Considerations on GEN IV safety goals and how to implement them in future Sodium-cooled Fast Reactors

P. Gauthé[1], J. Guidez[2], L. Bourgue[3], S. Beils[4], B. Carluec[4]

1 CEA, DEN, DER, SESI, F-13108, Saint Paul lez Durance, France.

2 CEA, DEN, F-91400, Saclay, France.

3 EDF SEPTEN, 12-14 avenue Dutrievoz, 69628 Villeurbanne, France

4 AREVA-NP, 10 rue J. Récamier, 69456 Lyon, France

E-mail contact of main author: paul.gauthe@cea.fr

Abstract. From a general perspective generation IV (GEN IV) reactors shall excel in safety and, as part of a continuous improvement process, provide safety enhancements. Safety objectives for GEN III reactors are already very ambitious and, therefore, relevant for GEN IV reactors. This notably concerns :

- Severe accident prevention;
- Severe accident mitigation which is considered in the frame of the fourth defense in depth level;
- Response to external hazards, including natural hazards of extreme intensity.

Concerning GEN IV sodium-cooled fast reactors (SFR), the achievement of these ambitious safety objectives and the reinforcement of the robustness of the safety demonstration, will be ensured :

- Firstly, by mastering the sensitive points of the SFR such as neutron reactivity potential of the core, chemical reactivity of sodium, in-service inspection of structures under sodium.
- Secondly, by taking full benefit in the design of the favorable characteristics of the SFR such as large thermal inertia, large margin to boiling, natural convection capabilities and by providing high diversification and independence between safety systems associated to different levels of defense in depth.

The paper presents some of these possible ways of safety improvement for the future SFR.

Key Words: SFR, GenIV, safety

1. Reminders of objectives and general safety principles for French GEN III pressurized water reactors

In France, the design of GEN III reactors is part of an overall continuous improvement process of nuclear safety, which is linked to the objective of limiting the accidental exposure of the public, the operators and the environment. This continuous process is reflected in developments resulting from the analysis of the Fukushima accident.(ref 4 , 5)

1.1. General objectives

The design aims to ensure that, in the event of incidents or accidents with potential releases of radioactive substances, their impact on the human and the environment are as low as reasonably possible, that is to say in particular, under economically acceptable conditions while taking advantage of the best available techniques :

- For accidents without core melt, the design aims to ensure that the radiological consequences shall not lead to the need to implement measures to protect populations.
- In the case of accidents with core melt, the necessary measures to protect populations shall be limited in terms of space and duration and there shall be sufficient time for their implementation.
- Accidents likely to lead to very large off-site radioactive releases, or with kinetics that would not allow for the timely implementation of necessary measures to protect populations, shall be rendered physically impossible or, failing that, extremely unlikely with a high degree of confidence (practical elimination).

The design approach of the facility with regard to these general objectives relies on a deterministic approach based on the principle of defense in depth, including a fourth level from the design stage. The purpose of this defense in depth level is to mitigate situations of core-melt accidents. This led to the implementation, for example, of a core catcher capable to maintain the corium in a safe state during long term.

The estimated frequency of the core melt must be less than 10^{-5} per year per reactor taking into account all types of failures (human, material) and hazards. This evaluation is supported by analyses of uncertainty and sensitivity.

1.2.Design extension domain

The "design extension” domain is defined with the objective of enhancing the facility’s ability to cope with more complex or severe events than those considered in the reference design domain. This domain includes situations with multiple failures, situations with core melt accidents referred to in the preceding paragraph, and natural external hazards more severe than the reference hazards defined by a benchmark frequency value of 10-4 per year. The extended design domain contributes to meeting the overall objectives, including achieving a core melting risk of less than 10-5.

1.3.Taking into account the lessons learned from the Fukushima accident

For natural external hazards in the design extension domain, sufficient design margins are provided to prevent a cliff-edge effect in terms of off-site radiological consequences. The installation must be autonomous for a period compatible with the time required for the implementation of the intervention means, in particular with regard to its electricity supply and its cold source. It should be taken into account that natural hazards may simultaneously affect reactors and storage pools of the whole site.

2. General safety objectives for GEN IV SFR

Despite a high prevention level of core melt, provisions for mitigation of core-melt accidents are taken in the frame of the fourth defense in depth level.

2.1.Objectives for limiting releases in the event of a core melt accident

In the event of a core melt accident, the objective is to have very low releases such that no off-site measures are necessary. If measures are nevertheless necessary (e.g., restrictions on consumption on a crop), they shall be limited in time and space with sufficient time for their implementation. Even temporary evacuation of populations should not be necessary and only sheltering, limited in time and space, shall be envisaged.

2.2. Quantitative probabilistic objectives

For the GEN IV SFR, the probabilistic objective of core melt accident prevention is kept identical to that retained for the GEN III pressurized water reactors (i.e., 10^{-5} per year). An additional prescriptive reduction of core melt frequency is not justified and could be counterproductive. Indeed, the current probabilistic objectives are already ambitious and reach the limits in terms of representativeness and confidence. In fact, the hardening of the probabilistic objectives for the already highly unlikely events could increase the complexity of the installation and its operation, thus reducing its safety on a daily basis, for a marginal gain in terms of core melt accident probability.

This probabilistic objective can be used for comparative purposes, but it should not be used as an absolute value for acceptance of the design. For GEN IV SFR, for which a limited experience feedback is available, the safety demonstration will rely primarily on deterministic methods to cover the levels of defense in depth and to extend the prevention and mitigation of the core melt accidents. Probabilistic methods, when relevant, will provide additional insights.

2.3. Response to extreme natural hazards

The main issues to make the plant more robust with regard to natural hazards are as follows:

- ensure the presence of sufficient design margins on the equipment needed to avoid the cliff-edge effects in terms of off-site radiological consequences, for natural hazards more severe than those taken into account in the design reference domain of the plant;
- develop a significant autonomy of the installation, with regard to the duration necessary for intervention;
- develop the provisions allowing the implementation of internal or external emergency measures on the degraded plant.

In general, for GEN IV SFR, the objectives are similar to those of GEN III reactors. These lessons are taken into account from the early stages of design, with due considerations for the specificities of the concept (e.g., by enhancing passive capabilities).

3. Safety ways of improvement for GEN IV SFR

The improvement paths for the SFR mainly concern the characteristics of the prevention and mitigation measures for incidents and accidents, as well as the robustness of the methods of analysis, by reinforcing as far as possible the control of uncertainties in order to demonstrate the achievement of objectives. For this purpose, particular emphasis is given in the design approach to characteristics with a favorable potential in terms of safety.

Reliability of core melt prevention

The core melt prevention must be carried out by provisions globally presenting a very high level of reliability with respect to each initiating event likely to lead to core melt. To this end, the architecture of systems for controlling reactivity and for removing residual power includes provisions with a high level of independence, redundancy and diversification among themselves in order to be globally not vulnerable to common mode failures. In addition, a favorable natural behavior of the reactor in the event of failure of the reactivity control systems is to be sought.

Core melt mitigation

Core melt mitigation is based on the analysis of physical phenomena. This mitigation is to be ensured by provisions that are as independent as possible of the scenarios resulting from the accident. The design of the reactor must be oriented so as to avoid high mechanical energy potential during the course of the accident.

Forgiving installation

The installation must be forgiving, that is to say it has low sensitivity to possible errors of the operators and to the failures of the operating systems.

Grace periods and autonomy

In the safety demonstration, it is sought to minimize the need for operator intervention. In addition, large grace periods are sought, making it possible to maximize the time available for any corrective interventions by the operator. A significant autonomy of the installation, at least of the order of several days, before external interventions, to avoid a cliff-edge effect in terms of radiological consequences, is also targeted.

Simplicity

The design of the plant and systems must be kept simple to make operation of the reactor easy for operators both in normal operation and in the event of an accident. Diagnoses are thus facilitated and the control of accidents and incidents improved. The simplicity of the installation also contributes to the clarity and exhaustiveness of the safety analyzes.

Passivity

Passive provisions in the installation are sought in order to diversify the active provisions with respect to the reactivity control and decay heat removal. These passive provisions make it possible in particular to prevent core melt in the event of total failure of the power electrical supply. The operation of these passive systems will have to be carried out by means diversified in relation to those used for the active systems. An operation initiated by evolutions of physical parameters (temperature, flow, levels...) is sought. These systems must be validated in terms of performance, reliability and periodic verification shall be envisaged.

4) Reminders of the strengths and weaknesses of SFR

The document on GenIV systems panorama produced by the IRSN [1] gives an assessment of the strengths and issues of each reactor concept and in particular the SFR.

The SFR safety demonstration benefits from some positive aspects:

- capacity to evacuate the decay heat of the core by natural convection, without needing external water supply and with air always available as heat sink;
- high margin between the temperature of sodium, in normal operation and its boiling point;
- favorable nature of the concept with regard to radiation protection;
- high thermal inertia of the primary circuit, which provides important grace periods for evacuating the decay heat;
- absence of pressurization of the primary and secondary circuits;
- simplicity of the operation and absence of neutron poisons (no xenon effect as opposed to thermal spectrum reactors);

- effective trapping by sodium of the some fission products (in particular iodine and cesium).

The definition of options shall take into account the sensitive points of the SFR identified in previous projects and which deserve special attention, namely:

- the core is not in its most reactive configuration ;
- the power density is generally high ;
- a large part of the core can have a positive reactivity effect in case of primary fluid voiding (the same happens in the event of the materials disappearing from the core structures) ;
- sodium reacts chemically with many elements, particularly with water and air, resulting in energy releases that can be significant, as well as hydrogen production in the reaction with the water. In contact with air, aerosols from a sodium fire are transformed into sodium hydroxide, then into sodium carbonate, before becoming fairly rapidly in the form of sodium bicarbonate, completely harmless ;
- the opacity and temperature of the liquid sodium makes it difficult to inspect the structures under sodium ;
- although some components may be designed to facilitate maintenance and replacements, this remains difficult on sodium circuits and components ;
- the duration of core unloading is longer than on a water reactor.

5) Development of safety objectives for a GEN IV SFR

It should be recalled that within the framework of the GenIV International Forum (GIF), an international working group has defined safety criteria for a GEN IV sodium reactor [2]. The improvements below are consistent with the proposals of these "Safety Design Criteria".

5.1.Mitigation or practical elimination of the core melt accident ?

To demonstrate that whole core melt cannot occur would be an interesting way if one could rely on its physical impossibility or a demonstration of practical elimination. This would make it possible to get rid of certain mitigation devices or even to simplify the overall design. It will be noted that this is a route that is tempted by some SFR designers. However, in the current state of knowledge, it seems difficult to present a reactor project without consideration of fourth level of defense in depth. At the present stage, the design objective is to maintain a high level of core melt prevention complemented by a mitigation capacity of the core melt accident.

5.2.Reactivity control

The proposed design rules for reactivity control systems provide complementary improvements over previous SFR. It is recommended to install two shutdown systems each one designed according to the single failure criterion with a high level of diversification, where the action of each system, minus the most efficient control rod, is sufficient to shut down the reactor and to keep it subcritical at sufficiently low temperature levels to exclude any significant thermal damage to the reactor structures. In the postulated situations of complete failure of both shutdown systems, the objective is to prevent core melt by developing the favorable natural behavior of the core. In addition to the natural behavior, passive anti-reactivity insertion devices are envisaged. These devices are inserted into the core in case of variations in physical parameters characteristic of the cooling of the core such as flow rate reduction or temperature increase.

5.3.Decay heat removal

The total loss of the decay heat removal function is a situation that must be practically eliminated. The primary natural convection of the primary circuit and decay heat removal systems is a strong characteristic of the liquid metal reactors that shall be developed. A set of redundant, diversified systems, including diversified localization, and combining active and passive systems, shall be implemented in order to make negligible the risk of common mode failure. Thermal transfer from the main vessel is an interesting solution, but options using radiative heat transfers have limitations. Nevertheless the decay heat decreasing with time, these options can ensure the decay heat removal function a certain time after the reactor shutdown. It is also important to maintain a sufficient primary sodium inventory to ensure decay heat is removal under all circumstances, particularly in the event of vessels' leakage. In case of a core melt accident, sufficient cooling means must be maintained to ensure post-accidental cooling of corium over the long term.

5.4.Confinement

One of the challenges in the case of a core melt accident is to control the risk of mechanical energy release that could damage the provisions ensuring the radiological confinement. The primary circuit shall be reinforced as long as it is reasonably feasible. Verification of containment behavior should have low sensitivity to assumptions about the course of the core melt accident and the corresponding energy release values. In addition, the design of confinement shall delay and limit potential radiological releases to the environment. A specific analysis of the systems able to by-pass the confinement barriers shall be carried out in order to implement adequate provisions.

5.5.Control of sodium fires

Leaks and sodium fires must not compromise the safety of the plant. In addition to preventing, detecting and managing leaks, the consequences of leaks and sodium fires shall not compromise the safety functions, in particular the confinement. In this regard, the design shall aim at separating the radiological risks and risks associated with sodium. The risk of toxic chemical releases of sodium-derived products to the environment shall be made acceptable by design. The techniques developed in the past for the control of "mixed" fires (fragmented jet combined with a pool fire) have to be re-assessed with regard to the risks of toxic chemical releases.

5.6.Control of Sodium Water Reactions

Experience feedback from the steam generators operation shows that:

- prevention of the risks of sodium / water reactions is already well ensured by design provisions and quality of manufacture ;
- sensitive and reliable detection means (e.g., hydrogen measurements) are available ;
- there are proven means for limiting the consequences of sodium / water reactions (e.g., isolation / decompression of the water / steam circuit and rapid draining of the secondary circuit, evacuation of the hydrogen formed).

The stakes for the future SFR are the consideration of enveloped accidents in terms of rupture kinetics and number of ruptured tubes. Progress is also needed in terms of the reliability of the means of detection and protection, in particular rapid isolation and decompression devices. Some accidents or hazards, such as aircraft crash, can bring water / air / sodium reaction. The provisions for the limitation of these consequences (e.g., hydrogen risk) shall be implemented.

An alternative solution would be the use of an inert gas instead of the water / steam cycle. The aspects related to the presence of large quantities of pressurized inert gas would then have to be assessed. In addition, the risks of sodium-water and sodium-water-air reaction must be managed in all areas of the plant where these fluids are likely to be present (considering where appropriate the water of the concrete, water from the washing processes of sodium equipment, etc.).

In general, the risk of chemical reaction between sodium and other reagents likely to be used must be assessed.

5.7.External hazards

The most plausible external (and internal) hazards are to be taken into account in the reference design domain in order to determine, on the basis of a conservative approach, the provisions making it possible to limit their effects. To determine the levels of hazard to be retained, a benchmark frequency value of 10^{-4} per / year in terms of annual frequency is targeted. The level of the hazard considered must include margins adapted to the available data to define the level of hazard to be retained. This depends on the site being considered.

External hazards of natural origin which are more severe than those of the reference design domain are to be studied in order to evaluate the behavior of the installation and, if necessary, to reinforce, on the basis of an adapted approach, the capacity of the installation to deal with it.

External hazards are likely to affect several levels of defense in depth. Consequently, sufficient provisions shall be robust to the hazards considered (reference and extended). Depending on the hazard, geographical separation can be valorized (aircraft crash).

The general objective with regard to reference hazards is to prevent core melt accidents. Concerning the design extension domain, the objective is to verify the absence of cliff-edge effect on the radiological consequences in the environment.

5.8.In service inspection

The objective is to design the reactor (choice of materials, limitation of operating stresses...) so that the safety does not depend on the need for periodic inspection of the structures. Nevertheless, the design of the reactor should aim at making it possible to inspect the structures, in particular those under sodium, in order to carry out an inspection if required. In addition, the possibility of repair or replacement of equipment, including those into sodium shall be considered.

5.9.Human factor

Although many passive or automatic systems are foreseen, the possibility of operator actions in the control room or at the local level, as well as local repair, remains an important aspect of safety, that shall be paid particular attention. The high inertia of primary sodium and the use of passive systems contribute to the achievement of significant allowable durations for operator actions.

5.10. Dosimetry and releases

The characteristics of the SFR make it possible to target lower dosimetry levels for personnel reactor staff. [3].

Design shall aim to limit effluent and waste inventories during operation and during decommissioning.

6) Conclusion

From a general point of view, the safety objectives for the GEN IV sodium-cooled fast neutron reactors (SFR) considered in this paper are similar to those of the most recent French GEN III reactor projects, with :

- taking into account of the defense in depth principle with regard to the prevention of core melt accident, and to the consideration of external natural hazards more severe than those of the reference design domain;.
- mitigation of the core melt accident, with the objective of very limited releases such that no off-site measures are necessary. If measures are nevertheless necessary (e.g., restrictions on consumption on a crop), they shall be limited in time and space with sufficient time for their implementation. Even temporary evacuation of populations should not be necessary and only sheltering, limited in time and space, shall be envisaged.

It is proposed to ensure that these objectives are met:

- on the one hand, by controlling the sensitive points of the SFR such as the neutron reactivity of the core, the chemical reactivity of the sodium, the in-service inspection of structures under sodium ;
- on the other hand, by relying on the favorable characteristics of the SFR, the natural behavior of the plant and the passive capabilities, the grace periods and autonomy durations, the diversification of the safety systems...

This makes it possible to reinforce the safety design and the robustness of the safety demonstration.

Acknowledgements

This position paper has been discussed during 2016 by the French Advisory Group on Safety. This group is a group of safety experts from CEA, EDF and AREVA, in charge to give safety propositions for the reactors of the future. So the authors of this paper wish to thank all previous and present members of this expert group, for all the fruitful discussions that lead to this common view paper.

References

1) IRSN report n°2014-00002 “Gen IV systems panorama”
2) “Safety Design Criteria for Generation IV Sodium Cooled Fast Reactor System”, prepared by the “Safety Design Criteria Task Force” of GIF
3) J. GUIDEZ, A. SATURNIN “Evolution of the collective radiation doses during nuclear reactors operation, from 2nd to 4th generation” Proceedings of FR17 conference - June 2017 – Iekaterinbourg
4) Report « Safety of new NPP designs », WENRA/RHWG (Mars 2013)
5) « Guidance document –Issue T : Natural Hazards », WENRA/RHWG (21 april 2015)