An intrinsically safe facility for forefront research and training on nuclear technologies —General description of the system*

L. Mansani[a], M. Bruzzone, S. Frambati, and M. Reale

Ansaldo Nucleare S.p.A. Genova, Via Lorenzi 8, 16152 Genova, Italy

Received: 2 August 2013 / Revised: 21 January 2014
Published online: 25 April 2014

Abstract. In the framework of research on generation-IV reactors, it is very important to have infrastructures specifically dedicated to the study of fundamental parameters in dynamics and kinetics of future fast-neutron reactors. Among various options pursued by international groups, Italy focused on lead-cooled reactors, which guarantee minimal neutron slowdown and capture and efficient cooling. In this paper it is described the design of a the low-power prototype generator, LEADS, that could be used within research facilities such as the National Laboratory of Legnaro of the INFN. The LEADS has a high safety standard in order to be used as a training facility, but it has also a good flexibility so as to allow a wide range of measurements and experiments. A high safety standard is achieved by limiting the reactor power to less than few hundred kW and the neutron multiplication factor k_{eff} to less than 0.95 (a limiting value for spent fuel pool), by using a pure-uranium fuel (no plutonium) and by using solid lead as a diffuser. The proposed core is therefore intrinsically subcritical and has to be driven by an external neutron source generated by a proton beam impinging in a target. Preliminary simulations, performed with the MCNPX code indicated, for a 0.75 mA continuous proton beam current at 70 MeV proton energy, a reactor power of about 190 kW when using a beryllium converter. The enriched-uranium fuel elements are immersed in a solid-lead matrix and contained within a steel vessel. The system is cooled by helium gas, which is transparent to neutrons and does not undergo activation. The gas is pumped by a compressor through specific holes at the entrance of the active volume with a temperature which varies according to the operating conditions and a pressure of about 1.1 MPa. The hot gas coming out of the vessel is cooled by an external helium-water heat exchanger. The beryllium converter is cooled by its dedicated helium gas cooling system. After shutdown, the decay is completely dissipated by conduction through the lead reflector and steel vessel, and then evacuated by irradiation from the vessel surface to the external ambient air.

1 General contest

Most of the nuclear power plants currently active in the world are based on thermal reactors, with a prominence of the uranium-based open fuel cycle: uranium is irradiated, discharged and replaced with fresh fuel. This choice has resulted, year after year, in the accumulation of important quantities of highly radioactive, highly toxic, long-lived nuclear materials, in the form of plutonium, minor actinides and long-lived fission products; ^{238}U, of which only a tiny fraction is fissioned during a typical cycle, is often treated as waste as well. Moreover, large quantities of depleted uranium have also been obtained as a by-product of fuel enrichment. In the sole European Union, annually, about 2500 tons of spent fuel are produced, of which about 25 tons are plutonium isotopes, 3.5 tons are minor actinides and about 3 tons are long-lived fission products. In some countries, spent fuel is reprocessed and used for the fabrication of mixed-oxide (MOX) fuels, although not in sufficient quantities to significantly impact the continuous build-up of these materials in interim storage sites.

Within this context, and with the goal of assuring a sustainable, safe and competitive future to nuclear energy, the US Department of Energy and the Generation IV International Forum have put forward a technology roadmap [1] which is centred on four main goals at which research and development should be aimed:

* Contribution to the Focus Point "An intrinsically safe facility for forefront research and training on nuclear technologies" edited by G. Ricco.

[a] e-mail: Luigi.Mansani@ann.ansaldo.it

– *Sustainability.* It is imperative to be able to meet the needs of the present while enhancing the ability of future generations to meet their own energy needs for the foreseeable future.
– *Competitiveness.* The nuclear life cycle, including financing, construction, decommissioning, waste management and financial/operational risks, has to be guaranteed to be continued at competitive costs with respect to other sources of energy.
– *Safety.* The safe and reliable operation of future nuclear power plant designs is to be guaranteed, with the goal of maintaining it reliable while improving accident management and mitigation of consequences, reducing the need for off-site emergency response and providing forms of investment protection. The safety of nuclear installations needs to be effectively communicated to the public and to be easily understandable.
– *Proliferation resistance.* Nuclear materials and facilities need to be always kept controlled and secure through both improved designs (which should only produce dangerous materials in a form which is not appealing for diversion) and physical protection.

With these goals firmly in mind, a wide and coordinated international effort is being undertaken by industries and research entities in order to develop innovative designs able to effectively answer to the above-detailed requirements. Six main reactor concepts were selected for future technological development under the coordination of the Generation IV International Forum, in which Italy participates as a member of Euratom.

Within this context, both fast critical reactors and accelerator-driven systems (ADS) are regarded as possible candidates for effective waste transmutation machines. However, in recent years, it has become clear that fast critical reactors, alone, cannot guarantee the sustainability of the back-end of the nuclear fuel cycle. In fact, safety problems inevitably arise whenever critical systems are loaded with an excessive amount of minor actinides, due to the lower fraction of delayed neutrons and the lower Doppler reactivity coefficient which spoil reactor controllability. Therefore, a special role is expected to be played in the future by the concept of accelerator-driven systems, which are particularly well suited to maximize the transmutation rate, while still operating in a highly safe regime.

Within the framework of generation-IV projects, one of the most pressing needs is the availability of infrastructures for research and study where the theoretical evaluations on the behaviour of these innovative systems can be experimentally tested. Experimental tests are necessary in order to validate measurement methodologies, simulation codes and data libraries, as well as to improve the status and appropriateness of the current theoretical understanding, with particular regard to the complex dynamic and kinetic effects in fast-neutron heavy metal-cooled sub-critical systems. Among generation-IV concepts, lead-cooled fast systems are of particular interest to the Italian research landscape, where companies such as Ansaldo Nucleare S.p.A. and research entities such as INFN and ENEA have gained much experience as main actors of many international research projects such as PDS-XADS [2], IP-EUROTRANS [3–5], ELSY [6–8], CDT [9] and LEADER [10].

Many of these research goals intersect with those arising in the context of potential future systems for the transmutation of nuclear waste, in the context of the IP-EUROTRANS programme, and of the many projects under its patronage. A coordinated effort by the international scientific community has been devoted to the development of a comprehensive list of basic R&D needs [3], which are essential for the fruitful pursuit of the programme. Such basic needs include, among others, the need to test and develop experimental methods for the on-line measurement of sub-criticality in ADS and the need for hands-on experience on the kinetic and dynamic behaviour in fast systems. Such an experience is essential in order to validate our theoretical understanding of the main processes and parameters underlying fast-neutron systems, but is also fundamental in order to assess the potential impact of these effects on safety, the potential regulatory hurdles and safeguards of fast and sub-critical systems, the characteristics of control mechanisms and the sub-criticality margin. It is of paramount importance to develop and build facilities which are powerful enough so as to show a majority of these aspects, but sufficiently low-power so as not to overcome the zone of comfortable, high-safety operation.

2 Goals

The guiding principle in designing the proposed system has been to provide a facility which could, ideally, be well suited for the study of many different R&D needs:

– qualification of sub-criticality monitoring methods;
– study of the core kinetics and of the dynamic behaviour of reactivity coefficients;
– measuring of the basic neutronic parameters of lead, and, possibly, also of minor actinides (fission cross-sections, neutronic yields) and long-lived fission products;
– aiding the development of instrumentation and methods for accurate fast-neutronic-flux measurements;
– increasing our knowledge of the behaviour of ADS during power-up and shutdown transients (beam equipment as well as potential stresses inside the reactor);
– experimentally verifying the impact of beam reliability on system operation, as well as potential methods for its improvement;

Table 1. Many present-day or proposed/planned experimental facilities able to fulfill the ECATS needs.

Objective \ Experiment	MUSE	SAD	YALINA	MEGAPIE	GUINEVERE	MYRRHA	Our Project
Keff monitoring	NO	YES	YES	NO	YES	YES	YES
Kinetics	NO	NO	NO	NO	NO	YES	YES
Dynamics	NO	NO	NO	NO	NO	YES	YES[(a)]
Power/beam current	NO	YES	YES	NO	YES	YES	YES
Startup/shutdown	NO	YES	YES	NO	YES	YES	YES
Physics and code validation	YES	YES	NO	NO	YES	YES	YES
Beam line & target	NO	YES	NO	YES	NO	YES	YES[(b)]
Safety and licensing	NO	YES	NO	YES	YES	YES	YES

[(a)] Only up to a certain margin below the melting temperature of lead ($\sim 327\,^{\circ}$C).
[(b)] Only for a beryllium target.

– acquiring data which could be useful, in the future, to better assess safety and licensing issues regarding fast systems;
– providing a facility, at the European Union level, for the training of students and researchers.

These goals overlap with the Experimental activities on the Coupling of an Accelerator, a spallation Target and a Sub-critical blanket (ECATS) put forward in the EUROTRANS [3]. In the same reference, various present-day and proposed/planned facilities are categorized according to their ability to provide answers to these needs. A simplified overview is given in table 1. The MUSE experiment [11,12], based on a pulsed beam, provided insights into the core physics of sub-critical systems and spawned the present list of experimental needs, but did not reach a continuous-beam operation. The SAD experiment [13] was unfortunately cancelled, as was the TRADE [14] experiment a few years ago. The YALINA-Booster experiment [15] is not a truly fast facility, since it contains graphite moderators which lead to spectra very different from those that can be expected in fast reactors. The MEGAPIE experiment [16], a completed experimental campaign, focused only on the beam target characterization. Under the on-going FREYA project [17], the GUINEVERE experiment [18] is a zero-power, deuteron-beam, solid-lead ADS which will provide a wide range of very important data, but will not, unfortunately, provide information on the kinetic and dynamic aspects of fast systems. At present, only the CDT project [9] with the planned MYRRHA facility [19], a full-scale high-power facility, will provide all the needed experimental capabilities.

In this international experimental context, the need clearly arises for an intermediate, low-power ($P_{\rm th} < 500\,$kW) and high-safety ($k_{\rm eff} \leq 0.95$) system which can be used to gain experience in most of these experimental fields (including kinetic and dynamic effects) before large facilities such as MYRRHA [9,19] or EFIT [20] are put into place.

3 Core and converter

The proposed system is a fast-neutron, solid-lead matrix sub-critical system driven by a 70 MeV, 0.75 mA proton beam impinging on a beryllium converter (fig. 1). Details about the proton beam are described in the companion papers of this *Focus Point*.

The reactor core fuel is composed of standard uranium fuel pellets enriched at 20 w/o ^{235}U, similar to those used for the Superphénix reactor, but completely filled with UO_2 (*i.e.*, without central holes) and plutonium free. The choice was made to exclude the use of plutonium in order to increase the safety of the system and simplify the licensing process, while also requiring less stringent security rules and thus allowing the facility to be easily operated as a training ground for researchers and students. Fuel pellets are stacked into fuel rods 87 cm high; two natural uranium fuel pellets are added above and below each fuel rod in order to provide thermal insulation and efficient neutron axial reflection, thus leading to a total active height of 90 cm (see fig. 2, left). Fuel pellets are held in place by standard upper and lower caps and a spring in the upper part. The basic fuel assembly is composed of a $92 \times 92\,\mathrm{mm}^2$ solid-lead block containing a square array of 81 fuel rods, disposed in a 9×9 matrix and each surrounded by a stainless-steel cladding ~ 0.7 mm thick. Since the fuel assembly is based on a solid matrix, there is no need to include a central steel support rod, so all locations can be used for the fuel. An array of 9×9 cooling channels, 2.5 mm in diameter, is also bored in the lead matrix, hosting a flow of helium gas for reactor cooling (fig. 2, right). Each channel is surrounded, for safety reasons, by an aluminium cladding 0.5 mm thick, in order to prevent blockage of the channel in the unlikely event of a localized overheating and melting of the surrounding lead matrix (fig. 3). Aluminium was chosen since it has a good thermal conductivity and a low neutron capture cross-section.

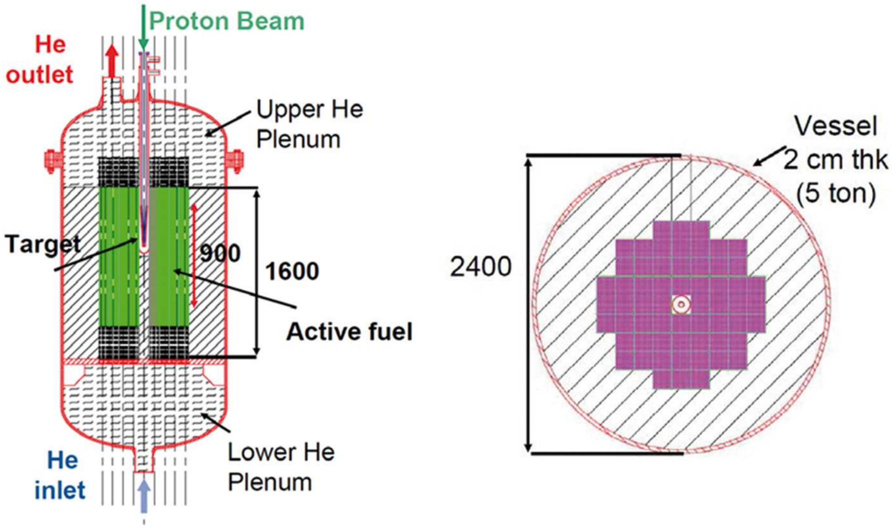

Fig. 1. Overview of the proposed facility. The lead radial reflector is not to scale in order to improve image readability. Left: side view of the facility, with the core (160 cm of height, 90 cm of which containing active fuel), lower and upper helium plena and inlet/outlet channels, axial and radial reflectors. The proton beam enters from the vessel upper head. Right: plane view of the active core, with 60 active elements, the radial reflector and the central convertor position.

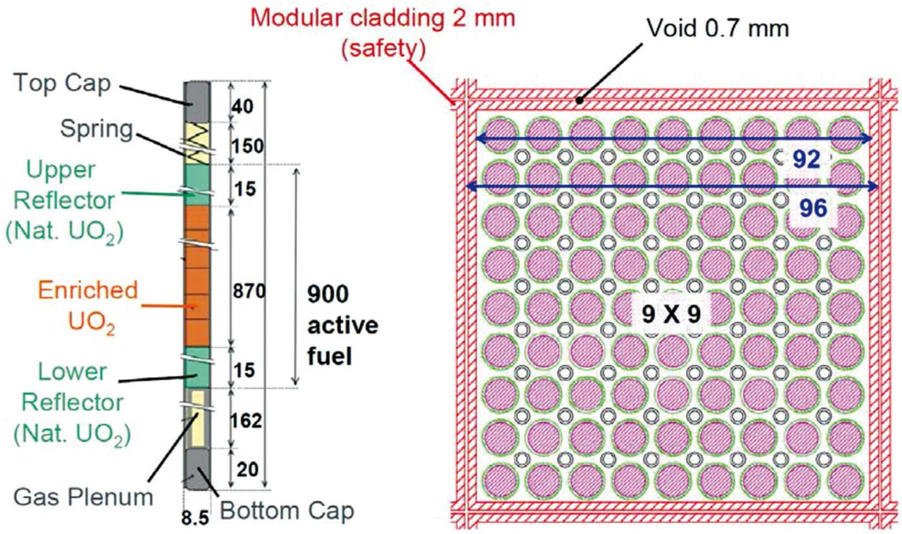

Fig. 2. Left: fuel rod used as a basic element for the core. The active height of 90 cm (composed of 87 cm of enriched uranium and 3 cm of natural uranium). Right: plane view of the basic fuel assembly, composed of an array of 9×9 fuel rods and 9×9 helium cooling channels. Each fuel assembly (FA) is surrounded by a 2 mm cladding. 0.7 mm of void are left between each cladding. If not otherwise specified, all dimensions are to be intended in mm.

Each fuel assembly is contained within a 2 mm thick stainless-steel box, which guarantees the integrity of the element even in the case of accidental falling, for example during refuelling operations; this event is often regarded as a design-basis accident by regulatory bodies and thus compliance to such a requirement is expected to be enforced during the licensing process. A ~ 0.7 mm void space is left between the fuel assemblies for constructive reasons and in order to allow for thermal expansion as well as for facilitating insertion and removal operations.

The core is composed by 60 active fuel elements (see fig. 4, left), with the central core position occupied by the proton channel and the beryllium converter. Some fuel rods can be removed and replaced with instrumentation or irradiation samples; the locations near the target, in particular, offer a very hard neutron spectrum, that can be useful for the study of the fission cross-sections of minor actinides.

The active core radius is about 50 cm, and it is surrounded by a radial solid-lead reflector about 70 cm thick (see fig. 4, right), bringing the total core radius to 120 cm. Analyses described elsewhere in the present report have shown that this configuration allows the system to achieve a very good neutron economy, minimizing neutron escapes and

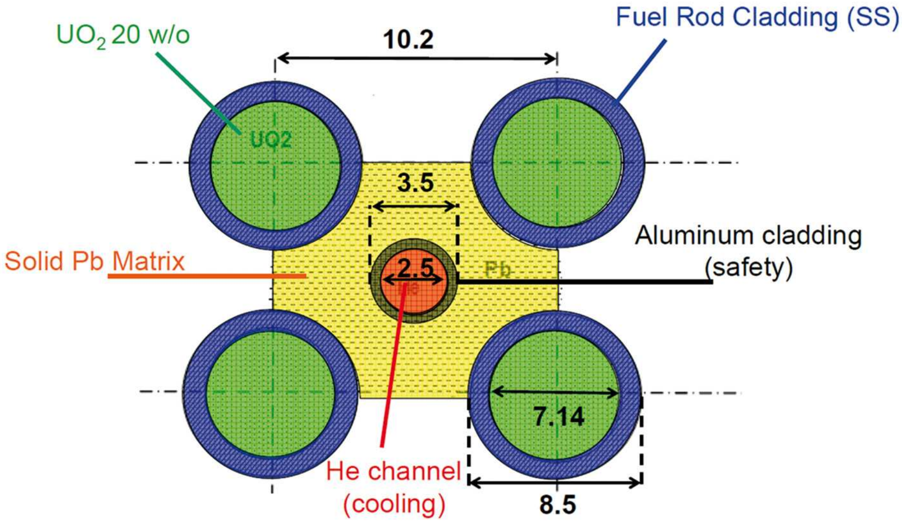

Fig. 3. Details of the basic array of fuel rods and helium channels composing the basic FA fuel rods which are surrounded by a stainless-steel cladding, while helium cooling channels are surrounded by an aluminium channel, which prevents the blockage of the channel in case of a partial melting of the surrounding Pb matrix. All dimensions are in mm.

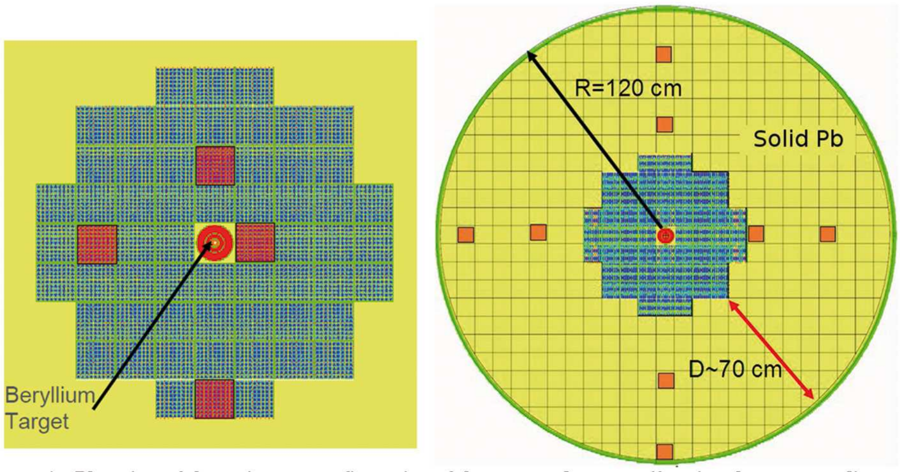

Fig. 4. Plane view of the main core configuration of the proposed system. Sixty active elements are disposed around the beryllium converter (left) and surrounded by about 70 cm of lead, acting as a radial reflector. The reflector is segmented in square elements that can be separately removed in order to allow for the insertion of instrumentation and irradiation samples, as the active fuel assemblies can. Locations in orange in the figure mark such possible locations, both inside (left) and outside (right) the fuel region.

reducing the amount of fuel to be used, thus lowering the cost of the facility. The radial reflector is segmented into a modular array of square elements, which can be removed so as to provide space for the insertion of instrumentation and monitoring equipment as well as material samples to be irradiated. Monitoring equipment in these positions can be expected to provide useful information on the neutronic properties of lead, while the more epithermal spectrum inside the reflector can be useful for the irradiation and possible transmutation of long-lived fission products. Two additional solid-lead cylinders 30 cm high are located above and below the core active fuel region to act as axial reflectors. The lead matrix is surrounded by a 20 mm thick stainless-steel vessel, with a 240 cm internal diameter. A summary of the main dimensions of the key core components is reported in table 2. With these characteristics, the core reaches a total power of about 200 kW_{th}, with $k_{eff} = 0.946$, thus satisfying the high-safety and low-power requirements of the facility. Detailed information on the core neutronics and power distribution, along with related simulations, can be found elsewhere in the present report.

The geometry of the beryllium target has been derived from the conical shape already used for the TRADE project [14, 21]. The conical surface allows the distribution of the beam power on a wide surface, thus helping target cooling. Beryllium was chosen both because it provides a very good proton-to-neutron conversion factor (mainly due to (n, xn) reactions on the ^{9}Be isotope), and due to its high thermal conductivity, about 6 times that of lead. Final

Table 2. Summary of the key dimension of the core of the proposed system.

Dimension		Unit	Value
Pellet outer diameter		mm	7.14
Rod	• Inner diameter	mm	7.14
	• Outer diameter	mm	8.5
	• Cladding thickness	mm	0.68
	• Total active length	mm	900
	• Active length of enriched uranium	mm	870
	• Length of each of the two natural uranium plugs	mm	15
	• Length of the gas plenum	mm	162
	• Pitch	mm	10.2
Number of rods per module			81
FA box	• Inner side	mm	92
	• Outer side	mm	96
	• Cladding thickness	mm	2
Void between FAs		mm	0.7
Cooling channel	• Inner diameter	mm	2.5
	• Aluminium cladding thickness	mm	0.5
	• Channel pitch	mm	10.2
Number of channels per module			81
Number of active fuel assemblies			60

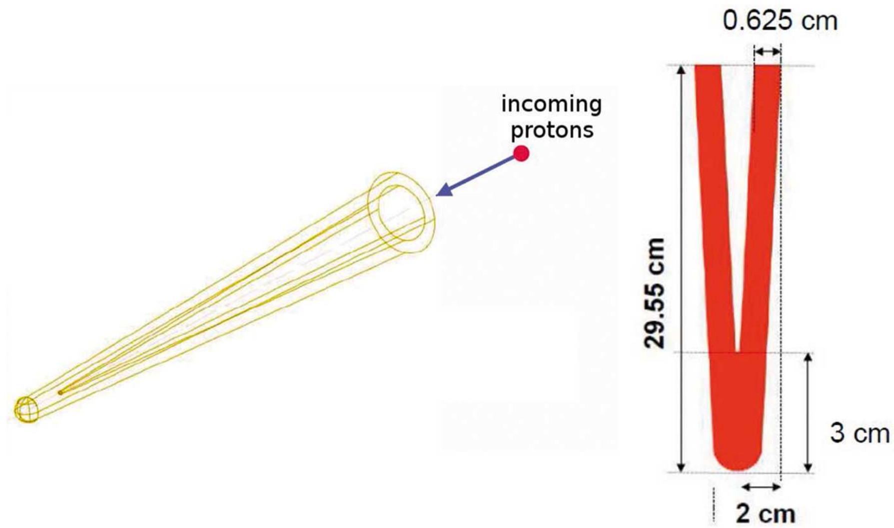

Fig. 5. Shape (left) and main dimensions (right) of the conical beryllium converter.

shape and dimensions, after suitable optimizations, are reported in fig. 5. A neutron production yield of 9.1% was reached, with very low proton losses ($\sim 2\%$). The total thermal power deposited on the target by the 70 MeV, 0.75 mA proton beam is about 50 kW. With this proton source, about $4 \cdot 10^{14}$ neutrons per second are produced. Analyses have shown that, in order to achieve the best possible coupling of the converter with the core (*i.e.*, achieving the best sub-critical multiplication parameter k_s), the converter is to be placed ~ 5 cm above the core midplane, due to the downward collimation of the produced neutrons. A sub-critical multiplication coefficient k_s of about 0.975 is obtained. The key dimensions of the converter are reported in table 3.

Table 3. Key dimensions of the beryllium converter.

Dimension	Unit	Value
Max thickness encountered by beam	mm	30
Min thickness encountered by beam	mm	6.25
Total width	mm	20
Total length	mm	295.5

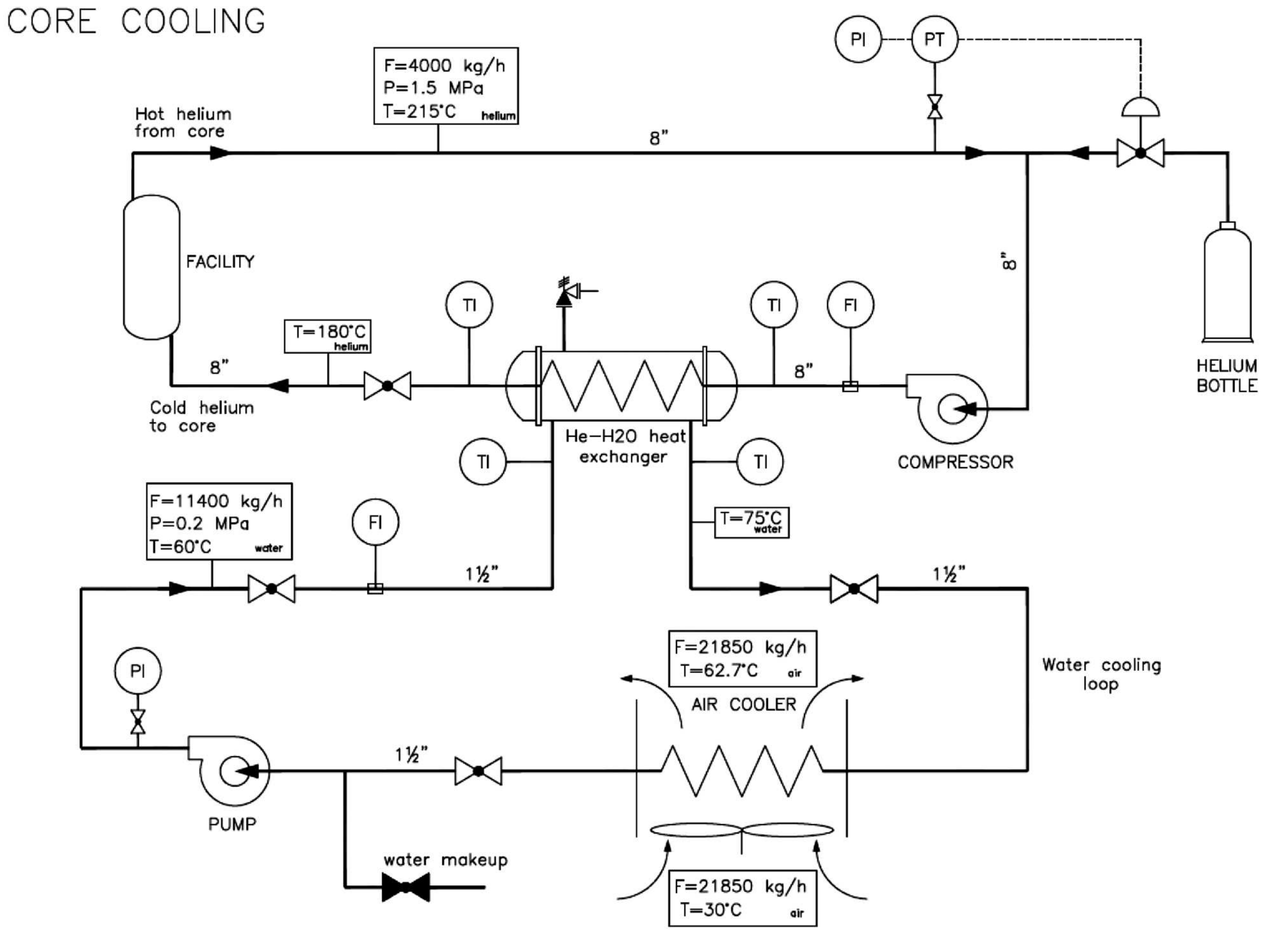

Fig. 6. A sketch of the core primary and secondary cooling loops. All temperatures are indicative and leave a margin for varying the system working point.

4 Cooling systems

System cooling is provided by the flow of helium gas through the previously described array of aluminium-cladded cooling channels. Helium inlet and outlet channels are located, respectively, at the bottom and top of the reactor vessel. The core cooling function is ensured by two systems arranged in series (see fig. 6). In the primary cooling loop, helium is circulated at a pressure of about 15 bar using a compressor. This component needs to have oil-free lubrication to maintain the cooling loop as clean as possible. Pressure is maintained by a helium bottle, which provides also helium makeup; many pressure and temperature gauges are attached to the system, providing an independent core power measuring system. The helium, heated in the core, subsequently passes through the tube side of a He-H_2O heat exchanger, where it exchanges heat with a water-based secondary loop. The typical helium flow is about 4000 kg/h, while the typical expected temperatures for helium entering and exiting the core are, respectively, 180 °C and 215 °C, although much freedom is granted by the possibility of changing the working regime of the active components in order to run the system at different temperatures, independently of the external source of the system.

The secondary loop is atmospheric, and works at a temperature between $\sim 60\,^{\circ}$C and $\sim 75\,^{\circ}$C, driven by a low-head pump (just what is needed to face up the pressure losses). Water passes in the shell side of the He-H_2O heat exchanger, where a safety relief valve is placed in order to prevent overpressurization of the loop in case of an accident.

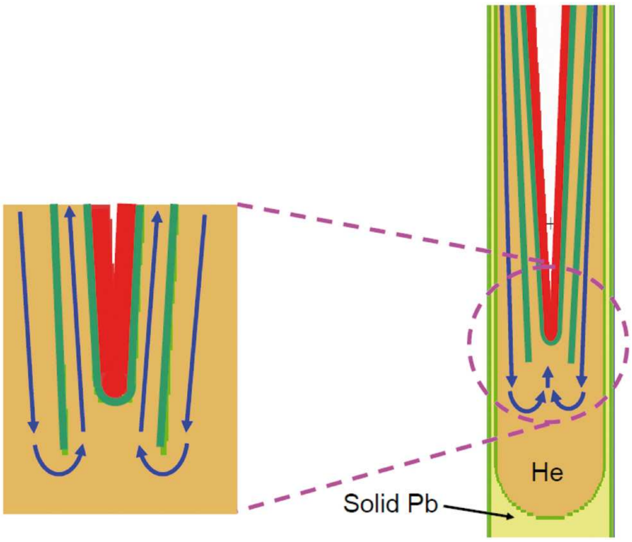

Fig. 7. Details of the bayonet-shaped cooling channel for the separate and dedicated converter cooling system.

The choice was made not to dump hot water directly into an external water reservoir such as a river, in order to prevent any possible thermal pollution of the environment. Water is instead cooled by an air cooler, from which, given a reasonable air flow, air exits with a relatively low temperature of about 60 °C. This cooling system was designed to have very high safety margins and to provide a high flexibility to the working point of the system, in order to effectively study thermal effects such as Doppler reactivity coefficients and dynamic effects during transients. All the components belonging to the loop are widely available on the market.

The beryllium converter is cooled using a bayonet-shaped cooling channel (fig. 7), which allows helium to enter and exit the cooling channel from the top of the reactor vessel. The helium inlet temperature is the same as for the core cooling loop described above; the outlet temperature is about 100 °C higher. The bayonet channel is part of the primary cooling loop of the two arranged in series. The system configuration, shown in fig. 8, is completely analogous to that used for core cooling; helium and water are kept at the same pressures used for the above-described loops, but flows and temperatures are suitably chosen according to the cooling needs of the beryllium converter. Air exits the air cooler with a temperature of about 50 °C.

Analyses [22] have shown that, given the low power of the system, after shutdown, the decay heat can be completely dissipated by conduction through the lead reflector and steel vessel, and then evacuated by irradiation from the vessel surface, provided that adequate ventilation is kept in the room containing the reactor (the assumed ambient temperature was 25 °C, but ample margins were taken into account). This means that the facility does not require active cooling after shutdown. This has two main positive consequences: first, in case of accident, after the shutdown of the external source, no external power or other action is needed to evacuate the decay heat. Secondly, the system can be flexibly operated and switched on and off on a daily basis, without any particular need for continuous operation, and thus it very well fits the proposed goal of operating as a training facility.

5 Conclusions

The main characteristics of the above-described system are reported in table 4. As can be seen, the goal of designing a facility with a high degree of safety and a power sufficiently low not to pose safety concerns, but sufficiently high so as to directly measure feedback and dynamic effects has been reached. It can be expected that most of the EUROTRANS project (ECATS) R&D needs described in sect. 2 of this paper can be at least partially explored by this facility, before being tested on large plants such as MYRRHA [9,19] or EFIT [20].

The proposed facility is a very low-cost machine, which does not require any special component and that can be flexibly operated on a daily basis. Nonetheless, it provides, through the use of an active cooling system, a wide range of working conditions, allowing the users to independently vary the working temperature, external source and core configuration. Moreover, it can be easily coupled to existing or planned accelerators, such as the SPES cyclotron currently being planned at the Legnaro INFN laboratories. A system with these characteristics is not a duplicate of existing or planned facilities, such as GUINEVERE [17,18], as it allows the study of kinetic and dynamic effects as well as the reliability of the proton beam and source. The system is, moreover, flexible enough to be used as a training facility for students and researchers.

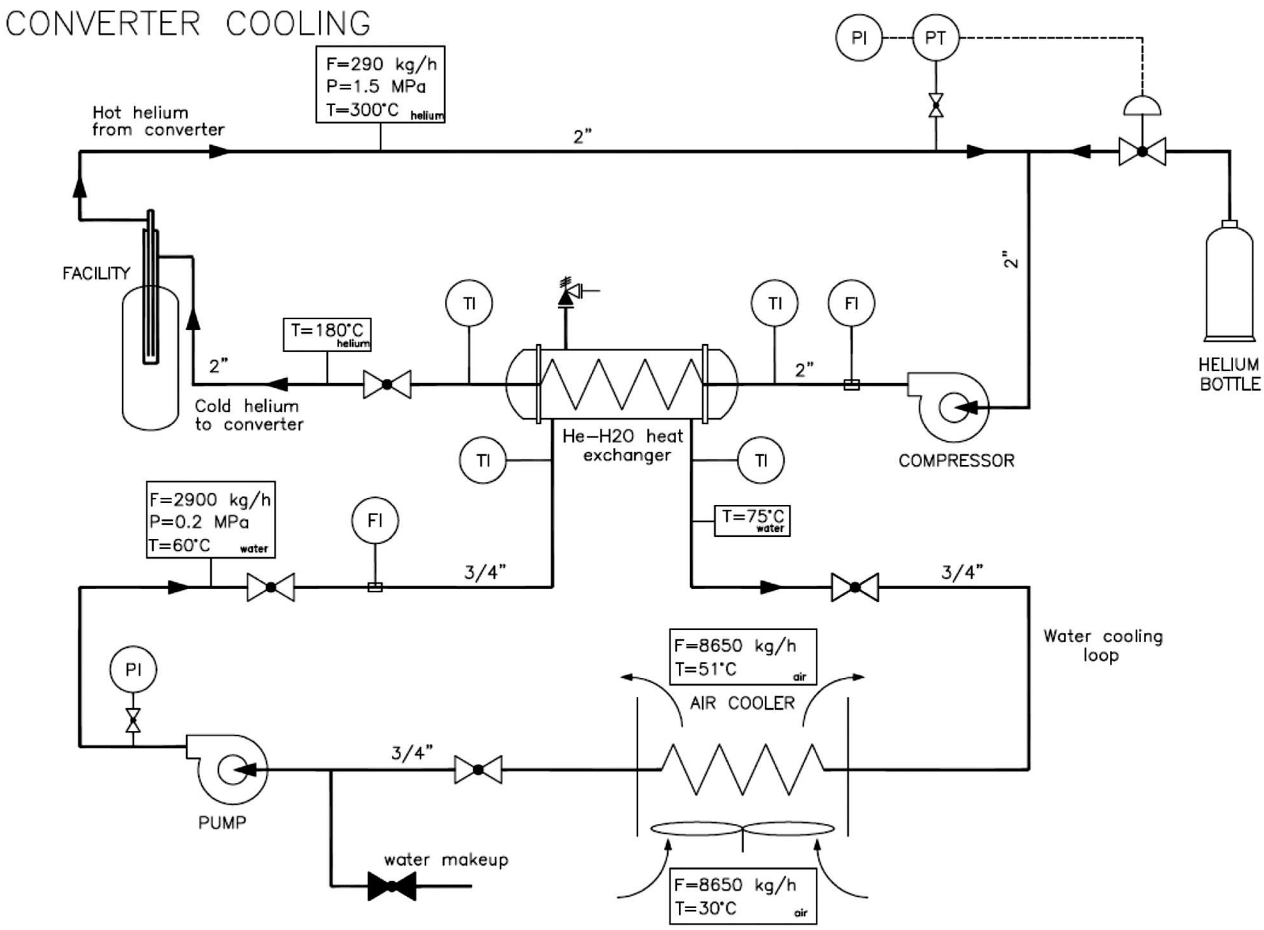

Fig. 8. A sketch of the converter primary and secondary cooling loops. These loops are completely analogous to the core cooling loops (see fig. 6), but suitably scaled to the lower power and different helium flow in the converter.

Table 4. Main reactor and converter parameters for the proposed configuration.

Parameter		Value	Error
Reactor	• k_{eff}	0.946	+0.007 −0.003
	• k_{s}	0.97450	7 pcm (stat.)
	• Total thermal power	199 kW	+29 kW −10 kW
	• Average flux	$4.19 \cdot 10^{12}$ n/cm^2-s	2%
	• Average neutron energy	0.48 MeV	4%
	• Sub-critical multiplication factor (M)	38.5	1.4 (stat.)
Converter	• Average energy deposited on the converter	49.3 kW	< 1%
	• Neutronic yield	9.1%	< 1%
	• Proton losses	2.1%	< 1%
	• Total neutron source	$4.3 \cdot 10^{14}$	< 1%

References

1. US Department of Energy Nuclear Energy Research Advisory Committee and Generation IV International Forum, *A Technology Roadmap for Generation IV Nuclear Energy Systems, GIF-002-00*, December 2002.
2. L. Cinotti, L. Mansani *et al.*, *Status of the Studies Performed by the European Industry on the LBE Cooled XADS*, in *Proceedings of the International Workshop on P&T and ADS Development, Mol, Belgium, October 6–8, 2003*.
3. G. Rimpault *et al.*, *General Synthesis Report of the Different ADS Design Status. Establishment of a Catalogue of the R&D needs*, Commissariat à l'Énergie Atomique et aux Énergies Alternatives, Direction de l'Énergie nucléaire, *SPRC/LEDC/R 10-2* (2010).
4. D. De Bruyn *et al.*, *Achievements and Lessons Learnt within the Domain 1 "DESIGN" of the Integrated Project EUROTRANS*, in *Proceedings of the Workshop on Technology and Components for Accelerator-driven Systems, Karlsruhe, Germany, March 15–17, 2010*.
5. G. Granget *et al.*, *EUROTRANS/ECATS or Neutronic Experiments for the Validation of XT-ADS and EFIT Monitoring*, in *Proceedings of the Workshop on Technology and Components for Accelerator-driven Systems, Karlsruhe, Germany, March 15–17, 2010*.
6. L. Cinotti, L. Mansani *et al.*, *The Potential of the LFR and the ELSY Project*, in *Proceedings of the ICAPP 2007 International Conference on Advances in Nuclear Power Plants, Nice, France, May 13–18, 2007*.
7. A. Alemberti *et al.*, *European Lead Fast Reactor ELSY*, in *Proceedings of the FISA 2009 Seventh European Commission conference on Euratom research and training in reactor systems, Prague, Czech Republic, June 22–24, 2009*.
8. L. Cinotti, L. Mansani *et al.*, J. Nucl. Mater. **415**, 245 (2011).
9. D. De Bruyn *et al.*, *The FP7 Central Design Team Project: towards a Fast-spectrum Transmutation experimental Facility*, in *Proceedings of the ICAPP 2010 International Conference on Advances in Nuclear Power Plants, San Diego, CA, USA, June 13–17, 2010*.
10. LEADER, *Lead-cooled European Advanced DEmonstrator Reactor*, funded under the Seventh Framework Programme for Research of the European Commission, contract No. 249668 (2009).
11. R. Soule *et al.*, *The MUSE Experiments for Sub-Critical Neutronics Validation and Proposal for a Computer Benchmark on Simulation of MASURCA Critical and Sub-Critical Experiments*, in *Proceedings of the 6th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, Madrid, Spain, December 11–13, 2000*.
12. R. Soule *et al.*, Nucl. Sci. Eng. **148**, 124 (2004).
13. V.N Schvetsov *et al.*, *The Subcritical Assembly at DUBNA (SAD): Coupling All Major Components of an Accelerator Driven System (ADS) for Nuclear Waste Incineration*, in *Proceedings of the International Conference on the Utilization of Accelerators, Dubrovnik, Croatia, June 5–9, 2005*, IAEA-CN-115.
14. C. Rubbia *et al.*, *TRADE: A Full Experimental Validation of the ADS Concept in a European Perspective*, in *Proceedings of the International Conference AccApp 2003 on Nuclear Applications of Accelerators, San Diego, CA, USA, June 1–5, 2003*.
15. V. Bournos *et al.*, *YALINA-Booster Benchmark Specifications for the IAEA Coordinated Research Projects on Analytical and Experimental Benchmark Analysis on Accelerator Driven Systems and Low Enriched Uranium Fuel Utilization in Accelerator-Driven Sub-Critical Assembly Systems*, (IAEA, 2007).
16. G.S. Bauer *et al.*, *MEGAPIE, a* 1 MW *Pilot Experiment for a Liquid Metal Spallation Target*, in *Proceedings of the 15th Meeting of the International Collaboration on Advanced Neutron Sources,* ***v.1****, Tsukuba, Japan, November 6–9, 2000*.
17. FREYA project, *Fast Reactor Experiments for hYbrid Applications*, funded under the Seventh Framework Programme for Research of the European Commission, contract No. 29665 (2011).
18. H. Aït Abderrahim *et al.*, *The GUINEVERE-project at the VENUS facility*, in *Proceedings of the Conference on Utilisation and Reliability of High Power Proton Accelerators, Mol, Belgium, May 6–9, 2007*.
19. H. Aït Abderrahim *et al.*, Nucl. Phys. News **20(1)**, 24 (2010).
20. L. Mansani *et al.*, *The designs of an experimental ADS facility (XT-ADS) and of an European Industrial Transmutation Demonstrator (EFIT)*, in *Proceedings of the Workshop on Technology and Components for Accelerator-driven Systems, Karlsruhe, Germany, March 15–17, 2010*.
21. Y. Kadi, *Spallation Target R&D for the EU Accelerator-Driven Sub-Critical System Project*, in *CARE04 (Coordinated Accelerator Research in Europe) Meeting, DESY, Hamburg, Germany, November 2–5, 2004*.
22. M. Frogheri *et al.*, *Progetto concettuale di un generatore di neutroni veloci con diffusore in piombo solido e refrigerato a gas, STU-ANNINFN-001 Rev.0*, Ansaldo Nucleare S.p.A. internal document.