ADS: STATUS OF THE STUDIES PERFORMED BY THE EUROPEAN INDUSTRY

Bernard Carluec
Framatome ANP Direction Novatome
10, rue Juliette-Récamier, 69456 Lyon CEDEX 06, France
Fax: +33 4 72 74 73 30
E-mail: bcarluec@framatome.fr

Luciano Cinotti
Ansaldo Nuclear Division
C.so Perrone, 25, 16161 Genova, Italy
Fax: +39 10 655 8400
E-mail: cinotti@ansaldo.it

1. Introduction

The transmutation of most of the long-lived nuclear waste is a promising solution, which could play a substantial role in the safety of the fuel cycle. The maximisation of the transmutation of minor actinides is obtained with a fast neutron spectrum. Due to the neutronic characteristics, a core dedicated to the fission of the minor actinides would have to be operated in a sub-critical state and controlled by an external neutron source. The accelerator driven systems (ADS) allow this request.

The feasibility of transmutation on an industrial scale, in the ADS has to be evaluated.

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.

Based on the recommendations of the TWG, the industrial companies, grouped in a European Industrial Partnership, have proposed preliminary concepts of the XADS.

The candidate cooling media of a fast neutron sub-critical core are liquid metals and gas. Sodium is well known and the most validated among the cooling media for fast neutron reactors. The concepts using both lead or lead-bismuth eutectic (LBE), and gas need significant R&D activities. Preliminary design studies of these concepts will be performed in the frame of the Fifth European Framework Programme. These studies will be performed on a common basis in order to be capable to make a consistent comparison of the concepts.

The purpose of the paper is to present the status of the design studies of the LBE- and gas-cooled concepts proposed respectively by Ansaldo and Framatome.

2. The need for an experimental facility

The need for an experimental facility has been clearly stated in the “Interim Report of the Technical Working Group on accelerator driven sub-critical systems” issued on October 12, 1998; from this document the following basic guidelines have been extracted.

The XADS programme should be of a sufficiently large breadth to permit to explore and eventually master most of the critical issues associated with the technology of the ADS concept. However, the XADS is not yet the prototype of the industrial device, although most of the problems of the latter should be explored separately and solved in realistic conditions by the XADS. The realisation of a XADS is deemed inevitable to make real progress in the field. In addition, the practical realisation of a unique European XADS constitutes the fastest and most cost effective way to conclusively assess the potentialities and the feasibility of a full-scale industrial programme based on ADS.

One of the main parameters of XADS is the maximum produced power of the sub-critical core. The optimum value is a compromise between the minimum value requested to validate the technological options (components, procedure, performance) at an industrial level; the minimum value for performing experimental irradiation; and the investment and operation costs. A preliminary value has already been set tentatively by the TWG to be of the order of 100 MW.

There is no specific need at the first XADS stage to make use of the heat produced that can be dissipated to the environment. A relatively low operating temperature can be used for the fuel and in the successive heat extraction process.

An important part of the experimental programme is the investigation of the transmutation capabilities of the XADS for minor actinides and long lived fission fragments, in particular ^{99}Tc and ^{129}I. An appropriate area at the periphery of the core should be planned and operated in parallel with the rest of the facility.

The mission of the XADS can be summarised as follows:

- Operability of the accelerator/spallation target/sub-critical assembly complex in realistic conditions and with a sufficient power (100 MW). The initial fuel could be an existing U-Pu oxide, like for instance the second, fresh core of Superphénix or an equivalent high enrichment fuel of commercial availability.
- Innovative fuels with a high minor actinide enrichment and fuel cycle qualification and operation.
- Demonstration of the capability to transmute various actinides fuels.
- Assessment of the capacity to transmute long-lived fission products at an industrial level.

3. XADS cooled by the Pb-Bi eutectic

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, though preliminary and not exhaustive, allow outlining a consistent XADS configuration. The main issues investigated and the associated solutions proposed (see Table 1 and Figure 1, *in fine*) are concisely described here below.

3.1 The accelerator drive

The process of selection of the accelerator type, a cyclotron or a linac or a combination of both all types presenting advantages and drawbacks is continuing at present. The results of investigations carried out so far support the confidence that the required facility can be obtained scaling up by a factor of 2 to 4 the power of existing facilities, such as the cyclotron installed at the PSI or the linac installed at Los Alamos. In particular the cyclotron-based facility has been analysed in detail and the modifications identified.

The INFN-LNS of Catania has carried out a scoping study aimed at identifying a compact accelerator system based on an upgraded design of currently operating facilities. This work has screened out a solution based on cyclotrons arranged in series and capable to supply a proton beam power in excess of 3 MW.

The main issues to be solved are stability and reliability of the present accelerator technology.

In an ADS, the ideal proton beam to be supplied to the sub-critical core, must be reliable and stable in time as required by the nuclear safety and investment protection.

Existing accelerators have been designed for purposes other than for use in ADS and it is apparent that they would not be suitable for operation in an ADS.

Considering that recorded unscheduled shutdowns of modern LWR’s are only a few per reactor per year, it appears necessary that the respective designers reach a compromise. More precisely, new accelerator-driven reactors should be designed to tolerate much more transients and accelerators should be substantially improved to become more stable and reliable.

3.2 The target

Target eutectic is kept separate from the reactor primary coolant by means of a retrievable target unit. Two target configuration concepts have been investigated, which differ in the separation barrier adopted at the interface between vacuum pipe and target lead-bismuth eutectic.

The “window” target configuration features a mechanical barrier of a material transparent to the largest possible extent to neutron and proton irradiation and engineered to withstand pressure and thermal loads, the eutectic circulates under natural circulation, cooled in the upper part of the target unit by the diathermic fluid of an auxiliary system.

In the “windowless” target configuration, the proton beam from the accelerator impinges directly on the target eutectic, that circulates driven by a stream of cover gas, according to the same gas lifting principle adopted for the primary system and is cooled by the reactor coolant in the heat exchanger located in the bottom part of the target unit.

3.3 The core

The basic fuel Sub-Assembly (SA) is a boxed hexagonal cluster of ninety highly enriched (about 20% Pu) Superphénix-like MOX fuel pins. The pin diameter is the same as in Superphénix, whereas the active length is slightly shorter (87 vs 100 cm) and the ratio of pin pitch to diameter is larger than in Superphénix.

The SA’s are arranged in an annular array of four rows surrounding the target cavity. Because six additional SA's couples have been added at the periphery of the core, the number of SA’s amounts to 120. The core multiplication factor results 0.97 at beginning of life and reduces to 0.94 at end of cycle, at full power.

k_{eff} = 0,97 is sufficiently low to ensure the safe operation of the reactor without control and shutdown rods; twelve absorber radially positioned by means of the refuelling machine, operating without target unit displacement, can bring the k_{eff} below 0.95 at refuelling conditions (200°C, zero power, target unit vertically displaced).

The core is surrounded by an outer region of four rows of dummy assemblies, which are empty duct structures. This offers a continuous fast-to-thermal neutron flux region, useable for burning tests of minor actinides and long life fission fragments SA’s.

3.4 *The primary coolant and the reactor configuration*

The eutectic lead-bismuth has been chosen instead of lead for the XADS, because, while behaving neutronically like lead, it allows a lower operating temperature of the reactor and its chemistry, in particular for the corrosion protection of the structural steels, can benefit from the Russian experience on reactors for the submarine propulsion. The preliminary tests made by ENEA at the Brasimone facility confirm the compatibility of known steels with LBE at the envisaged XADS operating temperature.

The major drawback of this eutectic is the formation of polonium from bismuth, in addition to the relative scarcity (and therefore high price) of this element. The pool-type, instead of the loop-type configuration, has been chosen for the reactor, because of the possibility to contain within the main vessel all the primary coolant with and of the large experience acquired with the design and operation of sodium-cooled, pool-type reactors. The loop-type configuration would additionally suffer of a major disadvantage, because molten lead should be pumped at low speed in order to limit corrosion/erosion and this would lead to larger diameter piping for a given volumetric flowrate, with high linear specific weight and difficulties and cost associated with the design of the seismic supports.

The design experience of sodium-cooled, pool-type reactors has been used extensively for the case of in-vessel and ex-vessel fuel handling machines and the rotating plug in the reactor roof.

Whenever this experience did not appear applicable to the specific tasks, however, solutions have been proposed, that, though being innovative in the nuclear field, are not new to the industrial practice. It is the case of the primary coolant circulation and of the choice of the secondary coolant.

The combination of more permeable fuel elements and lower average specific power of the core, can reduce the primary coolant pressure loss to few tenths of a bar, i.e. about one tenth of the pressure loss of the primary circuit of a sodium-cooled fast reactor.

Natural circulation allows a simple primary system configuration. This is apparent by comparison with the bulky pumping system of the primary coolant of a sodium-cooled fast reactor, that consists of primary pumps, designed to deliver some bar of pressure, of a pressure-plenum upstream of the core, and of interconnecting piping. The primary sodium is fed at high speed in order to reduce the piping diameter. Besides the fact that high speed in case of lead as a primary coolant should be avoided, owing to the associated erosion of the structures, some of the space made available on the reactor roof by the superfluous mechanical pumping system has been conveniently used to accommodate the proton-beam pipe and auxiliaries system, that is peculiar to an ADS reactor.

Natural circulation of the primary coolant presents, however, some drawbacks or design constraints as follows:

- The reactor vessel height must be increased by the head required to drive the natural circulation.
- The requirements of low-pressure loss through the core and the heat exchanger.
- The reduced controllability of the primary coolant flowrate, that would inherently limit the range of operating conditions of the reactor itself. This is a particularly important drawback, because a test campaign is essential part of the scope of the XADS.

As a conclusion, both the simple primary system configuration typical of the coolant circulation by natural convection and the merits of forced circulation are appealing to the designer. This fact have suggested to look for an innovative primary coolant circulation concept capable of featuring the basic advantages of both natural and forced circulation outlined above, while keeping the capability of full decay heat removal by natural circulation.

In the configuration of the XADS being designed by the Italian team (Figure 1), the lead-bismuth eutectic circulation is enhanced by a flow of about 100 Nl/s cover gas, injected into the bottom part of the twenty four, 0.2 m ID, identical pipes arranged in circle, which make up the riser. The natural draught alone provides the circulation needed for the safety-grade decay heat removal, as first step in the heat transfer route towards the reactor vessel air cooling system. This proposal [1] would combine the uncompromising reliability required by the safety function, ensured by the natural circulation, with the advantages of reactor compactness and operational flexibility characteristic of the forced circulation.

A simulation of the gas lifting process with air and water has been carried out early 1998 by means of a real size test rig installed in the Ansaldo’s own test facility in Genova. The test results have been used for the preliminary estimate of the gas flowrate capable to generate the required pressure differential between riser and downcomer in isothermal flow.

Looking at Figure 1, it will be noted that the XADS-Intermediate Heat Exchanger (IHX) is hung at the reactor roof as in conventional pool-type reactors, but has been installed free in the downcomer, i.e. without the usual physical separation between hot plenum and cold plenum, an inner structure (“redan” in French), that “forces” the coolant to flow through the IHX. With this XADS layout, the coolant flowrate route in the downcomer is substantially determined by the natural convection taking place within the IHX, that “forces” the coolant to flow through the IHX, while keeping the coolant quasi stagnating outside the IHX. In fact, the interface between hot plenum and cold plenum, that forms outside the IHX, may gently move in steady-state operation along its current shell, depending on occasional fluctuations of the IHX power level. This engineering choice gives the opportunity to illustrate another key-aspect of the design approach of the Italian team, i.e. simplification to the largest possible extent of equipment and fixed internals immersed in the lead-bismuth eutectic, in order to minimise the risks of their failure and the requirements of in-service inspection, that is difficult in liquid metals. The elimination of the primary pumps is an example of this design approach. The elimination of the redan structure is a second major example, with the relatively minor associated drawback of the need of larger-diameter IHX. This layout configuration has been adopted for the XADS, with the reserve that it shall be confirmed by the results of the thermal-mechanical analysis on the reactor vessel/cylindrical inner vessel assembly, and also it shall be compatible with the corrosion protection techniques that could be envisaged.

3.5 The secondary system

The secondary system is constituted by two safety-related loops, that in normal operation dissipates the heat generated by the reactor to the atmosphere.

Each secondary loop is made up of two IHX’s arranged in parallel and of three Air-fin Heat Exchangers (AHX) arranged in series, a circulation pump, and of the interconnecting piping. The system, as it has been designed, could re-use the six AHX’s belonging to the RSR circuit of the PEC reactor.

The thermal cycle temperatures, 320°C for the hot leg, and 280°C for the cold leg, are consistent with the choice of a synthetic diathermic fluid as the coolant, owing to the low vapour pressure of these fluids and the insurance of no fast chemical reactions, in case of leak, with the lead-bismuth eutectic or the air.

Diathermic fluids do not have so good heat transfer properties as molten metals (their thermal conductivity $\lambda_{oil} \cong 0.1$ W/m^{2}K is quite low with respect to lead, $\lambda_{Pb} \cong 15$). Nevertheless, the heat transfer coefficients achieved with these fluids in association with innovative-design IHX's are only slightly lower than in the case of lead. The still slightly better performance of lead is outbalanced, however, if the comparison is extended to the whole secondary circuit. In fact, the diathermic fluid has about 17 times as much heat capacity as lead and can be pumped at higher speed, so that the required circulating mass of the diathermic fluid is about 50 times less than the mass of lead.

3.6 Refuelling

Handling systems are similar, however not equal to the homonymous systems designed for sodium cooled reactors, because the SA's are lighter than lead-bismuth eutectic and rise, unless constrained.

The SA handled in lead-bismuth eutectic must be guided into position and locked to the rotor and the diagrid and vice-versa.

Fuel charge on the diagrid is done by means of:

- A rotor lift combined with a flask as the link between in-vessel and secondary fuel handling.
- A fixed-arm charge machine for in-vessel fuel transfer.

The SA's can be winched down from the flask and locked to the rotor, because forced to sink by the guided gripper pushed down by ballasts.

The fixed-arm charge machine grabs the head of the SA by means of a cylindrical-shaped constraint, puts the SA into position, locks its foot to the diagrid and, by the same kinematics link, unlocks the SA head.

Secondary fuel handling equipment transfers the SA into a flask, and eventually into a cask as intermediate storage. More precisely:

- The SA is lowered from the flask into the encapsulator and tight-sealed in a canister.
- The SA-bearing canister is placed in a storage rack immersed in a water pool.
- After sufficient decay time, the SA-bearing canister is placed in a cask and dry-stored away.

Table 1. **Main lead-bismuth eutectic XADS data by plant area**

Plant area	Reference solution
Plant power	80 MWth sub-critical system controlled by a 600 MeV, 6 mA proton beam
Target/Window	Two Options: a) Proton Window b) Windowless Target
Core	0.97 (at beginning of cycle) < k_{eff} < 0.94 (at end of cycle), at full power
Fuel	U and Pu MOX
Primary system	Pool configuration with four integrated IHXs
Primary coolant circulation	Circulation enhanced by gas injection in a natural-circulation reactor configuration
Secondary system	Two low vapour pressure organic diathermic fluid loops rejecting heat by means of air coolers
Thermal cycle	300°C at core inlet, 400°C at core outlet
Reactor roof	Metallic plate
Main vessel and safety vessel	Hung from a cold annular beam
Structural materials	Vessels and internals: 316L Target and fuel SA's: 9Cr 1Mo
In-vessel fuel handling	One rotating plug, one fixed arm, one rotor lifting machine
Secondary fuel handling	Flask, encapsulator, canister, lifting and translating equipment, water pool
Nuclear island	Common basement on anti-seismic support
Plant safety	Full passive system

4. XADS cooled by gas

The studies performed in France related to the fuel cycle, in particular in the frame of the research group GEDEON, have demonstrated the potential of the ADS concept for the reduction of the radiotoxicity of the nuclear wastes.

The need to develop a first experimental facility has been recognised for the demonstration on an industrial scale of the feasibility of the ADS concept.

The main options for the XADS have been defined in 1998 by a French working group leaded by the Ministry of Research and grouping CEA, CNRS, EDF and Framatome. The main technical options are as follows:

- A proton beam with energy between 400 MeV and 1 GeV, impacting a heavy metal spallation target.
- A sub-critical core in a fast neutron spectrum.

- A solid fuel for the transmutation of the radioactive wastes.
- A maximal power for the sub-critical core lower than 200 MW thermal.
- A physical separation ("window") between the accelerator and the spallation target.
- A physical separation between the spallation target and the reactor housing the sub-critical core.

Based on these main options, a XADS concept has been proposed by France at the European TWG. The concept is still preliminary and studies should be performed in the frame of the Fifth European Framework Programme to consolidate the proposed design.

Gas has been chosen as cooling medium of the sub-critical core. It had been judged that this option should be investigated in order to propose an alternative to the liquid metal concepts using sodium, lead or lead-bismuth eutectic. Compared to liquid metal concepts, the gas has intrinsic advantages. Mainly:

- Much less chemical interactions, and corrosion.
- Easier in-service inspection and repair, thanks to the transparency of the gas and the shutdown temperature which is close to the ambient temperature.

In addition, gas has been chosen because of the important experience feedback of this cooling fluid in various nuclear plants.

Helium has been preferred due to its thermal characteristics, and because the risk of chemical interactions, radiolyse and radioactive activation can be intrinsically excluded.

4.1 The accelerator drive

The French accelerator experts have concluded that the linac concept is the most suited to be used in an industrial ADS transmuter. This is due to the higher capabilities of linac related to the beam power and the beam availability which should be easier to obtain with linac than cyclotron. Therefore, in order to get experience, it is recommended to develop the linac techniques at the stage of the XADS. For these reasons, an oversized linac accelerator has been chosen. Moreover, the studies on the spallation efficiency have shown that the energy of about 1 GeV allows to optimise the neutron produced per proton and per GeV. The maximum beam intensity is fixed at 10 mA.

4.2 The target

Due to its high spallation efficiency combined with its thermal characteristics, the lead-bismuth eutectic has preliminarily been chosen as spallation target.

The spallation target is located in the centre of the core and, in order to maintain the core symmetry, the proton beam is introduced vertically from the top of the primary circuit. The lead-bismuth eutectic circulates in a circuit also located on the axis of the core, around the proton beam pipe. The circulation is driven by an electromagnetic pump; the lead-bismuth eutectic is cooled by a heat exchanger. The lead-bismuth velocity in the circuit is limited at 2 m/s.

The size of the window is defined assuming a maximum proton beam density of 30 μA/cm^2 allowing to limit the window damages.

4.3 *The core*

The basic fuel sub-assembly is a boxed hexagonal cluster of thirty-seven U-Pu oxide pins (Pu enrichment lower than 35%). The pin diameter is thirteen millimetres. In order to optimise the efficiency of the neutron source, the length of the active core is 1.5 meter.

The SA's are arranged in an annular array surrounding the target cavity. At the periphery of the core radioactive protection are implemented. An internal storage for fuel elements is located into the protection. In addition, special locations are foreseen for experimental devices.

The sub-critical level of the core is 0.95. This value is determined by a preliminary safety analysis assuming that the core has to be maintained in a sub-critical level taking into account all the credible events capable to lead rapidly to reactivity insertion. Additionally, in order to increase the margins during the shutdown states, particularly during handling states, and to avoid criticality, an absorber system is introduced in the core during the shutdown states.

4.4 *The reactor configuration*

The primary circuit consists of two pressure vessels, the core vessel and the power extraction vessel. The reactor vessel is shown in the Figure 2. The pressure of helium is 6 MPa. This value is lower than the pressure used in the High Temperature Reactor (HTR) plants.

The gas circulation in the core is preliminary defined from the bottom to the top. The core inlet temperature is 200°C, a low value but higher than the melting point of the lead-bismuth eutectic (125°C). The core outlet temperature is 450°C, low value that allows to avoid creep damages for the stainless steel structures.

The hot lead-bismuth eutectic temperature is the same as the core outlet temperature, 450°C. The cold lead-bismuth temperature is 300°C, which allows a significant margin compared to the melting point.

In order to eliminate the criticality risk due to water ingress in the core, no steam generator is implemented. The power of the sub-critical core is extracted by a direct cycle using a turbo-compressor. The heat sink is achieved by a heat exchanger. The secondary fluid is liquid water at low pressure. An alternator produces electricity, at least for supplying the accelerator needs.

In shutdown states, the core decay heat is removed by the shutdown reactor cooling system. Two redundant blowers and two redundant heat exchangers are implemented in the top of the reactor vessel. The system is fully redundant and electrically supplied. This system is also used in accidental conditions. In case of loss of internal and external electrical supply, the system is capable to remove the decay heat by natural circulation of the primary helium and the secondary circuit. In case of loss of the helium pressure, the decay heat removal is achieved by the redundant blowers electrically supplied.

5. Conclusion and design studies proposed at the Fifth European Framework Programme

The 21st century is coming with a number of challenges to sustainable growth. In particular the perspective of a growing energy demand satisfied primarily through the burning of fissile fuels, as is the case today, has a limited future with regard to resource management and an increasing awareness of the risk of climatic change. The nuclear fission power should take a substantial share, provided that its extended use will not become a challenge to future generations, mainly with respect to the closure of the fuel cycle.

The practicability of transmutation on an industrial scale requires operating an experimental accelerator driven system, which will demonstrate the coupling of the accelerator, the neutron producing target and the sub-critical core.

These objectives have been recognised by the European Atomic Energy Community (Euratom). Therefore, in the frame of the Fifth Framework Programme of Euratom for research and training in the field of nuclear energy, the European leading nuclear industrial companies and research centres, propose to join together for performing the design studies of the different XADS concepts in order to assess and compare them on a common basis and to recommend the development of the most adequate concepts.

For this purpose, the general specifications for the European XADS will be more precisely defined, a common safety approach based on the European safety requirements for future nuclear plants will be elaborated, the research and development needs supporting the development of the concepts will be identified, the technical feasibility concerns of each concept will be assessed, and a preliminary cost assessment of each concept will be done.

REFERENCE

[1] L. Cinotti, G. Corsini, 1997, *A Proposal For Enhancing The Primary Coolant Circulation in the EA*, International Workshop on Physics of Accelerator Driven Systems for Nuclear Transmutation and Clean Energy Production, Trento, Italy.

Figure 1. **Experimental accelerator driven system assembly drawing of an 80 MW facility cooled by Pb-Bi**

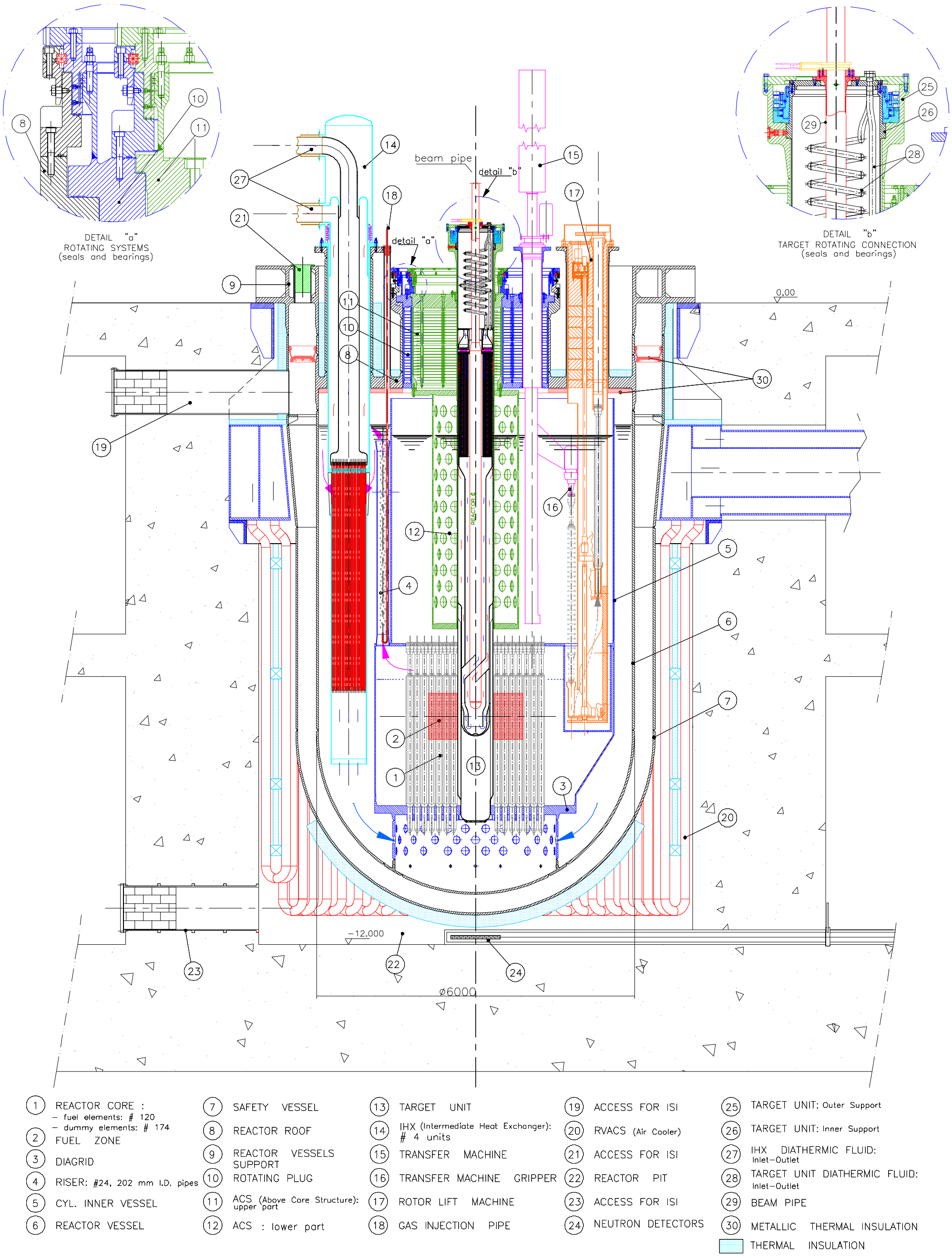

Figure 2. **Experimental accelerator driven system assembly drawing of a 100 MW facility cooled by gas**