Safety for the future Sodium cooled Fast Reactors

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Introduction

The content is structured in two parts:

1. Safety objectives and principles for future Sodium cooled Fast Reactors (SFR).
   – Prepared by the French Advisory Group on Safety *(GCFS : safety experts from CEA, EDF and AREVA)* to allow the selection of the safety options.

2. Strategy and the roadmap in support to the realization of the SFR
   – Given the analysis by GCFS and the integration of the experience feedback, a R&D program led jointly by CEA, EDF and AREVA is on-going.

The feedback gained through the design, operation and safety analysis of the Phénix and Creys-Malville (SPX1) plants and other SFR projects and their consideration by the French and European Safety authorities have been used in support to the work.

A. Safety objectives and principles for future reactors

- Safety goals for EPR^{TM} are already considered very ambitious and their attainment ensures a high level of protection.
- A further prescriptive reduction of risk is not justified and may even be counterproductive.

⇒ **The endorsement of these goals is proposed for future SFR.**

- The safety level for EPR^{TM} is achieved through, inter alia:
  - the treatment of severe accidents, both in terms of prevention and consequences control and mitigation,
  - the practical elimination of some situations whose consequences will not be considered by the design.
- **The approach advocated for future SFR emphasizes the need for a robust demonstration of safety.**
- The proposed design approach is essentially deterministic, based on the defence in depth principle and will benefit from insights provided by probabilistic studies.

A. Events considered in the safety demonstration

- The demonstration of the adequacy of the design with the safety objectives is made through the consideration of two comprehensive lists of events:
  - "Dealt with" events correspond to sequences associated with initiating events, the consequences of which are considered for the design of the plant.
  - "Practically eliminated" situations correspond to situations whose control of potential consequences is not reasonably practicable. For these situations the designer must implement a set of measures and perform analyses to show that there is no credible mechanism that can cause the failure. The corresponding risk will be demonstrated allowable.

A. Approach with regard to severe accidents for SFR

- The analysis of the consequences of such accidents will strongly affect the design options for future SFR.

- Two strategies are possible to consider such situations.
  - to practically eliminate scenarios leading to whole core melting;
  - to consider significant degraded state to define the measures necessary to control and mitigate their consequences.

- The currently engaged R&D actions will allow selecting the most suitable strategy.

A. Safety demonstration for the SFR

- The improvement of the safety demonstration of the SFR will be based on:
  - Taking into account feedback experience from previous SFR and progress made on other types of reactors, including the EPR™.
  - Preventing the occurrence of situations of whole core melting.
  - The conventional consideration of accidents with severe deterioration of the core.

A. Preventing situations with whole core melting

- **Probabilistic quantitative objectives**
  - As for the EPR™ : frequency of core melting less than 10^{-5} per reactor year (all events),
  - 10^{-6} per reactor year for the whole core melting initiated by internal events is suggested (EFR objective).
  - 10^{-6} per reactor year related to radiological releases requiring the implementation of emergency plans.

- **Implementation of the provisions involved in the accident prevention**
  - The method of lines of defence can be used. Alternative methods, such as the OPT / LOP are also possible.
  - Beyond the measures needed to achieve the probabilistic objective: use also of the ALARP approach
  - Verification of the effectiveness of the provisions will be made by analyzing TOP, LOF and LOHS.
  - These families will be supplemented by those associated with local degradation with the potential to propagate.

  ⇒ Requirements in terms of kinetics and magnitude of the maximum transient phenomena.

A. Preventing situations with whole core melting (cont.)

- **Areas of improvement**
  - Opportunities to improve prevention will be examined:
    - as regards the considered conditions (to look for exhaustiveness),
    - the management of uncertainties,
    - the verification of the existence of sufficient margins with regard to threshold effects,
    - the minimization of common modes.
  - The design should be based on generic solutions (i.e. linked as little as possible to specific scenarios) and forgiving solutions offering grace periods for possible corrective actions.

A. Mastering the consequences of situations with whole core melting

- **Provisions to control the consequences of the occurrence of whole core melting**
  - Way of significant progress is a better management and mitigation of the consequences of some situations of whole core melting and a more robust demonstration of this control.
    - The innovation in this area starts with the optimization of some physical characteristics of the SFR cores.
    - Sequences that can lead to core deterioration must be identified, as comprehensively as feasible.
    - Provisions required for these situations will not only be sized to withstand the loads they induce, but their behaviour will be verified fort more severe loads, searching for potential threshold effects.
- **Major events which can lead to releases of mechanical energy**
  - The main events that can lead to mechanical energy releases are essentially the result of situations that can abruptly insert reactivity (as sodium voiding, movement of molten fuel, movements of molten steel structures, possible compaction), or from interaction between sodium and molten fuel.
  - The importance of these situations depends on their kinetics and extent,
  - To control their effects, the design should favour their non coherency (temporal and spatial) so that these effects do not occur simultaneously and in a large part of the core.

A. Situations “practically eliminated”

- When the risk associated with a situation is unacceptable, provisions should be taken to make it acceptable.
- This will be achieved by the introduction of provisions to prevent.
- If it is not reasonably possible to reduce the consequences to an acceptable level, specific provisions of prevention will allow to “practically eliminate” the situation making the corresponding risk acceptable.
- The requirements for these provisions will be determined on a case by case basis.

B. Strategy and roadmap in support to the R&D

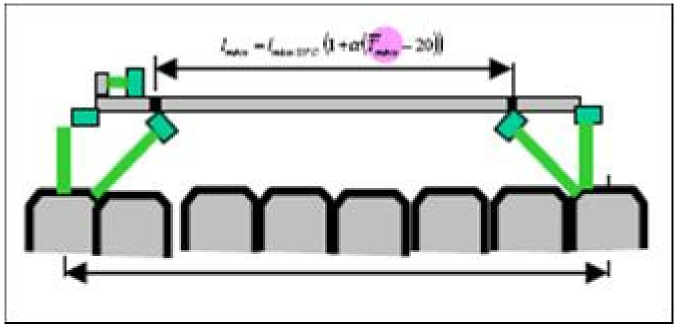
- From the recommendations of GCFS
- From the experience feedback of Phénix, Creys-Malville plant, and projects RNR-1500 and EFR

⇒ *a R&D program led jointly by CEA, EDF and AREVA is on-going.*

The following slides does not present exhaustively the content of the R&D program ; additional information are available in the paper.

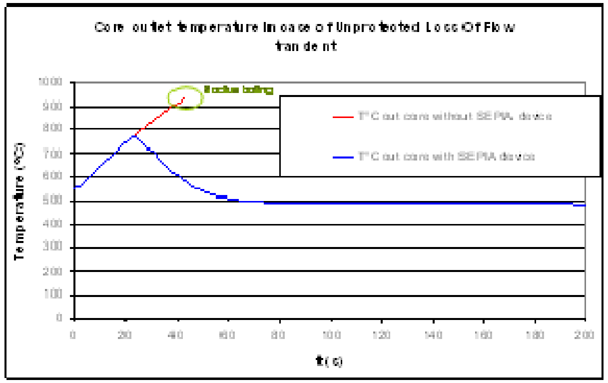
B. R&D program on reactivity control

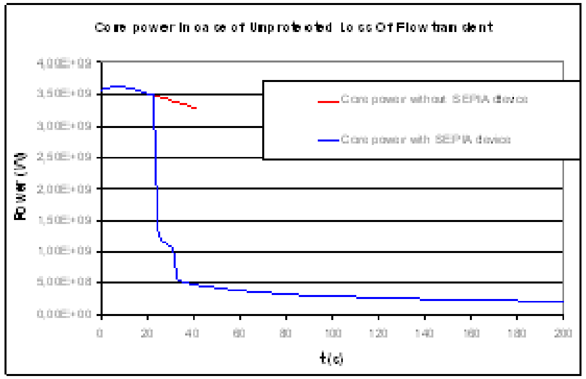
- Architecture of automatic shutdown system based on a minima two redundant and diversified shutdown systems.
- 1er axis: improvements from SPX1 and EFR architectures via:
  - the use of probabilistic safety assessment on these architectures in order to reduce the common modes of failure,
  - a strong effort on the core surveillance, by for examples improving *in-core neutronic* monitoring, detection of local core damage, *core geometry monitoring*, or sodium boiling acoustic detection,



B. R&D program on reactivity control (cont.)

- Improvements from SPX1 and EFR architectures via:
  - the definition of specifications for additional diverse systems (e.g. passive) for introducing *negative reactivity* to supplement the automatic shutdown system.



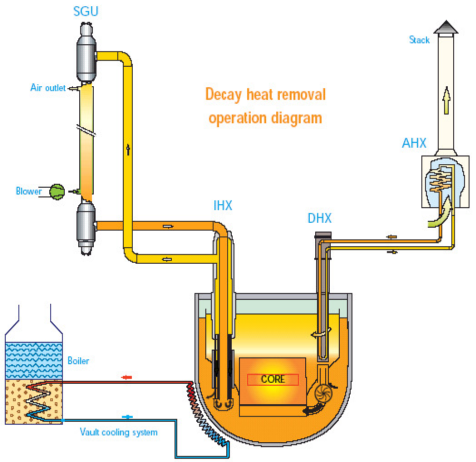


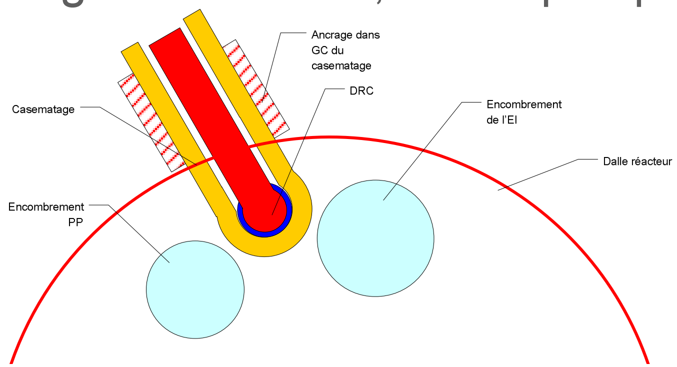
- **2nd axis: Development of innovative oxide core** for which it could be proved that the overall effect counter-reaction coefficient is negative for any situation (e.g., loss of flow, loss of heat sink, reactivity insertion, etc.)
  - A first core, called SFRv2B, presents more favourable characteristics than those from earlier SFR and is less sensitive too in case of an inadvertent control rod withdrawal.

+ Paper 07-02 “Comparative review on different fuels for Gen IV Sodium Fast Reactors: merits and drawbacks”

B. R&D program on Decay heat removal

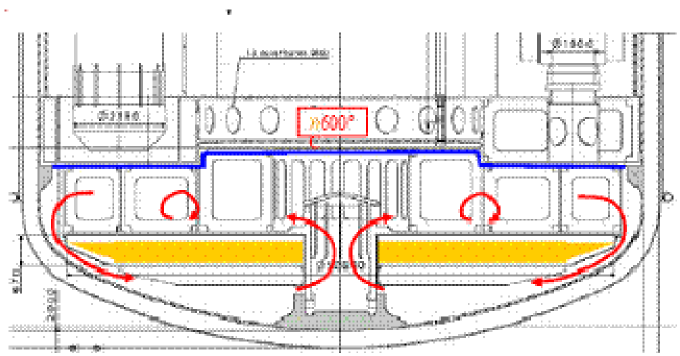
- R&D program is organized in order to reach the objective to practically eliminate the total loss of DHR systems.
  - Risk-informed demonstration, with the objective to verify that the long term loss of the DHR function has an impact below 10^{-7} per reactor and per year, including the uncertainties.
  - Improvement of the diversification and the redundancy, including the design of systems implemented on the steam generator or on the secondary circuit, and the improvement of the DHR capability through the reactor structures.
  - Minimisation of the sensitivity of the DHR systems to *potential common modes* (aggression, sodium fire or human error)
  - Enhancement of the natural convection capability.
  - Adaptation of the PSA methodology to the fact that the DHR function in a SFR is a long term mission, with repair possibilities.





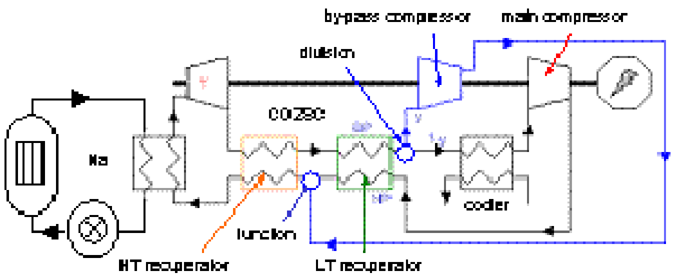
B. R&D program for the situations with core melting

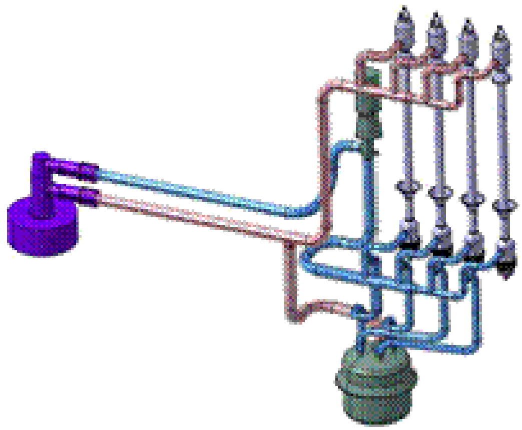
- Prevention of core damage → actions for improving the reliability of the detection for accident sequences, including the early detection of local core damage and the control rod withdrawal to avoid any risk for propagation.
- Mitigation of core damage
  - Innovative core by including, among the requirements, the objective to avoid all large mechanical energy release in case of a core melting accident,
  - Potential paths for the corium to a core catcher.
  - Core catcher, two options are under analysis : one *internal*, inside the primary vessel, and a second external, within the reactor pit, taking into account the problem of the *long term post accident DHR*



B. R&D program concerning sodium-water reaction

- Several options have been studied:
  - the minimisation of such risk by improving the steam generator design (designs studied include *modular SG*, double wall SG…),
  - the use of a energy conversion system that eliminates such risk, as for instance using a *gas energy conversion system*,
  - in case of a loop-type architecture, the replacement of a secondary circuit by a combined component heat exchanger + steam generator, coupled by a fluid non reactive with sodium and water.
  - Program on the hydrogen detection, partly through a cooperation between CEA and IGCAR, and the improvement of the reliability of the mitigation actions.





B. R&D program on other topics

- Confinement :
  - Design of provisions that could permit to avoid a large and early release, the minimisation of chemical risks, especially the releases of sodium byproducts and the optimisation of the confinement robustness in case of hazard (airplane, …) or in case of a severe accident.
  - These orientations have been applied on the different barriers: the selection of a promising material for the clad (ODS), the minimisation of bypass risk for the last barrier.
- ISI&R: *(see Paper 02-05 Challenges and R&D program for improving inspection of sodium cooled fast reactors and systems)*
  - Larger capabilities for inspection and repair with an acceptable impact on the availability rate are expected.
  - Progresses for the inspection of internal structures of the primary circuit are necessary, as such inspections are involved in some lines of protection.
- Minor actinides:
  - each task of the R&D program will be lead taking into account the presence or not of minor actinides in the reactor.

Conclusions

- This paper proposes firstly the safety principles and objectives for orientations of the R&D program of SFR, including its prototype. It incorporates the principles and objectives of the Technical Guidelines defined by licensing authority for the EPR^{TM} in France, which guarantee a high level of safety.
- The R&D program which implements these principles and objectives has been shortly reviewed, and is based on:
  1. the account of the specificities related to sodium-cooled fast reactors (taking account the feedback experience and specific risks)
  2. the possibility of designing innovative cores with safety characteristics more favourable than those of earlier cores
  3. the possibility of preventing the occurrence of situations of core degradation: the design should make it very unlikely
  4. the identification and the practical elimination, through the implementation of effective provisions, of situations whose consequences would be unacceptable
  5. the mitigation of consequences of situations with core degradation, together with the implementation of a robust containment
  6. the mitigation of specific risks related to the sodium technology taking into account the specificities dues to the use of this coolant: fires, sodium aerosols in the environment, sodium - water reactions, sodium hydroxide corrosion, hydrogen production, etc.