THE CIRCE TEST FACILITY FOR VERIFICATION AND VALIDATION OF THE LBE-COOLED XADS CONCEPT DESIGN CHOICES

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Abstract

CIRCE is a large-scale test facility designed for operation with lead-bismuth eutectic (LBE) and built, at the ENEA site of Brasimone (Bologna, Italy), for verification of key operating principles of the LBE-cooled concept of an 80 MW_{th} Experimental Accelerator-driven System (XADS). The XADS reference configuration was conceived and the supporting feasibility analyses were performed in Italy, with financial support from the Ministry of the University and the Scientific and Technological Research. The LBE-cooled XADS design is currently being assessed, versus a gas-cooled concept, in the frame of a contract with the Commission of the European Communities. Planned verifications in CIRCE will cover all important aspects of this lead- bismuth eutectic cooled system such as the contribution of natural draft and of the peculiar gas lift system to the primary system thermalhydraulics, the core pressure drops, the thermalhydraulic of a proposed windowless target, the technique envisaged for protecting the structural steels against corrosion, the operability of the basic mechanical links of the fuel handling machines in the XADS environment. Innovative instrumentation to measure LBE flowrate, differential pressure, levels and oxygen content has been adopted. The first experiments will cover the performance verification of the LBE circulation enhanced by Argon gas injection (first test section) and the thermalhydraulic verification of the concept of windowless target developed by ANSALDO (second test section). The basic configuration of CIRCE, inclusive of the first test section, has been constructed and commissioned in the second half of 2001. In its final prospective configuration CIRCE will test the whole XADS system.

1. Introduction

A fast neutron hybrid reactor, including a proton accelerator, a spallation target and a sub-critical core initially referred to as Energy Amplifier (EA), has been proposed by CERN of Geneva for addressing the radioactive waste problem and generating electric energy. [1]

Since early 1998, the Italian ENEA, INFN, CRS4 and Ansaldo have set up a team, led by Ansaldo, that has studied the design issues bound to the construction of an 80 MWth Lead-Bismuth Eutectic (LBE) cooled Experimental Accelerator-driven System (XADS), a key-step towards the assessment of the feasibility and operability of an ADS prototype. The results obtained so far, though preliminary and not exhaustive, allow to outline a consistent XADS configuration. [2]

The main features and associated working principles of the XADS are listed as follows:

- Simple Primary System layout. 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.
- Use of LBE as the primary coolant, to exploit its low melting point, and to allow a relatively low operating temperature, in order to eliminate risks of creep damage of the Reactor structures and to reduce their corrosion rate.
- Use of an organic diathermic fluid as the secondary coolant with low vapor pressure and chemically inert against the primary coolant.
- Components and construction materials of proven technology.
- Removable main components (Intermediate Heat Exchangers, Fuel Handling Machines, Target Unit).

In support to the XADS design an R&D activity programme is in progress, in particular:

- Preliminary R&D tests have been carried out on specific topics to produce data needed for the design.
- Large-scale tests in the Pb-Bi eutectic are under preparation by means the CIRCE test facility.

- Tests for validation of the concept of coupling of an accelerator to a target inside a sub-critical core at power are at the stage of feasibility evaluation by using the 1 MW ENEA TRIGA reactor

The object of this paper is the description of the CIRCE (CIRcuito Circolazione Eutettico) facility and of the associated test sections.

2. Test facility description

The CIRCE facility (Figure 1, [3]) at present mechanically complete and commissioned, is located at the Brasimone ENEA facility near Bologna (Italy). It basically consists of a full-height reduced diameter (1:5 the XADS vessel diameter), cylindrical vessel (Main Vessel S100) filled with about 90 tons of molten Lead-Bismuth Eutectic (LBE) with argon cover gas and re-circulation system (the set of volumetric compressors is located on the top near the local control panel and the gas-chromatograph), LBE heating and cooling systems, several test sections welded to, and hung from bolted vessel heads for separate-effect and integral testing, and auxiliary equipment for eutectic circulation and oxygen activity control in the melt for corrosion protection of the austenitic stainless steel structures. The facility is complete of an LBE storage tank (S200), of a small LBE transfer tank (S300) and of the data acquisition system. Figure 2 shows the Main Vessel with a bolted-on test section being lowered into its concrete pit.

Figure 1. **CIRCE test facility**

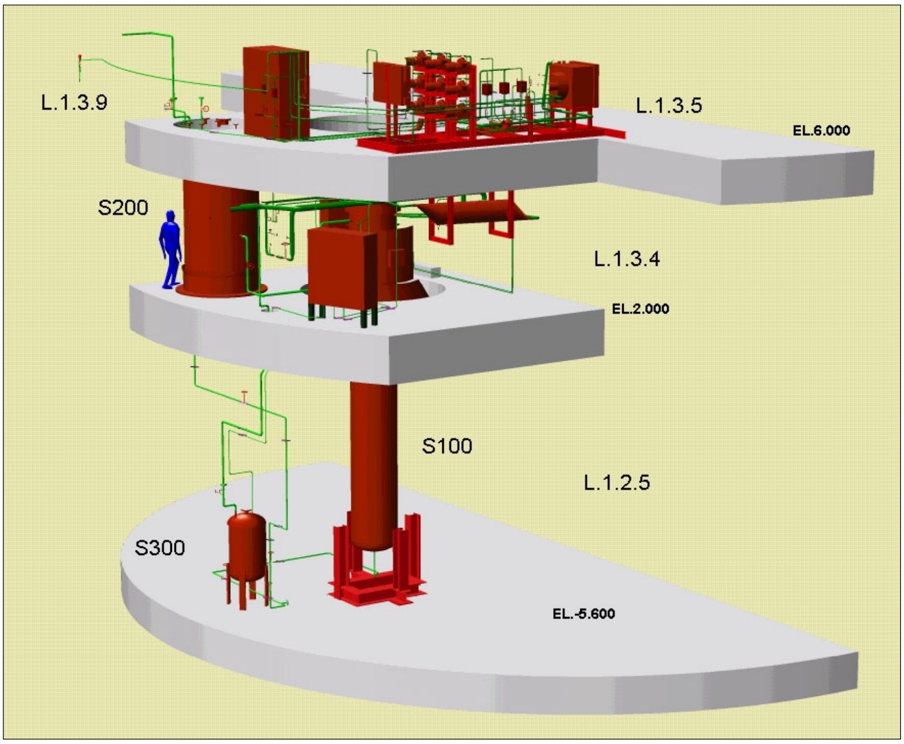


Figure 2. **Main vessel with bolted-on test section**

The synoptic panels of the LBE transfer between Storage Tank and Main Vessel and of the Ar cover gas re-circulation and injection system are shown in Figures 3 and 4 respectively. The operating principle of LBE circulation in the CIRCE facility is the same conceived for the XADS. It consists of cover gas injection into the riser of the relevant test section. Even a modest void fraction in the riser brings about a high pressure head, owing to the high density of LBE. This principle, illustrated in detail in Ref. [2], uses a closed-loop re-circulating cover gas system. The cover gas at nearly atmospheric intake pressure is fed by compressors via a submerged sparger into the bottom part of the riser. The rising LBE-gas mixture two-phase flow slows down at the top of the riser and bents over radially until LBE reverses its velocity and flows downwards. The cover gas cannot follow the path of LBE, because buoyancy prevails over entrainment, and separates at the interface with the cover gas plenum, thereby closing the gas loop. The two-phase LBE-gas mixture in the riser, being lighter than LBE alone in the downcomer by the amount corresponding to the mean void fraction in the riser, creates the driving force for the coolant circulation.

The on-line instrumentation is shown in Figure 4. Notice the gas chromatograph with pulsed discharge ionisation detector for measuring hydrogen concentrations down to a few ppm, and the moisture meter, both needed for the indirect measurement and control of the oxygen partial pressure in the argon cover gas. In fact, for the reference XADS design, the protection against corrosion-erosion of the austenitic structural steels in contact with the Lead-Bismuth Eutectic is obtained by means of a continuous, compact metal oxide film adherent to the metal substrate of the structures. This implies the presence of dissolved oxygen in the melt, which is proportional to the square root of its partial pressure above the melt (relationship known as Sievert's law). Because, however, the direct measurement of the required partial pressure would be unpractical, owing to its very low value, measurement of the partial pressures of the water vapour and hydrogen in the cover gas allows to calculate the partial pressure of oxygen via the knowledge of the equilibrium constant of water vapour dissociation. At low p_{O_2}, the measurement of the associated hydrogen partial pressure is easy.

The main parameters of the CIRCE facility are summarised in the following Table 1.

Table 1. **CIRCE facility main parameters**

Parameter	Value
Main Vessel	
Outside Diameter, mm	1 200
Wall thk, mm	15
Height, mm (from bottom head to top flange)	8 500
Material	AISI 316L
LBE inventory, kg (max)	~ 90 000
Electr. Heat tracing, kW	47
Cooling air flowrate, N-m^3/s	3
Temperature range, °C	200 to 550
Pressure	
Operating, kPa (gauge)	15
Design, kPa (gauge)	450
Argon gas	
Flowrate, N-liter/s	15
Injection pressure, kPa (gauge)	600
Electr.heaters (prospective) for core power simulation, MW	1.1

The testing approach gives CIRCE the flexibility not only to accommodate the several test sections that have been already envisaged but also to carry out experiments that may be conceived later by ENEA, Ansaldo or Third Parties.

The CIRCE facility will be eventually extended to include a secondary, diathermic organic fluid filled loop with air cooler and chimney stack, Figure 5.

The tests will give confirmation on the following topics:

- LBE coolant natural circulation;
- LBE coolant enhanced circulation by gas injection system;
- hydraulic characterisation of the fuel assembly;
- hydraulic behaviour of the target unit;
- performance of a complete secondary loop filled with organic diathermic fluid;
- overall plant performance and system interaction in normal operation and accident conditions;
- actuation of the kinematic links of handling machines in the cover gas (with controlled low oxygen partial pressure) and in the LBE melt (with controlled dissolved oxygen activity);
- ISI technology;
- instrumentation immersed in LBE;
- material corrosion in the pool with flowing LBE of controlled dissolved oxygen activity.

Figure 3. **LBE transfer system synoptic panel**

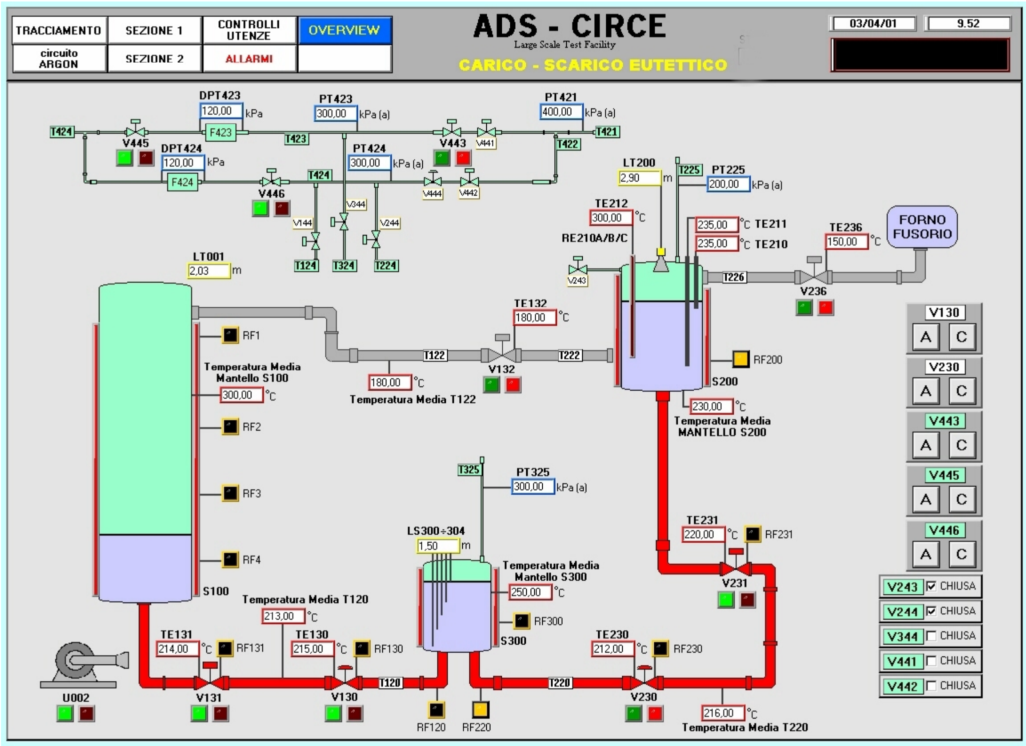
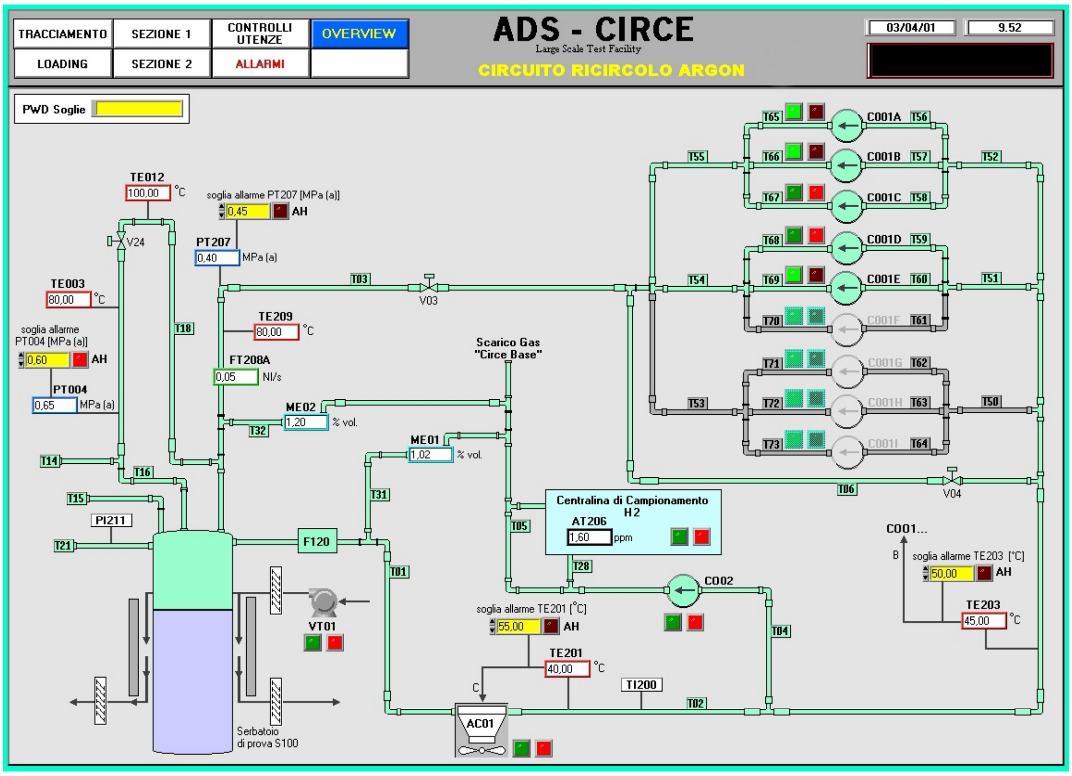


Figure 4. **Argon cover gas re-circulation and injection system synoptic panel**



3. The first and second test section

3.1 The test section for the verification of the LBE circulation by means of Argon cover gas lifting

The first test section (Figure 6) for testing the enhancement of LBE circulation by Ar cover gas injection has been constructed. It consists of one full-scale riser pipe, complete of gas injection nozzle, out of the 24 pipes that are provided in the XADS and of an inlet pipe designed to reproduce the pressure drop of the remaining portion of the XADS primary circuit. A quasi-stagnant plenum of LBE is connected to the test circuit by means of a variable flow area to simulate the plenum of the upper part of the cylindrical inner vessel of the XADS. The volume of the test section is 1:24 the volume of the XADS primary circuit, hence the 1-pipe test section reproduces to full scale the volume and mass velocity of the LBE riser pertinent to one out of the 24 riser pipes. The mutual influence of the several parallel channels (i.e. riser pipes) on the stability of the two-phase flow will be investigated by the prospective addition of a second riser pipe. The test campaign is scheduled for early 2003 with the following goals:

- Performance verification, including the control of the oxygen activity in the LBE melt;
- detection of Flow instability occurrences, if any;
- gas carry-under verification;
- gas injection system optimisation;
- acquisition of T/H data for computer code validation.

Test section characteristics and test conditions:

Scale	full scale
Geometry	single/multiple nozzle gas injection system one/two-pipe riser
Thermal conditions	isothermal
Temperature range	160-450°C
Gas mass flow rate	0-15 N-liter/s
Driving head	30÷60 kPa

Main measurements:

Pb-Bi flowrate;
gas flowrate;
pressure and differential pressure;
void fraction;
Pb-Bi level;
gas carry-under.

Figure 5. **CIRCE Isometric view complete with the prospective secondary loop and air cooler**

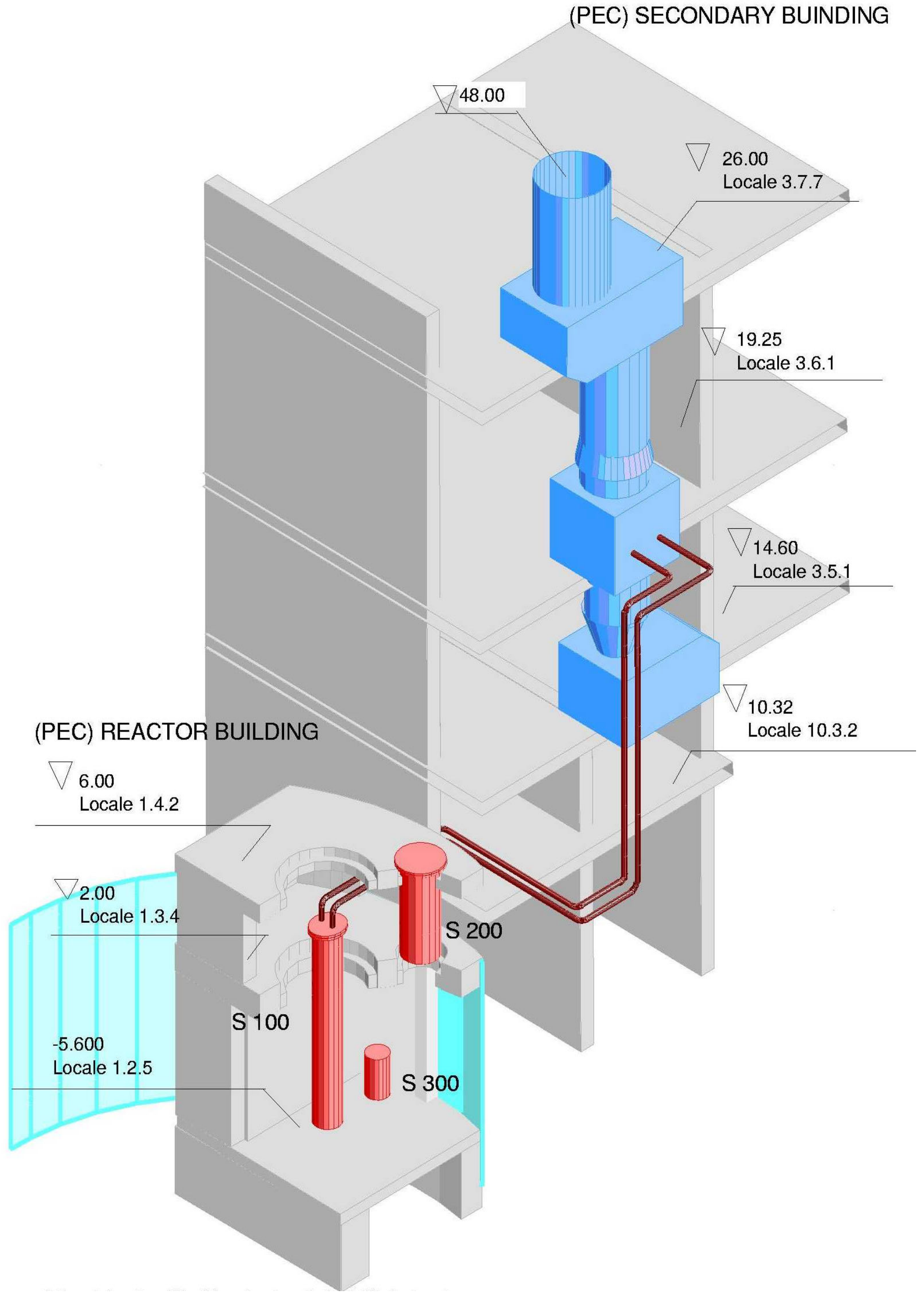


Figure 6. **CIRCE test section for gas lift LBE circulation testing**

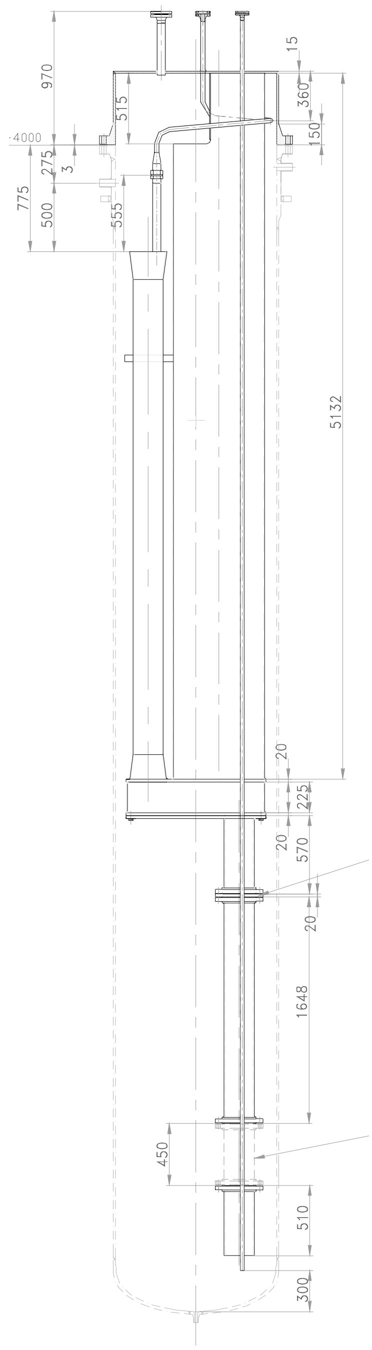


Figure 7 shows the constructed test section in the workshop. Figure 8 shows the assembled Main Vessel and Test Section. The test section instrumentation is shown in Figure 9, the synoptic panel of the gas-lift LBE circulation.

Figure 7. **Test section for gas lift LBE circulation testing after completion in the workshop**

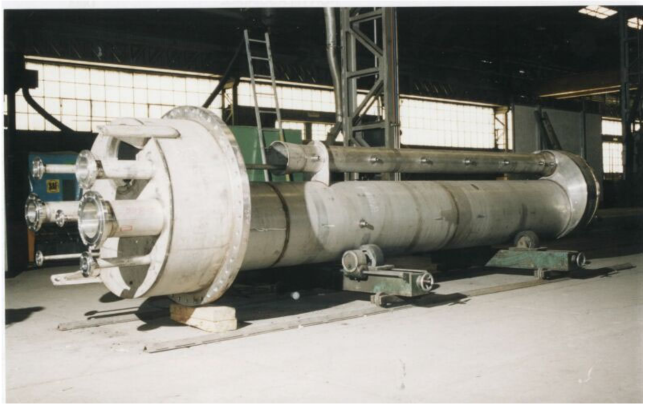


Figure 8. **Main vessel with bolted-on test section after completion in the workshop**

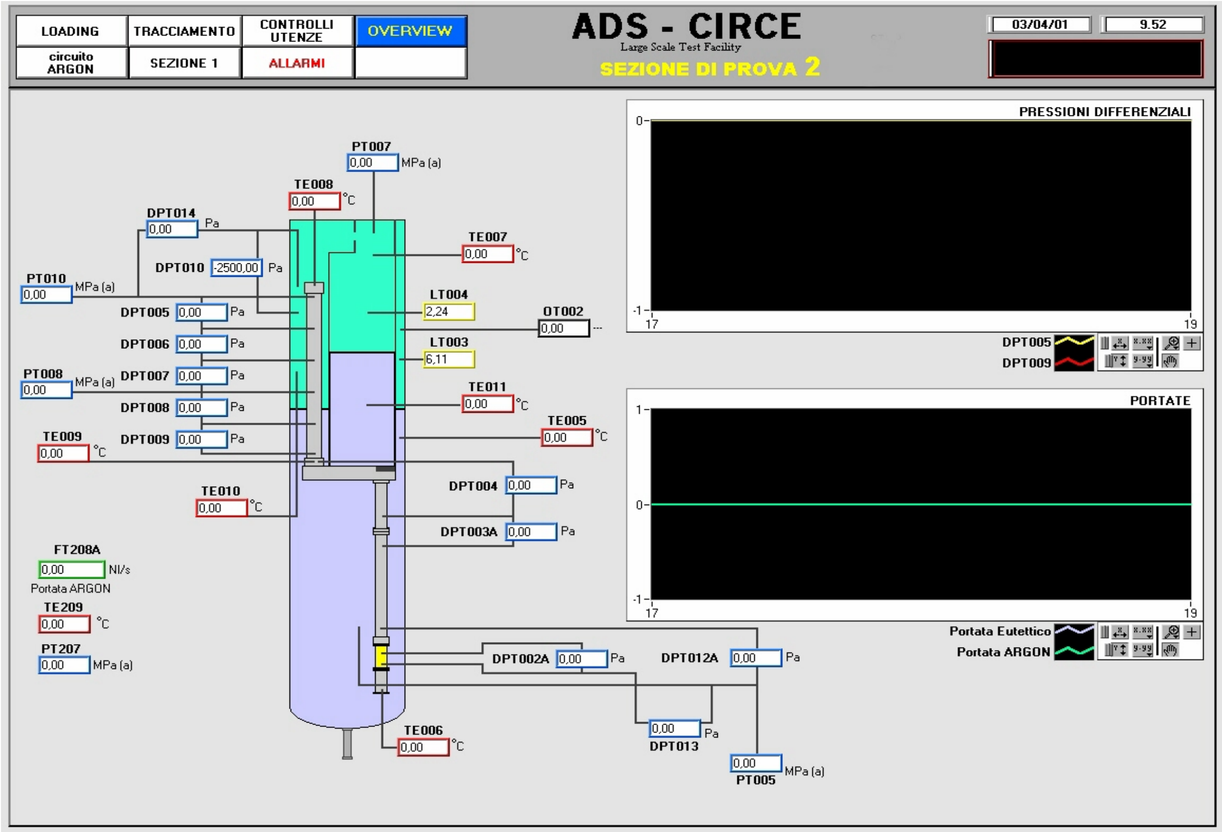
3.2 The test section for the verification of the thermalhydraulic of the Pb-Bi windowless target unit

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 option features a thin metallic sheet, called 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 Window is made of ferritic-martensitic 9Cr1Mo, a steel chosen to withstand the severe duty cycle, that encompasses thermal and pressure loads, ageing by the intense proton/neutron irradiation and erosion/corrosion by the flowing LBE melt. A combined-effects pilot experiment for the Window (Megapie) is planned at the PSI near Zurich.

In the Windowless Target Unit option (Figure 10) the proton beam impinges directly on the free surface of the liquid LBE target. In this case a natural circulation pattern in the cooling circuit is no longer possible, because the heat source near the free surface of the LBE is at a higher level due to the vacuum in the proton beam pipe. Thus the hotter LBE must be driven downwards to the heat exchanger by some means, in this case two mechanical pumps. This option has the advantage of avoiding issues related to material structural resistance against irradiation, but presents issues related to the proton beam impact area, flow stability and evaporation of LBE. A full-scale test section is programmed for construction at the end of 2003 which will be used for a test campaign in the CIRCE facility with the following goals:

- Study of the main thermal-hydraulic phenomena.
- Geometrical optimisation of the target region.

Figure 9. **Gas lift LBE circulation synoptic panel**



- Definition of the main parameters range to prevent zones of Pb-Bi stagnation in the target region.
- Definition of the requirements of the Pb-Bi flowrate control system.
- Definition of the requirements of the pipe vacuum control system.

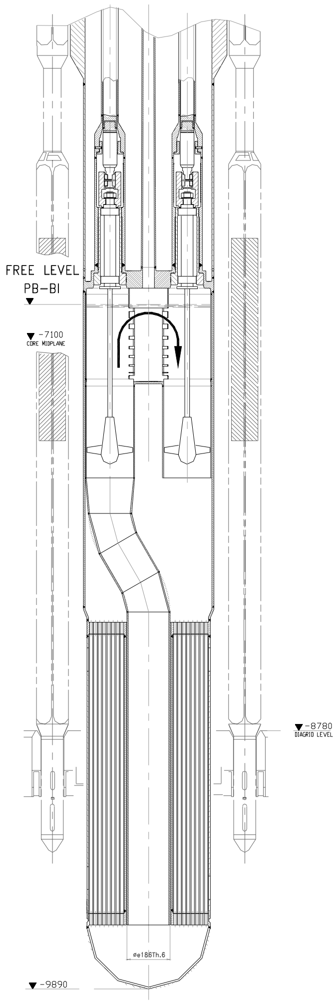
Test section characteristics and test conditions:

Scale	full-scale.
Geometry	same as the XADS Target Unit, but with a portion of the vacuum pipe and without the heat exchanger.
Thermal conditions	isothermal.
Temperature range	200 to 450°C.
Pumping system	two mechanical pumps in series.

Main measurements:

Pb-Bi flowrate;
Pb-Bi level;
Pb-Bi velocity field;
vacuum level.

Figure 10. **The LBE XADS windowless target**



Preliminary investigations on the hydraulic of the free level will be performed at the beginning of next year with a dedicated test section filled with water.

The main objectives of the planned isothermal (20°C) tests comprehend:

- the velocity field map along the flow path with particular emphasis to the spallation region. (Proper scaling of the mass flowrate circulating in the loop (10 to 30 kg/s) will ensure the facility water velocity field be representative of the reference target LBE one);
- verification of the loop mass flowrate threshold for the LBE circulation stability, if any;
- collection of T/H data for computer code validation.

4. The other test sections

Fuel assembly pressure drop

The LBE natural circulation enhanced by mean of a gas-lift pumping system is the solution adopted in the XADS primary circuit for circulating the coolant. This choice is allowed by the lower pressure drop through the core (few tens of kPa) with respect to the sodium-cooled fast reactors of classical design, owing to the somewhat larger fuel pin pitch of the fuel assemblies, possible in lead without significantly affecting the fast neutron spectrum. The gas injection in the plant risers allows to have the required driving force in a system of modest natural draft due to the short height. On the basis of the above great importance is assigned to the experimental verification of the fuel assembly pressure drop which will be obtained through a test campaign programmed in CIRCE. The adopted test section will use a (hydraulic) prototype fuel assembly of the XADS core (Figure 11) with the following test goals:

- Fuel assembly pressure drop verification.
- Fuel assembly bypass flow evaluation.
- Flow-induced vibration and fretting verification.
- Acquisition of T/H data for codes validation.

The investigation of the above phenomenologies will be performed at a steady isothermal condition at different LBE temperatures and mass flowrates representative of the LBE operating values in the XADS.

Corrosion samples in the Pb-Bi Eutectic Melt

Flowing molten lead and LBE are known to bring about erosion and corrosion of structural steels. No experience exists for geometries with large plena such as in the XADS pool-type reactor, where erosion is limited by the low LBE velocity and the amount of mass transfer by dilution/deposition between different temperature plena depends on the local activity of the dissolved oxygen. The CIRCE facility with its large mass of LBE, the isothermal and heterothermal conditions (200 to 450°C) and different velocity fields ranging from almost stagnant to velocities higher than the nominal XADS velocities (0 to 1.5 m/s), is ideally suited for sample corrosion testing. The main vessel itself and the test sections will be used along with the samples disseminated in the Main Vessel for the evaluation of the corrosion resistance of materials in operating conditions typical of the pool-type XADS.

Control of the oxygen activity in the Eutectic Melt

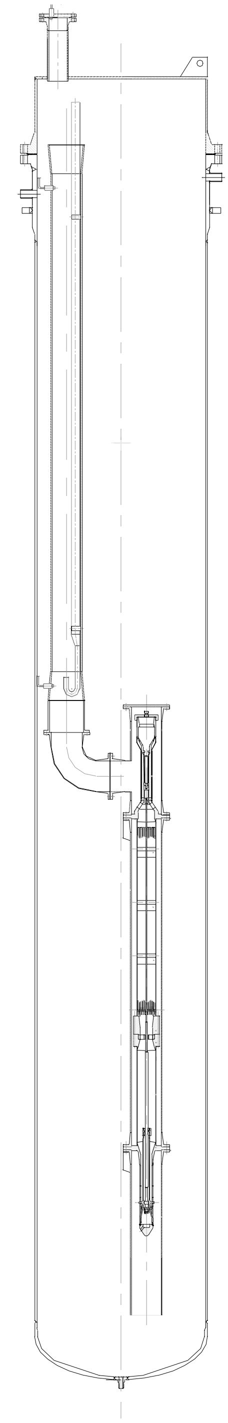
Prevention of corrosion-erosion of the austenitic structural steels in contact with the Lead-Bismuth Eutectic (LBE) melt is made, for the XADS, by maintaining a continuous, compact metal oxide film adherent to the metal substrate of the structures. This implies the presence of dissolved oxygen in the melt.

For the same reason of corrosion protection, the oxygen activity control shall be tested and the oxygen activity surveyed in all CIRCE test activities.

Basic kinematic links working in molten LBE

The presence of oxygen in the melt and in the cover gas favours the operability of the stainless steel links of the refueling machines stored *in situ*. The partial pressure of the oxygen gas is very low, however, so that the experimental verification is required that no mechanical seizure or unallowable deformation impacting the operability of the kinematic links (sliding, rotating and twisting links) occur. Basic mechanical links of the refueling machines will be constructed as a full scale model of the XADS ones, stored in the CIRCE main vessel and operated at steady state temperature of 200°C. Test in stand by condition of the links are also planned at isothermal temperature in the range 200°C to 400°C.

Figure 11. **Fuel assembly pressure drop test section scheme**



Integral system test

The construction of a suitably scaled reactor assembly of all significant systems is planned in order to guarantee that it performs satisfactory in normal operation, during anticipated transients and accidental conditions. The CIRCE facility will have then to be completed by adding the Intermediate Heat Exchanger placed in the Main Vessel, the secondary circuit filled with organic diathermic fluid, the air cooler and associated chimney stack. The core power will be supplied by electric heaters arranged in the same array of the XADS fuel assembly with coolant flowrate driven by natural draft enhanced by the gas-lift system. All primary and secondary systems will be scaled down (1:80) regarding power and volumes, but will have full-scale height, to reproduce all hydraulic phenomena relevant to the natural circulation. Figure 5 is the 3D view of the prospective, complete CIRCE facility for integral system testing and Figure 12 its sectional view.

Test goals

- Fuel clad/coolant heat transfer coefficient evaluation.
- Primary/secondary system heat transfer coefficient evaluation.
- Plant performance evaluation during normal operation and accident condition.
- Plant conditions reproduction for corrosion tests.
- Acquisition of T/H data for computer code validation for integral phenomena (systems interactions, velocity and temperature field, differential pressures, gas bubble carry-under), for separate effects (heat transfer coefficients, thermal stratification, thermal gradient stability, intermediate heat exchanger bypass) and core T/H phenomena (fuel clad/coolant heat transfer, temperature distribution). The acquired information will be also used to support the licensing procedure of the XADS.

The planned test swill investigate both steady and transient conditions, namely they will include:

- Steady-state tests at nominal and reduced power.
- Steady state tests at both reduced primary and secondary coolant flowrate (nominal primary mass flowrate: 70 kg/s).
- Accidental transient tests:
  - Decreasing reactor coolant flow rate.
  - Increasing reactor coolant flow rate.
  - Overpower transients.
  - Loss of reactor coolant inventory.
  - Decreasing heat removal from the secondary side.
  - Increasing heat removal from the secondary side.
  - Decreasing secondary coolant inventory.

5. Innovative instrumentation testing

Innovative instrumentation has been considered for monitoring CIRCE facility process parameters such as LBE flowrate, differential pressure, level and oxygen content. The verification of the proposed methodology for parameters measurement will be obtained through dedicated tests dealing with the investigation of the correct operation and reliability of the instruments.

Figure 12. **CIRCE facility in the integral system testing configuration**

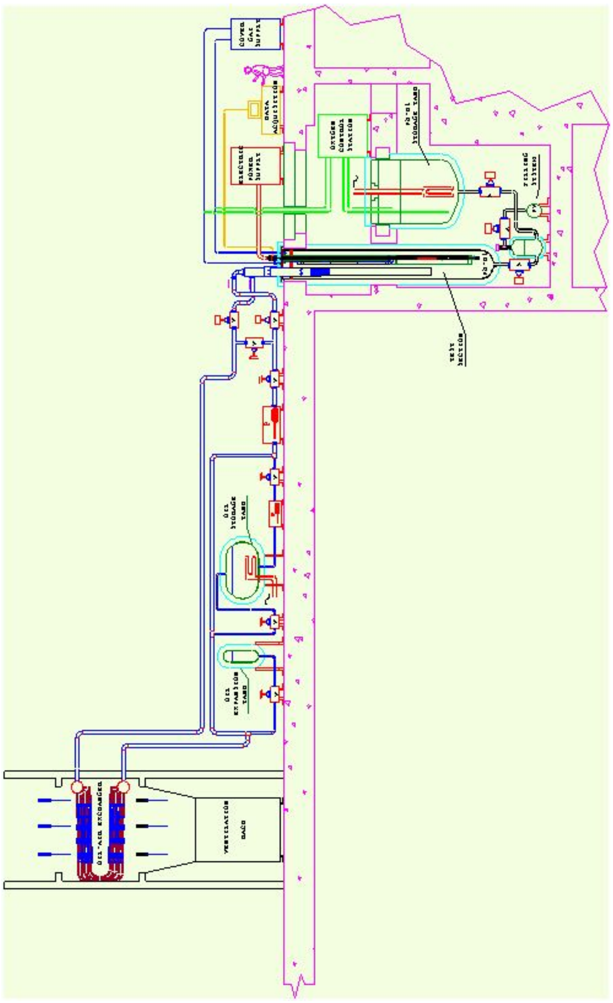
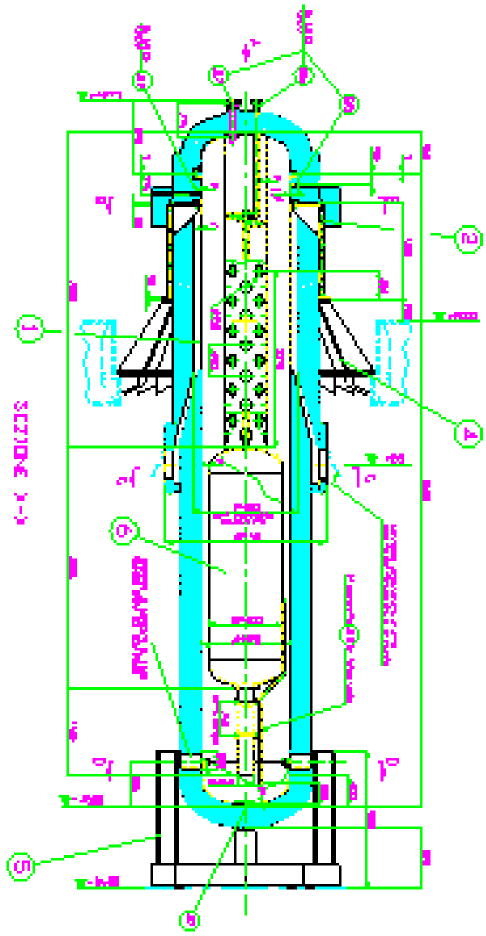


Figure 13 shows the test section for the calibration of the Venturi nozzle which will be used as LBE flow meter in CIRCE enhanced natural circulation tests.

In particular the LBE mass flow rate will be determined on the basis of the differential pressure measurements among the inlet and the throat of the Venturi. The pool type facility didn't allow in fact the use of tested instrumentation like electromagnetic flow meters commonly used in case of fluid metal mass flowrate measurements. The test section for the Venturi calibration consists of two coaxial compartments, filled with LBE, each having an independent Ar gas space. The compartments are connected at the bottom through the Venturi nozzle. The outer compartment is represented by the CIRCE main vessel, the inner compartment is the test section for the proposed test. The Venturi nozzle is installed in a 200 mm diameter pipe of representing the inlet pipe of test sections for LBE natural circulation test. The two Argon spaces are set at different pressure values thus causing different equilibrium LBE levels in the two compartments. A pipe line provided with a valve connects the two Argon spaces. When the valve opens the pressure equalisation in the two compartments causes a level redistribution with the LBE flowing from the inner to the outer compartment through the Venturi nozzles.

Figure 13. **Flow meter calibration test section**



The mass flowrate through the Venturi will be deduced on the basis of the level measurements in the compartments. Measurements of the differential pressure between the throat and the inlet of the Venturi nozzle are also performed thus allowing to determine the correlation between the Venturi pressure drop and the flowing LBE mass flowrate.

The tests will be isothermal and performed at various LBE temperatures (200°C, 300°C, 400°C).

The instrumented test section is shown in Figure 14, synoptic panel of the flow meter calibration test section, while Figure 15 shows the constructed test section in the workshop.

Innovative instrumentation has been considered also for differential pressure and level measurements. Problems related to the low LBE melting point or high LBE testing temperature inhibit the adoption of standard pressure differential meters. The new methodology proposed for pressure differential and level measurements is based on LBE pressure evaluation by mean of a gas (Ar) injection through a small pipe located in the facility positions of interest. To investigate the performance of this solution a mock-up has been constructed (Figure 16) and tests have been planned for October 2002.

Figure 14. **Flow meter calibration synoptic panel**

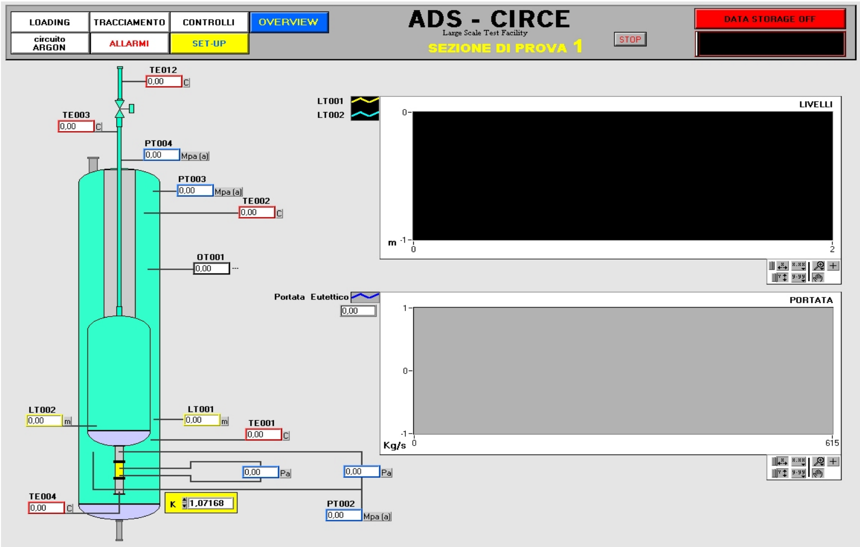
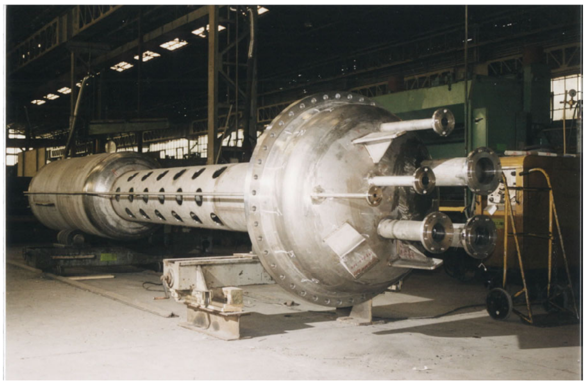


Figure 15. **Test section for flow meter calibration after completion in the workshop**



The test facility is constituted by two coaxial steel kettles, the inner containing lead-bismuth (diameter: 305 mm; height: 485 mm), the outer diathermic oil (diameter: 635 mm; height: 470 mm). The latter, heated by means of an electrical device located underneath the bottom, will allow to bring the Pb-Bi in the internal kettle at the required test temperature.

Holes are drilled in the internal kettle shell in order to accommodate different (six) configurations of the Argon pipe for pressure measurement. In particular different pipe diameters and geometry of the horizontal portion as well as different types of connection to the shell will be investigated. Two vertical gas pipes will be also tested; they are accommodated inside the Pb-Bi bulk and will be dedicated to eutectic level measurements.

The tests will start with absolute LBE pressure evaluation, then differential pressure and level.

The main goal is the verification of the reliability of the proposed measurement system and the tuning of the methodology to be adopted for correct evaluation of the parameters.

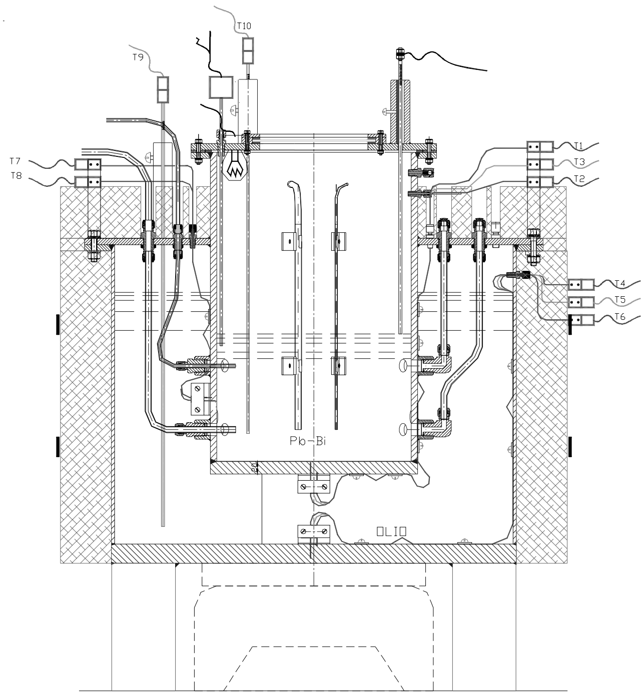
To the purpose the tests will look into the following issues:

- Pb-Bi stratification behaviour on the horizontal portion of the gas pipe.
- Time constant of the gas pipe (characteristic time to attain the pipe configuration allowing a correct measure).
- Hydraulic stability of the measurement system.
- Impact of the different configuration of the gas pipe.

These phenomenologies will be investigated over a gas flowrate range of [0.05, 2.4] l/h and at steady Pb-Bi temperatures of 160°C, 200°C, 250°C.

Measurements of oil and Pb-Bi temperature and wall temperature will allow also to determine wall heat transfer coefficient.

Figure 16. **Mock-up for pressure and level measurement testing**



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