the reactor pit, connected to atmospheric air by ducts and chimneys. The air flows pipe-side in natural circulation. The inlet pipe legs face the pit and are thermally decoupled from the return legs, that face the Safety Vessel. The decay heat transfer route is as follows : • Conduction through the Reactor Vessel • Radiation and convection from the Reactor Vessel to the Safety Vessel • Conduction through the Safety Vessel • Radiation and convection in the Reactor Pit from the Safety Vessel to the RVAC return pipe legs	• A full-passive system, that can perform the DHR function as a backup system, and guarantees Core cooling in Design Extension Conditions • It provides via the inlet pipe legs also the normal, continuous cooling of the reactor pit concrete
In-Vessel Fuel Handling	Rotating Above-Core Structure (ACS), one Rotating Plug, one offset-arm Charge Machine and one Rotor Lift combined with a Flask as the link to the secondary fuel handling	• Proven technology (e.g., SPX1) • The offset-arm machine is selected to avoid handling in Pb-Bi with the several kinematic links of the more complicated machines (e.g. pantographs) • The rotating ACS and Plug arrangement allows all Sub-Assemblies to be handled by the Charge Machine
Reactor Roof	Insulated metallic plate	• Easy manufacturing of a relatively small-diameter component
Reactor Vessel and Safety Vessel	Made of AISI 316 L austenitic steel, Hung from a common, cold support beam anchored to the civil structure The bottom head of the Safety Vessel is insulated to prevent overheating the concrete below.	• Hung arrangement according to Western countries experience in the LMR's field • 316 L steel should not present risk of fragility when used with Pb-Bi • 316 L steel has the advantage of a great manufacturing experience
Earthquake Protection	Reactor, Auxiliary, Fuel and Air-Coolers Building resting on a common basemat supported by horizontal seismic isolators.	• Reduction of seismic loads on Reactor Vessel, internals and components • Horizontal anti-seismic supports are a promising technology for nuclear plants, also because of the large experience available in civil engineering

TABLE 1-1

XADS Main Options by Plant Area (continued)

Plant Area	Reference Solution	Rationale for Selection
Hot Standby Temperature	300°C	• 300°C is a temperature well above the primary coolant freezing point • 300°C is a temperature sufficiently low for negligible pyrolysis of diathermic fluids • 300°C can be easily maintained with the selected secondary loop thermal cycle
Fuel Assembly Monitoring	Thermocouples and Failed Fuel Pins detection system	• Normal LMR's design practice
Pb-Bi Purification Unit	In-vessel purification by gravitational settling of metal oxides	• In-vessel, according to the LMR's practice • It avoids external primary Pb-Bi loops with potential Polonium release

3. Safety Analysis

A modified version of the RELAP5/MOD 3 computer program is employed to simulate the thermalhydraulic behaviour of the XADS primary and secondary System.

The abnormal and accident events have been identified and categorized with a systematic approach. Then the ones having the potential to challenge the established acceptance criteria for the physical barriers interposed between the radioactive fission, activation or spallation products and the external environment or to exceed the maximum allowable release of radioactivity to the environment have been identified and analysed to assess their consequences.

Fig 2, 3 and 4 present the behaviour of the XADS under three events selected which well describe system performances.

Fig 2 presents the predicted evolution of the main vessel temperature in case of complete loss of the Secondary System (cooling via RVACS only). The main vessel wall temperature reaches a maximum value of 471°C at 62.5 hours.

Fig 2 – Main vessel wall temperature (upper, central and lower)

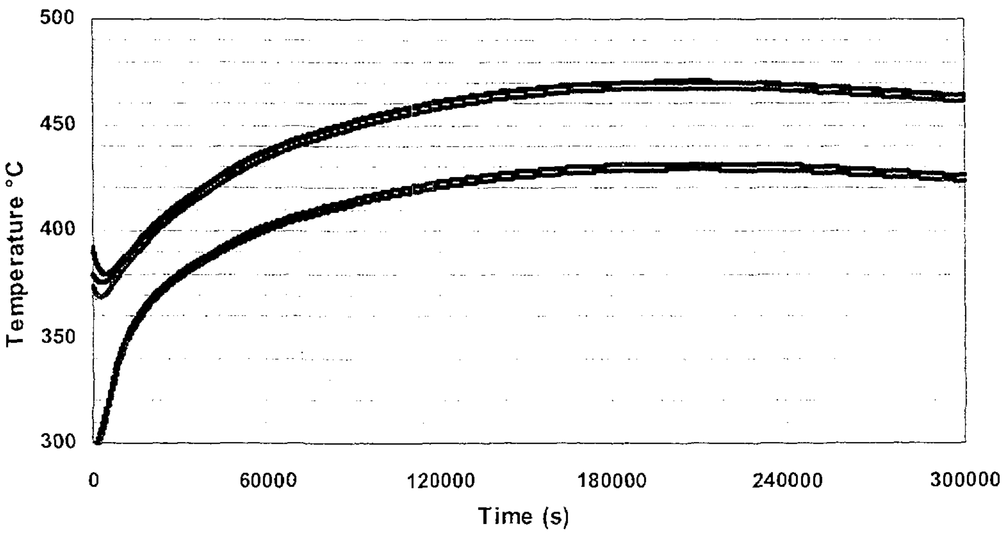


Fig 3 presents the predicted evolution of the Pb-Bi core inlet and outlet temperatures in case of Anticipated Transient Without Proton Beam Trip: loss of the air coolers of a secondary loop. The Pb-Bi core outlet temperature increases steadily, but at 800 s has reached only 450 °C giving to the operators time to stop the accelerator.

Fig 3 –Pb-Bi temperature at core inlet and outlet

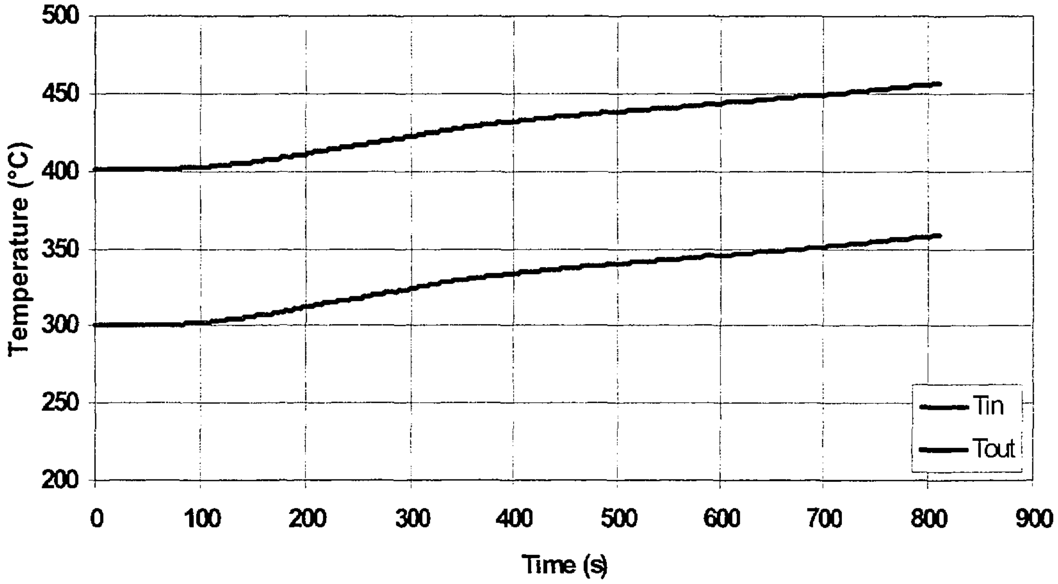
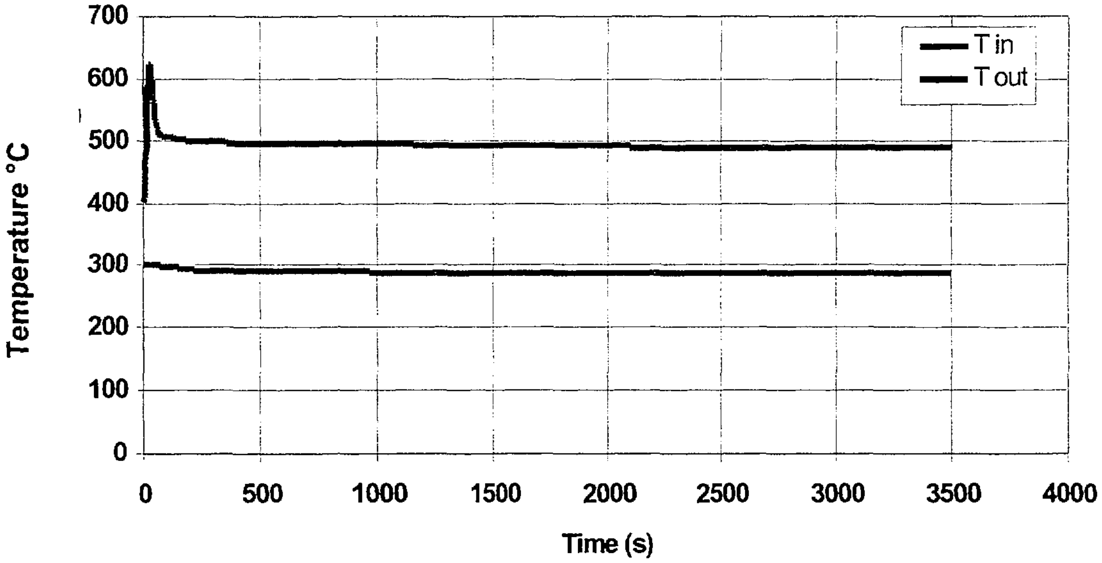


Fig 4 presents the predicted evolution of the Pb-Bi core inlet and outlet temperature in case of Anticipated Transient Without Proton Beam Trip: total loss of injected argon gas flowrate. The Pb-Bi core outlet temperature peaks at 630°C, then stabilises

Fig 4 – PB-Bi core inlet and otlet temperature



4. Supporting R&D activities

During the design phase preliminary simple R&D tests have been carried out on specific topics where information was lacking. These tests are listed as follows:

R&D by topic			
Topic	**Motivation**	**Test description**	**Test results**
Axisymmetric window target	Flow stability and prevention of stagnation	Mokeup with water	Stagnation observed about free-level centreline Asymmetric configuration for testing required
Mixture of diathermic fluid and hot LBE	No fouling on steel or foreign inclusions in the melt	Long lasting, high temperature testing of incapsulated diathermic fluid and LBE in oven	No evidence of fouling or inclusions by pre-tests at 400 °C Testing in progress
Radiolysis of the diathermic fluid	Assessment of radiolysis rate in realistic environment	Micro ampule irradiation in test reactor	The radiolysis extrapolated to the XADS environment is about one tenth the expected pyrolysis rate. Predicted cumulated degradation few %wt/year
Pressure loss through fuel sub-assembly	Improved accuracy of thermal-hydraulical computer code predictions	Water test with full-size sub-assembly mokeup	Measured pressure loss confirms expectations
Spike to diagrid locking-unlocking device	Assessement of margin to seizure	Repeated testing at imposed increased friction	Test planned for May 2001
Emissivity of steels extracted after immersion in the LBE melt	Assessment of decay heat removal by irradiation of spent fuel during handling	Calorimetric. Representative 316L and 9Cr1Mo surfaces after conditioning in the LBE melt.	Test in progress at Obninsk. Results by end of this year
Argon gas lift	Determination of parameters for subsequent test in LBE	Water test on full-size mockup	Test rig near completion. Results by May 2001.

The subject and status of R&D activities related to materials immersed in the LBE melt are not tabulated because they are the subject of this conference.

The R&D activities will be pursued forward by tests in CIRCE, the large test rig in LBE that allows a closer simulation of the XADS environment The first test deals with the LBE circulation by Ar cover gas lifting, with the following goals:

- ✓ Performance verification, including the control of the oxygen activity in the melt,
- ✓ Instability evaluation,
- ✓ Gas carry-under verification,
- ✓ Gas injection system optimization,
- ✓ Acquisition of T/H data for computer code validation.

The following additional test topics are envisaged, but not yet planned:

- ✓ hydraulic behavior of the target unit,
- ✓ performance of a complete secondary loop filled with organic diathermic fluid,
- ✓ LBE natural circulation,
- ✓ overall plant performance and system interaction in normal operation and accident conditions,
- ✓ actuation of the kinematic links of handling machines in very low-oxygen cover gas and in the LBE melt,
- ✓ ISI technology,
- ✓ instrumentation operating in LBE,
- ✓ material corrosion in the pool with flowing controlled-low-oxygen LBE,
- ✓ performance of different filtering systems for the LBE purification.