# On some safety aspects in Small Modular Reactors

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**Abstract**

The development of new types of Nuclear Power Plants (NPP) is now in the phase of expanding nuclear programs, with a new set of design under consideration: Small Modular Reactors (SMR). SMR and the decision to build them is considered for many reasons and the decisions on a certain type, combination, fuel cycle in general would need an extensive technical and safety review in the light of the existing experience and future needs. Results and some preliminary conclusions from various projects are presented in the paper.

## Background

Nuclear Power Plants (NPP) passed so far through various stages of evolution. For the Small Modular Reactors (SMR), which are part of this complex process valuable insights might result from a triple facet (sets of criteria) perspective, which was based on considering this type of NPP as a:

1. New reactor technology phase reflected in the safety principles evolution
2. An enlarged and more broad view on the specific acceptance criteria to implement the objectives set for safety goals
3. Consideration of the new types of NPPs as an envelope of technologies governed by reactor technology and subject to each technology transformation and their synergies.

The evaluation of the facets mentioned before was performed for some hypothetical case studies of Small Modular Reactors (SMR). These cases were also subject to previous projects [1-3] and the types are defined as per [1,2]:

A. Water cooled (W)

B. Gas cooled (G)

C. Molten salt (M)

## Evaluation of smr technical features

### SMR’s safety features

The development of NPPs so far underlined a set of important safety features to be considered for new plants. A list of them and an expert type evaluation for the cases W,G and M are in Table 1 and represented in Figure 1. The evaluations performed based on previous experience in licensing NPPs is reflecting the evolution of the weight of each criterion and the overall possible impact for diverse set of new designs. There are strong features in each design and one initial notice is that their combination in a sequential fuel cycle is a better approach, rather than consider only focusing on one type.

The criteria in Table 1 are related to safety in a direct or indirect manner, by considering the impact on the whole fuel cycle (front end, operation and back end), as follows:

* Criteria defined in expert opinion approach and related to the evaluation of safety level considering:
  + Credibility of uncertainties (CRU)
  + Credibility of the level of conservatism(CRC)
  + Evaluation of the adequacy of the type of method acceptable (deterministic -best estimate or not, probabilistic, combined) used in safety evaluations, performed by based on past similar experience (DPC)
  + Impact of capability to manage change control during the design and safety evaluation phases (CHC)
* Criteria defined in expert opinion approach by comparison with existing reference levels and related to the evaluation of safety level considering:
  + Level of conservatism (LEC)
  + Safety margin acceptability (SM)
  + Defence in depth Acceptance criteria for levels and in general (DiDA)
  + Defence in depth - Independence of levels(DiDI) and Cliff Edge Effects (CEE) confirmed by specialized methods as for instance probabilistic Risk Assessment (PRA)
* Criteria defined in expert opinion approach by comparison on nuclear projects with indirect impact on the plant safety, as for instance:
  + Impact of generation / technology phase and human factors (CGEN)
  + Impact of site selection predefined criteria (CSIT)
  + Emergency Plan and mitigating actions (CEP)
* Criteria defined in expert opinion approach for the elements of the fuel cycle with impact on operational safety (type of fuel used of the existing features of reprocessing or storage or any other synergy with other fuel cycles:
  + Front end fuel cycle (FEFC)
  + Back-end fuel cycle (BEFC)

A global aggregate criterion is considering all the criteria (CR TOT) as a guidance of the ranking in first iteration cycles in the context of evaluating safety levels from the phase of developing the plant concept (research and development phase to the First of a Kind (FOAK) phase and commercial phase (as represented in Table 1), For the three phases mentioned before a set of evaluation for the W, G and M plants were performed and are illustrated in Figure 2 (W1,2,3, G1,2,3, M1,2,3).

TABLE 1. SAFETY ASPECTS OF IMPORTANCE FOR NEW NPPS OF SMR TYPE

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Criteria to evaluate results | Description | PERIOD I RESEARCH & DEVELOPMENT | | | PERIOD II FIRST OF A KIND (FOAK) | | | PERIOD III OPERATION | | |
| W | G | M | W | G | M | W | G | M |
| CRU | Credibility of uncertainties | L | M | M | M | L | L | M | L | L |
| CRC | Credibility of the level of conservatism | H | M | L | H | M | L | M | L | L |
| LEC | Level of conservatism | M | H | M | M | H | L | M | M | M |
| SM | Safety margin acceptability | M | M | M | M | H | H | M | H | H |
| DiDA | Defence in depth Acceptance criteria for levels and in general | M | M | L | M | H | M | H | H | M |
| DiDI | Defence in depth - Independence of levels | L | L | M | L | M | L | M | M | M |
| CEE | Cliff edge effects | L | L | L | L | L | L | L | L | L |
| DPC | The adequacy of the type of method acceptable - deterministic (best estimate or not), probabilistic, combined, using past similar experience | M | M | L | M | H | L | M | L | M |
| CHC | Impact of capability to manage change control | L | L | L | L | L | L | M | M | M |
| CGEN | Impact of generation / technology phase & Human factors evaluations | L | M | M | M | H | M | H | H | H |
| CSIT | Impact of site selection predefined criteria | L | M | L | L | M | L | M | L | L |
| CEP | Emergency Plan and mitigating actions | L | M | L | L | M | L | M | M | M |
| FEFC | Front end fuel cycle | L | L | M | L | L | M | M | M | H |
| BEFC | Back-end fuel cycle | L | L | L | L | L | M | M | M | H |
| CR TOT | Global aggregate criterion | L | M | L | M | H | L | M | M | M |

The evaluations in Table 1 are represented in qualitative manner and the method was based on the approach described in detail and used for existing large reactors in [4,5,6]. The qualitative representation is based on numeric allocations of marks for criteria by using a scale from 1 to 10. Level L (Low Impact) corresponds to marks from 1 to 3, level M (Medium Impact) corresponds to mark from 4 to 7 and H (High Impact) corresponds to marks from 8 to 10.

FIG. 1 SAFETY ASPECTS OF IMPORTANCE FOR NEW SMR PLANTS

### Acceptance criteria

Demonstration of the successful implementation of safety objectives is necessary so that the special aspects of safety features, identified in the NPP’s experience so far as being of high importance are in general related to demonstration of safety margins and mostly in risk evaluations. The results so far in projects focusing on the case studies showed that risk analyses for Design Basis Accidents are important even from the research phase, and that in the regulatory environments there are not simplified requirements for these types of new builds. Operating experience and various accidents identified so far both the weak points to be verified and the expected evaluation methods (Figure 2).Safety margins and the risk levels evaluated and documented previously [5;6] are represented in Figure 2 for different NPP generations. The figure also illustrates the evolution of nuclear technologies and the major accidents with subsequent changes in safety dominant features to be considered for the post-accident period. In the lower part of the figure a set of international events taking place and having impact on the nuclear industry were also mentioned. The trends in SMRs safety are illustrated by all the post-accident lessons learnt and the safety features for the new small reactors are intended to implement the lessons learnt.



FIG. 2 SAFETY MARGIN AND RISK CRITERIA FOR NPP GENERATIONS AND THE METHODS DOMINATING PERIODS SO FAR [4,5,6]

One area of concern for SMRs is related to the Emergency Planning (EP). Preliminary evaluations illustrate also that the technical basis for EP is necessary even for cases apparently not requiring high limitations on zoning, due to improved safety features of the new NPPs of SMR type. [1-3]. The licensing steps for any SMR follow the existing set of regulations and standards applied for large nuclear power plants. However, as mentioned in [2] a highly specific feature of SMR is at present the existence of First of a Kind plants (FOAK).

The main consequence of FOAK status for all the SMRs is that the fabrication and commissioning tests are dominant in obtaining confirmations, confidence and clarifications on the actual safety level by comparison with the initial evaluations. Predefined list of postulated events and severe accidents is important to identify interconnections of the new designs by using probabilistic and risk approaches. However, the deterministic evaluations, probabilistic evaluations of failures of passive systems and extensive tests and calculations are the basis for increasing the credibility of results.

### SMR and new technologies

NPP evolved as a set of technologies for various generations, of which the technology of the reactor core is the governing one. Reactor core technology is not the only one characteristic to a new NPP, as manufacturing, instrumentation and measurement, plant control in general, digital, results from fundamental research in quantum mechanics, quantum computing, man-machine interface tightly connected to the management, leadership and specifics of human generations are all technologies of high impact in choosing a new plant. One supplementary element could be to understand better the lessons from nature as embedded in cases like Oklo reactor, which indicated a series of safety features to be considered in advanced nuclear reactors, as documented in [7]. For each of those technologies their lifecycle and moral ageing are different. The technology of the core is being enhanced from generation to generation (Figure 3) and considering the lessons learnt so far is necessary for the success of SMRs necessary for the success of SMRs.

A diagram of a safety line

Description automatically generated with medium confidence

FIG. 3. LESSONS LEARNT IN SAFETY FROM ONE NPP GENERATION TO ANOTHER [ 4,5,6]

The design of new SMRs has to consider all those aspects, as they are supposed to operate at least up to the end of this century. New SMR’s are to part of Industry 4.0 phase and has to take that into consideration, as moving from robotics and digital to AI (if feasible in nuclear) is of a potential immediate challenge.

Detailed results exist already and are applicable for all the cases considered [1,2] and the main aspects of consideration were presented in Table 1.

The evaluations performed were conducted for in depth calculations for all the cases from the perspective of EP and detailed presentations of similarities and differences are included in [1]. Even if the types are very different for evaluations of EP there are similarities given by the considered source term, the scenario of major accident and the mitigating barriers.

Therefore, from EP perspective common aspects are identified like expected source term in case of severe accident, plant release barriers and site characteristics.

However, for other aspects considering the SMRs as thermodynamic machines is the most dominant feature for further detailed evaluations of the safety objectives, which are under development in the project.

## Evaluation conclusions

Evaluations of various types of SMRs show some important aspects to be considered:

1. The development and implementation most probably will take place in phases: from research to FOAK and then commercial operation.
2. As the technical challenges are highly similar, the exchange of information and a coordinated manner for developing new plants will become essential for the success, mainly in the context of high importance allocated now to the proprietary, competition and patent aspects. The dominant technical challenges from safety perspective are similar.

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