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INSAG-28

Application of the Principle of Defence in Depth in Nuclear Safety to Small Modular Reactors

Addendum to INSAG-10

INSAG

A REPORT BY THE INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP

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APPLICATION OF THE PRINCIPLE OF DEFENCE IN DEPTH IN NUCLEAR SAFETY TO SMALL MODULAR REACTORS

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A report by the International Nuclear Safety Advisory Group

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FOREWORD

by the Chair of INSAG

Defence in depth is a fundamental principle of nuclear safety that applies to all types of nuclear installation. As noted in INSAG-12, Basic Safety Principles for Nuclear Power Plants, published in 1999 (itself an update of INSAG-3 from 1988), defence in depth at its core focuses on the strategy to provide multiple levels of protection to ensure that failures in carrying out safety activities, whether organizational, behavioural or equipment related, are corrected or compensated for without causing harm to individuals or the public at large. The International Nuclear Safety Advisory Group (INSAG) further elaborated on the concept in INSAG-10, Defence in Depth in Nuclear Safety, published in 1996, and noted that the concept was appropriate to guide the development of future nuclear installations.

The expanding interest in the design and deployment of small modular reactors (SMRs) prompted INSAG to re-examine INSAG-10 and its relevance to these emerging technologies. Consequently, INSAG has prepared this report as an addendum or supplement to INSAG-10 to specifically address the application of the defence in depth principle to SMRs. We emphasize that the concept of defence in depth and its underlying principles remain fundamental to the safety of nuclear installations. We also note that the type, extent and implementation of measures to address defence in depth may differ when considering the wide variability of SMR types as well as the application of the graded approach to nuclear safety.

We trust that this report will aid in the understanding of the principle of defence in depth and its ongoing application to new technologies.

The International Nuclear Safety Advisory Group (INSAG) is a group of experts with high professional competence in the field of nuclear and radiation safety and experience of working in regulatory organizations, nuclear industry, technical support organizations, research or academic institutions. INSAG is convened by the International Atomic Energy Agency (IAEA) with the objective of providing the Director General of the IAEA with authoritative advice and recommendations on current and emerging issues in nuclear and radiation safety approaches, policies and principles. INSAG addresses fundamental safety issues as well as current and emerging matters of importance relevant to the nuclear and radiation safety of all facilities and activities, including nuclear security issues insofar as they relate to nuclear and radiation safety.

EDITORIAL NOTE

The opinions and recommendations stated in this publication are those of INSAG and do not necessarily represent the views of the IAEA or its Member States.

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EXECUTIVE SUMMARY

This publication provides more specific context for the application of INSAG-10, Defence in Depth in Nuclear Safety [1], to small modular reactors (SMRs).

While INSAG-10 noted the application of the defence in depth concept to all types of nuclear power plant, and possible variations in how it is implemented, experience shows that its implementation needs to take full account of the adequate independence of the levels of defence in depth, redundancy, diversity and protection against internal and external hazards, with a focus on improving mitigation as well as prevention.

The defence in depth concept and its principles, including the number of levels, are valid and applicable to all SMRs. However, the type, extent and implementation of specific measures may differ, since SMRs vary in design. Thus, the application of this concept and its principles needs to be implemented on a case by case basis using a graded approach. Furthermore, any analysis or demonstration related to potential harm on or off the site has to be performed on a site basis, not only for an individual SMR.

1. INTRODUCTION

1. The aim of this publication is to provide the necessary background and information for the application of the defence in depth concept to small modular reactors (SMRs), which may be useful in their design and safety assessment. SMRs vary in their design, and the application of this concept needs to be adapted to individual designs of different types.

2. Small modular reactors are emerging as a potential source of electricity and heat, as well as for use in other applications such as hydrogen generation and desalination. Various countries are considering SMRs as a viable and safe option for a carbon free source of energy. Some SMRs have advanced safety features that may prove to significantly reduce the likelihood of having a severe accident compared with Generation III nuclear power plants.

3. More than 25 years have passed since the publication of INSAG-10, Defence in Depth in Nuclear Safety [1], which expanded on the concept of defence in depth and became an international milestone for assessing the safety of nuclear power plants. The IAEA has made wide use of this concept and has established requirements and provided recommendations related to defence in depth in many of its safety standards.

4. INSAG-10 was intended to be a comprehensive report addressing all types of nuclear power plant, including those designed in the future. In fact, it has a separate section entitled Development of Defence in Depth for Future Nuclear Power Plants. However, feedback since its publication (see Ref. [2]) shows that, while the defence in depth concept remains valid, implementation of the concept needs to be strengthened at all levels through adequate independence of the levels of defence in depth, redundancy, diversity and protection against internal and external hazards. In addition, there is a need to focus not only on accident prevention, but also on improving mitigation measures.

5. Taking into consideration the current interest and needs of the nuclear safety community, the objective of this report, which is to be read as providing additional context to INSAG-10, is to explore, at a high level, the ways in which INSAG-10 can be applied to various types and sizes of SMR in the present circumstances.

2. SMALL MODULAR REACTOR DESIGNS

6. Small modular reactors vary widely in their use of innovative features and in the maturity of their design. The IAEA defines six types of SMR [3]:

(1) Land based water cooled SMRs;
(2) Marine based water cooled SMRs;
(3) High temperature gas cooled SMRs;
(4) Liquid metal cooled fast neutron spectrum SMRs;
(5) Molten salt SMRs;
(6) Microreactors.

7. The variability in SMR designs is due to differences in the following:

— Power;
— Fuel and coolant characteristics;
— Innovative features (as opposed to evolutionary features);
— Maturity of development;
— Utilization (e.g. electricity to the grid, heat generation, dedicated power source).

Hence, each design needs to be considered on a case by case basis for the application of the defence in depth concept.

3. APPROACH OF INSAG-10 TO DEFENCE IN DEPTH

8. Paragraph 17 of INSAG-10 [1] outlines the objectives of defence in depth as follows:

"— to compensate for potential human and component failures;
— to maintain the effectiveness of the barriers by averting damage to the plant and to the barriers themselves; and
— to protect the public and the environment from harm in the event that these barriers are not fully effective."

9. These objectives are based on INSAG-3, Basic Safety Principles for Nuclear Power Plants[1]. They are performance based and their implementation is open to a graded approach, as provided for in para. 16 of INSAG-10 [1].

10. Section 5 of INSAG-10 is dedicated to a discussion of defence in depth for future nuclear power plants. This is generally focused on large evolutionary nuclear power plants, with the assumption that they would have "a probability of severe core damage below 10^{-5} per plant operating year combined with a further reduction by a factor of at least ten in the probability of a major release requiring a short term off-site response" [1].

11. Thus, as minimum objectives, a core damage frequency (CDF) of around 10^{-5}/a and a large early release frequency (LERF) of around 10^{-6}/a are specified. It is obvious that the considerations for future nuclear power plants outlined in section 5 of INSAG 10 [1] would change if the CDF and LERF values for those plants were significantly different. It is also worth mentioning that in para. 119 of INSAG-10 [1], it is stated that values much smaller than presented would be difficult to validate. Therefore, it is important to understand the uncertainties involved in the computation of such small probabilities. It is also particularly important to remember that section 5 of INSAG-10 [1] considers multiple failure events at level 3 of defence in depth and the fact 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" [1]. It also states that "Meeting the safety objectives set for the next generation of nuclear power plants will necessitate improving the strength and independence of the different levels of defence" [1].

4. APPLICATION TO SMALL MODULAR REACTORS

4.1. PASSIVE FEATURES OF SMRs COMPARED WITH LARGE EVOLUTIONARY NUCLEAR POWER PLANTS

12. Small modular reactors have smaller radionuclide inventories and generally make greater use of passive safety features (e.g. residual heat removal) than do large nuclear power plants. The failure modes of some passive systems tend to be

[1] INTERNATIONAL NUCLEAR SAFETY GROUP, Basic Safety Principles for Nuclear Power Plants, 75-INSAG-3, IAEA, Vienna (1988) (superseded by INSAG-12 [4]).

gradual compared with the failures of active systems. Thus, their design typically helps to more effectively avoid cliff edge failures of active components. On the basis of such features, some SMRs claim to lower the mentioned CDF and LERF values by about one order of magnitude.

4.2. COMMON CAUSE FAILURES

13. Small modular reactors might be more prone to common cause failures, especially with respect to external hazards at the same site. Sharing of some safety related systems and components (such as the control room, reactor pool and spent fuel pool) is another factor to consider. Furthermore, in order to preserve their ‘modular’ attribute (regarding their source term), more than one module failing because of an external hazard (or any other common cause) would lead to unacceptable off-site consequences if the regulatory limits were set for a single module. Therefore, robustness against common cause failures, including external hazards, is essential if the assumptions concerning the occurrence of severe accidents and considerations of the sizes of external zones are based only on the failure of a single module.

4.3. DEFENCE IN DEPTH

14. Principle 8 of the Fundamental Safety Principles [5] emphasizes the importance of defence in depth, stating:

> “Defence in depth is implemented primarily through the combination of a number of consecutive and independent levels of protection that would have to fail before harmful effects could be caused to people or to the environment.”

15. IAEA Safety Standards Series No. SSR-3, Safety of Research Reactors [6], presents five levels of defence (see para. 2.12), but notes that in the application of the defence in depth concept, the measures that will be necessary will depend on the source in terms of “the amount and the isotopic composition of the radionuclides, the effectiveness of the individual barriers, the possible internal and external hazards, and the potential consequences of barrier failures” (see para. 2.13).

16. An approach similar to that presented in SSR-3 [6] for research reactors might be applied in grading the application of the defence in depth concept for

SMRs, but recognition is needed of their function as nuclear power plants, not research reactors. In this respect, IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), Safety of Nuclear Power Plants: Design [7], may be more relevant. The implementation of the defence in depth concept and principles for most SMRs might not lead to a significant reduction in measures at the various defence levels, although in some cases (e.g. microreactors), it may be possible for designers to demonstrate that there can be a significant reduction in measures at higher levels of defence in depth. There are SMR designers who are working to improve the safety features of their designs to be able to relax some siting constraints, as these reactors would be used for urban heating or, for other reasons, may need to be sited near population centres.

17. Paragraph 3.22 of the Fundamental Safety Principles [5] refers to a graded approach in the assessment of what is reasonably achievable. IAEA Safety Standards Series No. GSR Part 4 (Rev. 1), Safety Assessment for Facilities and Activities [8], also presents the application of a graded approach as its first requirement. In some SMR designs, it may be possible to demonstrate convincingly that the measures needed at defence in depth level 4, whose definition would be based on the fact that the core could melt, would not be applicable. An in-depth analysis would be needed to justify the omission of core melt and the development of a new approach for a more appropriate definition of defence in depth level 4.

18. The justification presented above does not apply to level 5, which is not directly related to the design of the plant, but rather to the protection of society. Uncertainties in the analysis for levels 3 and 4 need to be considered, to provide for the unexpected.

19. For some SMR designs, the source term used as a basis for the emergency preparedness measures could be minor. Measures for level 5 should be based on a plant specific assessment of hazards.

20. Paragraph 50 of INSAG-12, Basic Safety Principles for Nuclear Power Plants [4], discusses the human aspects of defence in depth, including personnel qualification and training, and safety culture. This is important for SMRs used for district heating and other specific purposes, as new organizational solutions and structures may be needed in their construction, operation and ownership. The local district heating companies will not necessarily have the competence in their own organizations. Efficient cooperation and clear division of responsibilities are needed between the organizations taking part in such projects, as part of good safety culture. Paragraph 3.32 of the Fundamental Safety Principles [5] stresses

the need for a strong management commitment to safety and a strong safety culture among the elements providing defence in depth [5]. These are essential in the activities of all the organizations participating in such projects.

21. The independence of all levels of defence in depth for SMRs is a crucial issue of the concept. Implementation of independence and separation of these levels in all SMR designs may present some challenges, but the importance of the issue needs to be recognized.

4.4. GRADED APPROACH

22. The graded approach is based on the assessment of potential hazards associated with the facility and the consequences of systems or component failure in terms of the impact on facility safety, public health and the environment.

23. This approach defines the extent of analysis, documentation and actions necessary to meet regulatory requirements. Risk assessment in accordance with a graded approach considers the following:

(a) Rated power and intended application of the SMR;
(b) Siting characteristics (including external hazards);
(c) Inventory of fissile and fissionable material;
(d) Fuel characteristics and source term;
(e) Innovative features of SMRs.

24. The Fundamental Safety Principles present the principle of the graded approach in safety assessment (para. 3.15), stating that "Safety has to be assessed for all facilities and activities, consistent with a graded approach" [5]. The principle of optimization of protection, presented as Principle 5, refers to the graded approach in assessing whether radiation risks are as low as reasonably achievable. In addition, the application of a graded approach for safety assessment is presented in Requirement 1 of GSR Part 4 (Rev. 1) [8], which states:

> "**A graded approach shall be used in determining the scope and level of detail of the safety assessment carried out at a particular stage for any particular facility or activity, consistent with the magnitude of the possible radiation risks arising from the facility or activity.**"

25. This may lead to a simplification of assessments in site evaluation and implementation of the defence in depth concept and its principles. Similarly,

the application of requirements concerning staffing; scope and depth of safety analysis; safety classification of structures, systems and components; use of codes and industry standards; qualification of components; and quality assurance requirements might also be affected.

4.5. PERFORMANCE AND PRESCRIPTIVE BASED REGULATION

26. The wide variety of SMR types and their design characteristics necessitates consideration of mainly performance based regulations. The graded approach would be more difficult to apply if prescriptive requirements were in place, as these do not lend themselves so easily to a grading process.

5. CONCLUSIONS AND RECOMMENDATIONS

27. A large number of SMR designs will need to implement all levels of defence in depth as currently defined to comply with this concept and its principles. However, for some SMRs, the path to the implementation of defence in depth in design is not so evident. In this case, a new approach needs to be developed to adequately define the implementation of all levels of defence in depth. Moreover, the need for a graded approach is established in the Fundamental Safety Principles as part of the process of optimization of protection and safety [5]. The insights from the application of the requirements established in SSR-3 [6] to new research reactors might be applied in grading the application of the defence in depth concept for SMRs in an appropriate way. In this context, due consideration is needed of the difference in the nature and goals of research reactors, as compared with SMRs.

28. All relevant safety requirements have to be complied with in applying a graded approach to defence in depth. The application of this approach needs to be based both on the deterministic model and on all the relevant levels of probabilistic safety analyses, and unless there is clear justification for doing so, any modification of the way in which these requirements are implemented will be unlikely.

29. The starting point in the design of a nuclear power plant, including an SMR, should always be the five levels of defence in depth presented in INSAG-10 [1]. In the implementation of the defence in depth concept to SMRs, especially in the

range of low power SMRs, a graded approach could be used. For this purpose, an in-depth analysis should be performed to define the implementation of the defence in depth concept for the specific SMR design. This includes identifying a definition for, and practical implementation of, the fourth level of defence in depth. In some SMR designs, the term core melting is not valid, and the concept of barriers and containment can be quite different compared with that for existing nuclear power plants. Implementation of the concept of defence in depth for these designs may differ significantly from past practices. There is a lack of practical guidance to assess the implementation of the defence in depth concept to innovative reactor designs and SMRs.

30. The practical implementation of the fifth level of defence in depth should depend on the results of a plant specific hazard assessment. With regard to the fifth level of defence in depth, the lack of an internationally harmonized approach to the determination of emergency planning zones and associated requirements complicates this assessment. Harmonization and internationally agreed practices would be useful in terms of the source term assessment, dose criteria and determination of emergency planning zones, and other emergency preparedness arrangements. This would entail the review of the use of prescriptive approaches, which have been the traditional basis for regulatory appraisals in the past.

31. Efficient cooperation and clear division of responsibilities are essential elements of a strong safety culture in all applications of SMRs, and especially in applications for district heating and other purposes where new organizational solutions may be needed for the construction and operation of these facilities.

32. The need for independence of all levels of defence in depth is also emphasized in the application of the concept for SMRs. It is possible that the compactness of some SMRs may entail the multipurpose use of systems, which might have an impact on independence.

33. INSAG emphasizes that there is a need to be clear that the defence in depth concept and its principles remain valid, but the type, extent and implementation of measures to address all levels of defence in depth may differ considering the large variability of SMR types and in line with the application of the graded approach. Care needs to be taken in the way relevant information is expressed so that designers cannot think they can ‘eliminate’ or ‘not implement’ one or more levels of defence in depth, but rather they can demonstrate that the way to implement the concept meets all relevant safety principles and ensures the safety of design.

34. Analysis related to harm on and off the site has to be performed on a site basis. This is particularly important when multiple SMRs or other nuclear installations are situated on a single site and countermeasures need to be related to potential hazards at the entire site. This case by case approach needs, inter alia, to consider all external events associated with the site that might result in common cause failures.

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