DESIGN AND SUPPORTING R&D OF THE XT-ADS SPALLATION TARGET

P. Schuurmans, K. Van Tichelen, M. Dierckx, H. Aït Abderrahim
SCK•CEN, Boeretang 200, B-2400 Mol, Belgium
E-mail: Paul.Schuurmans@sckcen.be

A. Guertin, T. Kirchner, A. Cadiou, J.M. Buhour
Subatech, UMR 6457; École des Mines de Nantes – IN2P3/CNRS – Université de Nantes
4 rue A. Kastler, BP 20722, F-44307 Nantes Cedex 3

R. Stieglitz
Forschungszentrum Karlsruhe
P.O. Box 3640, D-76021 Karlsruhe, Germany

D. Coors
Areva
P.O. Box 3220, D-91050 Erlangen, Germany

L. Mansani
Ansaldo Nucleare
Corso F.M. Perrone, 25, Genoa, I-16161 Italy

F. Roelofs
NRG Petten
Westerduinweg 3, P.O. Box 25, NL-1755 ZG Petten, The Netherlands

Abstract

The XT-ADS is an experimental accelerator-driven system (ADS) that is being developed within the framework of the European FP6 EUROTRANS project that runs from 2005 to 2009. In this paper the current level of the design of the XT-ADS spallation target and the status of corresponding R&D topics with respect to LBE handling, thermal-hydraulics and spallation product confinement are discussed.

Introduction

The technology of accelerator-driven systems is an important track to be investigated with regard to transmutation of high-level nuclear waste. An ADS basically consists of a subcritical core to which neutrons from a accelerator-driven spallation neutron source are fed. Because the operation of the "reactor" system is no longer based on reaching criticality in the core but rather on the intensity of the neutron source, operation with any kind of fissile material is in principle possible. This feature makes an ADS particularly suited for waste transmutation.

The European project EUROTRANS is dedicated to the advancement of nuclear transmutation techniques [1]. The project aims to reach two main goals. On the one hand EUROTRANS will launch the conceptual design of the lead alloy European Transmutation Demonstrator (ETD) loaded with fuel especially dedicated for transmutation. The aim of the ETD, which would represent a modular unit of a large power system able to handle the European high-level nuclear waste, is to demonstrate the feasibility of transmutation at an industrial scale. The second major goal of the EUROTRANS project is the detailed design of the small-scale experimental XT-ADS aiming at the short-term realisation of the system.

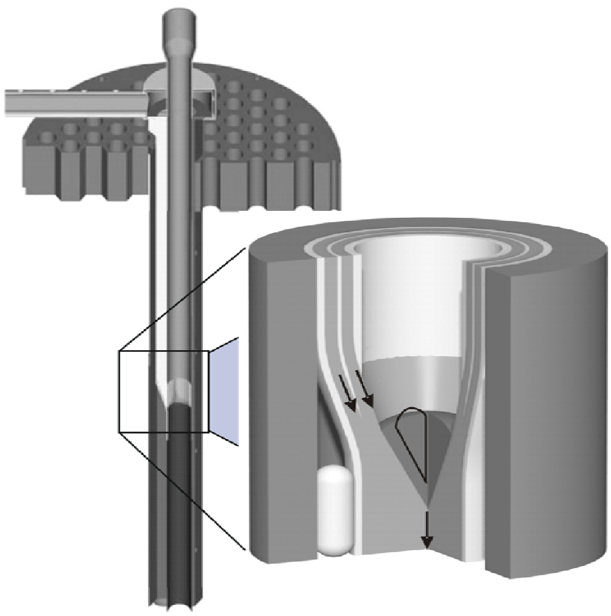
The XT-ADS will serve a twofold function. First, it will be an ADS concept demonstrator and component test bench for the industrial-level nuclear waste transmuter ETD. Secondly, the XT-ADS will be designed as a flexible experimental irradiation device for fuel, materials and radioactive isotope studies for present and future nuclear energy concepts. Because of its function as an experimental irradiation device, the XT-ADS subcritical core will need to be designed with a very compact geometry so as to achieve high flux levels (ϕ_{Tot} = ~3.10^{15} n/cm^2.s) [2] within a reasonably small core (~0.5 m^3). Evidently, the spallation target design must match the requirements determined by the general concept of the XT-ADS. It should produce a sufficient amount of neutrons to feed the subcritical core at its specific k_{eff} value (≈0.95). For this purpose the spallation target must accept the appropriate high-power proton beam that is currently set at 2.5 mA at 600 MeV. Because the thermal energy of about 1 MW that is deposited by the proton beam requires forced convection cooling, liquid lead-bismuth eutectic (LBE) is chosen as target material. LBE is likewise the coolant of the main vessel although both circuits are separated. In addition, the target must fit into the space that is available in the subcritical core. The target space is created by removing three of the hexagonal fuel assemblies in the centre of the core. Furthermore, the design of the target should not hamper the fundamental role of XT-ADS as a flexible high-intensity experimental irradiation device. Finally, although a replacement of the spallation target within the envisaged lifetime of the XT-ADS is unavoidable, this operation should not be required too often. Thus, the spallation target unit should be able to survive operation within the ADS system for a sufficient amount of time.

Spallation target design concepts

Due to the functional similarity between the XT-ADS and the MYRRHA concept developed earlier at SCK•CEN [3], the design of the latter spallation target was chosen as a starting point for the development of the XT-ADS target loop. As was the case with MYRRHA, the functional and spatial constraints mentioned above compel the selection of some fundamental design concepts. First, the limited space available in the core and the high proton current lead to very high proton beam densities of about 150 μA/cm^2. No structural material is expected to withstand these conditions at elevated temperatures during a reasonable lifetime of the spallation target (≥ 1 y). Thus, the spallation target is being designed without a hot window between the target area and the vacuum of the beam line, though a cold window further upstream is envisaged. It may be noted here that the focus of the EUROTRANS project on a windowless design is complementary to the work that was carried out in the FP5 programme PDS-XADS and the MEGAPIE initiative in which a window concept for a high-power spallation target was studied.

A result of the windowless target option is that at the interaction point, the spallation target is formed by a free liquid surface that must be properly shaped by careful design of the LBE flow. As before, the limited space is responsible for the choice of a vertical confluent flow as formation mechanism for the target free surface (Figure 1). The liquid LBE is fed to the target nozzle via a vertical three-lobed annular pipe to optimise the use of the available space in the core. The target nozzle itself is designed to ensure a stable free surface flow. In addition, monitoring of the free surface level is needed. The design and R&D efforts on this topic will be discussed below. The compact core of the XT-ADS only allows a passage of the LBE target material in one direction from top to bottom with the feeder line passing above the core and the return line underneath it thus interlinking the core. In this configuration the spallation target loop has off-axis housing for all active components. A split core base plate is necessary to allow removal of the spallation loop from the main vessel. The off-axis design of the spallation loop leaves the top and bottom of the subcritical core accessible for fuel manipulations and the installation of irradiation experiments. In addition, the main part of the spallation loop is moved away from the high radiation zone which is beneficial for its lifetime.

Figure 1. A schematic drawing of the vertical confluent flow concept



The common vacuum of the target zone and the proton beam line puts requirements on the vacuum system. First, the pressure directly above the spallation target should be below the 10^{-5}-10^{-6} Pa range to guarantee compatibility with the vacuum of the proton beam line and to avoid plasma formation caused by the interaction between the rest gas above the target and the proton beam. The pressure condition implies that the outgassing of the spallation target material must be limited and that care should be taken in the design of the vacuum system to ensure sufficient vacuum conductance and pumping capacity. The second essential function of the vacuum system is the confinement of volatile radioactive spallation products. Due to the spallation interaction of the proton beam with the target material, radioactive elements with a high vapour pressure (e.g. Hg isotopes) are produced. These products are likely to emanate from the free surface of the target and should be confined, either within the spallation loop or in the vacuum system. For this purpose the latter is equipped with a closed back-end composed of sorption and getter pumps. In order to minimise emanation of spallation products into the proton beam line, a large second free LBE surface is foreseen in the servicing vessel, directly underneath the main vacuum pumps.

The heat deposited in the spallation target by the proton beam amounts to about 975 kW for the present target configuration and a 2.5 mA, 600 MeV proton beam [4]. Forced convection by circulating liquid target material is used to evacuate the heat to the spallation target heat exchanger that is situated at the bottom of the off-axis part of the loop. The secondary side of the heat exchanger is cooled by the main vessel coolant. The flow rate of the LBE is about 10 l/s. The lower limit of this value is determined by the maximum temperature allowed in the target. In order to limit LBE evaporation and corrosion of structural materials in the target loop, this temperature is set at about 430°C. Because the spallation target material is cooled against the main vessel coolant, the lowest achievable temperature during normal operation of 330°C is mainly determined by the inlet temperature of the core (300°C).

The XT-ADS spallation target system has been designed to be compatible with the remote handling scheme envisaged for the entire XT-ADS. The full loop can be removed from the main vessel after unloading of the core. The prior unloading of the core is to avoid criticality issues, for general safety and to allow *in situ* commissioning of the target unit. In addition, all active elements are placed in a separate sub-unit which allows servicing of these parts without removal of full the spallation loop. The closed outer housing allows regular (yearly) replacement of the spallation target zone that will be required because of radiation-induced embrittlement and possible replacement of the heat exchanger. Maintenance, inspection and repair of the spallation unit are foreseen to be performed in the XT-ADS hall outside the main vessel pool under the cover of a protective inert atmosphere. This includes disconnection and reengagement of all service jumpers, replacement of the embrittled loop parts close to the target zone and removal and re-installation of the interior column with all active parts. Also the replacement of the heat exchanger fits into the scheme. Before and after maintenance the LBE loop is drained and later refilled into and from a special container. This allows safe storage of the LBE during maintenance and simultaneously permits conditioning of the material in a dedicated off-line system.

Spallation loop layout and operation

Figure 2 shows the sub-unit and outside housing of the spallation loop. In Figure 3 a cut of the interior of the spallation loop together with a schematic layout is shown. All components are indicated. The target LBE is fed from the off-centre spallation unit and traverses to the central axis of the subcritical core. It comes down through the three feeders surrounding the beam transport line. The target free surface is formed at the confluence point of the target nozzle in the centre of the subcritical core. Here the proton beam impinges from the top. The LBE subsequently flows away from the beam impact zone through the central tube, the lower U-bend and the heat exchanger to the pumping unit in the spallation housing.

For proper operation of the liquid target, the formation of the target free surface and a firm control over the size of the recirculation zone that is formed in the centre of the target free surface is essential. When the recirculation zone is too small, LBE droplets are ejected from the LBE confluent zone that may cause metal evaporation when hit by the beam. If the recirculation zone is too large, it will be directly heated by the proton beam causing the temperatures to increase very rapidly, which would also lead to excessive evaporation of LBE and other volatiles. The size of the recirculation zone can be determined indirectly by its height. The latter is measured by a LIDAR positioned in line with the beam. The laser light is reflected from the central recirculation zone of the target free surface. The LIDAR output is used to control the mechanical and MHD pump. The reason for this is that the target free surface is given by the balance between the nozzle in- and outflow.

Figure 2. Spallation sub-unit and outside housing of the spallation loop

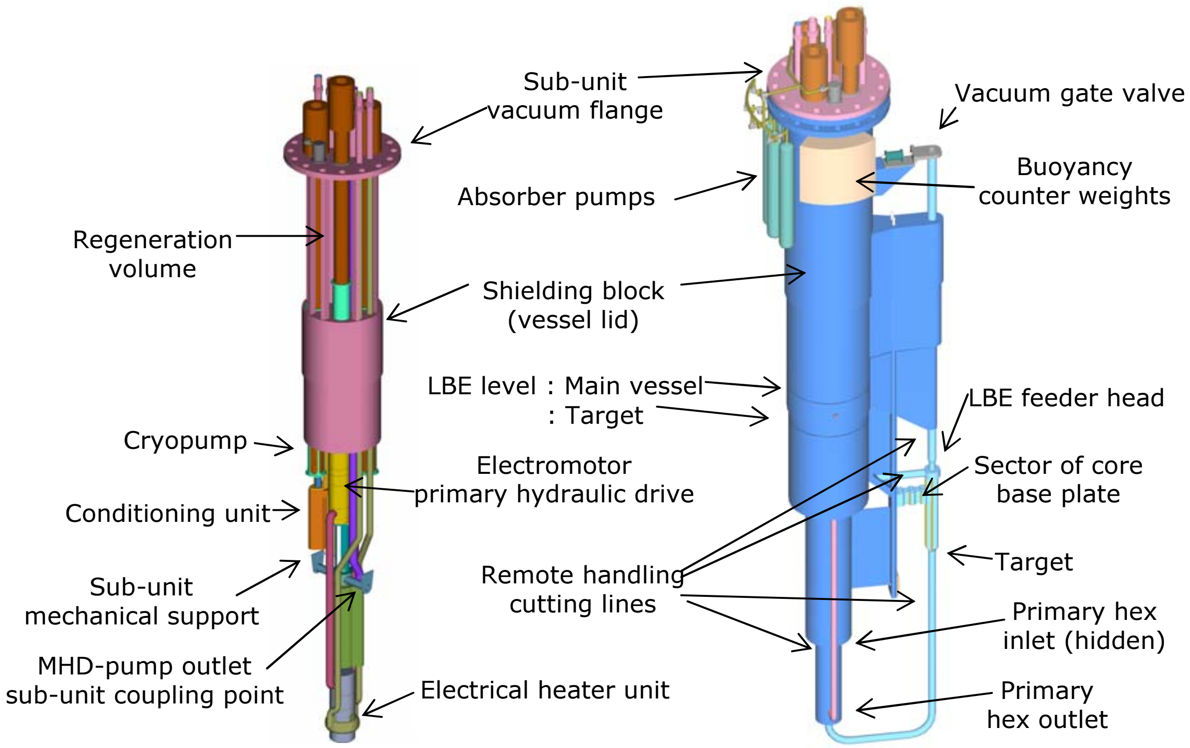
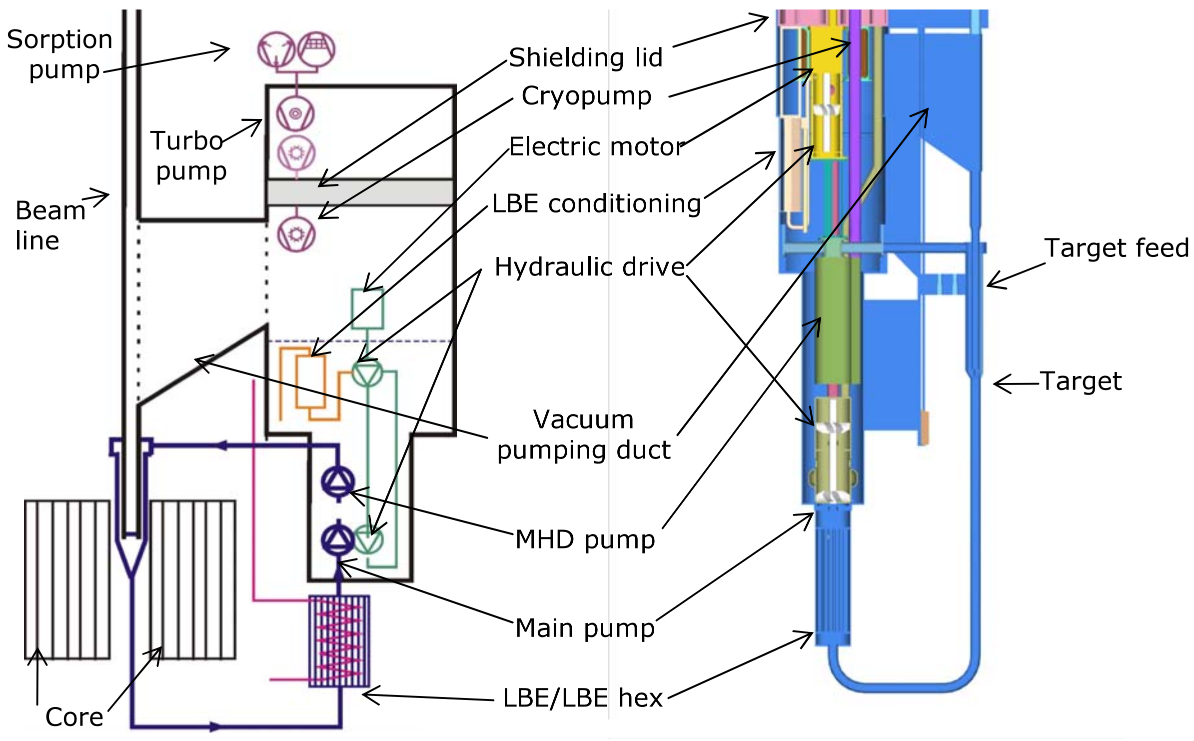


Figure 3. A schematic layout of the spallation loop and its interiors



The free surface level is particularly difficult to maintain under the dynamics changes caused by beam trips and during the start-up/shut-down procedures. In order to cope with these dynamics, a second free surface in the spallation loop main unit is maintained at about 2.5 m above the target free surface. The mechanical pump lifts the LBE that has passed the heat exchanger to the level of the second free surface. From here, the LBE flows through the feeder-line to the target nozzle by gravity. The MHD pump in the feeder-line provides the fine-tuning of the gravity-fed inflow in two-quadrant acceleration/deceleration operation. Normal operation of the pump, however, is slightly biased towards an accelerating action to avoid frequent reversal of the travelling wave. The three feeders are drag limited, exceeding the minimum drag of 1 bar/m necessary to compensate for the hydrostatic pressure, to prevent the spallation LBE to tear off and reach the target nozzle in free fall.

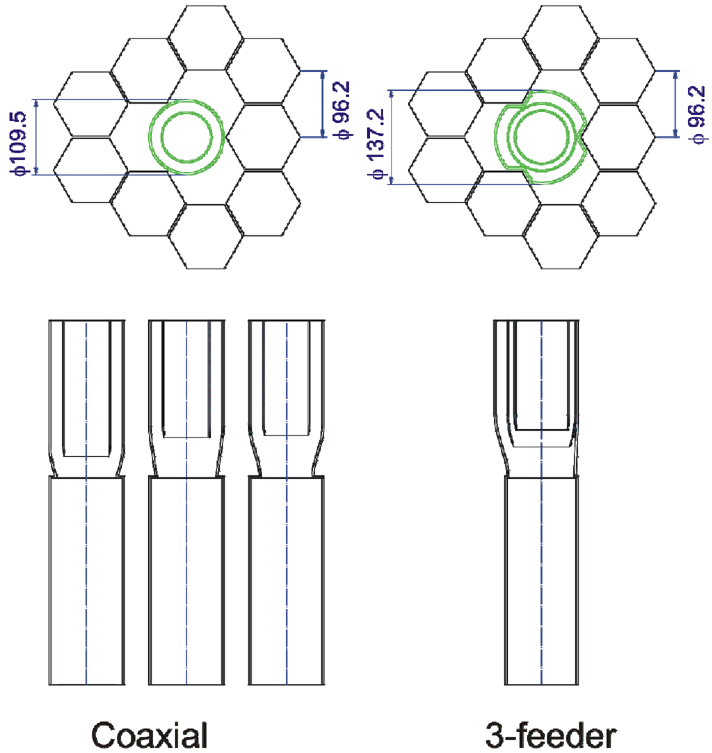
Spallation target nozzle design

Within the XT-ADS spallation target design work of the EUROTRANS project, a specific effort is placed on the development of the target nozzle. In the MYRRHA Draft 2 [3] that serves as the input for the XT-ADS, the target nozzle was designed to have a straight LBE flow without detachment of the LBE from the nozzle walls. However, real size water flow experiments performed at the Université Catholique de Louvain (UCL) and LBE flow experiments that were done at the KALLA laboratory of the Forschungszentrum Karsruhe (FzK) have shown that a more stable flow is achieved if some detachment of the LBE flow is allowed. Also, introducing a mild swirl has a stabilising effect. These results are now used as input for further development of the target nozzle. In this respect, three tracks are investigated. First, the feasibility of a target nozzle that explicitly forces flow detachment is studied. In order to achieve detachment at the right position and nowhere else, a rig in the nozzle wall is created. In addition, the nozzle shape and the in- and outflow cross-sections must be optimised. For this purpose, several nozzle proposals are looked into with CFD calculations (Figure 4), followed by experimental tests using water flow experiments at UCL. A similar strategy is being followed for the investigation of the influence of swirl on the LBE flow. Here, CFD calculations indicate that in the current geometry, 5% swirl, corresponding to a 1/20 ratio of the tangential relative to the axial LBE velocities, stabilises the position of the recirculation zone whereas at 10% swirl the onset of the creation of a hollow vortex in the centre of the nozzle is observed [5]. In water flow experiments similar results are obtained albeit that already at 5% swirl vortex formation is found. In the near future, water flow experiments with a target nozzle introducing less swirl will be carried out. The third modification in the target nozzle that is being studied in more detail is the three-feeder option for the LBE downcomer which has the advantage that optimal use is made of the available space in the ADS core. The strategy of the project is to investigate the three design modifications separately before they are integrated in one nozzle. The combined nozzle will be further studied using the water flow experiments and fine-tuned in LBE flow experiments at KALLA.

LBE pumps

In the present design the mechanical pump is powered by an indirect hydraulic drive that avoids the use of a long shaft. A canned electric motor drives a pump that transmits its power to the hydraulic drive/hydraulic pump in the lower part of the column. The hydraulic transmission fluid is taken to be the same as the LBE that it is circulating in the spallation loop (although at higher pressure). One option for the design of the pump-drive tandem is based on common impeller technology. The impeller direction of drive and pump are opposite in order to ease the axial bearing requirements. This design is shown in all pictures of the spallation loop. Another option is to design the pump/drive tandem based on a screw spindle technology. In this option the fluid smoothly follows the spindle motion without being subject to the accelerating or decelerating phases of impeller pumps. Such a smooth flow is

Figure 4. Different design options for target nozzle shapes with flow detachment



assumed to be less bothered by corrosion and cavitation problems. Although the hydraulic drive pump is at present the reference design, the long shaft option has not been ruled out. Here however, the proper design and testing of the shaft bearings is the most crucial point.

The basic concept for annular linear induction pump or magneto-hydrodynamic (MHD) pump is similar to the one used for the MEGAPIE Project at PSI (CH). The MEGAPIE pump is constructed at IPUL (University of Latvia). The MHD pump envisaged for the XT-ADS differs from this pump in certain respects in order to obtain the pressure gain of 1.2 bars as required by the spallation loop dynamics. The pump efficiency is almost doubled by better matching the LBE velocity to the mean magnetic field velocity thus decreasing the slip ratio. Furthermore, the pump length is increased to 1.2 m, including an integrated annular magnetic flow meter and the number of poles is increased accordingly. Taking into account the MEGAPIE model findings, the efficiency could be increased even more by grading the magnetic core flux over its length.

Vacuum system

The absence of the window implies that the target needs to be under vacuum to accommodate the vacuum of the accelerator. Thus a vacuum system must be provided that maintains sufficiently low pressures to avoid plasma formation. In addition, it must ensure sufficient confinement of volatile radioactive spallation products that may emanate from the target. In the present design the spallation unit is connected to the central beam line via a duct and is being pumped an integrated vacuum system to a pressure of less than 10^{-5} Pa. At the back-end of the system all radioactive volatile emanations are collected in absorption pumps from where they can be batch-wise removed. Because of the target vacuum, the LBE flow is optimised to keep the temperature of the free surface low in order to prevent excessive LBE evaporation into the beam line.

During target nozzle experiments it was observed that the fast-flowing LBE in the spallation target zone has a significant vacuum pumping effect since the pressure in the target module was reduced to two orders of magnitude below the minimum pressure reachable by the vacuum pump installed at that time. Although the effect has not been duly quantified in the present target geometry, it does open possibilities for a modification of the vacuum system design. Indeed, the vacuum pumping effect of the LBE may be sufficient to reduce the vacuum pressure in the target zone during normal operation to below the level required. In that scenario, the confinement of the spallation products can be improved by abandoning the vacuum duct between the beam line tube and the servicing vessel. In this way the vacuum chamber above the free surface in the main vessel has no contact with the beam line and thus migration of volatile radioactive spallation products that were emanated from this free surface to the beam line is prevented. Separation also allows operating the vacuum vessel at higher pressures of the order of 1-100 Pa which would simplify the vacuum system without changing the LBE flow behaviour significantly. In addition, the higher operating pressure allows envisaging a room temperature vapour trap in the vessel that would immobilise the bulk of the volatile spallation products, so that the load on the absorption pumps is reduced.

LBE conditioning

Conditioning of the LBE eutectic in the spallation loop is required for two main reasons: corrosion inhibition and the need to prevent conglomeration of insoluble impurities that may lead to a blocking of the flow. In the design of the MYRRHA ADS the main corrosion inhibition strategy followed is by controlling the oxygen content in the LBE target material to the level of ca 1.10^{-6} wt.%. For this a hydrogen and water vapour gas treatment system is foreseen to reduce the amount of oxygen in the LBE when required. However, since the spallation unit is a vacuum system the treatment is only possible during maintenance times. Because of the generally reducing nature of the spallation products and the hydrogen from the proton beam, the opposite reaction for adding oxygen is also included. For this purpose a dedicated conditioning unit is foreseen. Its active component is a heated basket with PbO pebbles housed in an insulated vessel. The exchange rate between the pebbles and the bypass LBE flow is governed by controlling the temperature of the basket. In addition, magnetic filtering is foreseen at the entrance of the MHD pump to extract magnetic corrosion products (mainly Fe and Ni compounds) that could otherwise block the MHD pump. Finally, at the top of the second free surface filtering/skimming is envisaged to remove floating debris.

Summary

The design of the XT-ADS spallation target is performed within the European integrated project EUROTRANS that was started in April 2005. At the current status of the spallation target design process, the boundary conditions for the spallation target loop with respect to the XT-ADS performance requirements and the design of the subcritical core and primary system have been established. The next steps will concentrate on further development of the spallation target nozzle, the vacuum and spallation product confinement system and the pumping system.

Acknowledgements

This work is accomplished in the frame of the FP6 Contract FI6W-516520.

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