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THE ASTRID PROJECT AND RELATED R&D ON NA TECHNOLOGY

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The pre-conceptual design of the ASTRID project was launched in 2010 by CEA. The objectives of this first phase are to consider innovative options to improve the safety level with progress made in SFR-specific fields. A few examples of these innovations are: a core with an overall negative sodium void effect, specific features to prevent and mitigate severe accidents, power conversion system decreasing drastically the sodium-water reaction risk, improvements in In-Service Inspection and Repair, etc. ASTRID will also be designed to pursue the R&D on sodium fast reactors and demonstrate the feasibility of transmutation of minor actinides. The paper describes the current status of the project, the mains results obtained during the pre-conceptual design and address also the main R&D needs and results, focused on sodium technology. Main R&D tracks and dedicated technological platforms have been identified, particularly thanks to the European project ADRIANA, and some more recent up-dates are described in this paper.

Introduction. The future of mankind is confronted with increasing energy demands, the gradual exhaustion of fossil fuels, and the pressure to reduce greenhouse gas emissions. This is why more and more countries are considering nuclear energy as a viable element of their energy mix. But a policy to preserve uranium resources must ,therefore, be developed to sustain this development. This is why a “fourth generation approach has been initiated at the beginning of this century, focussed on fast reactors which are able converting a large amount of uranium-238 into plutonium-239 while producing electricity. In this way, it will become possible to exploit more than 90% of natural uranium to generate electricity, rather than only 0.5 to 1% in light water reactors. The large quantities of depleted and reprocessed uranium available in France could be used to maintain the current electricity production for several thousand years. The worldwide availability of primary fissile resources could thus be multiplied by more than 50. The construction of fast reactors will also open the door to unlimited plutonium recycling (multi-recycling) by taking advantage of its energy potential, and to minor actinides (americium, neptunium, curium, etc.) transmutation.

The Generation IV Technology Roadmap has identified six systems for their potential to meet the new technology goals to improve Safety, Sustainability, Economic competitiveness and Proliferation resistance. Within the frame of Generation IV International Forum (GIF), four main objectives have been defined to characterize the future reactor systems that must be sustainable, cost-effective, safe and reliable, proliferation resistant and protected against any external hazards.

In Europe, the Strategic Research Agenda (SRA) of the Sustainable Nuclear Energy Technology Platform (SNETP) has selected these three Fast Neutron Reactor systems as a key structure in the deployment of sustainable nuclear fission energy, mostly characterized by their primary coolant: sodium, pure lead and helium.

Among the Fast Neutron Reactor Systems, the SFR has the most comprehensive technological basis as result of the experience gained from worldwide operation of several experimental, prototype, and commercial size reactors since the 1940’s. This experience corresponds to about 410 years of operation by the end of 2012.

Moreover, this concept is associated with the potential to meet the GEN IV criteria. This concept is currently considered as the Reference within the European Strategy. Six reactors are in operation: BOR60 and BN600 in Russia, Joyo and Monju in Japan, FBTR in India and CEFR in China. Two reactors are being built: PFBR (500MWe) in India and BN800 (800MWe) in Russia and several projects are being currently developed: FBR1&2 in India, BN1200 in Russia, JSFR in Japan, PGSFR in Korea, CDFR in China. In France, ASTRID, the Advanced Sodium Technological Reactor for Industrial Demonstration is currently under design, with the contribution of CEA and several partners. It is an industrial prototype and an irradiation tool [1].

1. Specifications for ASTRID. To meet the above-mentioned objectives, the Generation IV sodium fast reactor (SFR) concepts must be significantly improved, particularly, in the following fields:

- further reducing the probability of a core meltdown accident through improved preventive measures;
- integrating the impact of a mechanical energy release accident as early as the design phase if the demonstration of its 'practical elimination' is not sufficiently robust;
- taking into account the feedback from the Fukushima accident;
- improving the capacity to inspect structures in sodium, with efforts especially focused on structures ensuring a safety function;
- reducing the risks associated with the affinity between sodium and oxygen: sodium fires and sodium/water reactions;
- achieving a better availability factor than previous reactors, while aiming for the performance levels required by current commercial reactor operators;
- ensuring the transmutation of minor actinides if this radioactive waste management option is chosen by the French government;
- being competitive in relation to other energy sources with equivalent performance levels.

As an integrated technology demonstrator, ASTRID has the main objective of demonstrating advances at an industrial scale by qualifying innovative options in the above-mentioned fields. It must be possible to extrapolate its characteristics to future industrial high-power SFRs, particularly, in terms of safety and operability [2].

ASTRID will nevertheless differ from future commercial reactors for the following reasons.

ASTRID will be a 1500 MWth reactor, i.e. generating about 600 MWe, which is required to guarantee the representativeness of the reactor core and main components. This level will also compensate for the operational costs by generating a significant amount of electricity. A sensitivity study will be conducted on this power level.

It will be equipped for experiments. Its design must, therefore, be flexible enough to be able to eventually test innovative options that were not chosen for the initial design. Novel instrumentation technologies or new fuels will be tested in ASTRID.

It will be commissioned at approximately the same time as Generation III power plants, which means that its level of safety must be at least equivalent to these reactors, while taking into account the lessons from the Fukushima accident. Focus will nevertheless be placed on validating safety measures enabling the future reactors to ensure an even more robust safety level. This means taking into account core meltdown accident conditions from the design phase [1].

ASTRID's availability objective is below that of a commercial power plant due to its experimental capacity. However, the options chosen must demonstrate that a higher level of availability can be reached when extrapolated.

Without being a material testing reactor (MTR), ASTRID will be available for irradiation experiments like those conducted in PHENIX in the past. These experiments will help to improve the performance of the core and absorbers, as well as to test new fuels and structural materials, such as carbide fuel and oxide dispersion steel (ODS) cladding. ASTRID will be equipped with a hot cell for examining irradiation objects, built either in the plant or nearby.

ASTRID will be able to transmute radioactive waste so as to go on with the demonstration of this technique at larger scales for reducing the volume and lifespan of final radwaste. Though future fast reactor plants intend to be breeders, ASTRID will be a self-breeder considering the current nuclear material situation, while being able to demonstrate its breeding potential.

ASTRID must also integrate feedbacks from past reactors, especially PHENIX and SUPERPHENIX, while being clearly improved and belonging to Generation IV. It must take into account the current safety requirements, especially in terms of protection against both internal and external acts of malevolence, as well as the protection of nuclear materials, while meeting the latest requirements in terms of proliferation resistance, and controlling its costs by following a value analysis approach from design.

2. Project organisation. The CEA has been appointed by the French Government to manage the ASTRID Project. This involves:

- operational management by a project team which is also responsible for the industrial architecture, i.e. it defines the different engineering work packages;
- managing most of the R&D work and qualification of the options that will be chosen for ASTRID;
- assessment of studies carried out by its industrial partners in charge of technical work packages, or external engineering companies;
- direct responsibility of the core work package.

The CEA has set up partnerships with French and foreign industry players, who are providing both technical and financial support. These partnerships are based on bilateral contracts between the CEA and the relevant industrialist. To date, agreements have been signed with EDF, AREVA NP, ALSTOM, COMEX Nuclaire, BOUYGUES, TOSHIBA, JACOBS Nuclaire, ROLLS ROYCE, ASTRIUM.

About 550 people are currently working on the ASTRID project, half of them are provided by the industrial partners. The project remains open to other partnerships, either French or foreign.

Suck partnerships enable the CEA to concentrate on the ASTRID pre-conceptual design by implicating key industrial players, whose experience and skills in their respective fields will guarantee the project's success. The association of different industrial partners offers a number of advantages: it fosters innovation, ensures that the industrial issues are covered (operability, manufacturability, etc.) as early as the design phase, while providing a source of funding for the pre-conceptual design phases 1 and 2 since the partners have partially financed the project [2].

As the project owner, the CEA ensures the strategic and operational management of the project. It is also responsible for drafting the safety reports and maintaining dialogue with the French Nuclear Safety Authority (ASN).

The ASTRID project aims at integrating a number of innovative options to meet the objectives of the Generation IV reactors while fulfilling its specifications. It is, therefore, relying on an important R&D program at the CEA SFR R&D. This was launched in 2006 as part of the three-party framework agreement with EDF and AREVA, to provide in due time the data required to qualify the ASTRID options.

Since 2007, the CEA has also been setting up a series of international partnerships to consolidate and develop its R&D efforts. These partnerships make it possible to share the development costs and the use of heavy experimental infrastructures.

3. Current status and general schedule. The R&D actions performed within the scope of the three-party CEA-EDF-AREVA framework between 2007 and 2009 made it possible to establish the preliminary project orientations and to finalize a number of structuring concepts, e.g., the pool-type primary system and the UO_2-PuO_2 fuel. These actions provided the foundation for the project orientations file issued in September 2010, which lists the finalized structuring options and the remaining open options. By leaving some options open, this gives the project enough time to study a number of innovative solutions that could be integrated into the design with the aim at clearly positioning ASTRID as a Gen IV reactor.

The pre-conceptual design phase was launched in October 2010 and involved 3 phases:

• A preparatory phase which served to structure the project, formalize the project requirements, and define the main milestones and lead-times. It ended with an official review which launched the following phase in March 2011.

• The pre-conceptual design (dubbed AVP1 in French) aims at analyzing the open options – particularly the most innovative – so as to choose the reference design by the end of 2012, at least at the beginning of 2013.

• The conceptual design (dubbed in AVP2 in French) started in January 2013 and aims at consolidating the project data to obtain a final and consistent conceptual design by late 2015. It will include a cost estimate and a more detailed schedule, facilitating the decision-making process for the next phases of the project.

• The basic design phase is planned from 2016 to 2018.

Several options were investigated in parallel during the pre-conceptual design [2, 3]. This involved examining a number of innovations with the potential to provide significant improvements compared with previous reactors. This phase was concluded with several design option reviews to finalize the project as much as possible before launching the second phase of the pre-conceptual design.

Main options have been selected by the end of 2012. The conceptual design – lasting until late 2015 – will consolidate the first phase, allowing to optimize the design, confirm or question some options, and providing more information and greater consistency.

Dialogue has been instigated with the French Nuclear Safety Authority (ASN) during the first phase of the pre-conceptual design, which resulted in a "safety orientations report" submitted in June 2012. The safety options report will be written and submitted to ASN at the end of the conceptual design (AVP2).

4. Examples of options studied and decided during the pre-conceptual design.

Low void effect core. The CFV[1] core concept is based on a low sodium void effect. This core concept involves heterogeneous axial $UPuO_2$ fuel with a thick

[1]French abbreviation for "*Coeur à Faible effet de Vide sodium*", meaning a low void effect core.

fertile plate in the inner core and is characterised by an asymmetric, crucible-shaped core with a sodium plenum above the fissile area.

The CFV core concept is focused on optimising the core neutron feedback parameters (reactivity coefficients) so as to obtain improved natural core behaviour during accident conditions leading to the overall core heating. The CFV concept also retains a low reactivity loss thanks to the fuel pins with a larger diameter. Generally speaking, the CFV core retains a number of key advantages in terms of longer cycles and fuel residence times, as well as improved behaviour during an accidental control rod ejection transient with respect to conventional core designs.The CFV core has been chosen as a reference option for the conceptual design studies.

Malevolent hazards. Hazards of both internal and external (aeroplane impact) origin are taken into account from design.

Decay heat removal. The objective is to design decay heat removal systems that are sufficiently redundant and diversified so that the practical elimination of their total failure over a long period of time can be supported by a robust demonstration. To meet this goal, both water and air will be used as cold sources. Furthermore we will take advantage of the favourable characteristics of sodium reactors in terms of their high thermal inertia, large safety margins before sodium boiling and their capability to cope with natural convection flows. Different systems have been studied during the pre-conceptual design and selected for further studies.

Mitigation of potential core meltdown/mechanical energy release accident. To provide defense in depth against scenarios such as the melting of the core, the ASTRID reactor will be equipped with a core catcher. It will be designed to recover the entire core, maintain the corium in a sub-critical state while ensuring its long-term cooling. As other equipments important for safety, it must be inspectable. Several options have being investigated in terms of the possible core-catcher technologies, locations (in-vessel or outside the vessel) and attainable performance levels, Fig. 1. A sustained R&D effort will remain necessary in parallel on such subject, to help for the selection of the more promising technical solutions. The choice of in-vessel option for the conceptual design studies was done by the end of 2013.

Containment. The containment will be designed to resist the release of mechanical energy caused by a hypothetical core accident or large sodium fires, to make sure that no counter measures are necessary outside the site in the event of an accident.

4.1. Capability to inspect structures in sodium. Contrary to the PHENIX and SUPERPHENIX reactors, the periodic inspection of the reactor block internal structures has been integrated at the early stage of the design. The design of these

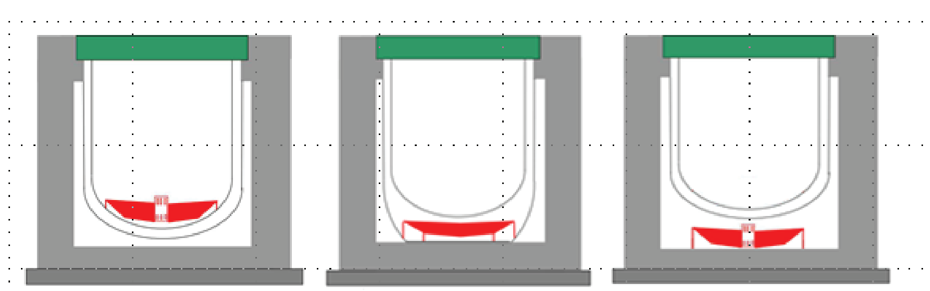

Fig. 1. Three options for core catcher location.

structures and, particularly, those contributing to the core support, were conceived to make easier their inspection. Technologies now exist that enable this inspection either from outside or inside the vessel. They mainly use optical and ultrasonic methods.

Architecture of primary and secondary circuits. During the pre-conceptual design phase, a pool-type reactor with conical 'redan' (inner vessel) has been early selected: a solution extrapolated from previous reactors and the EFR project. This solution has the advantage of being well-known; simplications have been made to allow for extended ISIR access. In terms of the reactor block, it has been decided to use three primary pumps together with four intermediate heat exchangers, each one associated with a secondary sodium loop which includes modular stream generators or sodium-gas heat exchangers. The choice is currently focused on electromagnetic pumps to equip the secondary loops, on the basis of one pump per loop.

Steam or gas power conversion system (PCS). In order to reduce the risks associated with the affinity between sodium and water, studies have been carried out on two power conversion systems:

To improve the safety and acceptability of the reactor with the de facto elimination of the risks associated with sodium-water reactions, an innovative energy conversion system is considered that uses gas (nitrogen) for the thermodynamic transformations (Brayton cycle). This type of system has never been built for the pressure and power ranges required in ASTRID, so it will first be necessary to make sure of its feasibility, cost and compatibility with SFR constraints. In any case, this concept would be coupled to the reactor through an intermediate sodium system, in order to exclude any risk of gas entrainment into the core.

For the water-steam PCS option, the following improvements were investigated: modular steam generators (heat exchange power of each module about 150 MWth), steam generator concepts ensuring better protection against wastage, and finally reinforcement of the redundancy and performance of the leak detection systems. The monolythic helical steam generator has been chosen for the water-steam PCS option, mostly on the basis of its reliability and cost.

The very innovative gas PCS option has been selected to be deeply investigated during the conceptual design phase, the water-steam PCS being the back-up option.

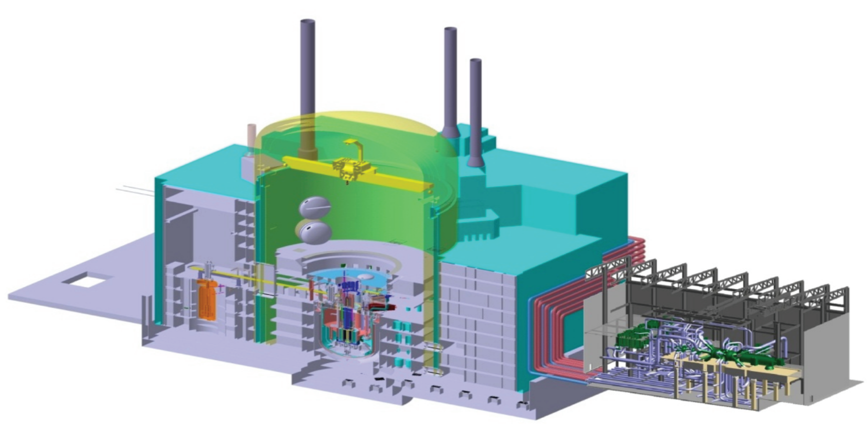

Fig. 2. ASTRID lay-out.

Fuel handling. At the beginning of the ASTRID project, it was decided to use a sodium environment in which to load and unload the fuel sub-assemblies. This implied a sodium external vessel storage tank (EVST) whose capacity depended on whether a whole core unloads is deemed necessary or not. During a cost killing phase, every choice made in the AVP1 phase has been reviewed and, for economic reasons, it was decided to suppress the ex-vessel storage tank for the conceptual phase and to move a gas route for fuel handling.

Transmutation capabilities. The transmutation of minor actinides is part of the ASTRID specifications. Only americium and neptunium are considered. With a percentage of 2% of minor actinides in a homogeneous core or 10% in dedicated blankets, there is no major impact on the plant design.

5. Main R&D needs in support to ASTRID. Deriving from the feedback of experience, very high levels of requirements have been set for the ASTRID reactor. Innovations are needed to further enhance safety, reduce capital cost and improve efficiency, reliability and operability, making the Generation IV SFR an attractive option for electricity production. Within the frame of the 6th PCRD and the ADRIANA Project, a first review of the R&D needs has been done [4]. It was consolidated through the evolution of the ASTRID project. The main R&D developments are driven by some major topics [4, 5]:

• *Thermal-hydraulic behavior (operation and safety).* This large topic covers many subjects to be studied. Of course it relies on the use of several specific codes, like TRIO-U. But some complementary experimental validation and qualification are needed, such as the internal thermal-hydraulics of the fuel bundle, pressure drop, cavitation. These tests can be performed in water. Tests in Na have to be performed for testing their behaviour in transient conditions, and characterizing the fluid behaviour at the outlet for the FA due to sodium flow in the inter assemblies space, for example.

• *Improvement of system reliability and operation (availability, safety, investment protection, etc.).* This objective mainly relies on the performance of instrumentation for continuous monitoring, but also on ISIR (In-Service Inspection and Repair). First, continuous monitoring acts during the normal operation phase and is based on the control of operating parameters and on measurements which give structure and component health state. Moreover, this instrumentation allows detecting any initiator of incidents and accidents or the first consequences of the discrepancies with nominal operational conditions.

• *Improvement of decay heat removal (safety).* Decay heat removal is a major challenge for all types of nuclear reactors. For sodium cooled fast reactors, passive decay heat removal based on Na natural convection is possible. This is one of the important advantages of these reactors. The behaviour of these systems operating in natural convection is a key point to demonstrate its reliability in case of total plant black out, for example. The CATHARE and TRIO-U codes, developed in France, are the key tool for system calculations and simulations. A qualification study of these systems has to be carried out based on some experimental validation.

• *Improvement of the reactivity control (safety).* At first, the arrangement of the SFR could be optimized in order limit the sodium void effect, but in complement, a very deterministic approach could likely be used. For example, hydraulically sustained control rods and a 3rd level of emergency shutdown system could be used. And then their qualification in representative conditions is needed: hydraulic tests (vibrations, risks of up-loading, pressure drop, cavitation, etc.) and mechanical tests in order to demonstrate the feasibility of shut-down (rod gripping system) and insertion in relevant normal or abnormal conditions.

• *Optimization of the handling route (availability, economics).* The main goals are to reduce investments costs with improvement of the In Vessel Fuel Handling System compactness and duration of FA loading/unloading operations. As there is no external fuel storage in the current ASTRID design, the reliability of the different steps of the fuel handling route is a major issue. Then two main constraints have to be considered: the handling of assemblies with high residual power and the requirement to treat on-line the fuel assemblies form the sodium internal storage to the in-use fuel assemblies' pool. They induce the necessity to develop innovative handling systems, in comparison with the previous ones, and more efficient fuel assemblies cleaning processes (to be defined and qualified).

• *Design simplification (economics, performances, periodical inspection).* This topic covers very different actions. It can concern the primary vessel and its internals design (for example, to be able to address all the periodical inspection), but also the development of electromagnetic pumps for the secondary circuit (components requiring few maintenance actions and presenting the advantage of having almost no halving time).

• *Elimination of the occurrence of a large sodium/water reaction (economics, availability and safety).* Risk of sodium-water interaction concerns sodium of the secondary circuit and water of the ternary circuit in the steam generator. This interaction can be accompanied by relatively complex phenomena (such as wastage and multiple tubes rupture). The sodium-water-air reaction is also envisaged when two leaks of water and sodium intervene in the same premise due to an external accident event. This reaction could occur during operation (including cleaning of components). The risk of explosions has to be deeply considered for two cases: explosion of hydrogen in the presence of air and also thermal explosion (fast vaporization) of water in contact with hot sodium. There is a need of a validated model for such phenomena, and validations.

• *Some cross-cutting topics like material studies, improvement of system reliability, etc.* The SFR system raises a number of material issues due its environment, i.e. corrosion phenomena, among them generalized corrosion (limited for stainless steel in contact with high quality sodium (low impurities level few ppm of O)) and related mass transfer, mechanical behaviour of structures for vessels, pipes and internal components, and a special focus on cladding material used for the fuel assemblies. The main goal is to confirm performances of new structural materials of, e.g., cladding (ODS), reactor vessel, internals, heat exchangers, coatings, etc. with regards to the expected operating conditions (high burn-up, temperature, dose, stress, etc.), new potential intermediate coolant, new innovative Energy Conversion System (ECS), and so on.

• *Improvement of behaviour in severe accident conditions.* The development and qualification of severe accident codes and mitigation devices for ASTRID require a comprehensive experimental program. It encompasses in-pile experiments, prototypic corium experiments and simulant material tests. In particular, in-pile experiments are necessary to study the behaviour of large pins, of the ASTRID CFV heterogeneous sub-assemblies during severe accident transients and of in-core mitigation devices. Corium experiments are required at small medium scale and at large scale (mainly for Fluid Corium Interaction, corium relocation and core catcher issues).

6. R&D platforms dedicated to ASTRID. The number of facilities identified to support the ASTRID program is quite large (around 40 facilities or specific programs). Therefore, for the sake of simplicity and to rationalize the renovation and design works, this amount of facilities was shared into four technological plat-

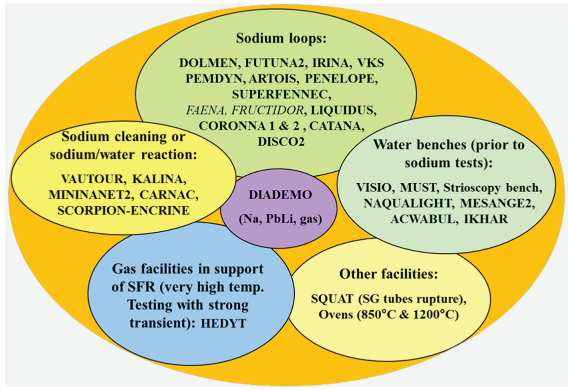

Fig. 3. Overall perimeter of the PAPIRUS platform.

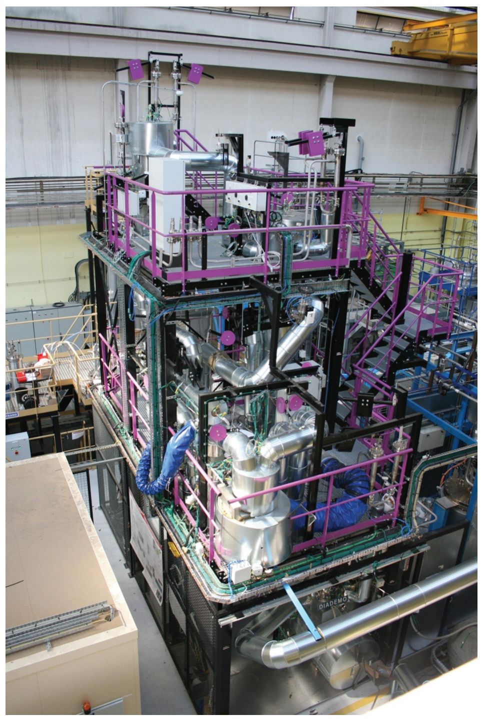

Fig. 4. Overall view of the DIADEMO-Na facility.

forms covering the entire R&D and component qualification domains. These four platforms are [6]:

• *PAPIRUS platform.* It is a set of small or medium size sodium loops for sodium experimental tests. These facilities can be devoted for modelling code validation, in sodium instrumentation studies and validation, specific technological validation of mechanical concepts or components mock-up, or determination of dissolution and corrosion laws in sodium for core or structure materials. This platform is currently 90% achieved. Some new facilities are under construction.

• *GISEH platform.* It is a set of loops and mock-ups used with a simulant fluid (water and air) allowing the qualification of thermo-hydraulic codes or validating hydraulic data of the primary vessel (hot/cold plenum), or some complex part of specific SFR components (water collector in the steam generator, or compact heat exchangers mock-ups, hydraulic in fuel assemblies). This platform is under construction. Some facilities already exist.

• *CHEOPS platform.* This platform is a group of large sodium facilities devoted to run R&D requiring large scale conditions. It allows to realize some qualification of mock-up of ASTRID components at significant and representative scale (sodium/gas heat exchanger in case of selection of a gas Brayton cycle [13]).

• *PLINIUS 2 platform.* PLINIUS is an existing platform. It is a set of facilities dedicated to studies linked to severe accident for GEN 2/ GEN 3 reactors. PLINIUS 2 will be a new set of facilities completing the existing platform and insuring the future R&D program in this field. One of its first specificity is to take into account the possibility to study the sodium corium interaction.

In some specific cases, CEA identified some technological gaps that could be covered by a foreign facility. This has led to identify some international collaborative works. One significant example is the wastage tests performed at O Arai research centre (Japan) by JAEA in 2011 or the aerosol carbonation tests carried out at the Indian ATF sodium facility belonging to IGCAR. New possibilities of collaborations are under investigation, with organizations involved in SFR design or European organizations through ARDECO bilateral collaborative projects.

7. Conclusion. By pursuing R&D and launching the ASTRID program, France is clearly on the path to developing a concept of Generation IV reactors based on the sodium-cooled fast reactor technology, which could become operational at the industrial level, if necessary, in the middle of the 21st century to offer a sustainable use of the uranium and plutonium resources, based on the demonstration ensured by the erection, commissioning and operation of ASTRID in the mid term. The ASTRID reactor would also contribute to the R&D effort on the transmutation of minor actinides. This paper has also underlined the needs in term of experimental testing, for development, validation and qualification of systems devoted to SFRs and recalled the development strategy of experimental platforms in support of the ASTRID program.

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