Radiological objectives and severe accident mitigation strategy for the generation II PWRs in France in the framework of PLE

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Abstract: In France, EDF is involved in the construction of a first generation III (Gen III) reactor (European Pressurized Reactor - EPR) on Flamanville site next to two PWRs. Plant Life Extension (PLE) of reactors will consequently lead to simultaneous operation of Gen III and Gen II reactors during a long period of time. As a consequence, EDF was requested by the French Nuclear Safety Authority to prepare a PWR life management program including, in addition to an ageing management of Systems, Structures and Components, a consequent reactor safety enhancement program. The objective was stated to EDF by the French Nuclear Safety Authority: “the safety objectives of the Gen III reactors should be used as a reference for all studies undertaken in the frame of PLE”. One part of the EDF program deals with additional arrangements able to reduce more drastically the consequences of any accident. The relevance, according to IRSN, of the EDF radiological objectives for Design Basis Accidents, of the new EDF objectives for Severe Accidents (SA) and of the EDF potential modifications for SA mitigation are presented.

1. Introduction

The French electrical utility Électricité de France (EDF) is operating a fleet of 58 standarized pressurized water reactors (PWRs) (3 series of 900, 1300 and 1450 MWe) built in a rather short period of time (1977-1999). Periodic Safety Reviews (PSRs) are conducted every 10 years.

In 2009, EDF presented a Plant Life Extension (PLE) strategy from 40 to 60 years. The French regulatory framework does not grant a fixed period of operation for nuclear installations and the decision for extended operation of reactors will be taken on a case by case basis.

In France, EDF is also involved in the construction of a first generation III (Gen III) reactor (European Pressurized Reactor - EPR) next to two Gen II PWRs on Flamanville site. PLE of reactors will consequently lead to simultaneous operation of Gen III and Gen II PWRs during a long period of time. The design requirements regarding the amplitude of any release in case of accident are highly more ambitious for the EPR. Consequently, to accept Gen II reactors PLE technically as well as societally, a consequent safety enhancement program is needed. This objective was stated to EDF by the French Nuclear Safety Authority: “the safety objectives of the Gen III reactors should be used as a reference for all studies undertaken in the frame of PLE”. This statement is consistent with the Western European Nuclear Regulators’ Association position on safety objectives for new nuclear power plants. As a consequence, in addition to an ageing management of Systems, Structures and Components (SSCs), the EDF PWR life management program includes a reactor safety enhancement part.

IRSN has analyzed this program and presented its conclusions to the French Advisory Committee for Nuclear Reactor Safety in January 2012.

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1 PSR is carried out for the whole series considered. Associated studies must be completed early enough so that the modifications to equipment and documents can be deployed on reactors from the start of their ten-yearly outage (for the 900 MWe PWRs (34 reactors): 4th PSR [2013-2018] and ten-yearly outage [2019-2029]; for the 1300 MWe PWRs (20 reactors): 4th PSR [2020-2024] and ten-yearly outage [2025-2031])

2 The safety objectives address new civil nuclear power plant projects. However, these objectives should be used as a reference for identifying reasonably practicable safety improvements for “deferred plants” and existing plants during periodic safety reviews” (WENRA [1], November 2010)
One part of the EDF program deals with additional arrangements able to reduce more drastically the consequences of any accident. According to IRSN, this part of the program should be based on equipment or on management procedures modifications so as to reduce as low as reasonably achievable the radioactive release for Design Basis Accidents (DBA) and Severe Accidents (SA) even if all French operating plants include already SA management equipment (Passive Autocatalytic Hydrogen Recombiners (PARs), Emergency Filtered Containment Venting System (EFCVS), SA instrumentation…) as a result of previous SA management reviews (PSRs, …).

In this paper, the IRSN conclusions for the relevance of the radiological objectives for DBA, for the new SA safety objectives of the EDF program as well as for the EDF program related to potential modifications for SA mitigation are presented. Moreover, some relevant information as a consequence of the Fukushima Daiichi event and coming from the French stress tests are listed.

2. French radiological objectives for DBA and safety objectives for SA in the framework of PLE

2.1 Design basis accidents

The EDF objective for DBA in the framework of PLE is “to avoid any necessity of protective measures for people living in the vicinity of the damaged plant”. EDF underlines that this objective meets the one for the new reactors: “no need of protective measures for people living in the vicinity of the damaged plant”.

To reach such an objective, EDF proposes to implement new equipment and management procedures and refers to the “implementation levels” for protective measures (sheltering, evacuation and non-radioactive iodine intake) in case of a nuclear emergency defined in the French order dated November 20, 2009.

According to its analysis, IRSN has deemed satisfactory:

- firstly, the EDF approach to use qualitative radiological objectives for DBA for the “short term” period of time,
- secondly, the chosen objective, i.e. “no necessity of protective measures for people living in the vicinity of the damaged plant”.

The EDF objective deals with the so-called “short term” period of time (from some hours to some days after the accident) for which three exposure pathways are considered: exposure due to the plume, inhalation and exposure due to the deposits. IRSN has asked EDF to define a qualitative radiological objective for the so-called “long term” period of time based on the methodology called “4 exposition pathways – 50 years” for which, in addition to the short term exposition pathways, the ingestion is also taken into account. EDF will define such qualitative radiological objective for the “long term” period of time within one year.

Regarding the fact that EDF refers to the French order dated November 20, 2009, IRSN has pointed out that this order deals only with “implementation levels” for protective measures (sheltering, evacuation and non-radioactive iodine intake) in case of a nuclear emergency and is not intended to define any quantitative radiological objectives for the safety demonstration. Moreover, IRSN has reminded that, in a general manner, any existing levels used as radiological objectives can never be considered as criteria to assess the acceptability of the consequences of any accidents. IRSN considers that the assessment of radiological consequences of any accidents has to be integrated in a “continuous enhancing of the safety” process linked to the mitigation of the accidental exposure due to radioactive

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3 According to the French order dated November 20, 2009, the “implementation levels” for population protective measures in case of radiological emergency are:
- an effective dose of 10 mSv for sheltering
- an effective dose of 50 mSv for evacuation
- a thyroid equivalent dose of 50 mSv for non-radioactive iodine intake
release for the persons of the public, the workers and the environment. It means that, at each PSR, all measures have to be taken to reduce “as low as reasonably achievable” the radioactive release and their impact on the population and on the environment. This approach has to be applied, in a first priority, for the DBA leading to the relative higher radioactive release, even if previous radiological objectives were met.

Consequently, IRSN deems that the EDF qualitative radiological objective “to avoid any necessity of protective measures for people living in the vicinity of the damaged plant” can be quantified, during future PSR, by doses lower than the ones defined in the French order dated November 20, 2009.

2.2 Severe accidents

Regarding SA, i.e. accidents leading to core melt, EDF intends “to check”, by means of probabilistic safety assessment (PSA), the low occurrence of such accidents taking into account any equipment or management procedures modifications already implemented or foreseen in the frame of PLE.

Beside of these PSA studies, EDF will pursue improving the reactor containment function and decreasing the frequency of accidents leading to large early release. EDF points out that the feasibility and the relevance of equipment or management procedures modifications to decrease as low as reasonably achievable the risks of radioactive release “under acceptable economical conditions” will be studied taking into account their probability of occurrence.

IRSN has deemed relevant the EDF intent to decrease the frequency of accidents leading to large early release. Nevertheless, IRSN has reminded that, at each PSR and in particular in the framework of PLE when using the safety objectives of the Gen III reactors as a reference (“only very limited protective measures in area and in time for the public”), all measures have to be taken to reduce “as low as reasonably achievable” the SA occurrence frequency and the radiological consequences.

When looking at the SA prevention and mitigation enhancement by means of equipment or management procedures modifications as contained presently in the EDF program in the framework of PLE, IRSN has recognized the real safety enhancement that should be gained by the EDF proposals.

3. Severe accident mitigation strategy in the framework of PLE

The EDF SA Management Guide (SAMG) and the mitigation of large early release accidents have already undergone previous SA management reviews (PSRs, …) [2] resulting in several new equipments implementation (EFCVS, PARs implemented on all French reactors, SA instrumentation, containment strengthening,...).

Regarding the safety enhancement for SA in the framework of PLE, EDF intends to simultaneously examine solutions able to:

— improve the efficiency of the present EFCVS,
— improve the possibility to remove the containment decay heat without opening the EFCVS,
— avoid reactor concrete basemat melt-through by the molten core (corium) after Reactor Pressure Vessel (RPV) failure.

According to its analysis, IRSN has deemed quite satisfactory the EDF safety enhancement program for SA in the framework of PLE.

3.1 Improve the efficiency of the present emergency filtered containment venting system

Following the TMI-2 accident, EDF decided to install an EFCVS based on a sand bed filter concept in order to ensure a voluntary filtered containment venting during a SA, if necessary. All French EDF PWRs presently in operation are consequently fitted out with sand bed filters with prefiltration (metallic filter) in the containment building at the entrance of the system (FIG. 1) [3].
FIG. 1 Sketch of French sand bed filter
1 = metallic prefilter in the containment building at the entrance of the system
2 = manual containment isolation valves operated by reach rods from behind shielding;
3 = pressure letdown orifice;
4 = filtered dry air supply during normal operation; pre-heating in case of severe accident;
5 = sand bed filter; 6 = released activity measurement device; 7 = stack

For almost all plants the sand bed filter is installed on the roof of the nuclear auxiliary building. There is a sand bed filter for each plant of the 1300 and 1450 MWe series. The 900 MWe plants are fitted out with a common sand bed filter for two twin units.

Experiments performed from 1982 to 1990, including a full scale experimental programme (FUCHIA [3]) performed in Commissariat à l’Energie Atomique (CEA, France), have validated the design. The minimal decontamination factors of the system are presented on Table 1.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Sand bed filter (alone)</th>
<th>EDF EFCVS Prefiltration + Sand bed filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular iodine (I₂)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Organic iodine (ICH₃)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Aerosols (Cs, RuO₂)</td>
<td>100</td>
<td>1000</td>
</tr>
</tbody>
</table>

It is well known that during a SA, noble gas and iodine release into the environment represent a major part of the radioactive doses for the short term. In the framework of PLE, one of the EDF line of work, in addition to decrease as low as possible the opening frequency of the EFCVS (see paragraph 3.2), is to study:

- the advantages and efficiency to “separate” the noble gas by the opening of the EFCVS:
  - gaseous diffusion could be ensured through several steps of barriers made of porous ceramic allowing particular species to be separated from the main gas flow and finally stocked into tanks. A feasibility study is presently on-going.
the advantages and the feasibility of new systems ensuring a better fission products filtration (in particular for iodine) during the containment venting, as compared to the present EFCVS.

EDF plans to achieve such studies by the end of 2012.

IRSN has deemed satisfactory the EDF working plan. As a matter of fact, regarding the efficiency of the current French EFCVS, IRSN has noticed that, according to the vendors of different scrubber filter devices, further reduction of fission products release (mainly molecular and organic iodine but also other fission products) in case of SA may be nowadays achievable.

IRSN also pointed out that an EFCVS key point is their autonomy: as an example, the filtration efficiency of a scrubber filter device may decrease when the scrubbing water temperature increases (the autonomy duration of such filters is typically 24 h and after this time cold water supply is probably needed).

Moreover, IRSN asked EDF to study the hydrogen risk not only into the EFCVS but also at its exit, in particular in the case of station blackout.

### 3.2 Improve the possibility to remove the decay heat from the containment without opening the emergency filtered containment venting system

In order to improve the possibility to remove the decay heat from the containment without opening the EFCVS during SA, EDF intends both to increase the possibility to maintain the corium in the vessel and to cool the containment atmosphere using the containment spray system.

EDF states that maintaining the corium in the vessel avoids the ex-vessel corium-concrete interaction phase and thus contributes to the goal of maintaining the integrity of the containment. Stabilisation of the situation in the vessel entails restoring a means of injecting borated water into the reactor coolant system (RCS) (using either direct injection or water recirculation) within a sufficiently short period of time to avoid RPV failure, in other words before core damage is too far advanced to enable it to be cooled in the RPV.

Increasing the possibility to cool the containment atmosphere using the containment spray system is proposed by additional means of injecting cold water into the system.

In both strategies, water injection is proposed to be fulfilled by a dedicated pump for each plant, qualified under SA conditions, available even in case of a long-duration total loss of electrical power supply thanks to an “ultimate backup diesel generator”. EDF proposes to use dedicated extra-lineage possibility to cool the water using one heat exchanger of the containment spray system.

EDF also intends to look at what is done in the other countries for the decay heat removal from the containment without opening the EFCVS.

This strategy was not challenged by IRSN and, due to the strong link with the French stress tests will be analyzed in the framework of the following work linked to these stress tests.

### 3.3 Examine appropriate solutions able to avoid reactor concrete basemat melt-through by the molten core after RPV failure

Regarding appropriate solutions able to avoid reactor concrete basemat melt-through by the molten core after RPV failure, the EDF program includes work simultaneously on 3 solutions:

- flooding of the reactor pit prior RPV failure,
- injecting water on the top of the corium,
- injecting water into the corium from below.
3.3.1 Flooding of the reactor pit prior RPV failure

For French Gen II reactors, flooding of the reactor pit prior RPV failure is linked to operation of the containment spray system before entering a SA. The reactor pit can be actually flooded up to the RCS loops level within some hours of spray system functioning to reduce, according to EDF, the probability of vessel lower head failure.

During previous PSRs, IRSN has pointed out the fact that an energetic steam explosion in the flooded reactor cavity could threaten the inner structures of the reactor building and the containment tightness. Nevertheless, according to EDF, if the reactor pit is flooded only up to the level of RPV bottom head, this can significantly reduce the risk of energetic fuel coolant interactions. This can also reduce the risk of the basemat melt-through, as the retention of a part of the cooled corium in RPV and corium contact with the water in the reactor pit reduces the quantity of corium that will contribute to the corium-concrete interaction.

IRSN analysis of this EDF strategy is on going in the frame of the 3\textsuperscript{rd} PSR of the 1300 MWe series.

3.3.2 Injecting water on the top of the corium

Injecting water on the top of the corium subsequent to RPV failure could be performed using RCS make-up through the vessel breach or using a dedicated system.

EDF states that this strategy should be able to slow down or even prevent basemat melt-through. According to EDF, the conclusions of the dedicated OECD MCCI program [5] provide a tendency towards a good efficiency of this ex-vessel reflooding strategy. A complementary corium-concrete interaction test\textsuperscript{4} (test CCI-7) is planned in June 2012 to confirm the possible stabilisation of a corium pool by means of flooding from above.

IRSN has deemed that the tests performed in the frame of the MCCI program up to day were not conclusive as regards to get confidence to a complete corium cooling by injecting water on its surface (only 3 out of 8 tests exhibit cooling of the corium pool). Nevertheless, IRSN has also noticed that injecting water on the top of the corium was beneficial for corium cooling if the corium concrete interaction was releasing a lot of gas, which was the case when the concrete was a limestone common sand one. The future test (CCI-7) should clarify the efficiency of injecting water on the top of the corium also for plants with a low gas content siliceous concrete basemat. The test specifications have been discussed in details in order to drive conclusions from the experimental results.

As a conclusion, after some complementary assessment accepted by EDF (such as describing the mechanical behavior of the corium crust when water is covering the corium), IRSN has deemed satisfactory the EDF program.

3.3.3 Injecting water into the corium from below

One existing design using the water injection from below to stop and cool a corium interacting with the concrete and qualified by means of an extensive experimental program with simulant and real material is the so-called “Comet” concept developed by KIT (former FZK), Karlsruhe, Germany [6].

The advantages of this concept are the fast cool-down and complete solidification of the melt within 1 h typically. A drawback may be the fast release of steam during the quenching process which results in a steam pressurisation of the containment, although condensation would subsequently reduce the steam pressure. Three variants of the Comet design exist for the basic processes of passive flooding and cooling, which have been evaluated by experiments. As an example, only the CometPC (Porous Concrete) design is shown in FIG. 2.

\textsuperscript{4}This test is funded by EDF, IRSN, US-NRC and operated by Argone National Laboratory
FIG. 2: Sketch of CometPC bottom plate for water injection through two layers of porous concrete [6]

A layer of sacrificial concrete is covering two layers of porous concrete. An uniform horizontal distribution of the water into the upper porous concrete layer is achieved by the high porosity of the lower porous concrete layer. The low porosity of the upper porous concrete layer is adjusted to yield an appropriate coolant water flow into the melt, once the sacrificial concrete is eroded by this melt.

EDF intends to study such Comet concept (efficiency, advantages, drawback) and to look at the feasibility to implement such one into the reactor pit of a French PWR. EDF plans to achieve such studies by the end of 2012.

If, according to IRSN, experiments injecting water on the top of the corium interacting with the basemat concrete are not up to now conclusive regarding the prevention of the reactor basemat corium melt-through, IRSN has deemed that the experiments injecting water from below performed up to now exhibit this process to be very efficient to cool the corium and prevent the reactor basemat corium melt-through, even if it is not the unique possible backfit solution. IRSN recognizes that efforts are needed to design such systems at reactor scale. The design must also include provisions for workers radioprotection during implementation.

After some complementary assessment accepted by EDF (such as describing the concept behavior in case of several corium pours from the RPV or in case of non homogeneous corium interaction), IRSN has deemed satisfactory the EDF work plan.

4. Examine solutions to mitigate the ground water contamination

To mitigate the ground water contamination in case of concrete basemat melt-through by the molten core, IRSN asked EDF to perform feasibility studies in order to implement, as a preventive way, vertical geotechnical barrier(s) for each PWR site. This request was confirmed by the French Advisory Committee for Nuclear Reactor Safety.

5. Relevant information coming from the French stress tests

One should be aware that the EDF program for safety enhancement in the framework of PLE was developed before the Fukushima accident. As regards to the SA mitigation strategy, some actions taken by EDF during the stress tests had been already planned in the PLE framework, such as using an “ultimate backup diesel generator” in case of a total loss of electrical power supply.

A new SA mitigation means proposed by EDF in the frame of the stress tests is to study a system allowing to keep an alkanealize pH in the water of the containment sump (presently, this is achieved on French PWRs when actuating the containment spray system).

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5 The stress tests are named « Complementary Safety Assessment » in France. In June 2012, EDF has to present the list of SA equipments and the requirements applied which shall be included in the so-called “hardened safety core” of material and organisational measures able to manage the basic safety functions in the exceptional situations of the stress tests.
The stress tests conclusions confirm the orientations defined in previous PSRs and PLE before the Fukushima accident and add new requirements, especially regarding the robustness of SA equipments against external hazards. Some complements to the initial EDF program are forwarded (instrumentation, provisions for multi accidents management,…).

6. Conclusions

In the framework of PLE, EDF was requested by the French Nuclear Safety Authority to prepare a PWR life management program including, in addition to an ageing management of SSCs, a consequent reactor safety enhancement program. The objective was stated to EDF by the French Nuclear Safety Authority: “the safety objectives of the Gen III reactors should be used as a reference for all studies undertaken in the frame of PLE”.

One part of the EDF program deals with additional arrangements able to reduce more drastically the consequences of any accident. According to IRSN, this part of the EDF program should be based on equipment or on management procedures modifications so as to reduce as low as reasonably achievable the radioactive release for DBA and SA, even if all French operating plants include already SA management equipment (PARs, EFCVS, SA instrumentation…) as a result of previous SA management reviews (PSRs, …).

The EDF objective for DBA in the framework of PLE, agreed by IRSN, is “to avoid any necessity of protective measures for people living in the vicinity of the damaged plant”. To reach such an objective, EDF proposes to implement new equipment and management procedures.

EDF will also study several solutions to reduce drastically the SA consequences by improving the efficiency of the present EFCVS and also the possibility to remove the decay heat from the containment without opening the EFCVS. Besides, EDF will study appropriate solutions able to avoid concrete basemat melt-through by the molten core after the reactor pressure vessel failure or able to mitigate ground water contamination in case of basemat melt-through by the molten core. IRSN has recognized the real safety enhancement that should be gained by this EDF work.

All these improvements are in line with continuous plant improvements defined during PSRs and will be reinforced after the post-Fukushima stress tests review.

REFERENCES


