SAFETY APPROACHES

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The “practical elimination” approach of accident situations for water-cooled nuclear power reactors

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SUMMARY

The implementation of the defence in depth principle and current regulations have lead applicants to define provisions to prevent accidents, including severe accidents, and to limit their consequences should they occur.

However, while defining the design orientations for a new water-cooled power reactor, applicants shall use the “practical elimination” approach for severe accident situations (in the reactor core or the spent fuel pool) potentially leading to large early radiological releases, where it appears impossible to define realistic and demonstrable provisions to limit their consequences according to current knowledge and the techniques available at the time.

The use of this approach should be discussed between the applicant and the safety authority at the design orientations stage; the authority will specify on a case-by-case basis the conditions for its approval.

In order to “practically eliminate” a situation, the designer shall first examine the possibility for making it physically impossible. Where physical impossibility cannot be achieved, provisions shall be implemented to justify with a high degree of confidence that the situation is extremely unlikely.

Situations likely to be “practically eliminated” are diverse (massive and rapid reactivity insertion accidents, explosions, containment bypasses, etc.); the justification of “practical elimination” can only be assessed on a case-by-case basis, using deterministic considerations complemented by a probabilistic analysis. The assessment relies on the reactor physical characteristics as well as on the robustness and reliability of the lines of defence implemented to prevent the situation to be “practically eliminated”. The implemented provisions shall be subject to strong design, manufacturing and operation requirements; considerations related to human factors and hazards shall also be taken into account.

This document is an orientation text which defines IRSN approach to “practical elimination” and its place in safety demonstration.

ABSTRACT

KEYWORDS

“practical elimination”, safety demonstration, severe accident, radioactive releases

SUMMARY

REFERENCES

[1] General safety objectives for the next generation of pressurised water reactors - 1993

[2] Defence in depth in nuclear safety - INSAG-10, 1996

[3] Basic safety principles for nuclear power plants 75 - INSAG-3 Rev.1 INSAG-12, 1999

[4] Technical guidelines for the design and construction of the next generation of nuclear power plants with pressurized water reactors, adopted by the Advisory Committee for Nuclear Reactors (GPR) and German experts in 2000

[5] WENRA - RHWG safety of new NPP designs – March 2013, including the document “WENRA statement on safety objectives for new nuclear power plants” – November 2010

[6] Order of 7 February 2012 setting the general rules for basic nuclear installations

[7] IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), Safety of Nuclear Power Plants: Design – Specific Safety Requirements, 2016

1 INTRODUCTION

Following the Three Mile Island and Chernobyl accidents, the need of a significant improvement of the safety of reactors to be built from the start of the 21st century compared to the ones in operation or under construction at the end of the 20th century has been recognized at the international level. This improvement seemed to be achievable for water-cooled reactors taking into account the state of knowledge achieved on core melt accidents.

It was in this context that the fourth level of defence in depth was developed, implying the implementation of design provisions aimed at limiting the consequences of accidents with reactor core melt. However, in some core melt situations that could be envisaged at least theoretically, it appeared impossible to implement realistic provisions that would reduce the radiological consequences at an acceptable level and to demonstrate their robustness. For this reason the concept of “practical elimination” was introduced during the 1990s.

For water-cooled reactors, these situations were characterized by rapid high-energy phenomena that could drive to a sudden failure of the containment and lead to “large early releases”. An objective of elimination was set for these situations, but since the elimination was not strictly demonstrable except in case of physical impossibility, the term “practically eliminated” was coined, meaning that the applicant shall implement “all reasonable provisions” to ensure that the accident situation could, by mutual agreement with the relevant safety authority, be considered extremely unlikely with a high degree of confidence.

The term “practical elimination” appeared for the first time in 1993 in the definition of the general safety objectives for the future pressurised water reactors [1]. These objectives have been then developed in the “Technical guidelines for the design and construction of the next generation of nuclear power plants with pressurized water reactors” [4]:

“d) […] an important objective is to achieve a significant reduction of potential radioactive releases due to all conceivable accidents, including core melt accidents. […]

Accident situations with core melt which would lead to large early releases have to be "practically eliminated": if they cannot be considered as physically impossible, design provisions have to be taken to design them out. This objective applies notably to high pressure core melt sequences.

Low pressure core melt sequences have to be dealt with so that the associated maximum conceivable releases would necessitate only very limited protective measures in area and in time for the public.”

Without explicitly referring to the concept of “practical elimination”, Article 3.9 of the Order of 7 February 2012 [6] also includes this objective: “*The demonstration of nuclear safety must prove that accidents that could lead to large releases of hazardous substances or to hazardous effects off the site that develop too rapidly to allow timely deployment of the necessary population protection measures are physically impossible or, if physical impossibility cannot be demonstrated, that the measures taken on or for the installation render such accidents extremely improbable with a high level of confidence*”.

At international level, INSAG 10 [2] stated in 1996 that: “*For advanced designs, it would be demonstrated, by deterministic and probabilistic means, that hypothetical severe accident sequences that could lead to large radioactive releases due to early containment failure are essentially eliminated with a high degree of confidence”.*

Then, in 1999, INSAG 12 [3] stated: "*27 - the target for existing nuclear power plants consistent with the technical safety objective is a frequency of occurrence of severe core damage that is below about 10^{-4} events per plant operating year. Severe accident management and mitigation measures could reduce by a factor of at least 10 the probability of large off-site releases requiring short-term off-site response. Application of all safety principles and the objectives of para.25*[1] *to future plants could lead to the achievement of an improved goal of not more than 10^{-5} severe core damage events per plant operating year. Another objective for these future plants is the practical elimination of accident sequences that could lead to* ***large early radioactive releases****, whereas severe accidents that could imply late containment failure would be considered in the design process with realistic assumptions and best estimate analyses so that their consequences would necessitate only protective measures limited in area and in time*".

The most recent international texts, particularly those issued by WENRA and the IAEA, state that "practical elimination" should be applied to core melt situations likely to lead to **early or large releases** [5] [7], thus widening the range of situations potentially concerned. According to this wording, the "practical elimination" approach could be used for all core melt situations that can cause large releases, whether or not they lead to early releases.

2 THE "PRACTICAL ELIMINATION" APPROACH: GENERAL CONSIDERATIONS

Nuclear facilities are designed according to the defence in depth principle: a series of provisions are defined on the one hand to prevent accidents and on the other to limit the consequences of any accidents that do occur despite the provisions taken to prevent them. There are today five levels of defence in depth for nuclear reactors; each level aims to limit the consequences of the failure of the previous level and to prevent challenging the next one, in compliance with the general safety objectives set for these reactors:

- the first four levels rely on physical, human and organisational provisions defined by the applicant;
- the fifth level, of different nature[2], essentially consists of organisational provisions implemented by the utility and the governmental authorities in case of emergency potentially leading to off-site consequences. Actions to protect the population foreseen in the off-site emergency plans can then be implemented if needed.

The design mainly focusses on the first four levels of defence in depth, aiming to limit as far as possible the risk of off-site radioactive releases. The safety approach used for the design of new nuclear facilities aims to enhance defence in depth improving the robustness of the different levels, increasing their independence, improving the way hazards are taken into account, etc.. However, it is important to point out that the implementation of defence in depth has its limitations and that it is not possible, for facilities where large quantities of radioactive materials coexist with the energy able to disperse them, to limit the consequences to an acceptable level in all cases.

[1] "*25. For future nuclear power plants, consideration of multiple failures and severe accidents will be achieved in a more systematic and complete way from the design stage…*"

[2] For the first four levels of defence in depth, the applicant has an obligation of "results", i.e. it shall demonstrate that the provisions taken at the design stage and during operation allow the safety objectives of the facility to be met while the fifth level of defence in depth is essentially an obligation of "means".

So situations likely to lead to large releases, because of the simultaneous or successive loss of integrity of all the containment barriers or because of the bypass of these barriers (containment bypass situations):

- either lead to define provisions allowing to significantly limit their consequences;
- or shall be "practically eliminated" where it appears to be impossible to define such provisions or to demonstrate their adequacy with the knowledge and techniques available at the time of the design orientations.

For French water-cooled reactors, for example, the situations likely to lead to large radioactive releases are:

- core melt with loss of containment integrity - case 1;
- core melt with containment bypass - case 2;
- core melt when the containment is open (shutdown states) - case 3;
- melting of spent fuel assemblies being handled or stored in the spent fuel pool - case 4.

<u>Cases 1 and 2</u>: the integrity of the containment, or more generally of the third containment barrier or its extension[3], could be affected suddenly by the occurrence of a high-energy phenomenon (e.g. massive and rapid reactivity insertion, hydrogen detonation, etc.) or by the failure of one or more items of equipment contributing to the containment function[4], or more gradually due to the loss of the containment heat removal function (slow increase of temperature and pressure inside the containment, erosion of the basemat by the corium, etc.). In the latter case, the uncertainties associated with possible evolutions of the plant conditions are smaller and the operator would have some time to act before large releases occur. The definition of provisions to limit the consequences of these situations and the justification of their sufficiency are possible. This is why only fuel melt situations that could lead to <u>large early</u> releases shall be "practically eliminated"; for other situations, provisions to limit releases into the environment shall be defined by the applicant.

<u>Case 3</u>: this case results from the impossibility of keeping the containment permanently closed, due to operating imperatives. The applicant shall take provisions to "practically eliminate" situations leading to a severe degradation of the first two containment barriers in this state, which could also lead to large early releases;

<u>Case 4</u>: for this case, the implementation of provisions to limit releases due to the melt of spent fuel assemblies could technically be envisaged. However, in France, the spent fuel pool is located outside the containment, given the relatively slow kinetics of accidents likely to lead to a severe degradation of these assemblies and the potential for intervention in the corresponding building. This option has been considered as acceptable up to now. Hence, given the scale of the releases that could result from fuel melt in the spent fuel pool, the "practical elimination" approach shall be used also for these situations.

Therefore, while defining the design orientations for a new water-cooled power reactor, applicants shall use the "practical elimination" approach for severe accident situations (in the reactor core or in the spent fuel pool) potentially leading to large early radiological releases, where it seems impossible to define realistic and

[3] The extension of the third barrier refers to the envelope of circuits belonging to the systems whose operation is needed in incident or accident conditions to ensure a safety function and carrying radioactive fluids (reactor coolant, containment atmosphere) outside the containment.

[4] It is aimed in particular at core melt situations with steam generator tube(s) rupture as well as bypasses leading to core melt.

demonstrable provisions to limit their consequences according to current knowledge and the techniques available at the time.

The concept of "practical elimination" of accident situations should not be extended beyond the framework described above. Particularly, it should not be applied without discussions to accident situations for which no provisions would have been implemented to limit their consequences. This highlights how important the discussions between applicants and safety authorities in the early stages of a new design are, primarily with the intention of improving the defence-in-depth.

3 SITUATIONS FOR WHICH A "PRACTICAL ELIMINATION" APPROACH CAN BE USED

In the general design approach, applicants identify the operating and accident conditions, which are classified into categories associated with objectives for limiting off-site consequences, depending on the estimated frequency of occurrence of the conditions. At this stage, a number of single initiating events and multiple failures are "excluded" since considered as not plausible; thus, their consequences are not studied deterministically in the safety demonstration and no mitigation provisions are defined.

In order to consider situations likely to lead to large early releases as "excluded", the applicant shall use the "practical elimination" approach. These situations are identified on the basis of the analysis of the third barrier (or its extension) possible failure modes.

With regard to this, IRSN emphasises that the acceptance of a new design at a given time is based on considerations relating to both the probability of accident situations occurring and the possible consequences of those situations, in view of the knowledge and technical possibilities available at the time. This is why it is important for discussions between applicants and safety authorities to begin as early as the conceptual design stage, with the authority concerned setting objectives and the applicants proposing safety options able to meet these objectives. This was what happened in 1993 when the design orientations of the pressurised water reactors to be operated in France and Germany in the early 21st century were being developed. The design of a nuclear facility being an iterative process, discussions should continue throughout the licensing process; the conclusions of these discussions should be formally recorded at certain stages of the process.

Situations for "practical elimination" should be characterised taking account of uncertainties due to limited knowledge of certain physical phenomena. This characterisation should rely as much as possible on dedicated studies or research and development activities (identification of the relevant sequences and determination of the limit values of key parameters beyond which provisions to limit the consequences could not be taken (e.g. threshold value for a reactivity insertion in pcm/s)).

It is important that, from the early design stages, the applicant specifies the provisions it envisages to prevent the situations to be "practically eliminated" and the approach to justify the "practical elimination" of these situations.

4 JUSTIFICATION OF "PRACTICAL ELIMINATION"

The Technical Guidelines (A.1.4) [4] state:

"However, the "practical elimination" of accident situations which could lead to large early releases is a matter of judgement and each type of sequence has to be assessed separately. Their "practical elimination" can be demonstrated by deterministic and/or probabilistic considerations, taking into account the uncertainties due to the limited knowledge of some physical phenomena. It is stressed that "practical elimination" cannot be demonstrated by compliance with a general "cut-off" probabilistic value."

The situations for which the "practical elimination" approach can be applied are very diverse and proof that they are physically impossible or, failing that, extremely unlikely with a high degree of confidence, can only be achieved through analysis on a case-by-case basis.

The justification of "practical elimination" shall preferably rely on the physical impossibility of the situation (see Section 4.1 below). Where this is not possible, the applicant shall demonstrate with a high degree of confidence that the situation is extremely unlikely (see Section 4.2 below).

4.1 PHYSICALLY IMPOSSIBLE SITUATIONS

Demonstration of the physical impossibility of a situation can be based on various considerations, for example:

- **intrinsic characteristics that guarantee the non-occurrence of certain dreaded phenomena** (e.g. neutron feedback);
- **design choices limiting the quantities of substances likely to produce energetic phenomena** (e.g. limitation of the capacity of deborated water tanks for the circuits connected to the reactor primary circuit in order to prevent heterogeneous dilutions, which would lead to a reactivity-initiated accident);
- **passive static equipment that cannot fail** (such as construction provisions allowing to prevent a heavy load drop from seriously damaging the structural integrity of the spent fuel pool and causing the uncovery of spent fuel assemblies or an assembly being handled).

It should be noted that the demonstration of physical impossibility shall not, under any circumstances, be based on measures requiring active components, since any active component has a non-zero probability of failure.

4.2 SITUATIONS EXTREMELY UNLIKELY WITH A HIGH DEGREE OF CONFIDENCE

If physical impossibility cannot be demonstrated, it has to be proved that the situation is extremely unlikely with a high degree of confidence. The justification, assessed on a case-by-case basis, is based on a deterministic approach, generally complemented by probabilistic analysis and relies on the following principles:

- the deterministic justification for a situation being "practically eliminated" shall be based on both the existence of a sufficient number of lines of defence consisting of material and organizational provisions and the robustness and independence of these different lines of defence;
- material provisions defined within the scope of the "practical elimination" of an accident situation shall be subject to requirements[5] concerning the design (redundancy, diversification, geographical separation, backup power, qualification, reliability, etc.), manufacturing (quality control) and operation (operation

5 It should be pointed out that functions and equipment already subject to requirements in accordance with accident studies may contribute to the justification of "practical elimination" of an accident situation.

monitoring...). This also applies to the instrumentation used to check the functions fulfilled by these provisions. The more a provision or a set of provisions contributes to reduce the probability of a situation occurring, the more the requirements are stringent.

- Provisions defined within the scope of the "practical elimination" of an accident situation shall be tolerant to human actions and errors:
  - the applicant shall prove that these provisions cannot be challenged because of human errors prior to the accident (e.g. maintenance) or that it takes all necessary measures to limit the probability of such errors;
  - if the justification for "practical elimination" is partly based on human actions (e.g. the depressurisation valves in the Flamanville 3 EPR main coolant circuit, which have to be opened manually by the operators to "practically eliminate" high-pressure core melt situations), the operators shall have the necessary information for carrying out these actions without misunderstandings and for checking their effectiveness. The detection systems shall be reliable, clear and explicit, and the time scales within which the actions have to be carried out following the alert shall be long enough, particularly given the conditions of intervention, so that the actions can be considered to have a very low probability of failure.
- Provisions defined within the scope of the "practical elimination" of an accident situation shall be tolerant to internal and external hazards; in particular, the occurrence of rare and severe external hazards shall not challenge a "practical elimination" justification. Preference should be given to the implementation of provisions that are tolerant to the loss of support functions.
- Although probabilistic safety assessments (PSA) can be used to assess the exhaustiveness of the measures taken to avoid certain accident situations (in particular their investigation methods can identify situations resulting from multiple failures not identified deterministically (support system failures, common cause failures, human errors, etc.)), they should be used with care for assessing the extreme unlikeliness of situations for "practical elimination" because of the impact that the models used and the assumptions taken into account can have on the results.
- if the situation to be "practically eliminated" is the result of a single event corresponding to the failure of a mechanical component of the facility, the justification of "practical elimination" is based on the "non ruptible" nature of this component (e.g. reactor vessel, steam generators external envelope).

5 CONCLUSION

The "practical elimination" approach is used in the design of pressurised water reactors for severe accident situations that can lead to large early releases, where it appears impossible to define realistic and demonstrable provisions to limit the consequences of these situations.

The situations for which this approach can be used shall be discussed by applicants and safety authorities from the initial design stages of a new reactor type. The discussions should continue throughout the entire licensing process.

However, any agreements resulting from these discussions are time limited given that they take account of current knowledge and technical possibilities. Although using the "practical elimination" concept means that the consequences of the accident situations concerned are not studied in detail and are not included in the formal safety demonstration, this should not stifle continuous efforts to improve safety, further reflection leading to potential safety improvements may still be carried out later on, after the initial design phase, for example during periodic safety reviews.

In order to "practically eliminate" an accident situation, the applicant shall first examine the possibility for making it physically impossible. If this cannot be achieved, provisions shall be taken that enable the situation to be considered extremely unlikely with a high degree of confidence. These provisions shall be subject to requirements in terms of design, manufacturing and operation; they shall be tolerant to human actions, human error or hazards. The justification of "practical elimination" should be examined on a case-by-case basis, using deterministic considerations, complemented by a probabilistic assessment.

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