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The Pb–Bi cooled XADS status of development

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Abstract

In 1998, the research ministers of France, Italy and Spain have decided to set up a group of advisors for the definition of a common R&D European platform on accelerator driven systems (ADS). The advisors in turn, have established a Technical Working Group (TWG), chaired by Professor Carlo Rubbia, and now extended to the most part of the European Union member countries, in order to identify the critical technical issues for which R&D is needed. The recommendations of the TWG, included in the recently issued document 'A European roadmap for developing ADS for nuclear waste incineration' [April 2001] clearly indicate the need to design and operate, approximately in 12–15 years, an XADS at a sufficiently large scale to assess the feasibility of an industrial ADS for transmutation of nuclear waste. The European Community, through the 5th Framework Program, has launched a large program on partitioning and transmutation. This program which includes R&D and preliminary design will constitute a reference for the choice of the technical solutions to be pursued forward during the 6th Framework Program. In Italy, since early 1998, the ENEA (National Research Organization for Innovative Energy), INFN (National Institute for Nuclear Physics), CRS4 (Research Institute) and Ansaldo have set up a team, led by Ansaldo, to design an 80 MWth XADS. The results obtained so far allow a consistent XADS configuration to be outlined. The main issues investigated and the associated solutions adopted are concisely described in the paper. © 2002 Elsevier Science B.V. All rights reserved.

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1. XADS plant description

The 80MWth Pb–Bi cooled eXperimental Accelerator Driven System (XADS) conceived and under development in the Italian context follows the guidelines of the recently issued document 'A European Roadmap for developing Accelerator Driven Systems (ADS) for nuclear waste incineration' [1]. In the Roadmap, the technical working group (consisting of representatives from Austria, Belgium, Finland, France, Germany, Italy, Portugal, Spain, Sweden and the JRC) has identified the steps necessary to start the construction of an experimental accelerator driven system towards the end of the decade. This is considered as an essential prerequisite to assess the safe and efficient behaviour of such systems for a large-scale deployment for transmutation purposes in the first half of this century. The main engineering choices of the Italian XADS by plant area are summarized in Table 1. The main features and associated working principles of the reference configuration of the XADS are the following: the Nuclear Island consists of four main buildings, viz. a cylindrical reactor building, the main room and service building, the fuel and active component handling building and the air coolers building. The whole of the Nuclear Island rests on a single foundation consisting of an upper reinforced concrete basement and a 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 (Fig. 1, XADS reactor assembly). The heat source (the core), located below the riser, and the heat sink (the intermediate heat exchangers) at the top of the downcomer,

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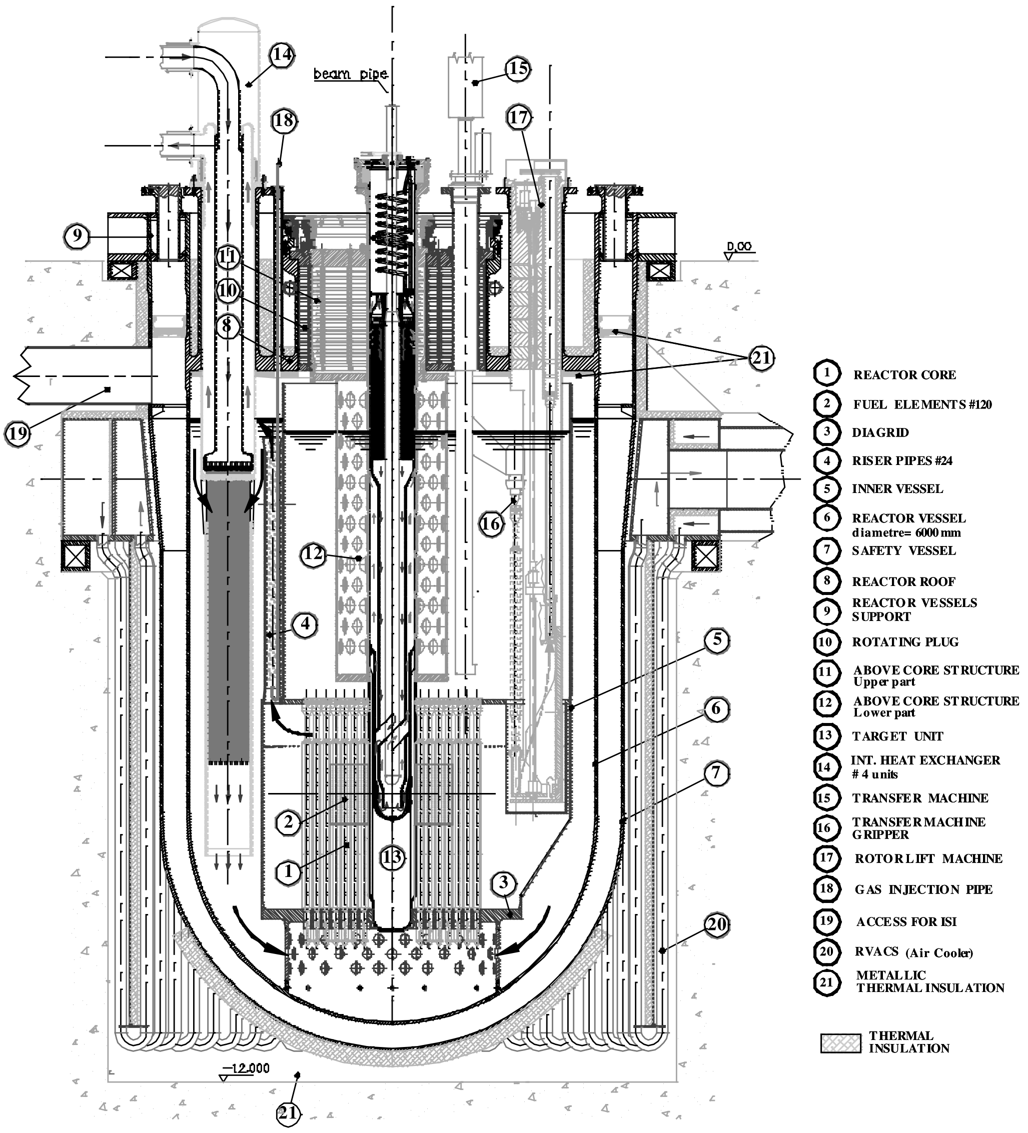

Fig. 1. XADS reactor assembly.

allow an efficient natural circulation of the coolant. The additional means provided to enhance the primary coolant flow rate 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 the nominal flow rate, the level of which can be controlled by the amount of gas injected [2].

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 bubble to primary coolant interface area for faster reaching the equilibrium dissolution of atomic oxygen in the LBE. The operability of the oxygen control in the melt which is the technique adopted to control the corrosion of the structural steels will be proven in the CIRCE loop, as explained in the section related to R&D activities.

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 requirement of large operational flexibility can be better achieved if no constraints from electric energy

Table 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.
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 2–4 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.	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.
	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).	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.
	Windowless: Protons impinge directly on the LBE target. Forced circulation. Cooling by primary coolant.	*Note:* 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.
Core	Sub-critical over lifetime with $K_{\text{eff}} \sim 0.97$ at BOL decreasing to 0.94 at EOL, at full power.	The K_{eff} at BOL is sufficiently low to ensure safety without control and shutdown rods.
Fuel	U and Pu MOX. The 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 fuel.
Primary coolant system	LBE as primary coolant.	The hot plenum remains below the creep temperature of the structural steel.
	Thermal cycle: 300 °C at core inlet, 400 °C at core outlet.	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.
	Natural-circulation flow rate enhanced by cover gas injection, fed by a compressor, into the bottom part of the riser, made of pipes arranged at the outside periphery in the inner vessel. The bi-phase, eutectic–gas mixture 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 flow rate distribution dictated by convection within the IHX.	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 LBE. The solution cumulates most of the advantages of a natural-circulation reactor configuration:

Table 1 (*continued*)

Plant area	Reference solution	Rationale for selection
Primary coolant system (cont.)	The quasi-stagnant LBE plenum inside the inner vessel upper part and the LBE plena outside are hydraulically connected by high-friction flow paths in order to improve the stability of the primary coolant flow rate.	• 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 flow rate. • Reduced vessel height.
Secondary coolant system	The secondary coolant is a low vapour pressure, synthetic organic diathermic fluid. The thermal cycle is 280–320 °C at full power.	Low pyrolysis at high temperature (up to 340 °C) in continuous operation. Low radiolysis because of the low radiation level at the IHX bottom.
	The Secondary Coolant System is made of two independent loops. Each loop consists of two IHXs immersed in the primary coolant, of three air coolers arranged in series, of a mechanical pump and interconnecting piping.	Vapour pressure lower than atmospheric pressure over the selected operating temperature range.
	Each loop is capable of removing the decay heat in natural circulation, with only one air cooler in operation. This latter configuration is safety related.	No chemical reaction with LBE. Self-ignition point far above the operating temperature No activation (sodium traces below 1 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.	One loop in natural circulation with one air cooler is sufficient to remove the decay heat.
RVACS	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.	A full-passive system that can perform the DHR function as a backup system and guarantees core cooling in design extension conditions, maintaining the reactor vessel in condition of negligible creep damage (according to the RCC-MR French mechanical design rules).
	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 from the safety vessel to the RVACS.	It provides via the inlet pipe legs also the normal, continuous cooling of the reactor pit concrete.

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Table 1 (*continued*)

Plant area	Reference solution	Rationale for selection
In-vessel fuel handling	Rotating ACS, one rotating plug, one offset-arm transfer 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 transfer machine.
Reactor vessel and safety vessel	Made of AISI 316 L austenitic steel, hung from a common, cold support beam anchored to the civil structure.	Hung arrangement according to Western countries experience in the LMRs field. 316 L steel should not present risk of fragility when used with Pb–Bi and 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.

generation are superimposed to the XADS, and hence the reactor power will be dissipated to the external atmosphere by means of air coolers.

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 allow the use of an organic diathermic fluid as secondary coolant that is chemically inert against the primary coolant and has a low vapor pressure at the operating temperature range (280–320 °C).

The accelerator design is compatible with the XADS construction time scale. This reference configuration of the XADS embodies features that cope with its demonstration duties and is flexible enough to be adapted to 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 thermalization. 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 flow rates and pressure losses, in order to cool different-configuration cores. The spallation neutrons are generated in the liquid LBE target that constitutes the connection of the accelerator system to the sub-critical core [3]. There are four main constraints to be complied with while engineering this connection:

- the proton beam must travel in vacuo,
- the proton beam must impinge on the target at or near the centre of the core,
- the power generated by the spallation reactions must be removed, without overheating LBE or interposed structures,
- the radioactive elements produced in the LBE by the spallation reactions must be kept confined.

The LBE melt containing the spallation products is kept confined within a structure called target unit (or spallation module), in order to prevent the contamination of the primary LBE coolant. The target unit has been designed as a removable unit, because its service life is anticipated to be shorter than the reactor lifetime, owing to the intense irradiation and local high thermal stresses. The target unit is a slim component of cylindrical form, positioned co-axially with the reactor vessel and hung from the above-core structure (ACS). Because it serves also as inner radial restraint of the core, the outline of its shell fits the inner outline of the core. Its component parts are the proton beam pipe, the heat exchanger and the LBE circulation system, that can be designed to operate in forced or natural circulation, depending on the design option.

Two target unit options have been designed for the XADS. Both options present the target at the centre of the core, but they differ in the target to the proton beam pipe interface principle. The hot-window target unit features a thin metallic sheet, called hereinafter the hot window (i.e. proton beam entrance) or more simply the window, as a barrier between the liquid target and the proton beam vacuum pipe. The heat generated by the spallation reactions is removed by natural convection. The LBE recirculates from the heat source to the heat exchanger located at a higher level, an arrangement typical of natural-circulation cooling circuits. The cooling circuit of the target unit is filled with organic diathermic fluid and back-cooled by water. The use of a diathermic fluid gives higher flexibility in the choice of the thermal cycle of the target LBE that allows to remain below 500 °C at 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. In this case a natural-circulation pattern of the cooling circuit is no longer possible, because the heat source near the free surface of the LBE is kept at a higher level by vacuum in the proton beam pipe. Thus the hotter LBE must be driven downwards to the heat exchanger by some means, in this case a dedicated cover gas lifting system. A stream of primary LBE is diverted from the cold plenum 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 issues related to material structural resistance, but presents issues related to the proton beam impact area, flow stability and evaporation of LBE. The design currently being developed presents an asymmetric free surface and offset downcomer.

2. Safety analysis

The same approach to safety employed in the design of conventional nuclear power plants is used, to the widest possible extent, for the XADS. The primary objective in the design of the XADS is to ensure that the likelihood of an accident is very low, an accident being defined as any condition that has the potential to give rise directly or indirectly to a public hazard. A modified version of the RELAP5/MOD 3 computer program is employed to simulate the thermal-hydraulic behaviour of the XADS primary and secondary systems. The abnormal and accident events have been identified and categorized with a systematic approach. The events 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.

Figs. 2–4 present the behaviour of the XADS following three selected events 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. The reactor vessel air cooling system (RVACS) can reject the decay heat with a moderate increase of the main vessel wall temperature which reaches a maximum value of 471 °C at 62.5 h. Fig. 3 presents the predicted evolution of the Pb–Bi temperatures at core inlet and outlet in case of loss of the air coolers of a secondary loop without proton beam trip. The Pb–Bi core outlet temperature increases steadily but at 800 s has reached only 450 °C giving the operators time to stop the accelerator. All the internal structures of the reactor heat up with the same rate. Fig. 4 presents the predicted evolution of the Pb–Bi temperature at core inlet and outlet in case of loss of argon gas injection into

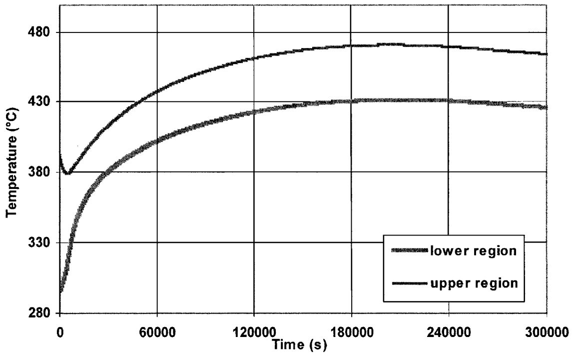

Fig. 2. Main vessel wall temperature (upper and lower region).

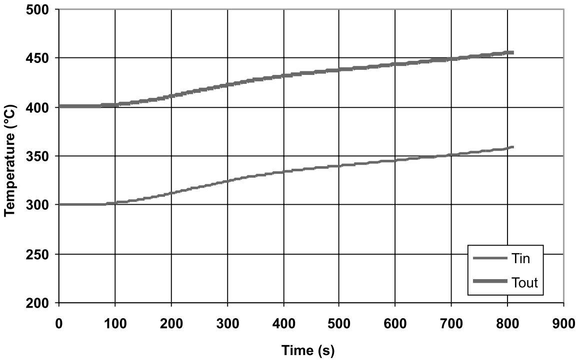

Fig. 3. Pb–Bi temperature at core inlet and outlet.

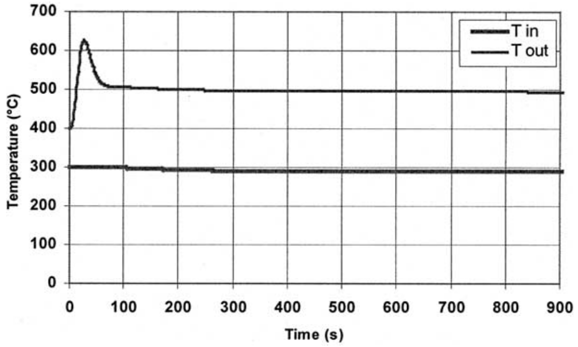

Fig. 4. Pb–Bi core inlet and outlet temperature.

the riser pipes without proton beam trip. The Pb–Bi core outlet temperature peaks at 630 °C, then stabilizes with the Pb–Bi core flow in natural circulation at about 50% of the nominal flow rate.

The performed safety analysis has shown that, by virtue of the design choices (e.g. the lead–bismuth coolant and a primary system pool configuration with main and safety vessel, with no lead–bismuth circulation outside the main vessel) and of the engineered protective actions, there are no abnormal or accident events that cause the loss of the first two physical barriers (the fuel rods cladding and the primary system boundary). Events that have the potential to damage the fuel rods cladding do not jeopardize the primary system integrity while events that break the primary system do not damage the fuel rods cladding.

3. Supporting R&D activities

During the design phase basic R&D tests have been carried out on specific topics where information was lacking. These tests which are peculiar of the design choices, and are complementary to the tests being carried out in Europe on the compatibility of the structural steels with LBE, are related to the

- thermal-hydraulics of the windowless target,
- compatibility of the diathermic organic fluid with the LBE,
- diathermic fluid radiolysis under neutron irradiation,
- pressure loss of the fuel elements,
- operability of the locking–unlocking device of the fuel elements to the diagrid,
- emissivity of the steel extracted from the LBE melt,
- efficiency of the argon gas lift.

The R&D activities will be pursued further by tests in CIRCE, a 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 behaviour 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 and accident conditions,
- actuation of the kinematic links of handling machines 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.

4. Summary and conclusion

The XADS is a simplified facility designed for demonstrating basic aspects of the ADS such as the operability of the sub-critical reactor driven by the accelerator. With the appropriate selection of main operational parameters such as low coolant temperature and speed, low core power density and proven fuel and core power removal to the atmosphere, the XADS can be engineered on the basis of a mid-term R&D programme. The performed safety analysis has shown that, by virtue both of design choices and of engineered protective actions, there are no abnormal or accident events that cause the consequential loss of the first two physical barriers: the fuel rods cladding and the primary system boundary. The feedback from the operation of the XADS and the answers provided by the long-term R&D programme will be the base, in turn, for the development of the lead-cooled power ADS series.

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