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Generation IV reactors and the ASTRID prototype: Lessons from the Fukushima accident

Les réacteurs de 4ème génération et le prototype ASTRID : Les enseignements de l'accident de Fukushima

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ABSTRACT

In France, the ASTRID prototype is a sodium-cooled fast neutron industrial demonstrator, fulfilling the criteria for Generation IV reactors. ASTRID will meet safety requirements as stringent as for 3rd generation reactors, and take into account lessons from the Fukushima accident. The objectives are to reinforce the robustness of the safety demonstration for all safety functions. ASTRID will feature an innovative core with a negative sodium void coefficient, take advantage of the large thermal inertia of SFRs for decay heat removal, and provide for a design either eliminating the sodium–water reaction, or guaranteeing no consequences for safety in case such reaction would take place.

RÉSUMÉ

En France, le prototype ASTRID est un démonstrateur industriel à neutrons rapides, refroidi au sodium, répondant aux critères des réacteurs de 4ème génération. ASTRID sera soumis à des critères de sûreté aussi sévères que pour les réacteurs de 3ème génération, et prendra en compte les enseignements de l'accident de Fukushima. L'objectif est de renforcer la robustesse de la démonstration de sûreté pour l'ensemble des fonctions de sûreté. ASTRID aura un cœur innovant à coefficient de vidange sodium négatif, bénéficiera de la grande inertie thermique des RNR-Na pour l'évacuation de la puissance résiduelle, et soit éliminera par conception la réaction sodium–eau, soit garantira l'absence de conséquences sur la sûreté le cas échéant.

1. Introduction

After the hearings in May 2011 in the framework of the "Solidarity Japan" working group, the conference-debate organized by the French Académie des sciences on October 18th, 2011, was the opportunity to present to a larger audience the works performed by CEA and its partners on Generation IV reactors and their safety. This article summarizes the presentation made at that occasion.

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2. Generation IV systems objectives

The objectives for Generation IV systems are the following:

– ability to multirecycle plutonium associated to the best possible use of uranium resource. This calls for fast neutron spectrum reactors coupled to a closed fuel cycle;
– if this option is decided, ability to perform transmutation and burning of certain minor actinides. This also calls for fast neutron reactors;
– safety level at least equivalent to 3rd generation reactors that are put into service at the same time. For ASTRID prototype, this means a safety level at least equivalent to 3rd generation reactors associated with the integration from design on of lessons learnt from Fukushima accident;
– reach a good economic competitiveness depending on the service that is rendered;
– show good guarantees in terms of proliferation resistance.

3. Generation IV International Forum technologies

The international framework of cooperation on 4th generation nuclear systems is the Generation IV International Forum (GIF). The objective is to perform R&D on nuclear systems (reactors and their fuel cycle) meeting the criteria of sustainable nuclear energy.

The GIF is an intergovernmental body launched in 2000 on the initiative of the US Department of Energy. The GIF encompasses today 13 members[2] bound together by a charter recognizing the importance of future nuclear energy systems and the necessity to preserve the environment and to ensure protection against proliferation risks.

The GIF has selected six concepts, based on fast or thermal[3] neutrons, and has defined an R&D work plan to foster the necessary innovations for their deployment.

It is worth noting that the technological maturity of the concepts selected by the GIF is very variable. As far as CEA is concerned, the efforts are focused on sodium-cooled fast neutron reactors (SFR), and to a lesser extent on gas-cooled fast neutron reactor technology (GFR) with emphasis on innovation on materials, in a very long term perspective. Most R&D on those subjects is supported in France by CEA, AREVA and EDF.

Beyond differences of technological maturity, GIF concepts show advantages and drawbacks that would be too long to develop here. However, in the French case, the focus is put on fast neutron technologies, excluding very high temperature (VHTR) or super-critical water (SCWR) concepts. The molten-salt reactor concept shows difficulties in the safety demonstration and on the operability side, since there is no first barrier for the fuel, putting serious doubts on its industrial feasibility. As far as the lead-cooled fast neutron reactor (LFR) is concerned, corrosion issues and the management of liquid lead at high temperature make this concept less attractive than the SFR whose industrial feasibility was already proven in the past, including the safety demonstration.

The gas-cooled fast neutron reactor needs the development of a refractory fuel composed of uranium–plutonium carbide fuel pellets with silicon carbide ceramics cladding. The fuel represents the key element of the safety demonstration in the case of loss of heat removal systems or in case of depressurization of the primary circuit.

CEA is working on two types of fast neutron reactors:

– CEA is contributing to fuel and safety studies for experimental reactor project Allegro with a thermal power of 80 MWth, to be built around 2025–2030 in Central Europe by a consortium of Czech Republic, Hungary, and Slovakia;
– CEA is in charge of the 4th generation, sodium-cooled fast reactor prototype ASTRID, with an electrical output power of 600 MWe, to be put into operation around 2020.

4. Fast neutron reactors

Fast neutrons reactors have very interesting features in terms of sustainable energy:

– excellent use of uranium resource and ability to recycle plutonium without limitation (multirecycling). Unlike the vast majority of reactors currently in operation or in construction worldwide, using only about 1% of natural uranium, fast neutron reactors are able to use more than 80% of the uranium resource. For instance, the current stockpile of depleted uranium available on French territory could feed the needs for electricity production at current rate for thousands of years;
– fast neutron reactors are an intensive energy source, which process does not emit greenhouse gases;
– fast neutron reactors are able to burn minor actinides to produce electricity, thus reducing the quantity, the half life and the toxicity of ultimate waste.

[2] South Africa, Argentina, Brazil, Canada, China, USA, Euratom, France, Japan, South Korea, UK, Russia, Switzerland.
[3] Fast neutrons: Sodium-cooled fast Reactor (SFR), Gas-cooled Fast Reactor (GFR), Molten Salt Reactor (MSR), Lead-cooled Fast Reactor (LFR). Thermal neutrons: Super Critical Water-cooled Reactor (SCWR), Very High Temperature Reactor (VHTR).

Table 1
Physical properties of sodium compared to water and lead.

	T [°C]	P [bar]	Mass density [$kg\,m^{-3}$]	Specific heat capacity [$J\,kg^{-1}\,K^{-1}$]	Dynamic viscosity [Pa s]	Thermal conductivity [$W\,m^{-1}\,K^{-1}$]	Ref.
Water	300	155	727	5460	0.09×10^{-3}	0.6	[1]
Sodium	400	1	856	1278	0.28×10^{-3}	72	[2]
Lead	400	1	10 508	147	2.25×10^{-3}	17	[3]

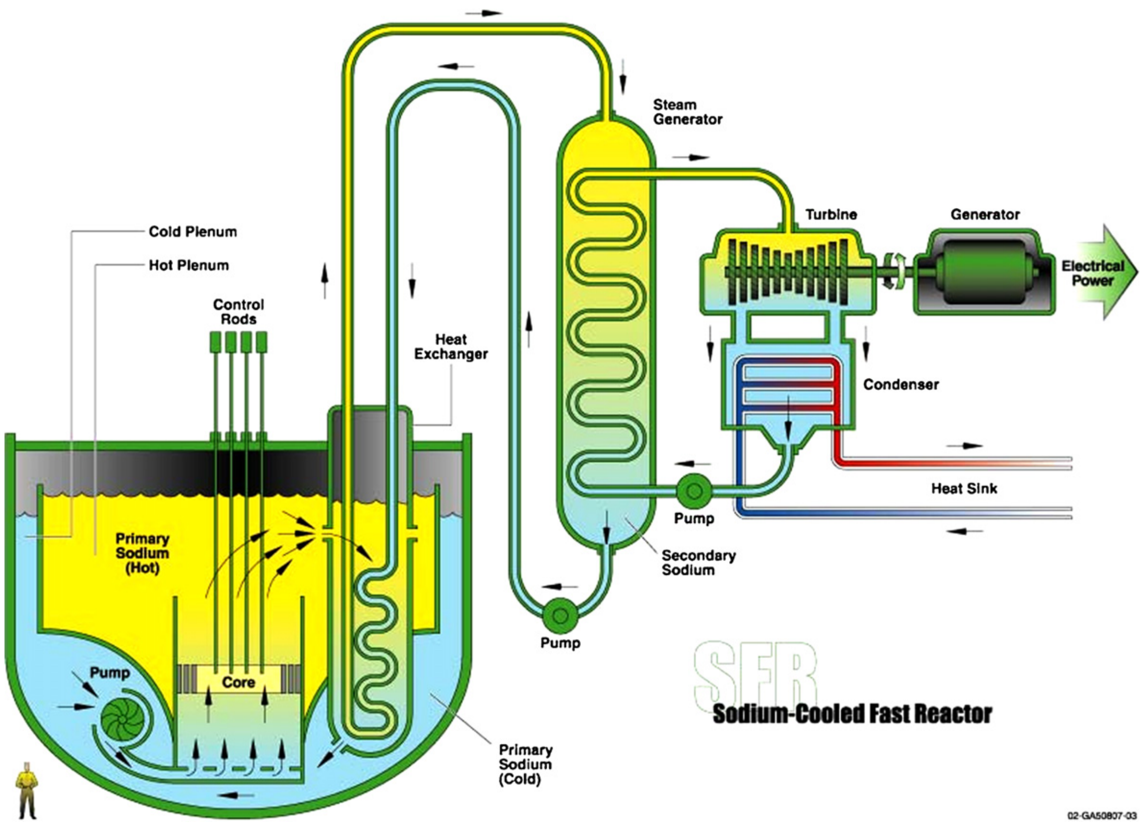

Fig. 1. A Sodium-cooled Fast Reactor (SFR).

5. Reminder about sodium-cooled fast neutron reactors, SFR

The choice of sodium as coolant for the reactor is based on a multicriteria analysis. There is a need of a coolant that does not slow down the neutrons, but thermal properties, viscosity, compatibility with steel, etc. are of outmost importance too.

As an example, Table 1 gives some properties of interest for sodium compared to water and lead.

The main drawbacks of sodium are its opacity and its chemical reactivity with air and water.

Fig. 1 shows the function diagram of an SFR (pool-type).

Compared to a pressurized-water reactor, the pool-type sodium-cooled fast reactors show the following particularities:

– the main vessel contains the whole primary system including the core, intermediate heat exchangers and primary pumps;
– the intermediate system (or secondary system) uses sodium loops to transfer the energy from the primary circuit to the main heat exchangers (in the case of a classical water-steam energy conversion system, those are the steam generators) and provides for an additional barrier;
– the primary system is not pressurized and provides for a very large thermal inertia, increasing the “grace time” in case of loss of cooling;
– the margin to boiling is very large (typically 300 °C);
– the pool-type architecture (as shown on the diagram) allows easy start of natural circulation;

- it is then possible to design decay heat removal systems that are active and/or passive, diversified, already constructed and tested in the past;
- the overall architecture provides for an excellent radiation protection of workers compared to other types of reactors.

Many SFRs were operated in different countries, and totalize more than 400 reactor. years of operation.

The following reactors are currently under operation:

- India (FBTR (40 MWth) 1985–);
- Russia (BOR-60 (60 MWth) 1968–, BN-600 (600 MWe) 1980–);
- China (CEFR (25 MWe) 2010–);
- Japan (Joyo (140 MWth)1994–, Monju (280 MWe) 1994–) (NB: these two reactors are in stand-by after technical breakdowns but Japan wishes to pursue their operation).

Plans for new reactors are the following:

- Russia: BN-800 (800 MWe) under construction, design of BN-1200;
- India: PFBR (500 MWe) under construction, 6 CFBR in planning;
- China: tens of SFRs by 2050;
- South Korea (KALIMER-2035);
- Japan (JSFR project);
- France (ASTRID project).

6. Safety of SFRs

It would be too long to develop here all aspects of SFR safety demonstration, also because the objective of ASTRID conceptual design studies is to bring the safety level of SFR up to the standards expected under Generation IV criteria. For more detail, following references are recommended:

- *G.L. Fiorini et al., Safety for the future sodium cooled fast reactors, in: International Conference on Fast Reactors & Related Fuel Cycles: Challenges and Opportunities (IAEA-FR-2009), Dec. 2009, Kyoto, Japan*;
- *Science and technology of Fast Reactor Safety, in: Proceedings of an International Conference Held in Guernsey on 12–16 May 1986, British Nuclear Energy Society, London, ISBN 0 7277 0359 5 (two volumes)*;
- *Alan E. Waltar, Albert B. Reynolds, Fast Breeder Reactors, Pergamon Press, 1981*.

The safety demonstration concerns the following safety functions: reactor reactivity control, reactor cooling, reactor containment.

For many years, the R&D conducted at CEA in partnership with EDF and AREVA has had the objective of increasing the lines of defense and the robustness of the safety demonstration on all the safety functions, especially as far as specificities of SFRs are concerned, meaning (the list being not exhaustive):

- design of the core;
- decay heat removal systems (Fig. 2);
- sodium–water reactions.

That is why CEA, EDF and AREVA have been developing a core called CFV which has got the particularity to feature a negative sodium void coefficient contrary to former reactors (a positive sodium void coefficient means that the core reactivity increases in case of loss of sodium, through boiling for instance). It is important to note at this stage that these very promising studies are not completed yet and works are on going to confirm the potential of such design towards an increased safety. If this confirmation is provided, this would mean an essential advantage in terms of safety.

As far as decay heat removal is concerned, the importance of thermal inertia is worth mentioning, meaning the masses of primary coolant and structures times their specific heat capacity. The larger the thermal inertia, the more resistant the reactor will be in case of loss of decay heat removal function. The comparison between a pool-type SFR and a PWR shows a thermal inertia almost 20 times higher for the SFR.

The thermal inertia alone is not sufficient for the safety demonstration. It is important to consider the whole incidental sequence, like total loss of station service power, and estimate which safety systems are available in such case. That is why former SFR were equipped with a combination of decay heat removal (DHR) systems, passive and active, redundant and diversified, allowing removal of decay heat from scram on, even in the case of loss of electrical power and water heat sink. Some of these systems use natural circulation and the atmosphere as heat sink. Their efficiency was verified several times through tests in Phenix and Superphenix.

Lastly, as far as sodium–water reaction is concerned, the objective is to design reactors, either eliminating any possibility of such reaction by the use of an alternative fluid (for ASTRID, a nitrogen energy conversion system is currently under study

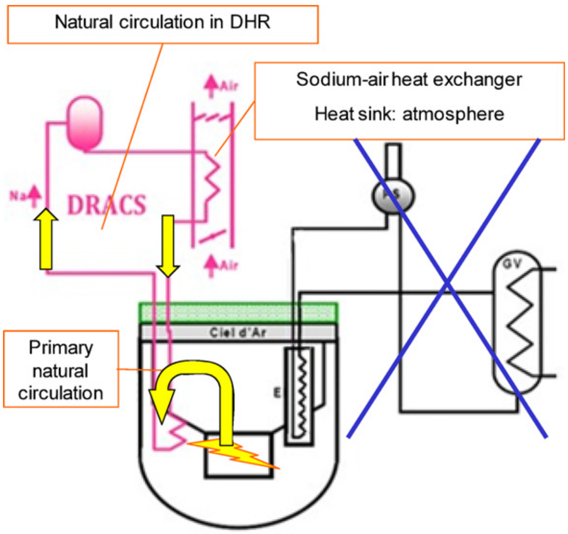

Fig. 2. Autonomous Decay Heat Removal in a SFR.

as a possible option), or guaranteeing no consequence on safety in case such reaction would occur despite all other lines of defense (design of modular steam generators).

7. The ASTRID prototype

Based upon the experience accumulated in former SFRs (Phenix, Superphenix, but also reactors under operation like BN600), CEA and its partners are focusing on the following innovations to develop a 4th generation reactor, ASTRID, which will present significant improvements especially in terms of safety demonstration:

- improved core design with negative sodium void coefficient. This core is a major improvement in terms of safety and brings a favorable natural behavior of the core in case of loss of cooling;
- energy conversion system with modular steam generators (to limit the consequences of a sodium–water reaction) or with sodium–nitrogen heat exchangers (to fully eliminate water in the sodium heat exchangers);
- large thermal inertia, natural circulation, passive and active, redundant and diversified decay heat removal systems (heat sink: water but also atmosphere);
- external aggressions taken into account from design on (earthquake, flooding, airplane crash...) with enough margins to prevent cliff edge effects (ability of the reactor to return to a safe state);
- overall layout of the reactor to ensure improved proliferation resistance.

The ASTRID prototype is the key step to ensure industrial demonstration of a Generation IV reactor, given that in the next decades, tensions on climate and energy will most probably become acuter. ASTRID will guarantee a safety and security level at least equivalent to a 3rd generation reactor, will take into account the lessons learnt from the Fukushima accident and will provide significant improvements in terms of industrial operation.

The objective of ASTRID is to demonstrate at industrial scale significant improvement and to qualify innovative options in well defined areas (safety and operability), while providing a test bench for advanced in-service inspection and repair techniques. ASTRID will also have provisions for feasibility experiments of transmutation of minor actinides up to significant quantities.

The ASTRID program (Fig. 3) encompasses the ASTRID reactor itself, the realization of sodium technological loops and the validation of components, as well as the construction of a fuel manufacturing workshop. The reactor is expected to operate around 2020.

The first deadline in 2012 is fixed by the law on nuclear waste of June 28th, 2006. At that date, the French authorities will need first technical and budgetary elements (costs, schedule) to decide whether to continue the design studies in view of the construction. That is why CEA started in 2010 the first phase of a conceptual design to define innovative technical options and safety orientations, and provide a first cost estimate.

The second phase of the conceptual design is foreseen in 2013 and 2014. The basic design will take place between 2015 and 2017. The detailed studies and construction phase will start after that.

Design reviews are foreseen at each stage to ensure compliance with Generation IV expectations.

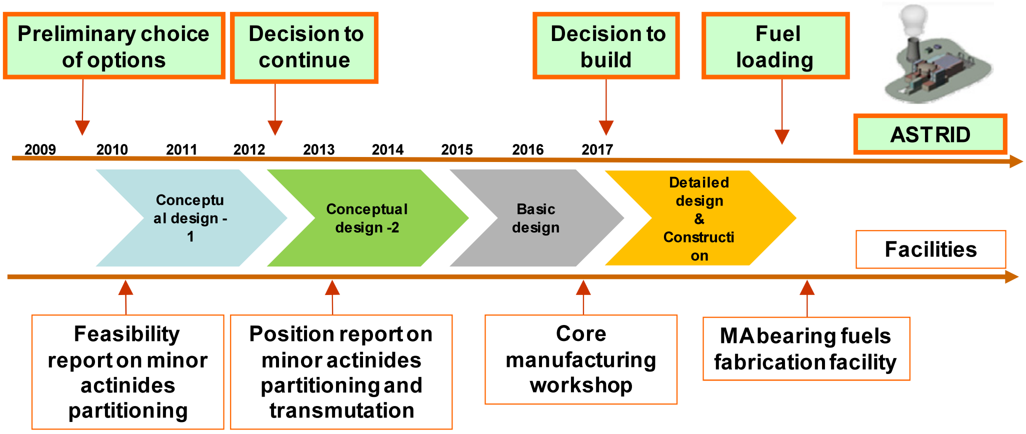

Fig. 3. The program for ASTRID.

ASTRID design studies are financed through governmental funds until the end of the basic design. These funds cover also the design studies for the core manufacturing workshop and the refurbishment or construction of large test loops. Until 2017, € 650 m are foreseen for the ASTRID program.

8. ASTRID: a 4th generation reactor with significant improvements

8.1. The objectives for ASTRID

Ambitious objectives are set for ASTRID, in order to design a true 4th generation reactor. All along the design, a verification of these objectives will be regularly made.

8.1.1. Safety

A safety level equivalent to a 3rd generation PWR is proposed, with additional, significant improvements on specific sodium issues (improved behavior of the core, inspection, sodium reactions, internal and external aggressions...). These safety objectives are formalized in WENRA[4] document "Safety Objectives for New Nuclear Power Plants" (2010). The associated safety demonstration needs the quality corresponding to the state-of-the-art expected by the French Nuclear Safety Authority. ASTRID will also take into account the specifications coming out of the lessons learnt from Fukushima accident, knowing the fact that pool-type SFRs provide intrinsically a good resistance against loss of cooling due to the very large thermal inertia of the primary circuit.

8.1.2. Operability

After a learning curve of a few years, ASTRID will demonstrate a load factor comparable to the current fleet of PWRs (availability around 80%), after deduction of experimental irradiations. This is made possible through improvements in in-service inspection techniques and the design of an innovative fuel handling system.

8.1.3. Transmutation of ultimate waste

Phenix tested at experimental scale the feasibility of minor actinides transmutation, reducing the quantity, the toxicity and the half life of ultimate radioactive waste. ASTRID will continue this demonstration at higher scales.

8.1.4. Investment costs

ASTRID will be an industrial prototype with the objective to first validate innovations and improvements. However, a particular effort will be made to contain the investment costs as much as possible. The partnership with industry since the conceptual design phase will provide safeguards in this domain. Modern analytic tools will also be applied to the design of ASTRID, like value engineering, thus allowing significant cost savings on the project.

8.2. Current R&D and envisaged options for ASTRID (or to be tested in ASTRID)

8.2.1. Safety: more robust design and safety demonstration

– Prevention and mitigation of the risk of core melting:
  (a) design of an innovating core with negative sodium void coefficient;

[4] Western European Nuclear Regulators' Association.

(b) possible installation of additional core safety systems: passive insertion of negative reactivity (SEPIA) equivalent to a 3rd shut-down system, allowing the return to a safe state in case of a loss of cooling accident without scram, reinforced fuel hex cans to prevent core compaction;
(c) robust design of core support structure to eliminate the risk of its failure;
(d) increase in instrumentation performances (subassembly thermocouples, fission chambers for neutronic detection, ultra-sound technologies, acoustic detection of boiling, flow meters…).

- practical elimination (in IAEA meaning) of loss of decay heat removal function: architecture with decay heat removal systems that are redundant, active and passive, diversified with absence of common mode (heat sink: water but also atmosphere);
- elimination of big sodium fires: containment, inert gas;
- elimination of sodium–water reactions with large energetic release. 2 options are under study: 1) water-steam system to limit the quantity of reacting sodium, design of modular steam generators, improved hydrogen detection, 2) replacement of water by nitrogen, thus fully eliminating the risk of sodium-water reaction;
- earthquake resistance: design of reactor building with seismic pads;
- state-of-the-art in terms of resistance against external aggressions (concrete shield against airplane crash, protection against flooding…) and lessons learnt from Fukushima accident.

8.2.2. Operability and economy: an availability up to industry standards

The design of ASTRID will take into account provisions allowing a better availability:

- reduced length of fuel loading outages: improvement of fuel handling systems;
- increased fuel burn-up and cycle length;
- improved manufacturing quality for sodium pipes and tanks;
- improved instrumentation performances on sodium leak detection and localization.

The In-Service Inspection & Repair (ISI&R) will be taken into account from design on:

- overall simplification of primary circuit;
- possibility to inspect all structures that have a safety function (accessibility, inspection from the outside of the vessel, robotics…);
- possibility to remove certain components for repair or replacement;
- accessibility and space around components and structures.

Lastly, ASTRID will be designed with a 60 year lifetime, as for EPR and 4th generation commercial SFRs (following EDF specifications). Phenix and Superphenix design lifetime were respectively 20 and 30 years. The ASTRID lifetime will be supported by judicious choices of materials, confirmed by simulation (aging) and by adapted maintenance strategies.

8.3. Industrial partnerships around ASTRID

Since 2010, several industrial partners have joined CEA to perform the ASTRID design studies through collaboration agreements, foreseeing contribution on the industrial partners' own budget. Thus, while CEA keeps the overall responsibility over the overall architecture, the core and the fuel, the following engineering batches are the contribution of different industrial partners:

- AREVA: nuclear steam supply system, instrumentation and control;
- EDF: specialized support to the owner, operability, safety studies;
- ALSTOM: energy conversion system (water–steam, nitrogen);
- COMEX Nucleaire: innovations on robotics and fuel handling.

End of 2011, the status of these industrial collaborations is very positive. For instance, more than 450 people are now involved in ASTRID design studies (CEA and industrial partners).

Discussions are on-going with other potential partners: Bouygues, Toshiba, Rolls-Royce, AMEC, ASTRIUM… More generally, international collaboration are put into place with major players in the field of SFRs (Russia, Japan, China, India, USA).

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