Licensing fusion facilities based on the ITER and DEMO paradigms

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ABSTRACT

The evolution of fusion technology mandates the need for formulating a regulatory framework suitable for licensing future fusion power plants (FPPs). On that direction, selected findings of a review performed – in the framework of the HARMONISE project – on the existing safety case documentation of fusion facilities being at different lifetime phases are outlined and, in sum, examined. The works are based on a framework established by the IAEA and their outcome is a set of observations and recommendations whose adoption in the quest for harmonising the licensing process of FPPs ought to be looked into.

1 INTRODUCTION

The safety assessment for an authorized facility is performed in order to evaluate its compliance with the set of safety requirements and provide evidence of achieving the safety objectives. It is prepared by the licensee as a structured document – safety case whose content depends on the national legislation and the nature, purpose and development phase of the facility. With regard to the DEMOnstration Power Plant (DEMO) and ITER facilities, the objective of the preliminary safety case documentation is to demonstrate the achievement of six, top-level safety objectives [1].

Within HARMONISE [2], three questions were posed while reviewing the available safety case documentation of the ITER and DEMO facilities from the point of view of the licensing process:

1. What are the important outcomes that ought to be considered in the future licensing process of FPPs?
2. What improvements could be introduced in the future licensing process of FPPs?
3. What R&D tasks are required to support the future licensing process of FPPs?

The review carried out has taken as a basis the requirements listed in the IAEA GSR Part 4 [3] document with the intention to find constituents that will contribute towards the licensing harmonization of FPPs in the future. As such, the facilities under consideration – an experimental and a demonstration infrastructures – represent successive implementations towards a fully operational FPP. Because of their radioactive contents, both ITER and DEMO are characterized as facilities in need of an authorization from a regulatory body. While the first has received it from the French nuclear safety regulator ASN, the latter being in the conceptualization phase has yet to be submitted to the licensing process that will be formulated in accordance with the regulatory framework of its hosting State.

In agreement with IAEA GSR Part 4 [3] that dictates: "*A graded approach shall be used in determining the scope and level of detail of the safety assessment carried out* …" the safety case related documentation was assessed for the two facilities at the principle level considered during designing the safety architecture of each facility with a level of detail that depends upon the information available.

A summary of the methodology and reference documents employed in the task appears in the following section. A concise profile of the assessment findings is given in Section 3, while the recommendations stemming from its outcomes are listed in Section 4. Finally, the conclusions drawn from these efforts, that originate from specific designs utilizing deuterium-tritium plasmas shaped and confined by magnetic forces, appear in the last section.

2 DOCUMENTATION AND EVALUATION METHOD

2.1 Evaluation method

The safety assessment objective is to evaluate the facility compliance with the safety requirements while it is documented by the licensee in a structured document – the Safety Analysis Report.

In that framework, a systematic approach was devised to review the DEMO and ITER safety cases with respect to the IAEA safety objectives while focusing on the licensing process of the future FPPs. An illustration of the sequential process appears in Figure 1, where the method contrived was limited by the top-level safety case documentation that was available, whereas the proper IAEA documentation was identified and technology neutral objectives, principles and requirements were singled out via a systematic procedure. The identified technology neutral elements found a use in the review of the safety case documentation of the fusion facilities.

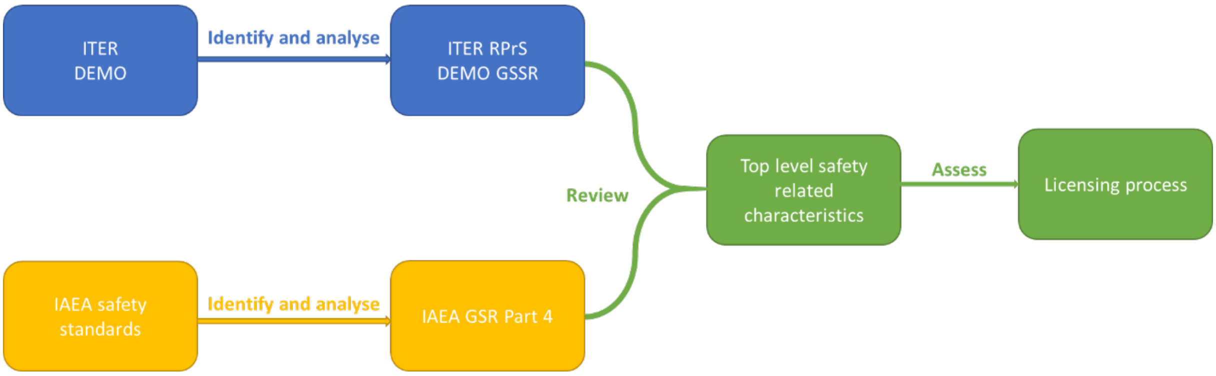

Figure 1: A schematic depiction of the review process

2.2 Documentation

The safety case assessment has been materialized from the licensing process point of view taking as a reference the IAEA safety objectives at a level of detail suitable for the task at hand. Thus, the IAEA documentation has been examined under the prism of its applicability as a reference framework to the documents portraying the status of ITER and DEMO. The screening outcome lists IAEA GSR Part 4 [3] and IAEA SF-1 [4] with IAEA SSG-2 [5], IAEA SSG-12 [6] and IAEA TECDOC-1851 [7] as supporting to the process documents.

The fusion installation documents examined are the preliminary safety report (RPrS) [8] for ITER and the generic site safety report (GSSR) [9] – currently under development – for DEMO. The second reference has been perceived as a relevant safety case documentation.

3 SAFETY CASE REVIEW

Reviewing the safety case documentation of the ITER and DEMO facilities is based on IAEA documentation. The objective has been to sketch the steps leading to an efficient and harmonized licensing process of future FPPs. Since the two facilities are going through different phases, the levels of maturity and detail for the ITER safety case are higher than those of DEMO. Hence, the dissimilar granularity levels of the available data, along with the different levels of potential radiation risks associated with the two facilities, mandated reviewing their safety cases at the level of the principles adopted for designing the safety architecture of each facility whereas the degree of detail depends on the information available.

Indicative observations drawn from reviewing the safety case documentation of the two fusion facilities with respect to requirements catalogued in IAEA GSR Part 4 [3] are profiled in the following subsections. A detailed account of the task fulfilled and its outputs has been documented in deliverable D1.6 “Assessment of the safety cases of large fusion facilities” that is to become publicly available.

3.1 ITER

Possible radiation risks – ITER features a highly distributed source term along many systems and throughout major facility parts. Notwithstanding its systematic accident selection, it is currently lacking a risk-informed approach. At the moment, the analysis status of the radiological consequences through the identification of radioactive sources in all modes of operation alongside the release routes from all hazard locations to the outside environment appears to be acceptable. Nonetheless, a number of the accident precursors and aggravated events are still in need of further elaboration.

Safety functions – With respect to the IAEA GSR Part 4 Requirement 7 (*Assessment of safety functions*) [3] the RPrS is accommodative, both in terms of requirement applicability to fusion installations and compliance of the ITER RPrS, to the requirement claims. Nevertheless, a recommendation regarding the licensing of future FPPs has been put forward.

Site characteristics – The RPrS addresses elements required for assessing the site characteristics while the list of external events is specified in a separate report.

Provisions for radiation protection – Part of the RPrS deals with demonstrating the control of radiological consequences due to ITER operation in normal and abnormal conditions. However, large uncertainties occur in assessing the occupational cumulative dose, while limited experience on unique component maintenance affects its findings.

Therefore, dose minimization to workers, the public and the environment dictates pursuing R&D activities on mitigation strategies and systems.

Engineering aspects – A preliminary conclusion is that the RPrS, in general, complies with IAEA GSR Part 4 Requirement 10 *(Assessment of engineering aspects*) [3] while areas of consideration for the licensing process of future FPPs are recognized.

Human factors – The RPrS addresses elements of the IAEA GRS Part 4 Requirement 11 (*Assessment of human factors*) [3] and fully complies with it regarding human factor assessment.

Safety over the lifetime of a facility or activity – According to the information listed in RPrS, assessment of the radiation risk appears to be under consideration during all stages of the ITER lifetime.

Defence-in-depth – There is a reference within RPrS to defence-in-depth (DiD) implementation, albeit limited information is made available. The specific nature of ITER has an extremely low source term even in the most severe accident conditions which, in return, warrants safety objective verification. However, it is unknown if subsequent design improvements – in terms of ALARA (as low as reasonably achievable) – are possible.

Scope of the safety analysis – The RPrS addresses elements listed under 'Scope' of the safety analysis in IAEA GSR Part 4 [3]. However, a recommendation is made to enhance the detail level on the ITER safety methodology in the safety case report, while it is worth considering at the next licensing step the lessons learnt from the Fukushima Dai-ichi accident. An ASN decision instigated the performance of an additional assessment of the nuclear facility safety with regard to the Fukushima Dai-ichi accident [10].

Deterministic and probabilistic approaches – A probabilistic safety assessment (PSA) has yet to be applied to ITER beyond frequency assignment to the postulated initiating events. Upon facility operation, it is anticipated that a failure database for safety systems, structures and components will be gradually comprehensive enough to facilitate PSA.

Criteria for judging safety – A recommendation is presented to establish detailed criteria assisting compliance assessment with the ITER general safety objectives, including risk criteria that relate to the likelihood of anticipated operational occurrences (AOOs) and accidents.

Uncertainty and sensitivity analysis – With respect to IAEA GSR Part 4 Requirement 17 (*Uncertainty and sensitivity analysis*) [3] recommendations are brought forward to: (a) adopt R&D activities to improve uncertainty quantification of input data along with sensitivity analysis of the results obtained, (b) identify key safety parameters for sensitivity analyses and uncertainty quantification, (c) improve the completeness and accuracy of the uncertainty of the input data, (d) do sensitivity analyses when the simulation code validation is scarce and (e) execute uncertainty and sensitivity analyses for selected enveloping accident scenarios.

Use of computer codes – It is understood that experiments are needed to validate a wealth of simulation tools (both codes and input data sets) used in the safety demonstration of fusion facilities. These include system codes (e.g. MELCOR, ASTEC, RELAP), codes for plasma interaction, tools for source term quantification, codes for radiological release, CFD codes and neutronics calculation schemes.

Use of operating experience data – Licensing and safety demonstration of future FPPs require the collection of safety related data in a structured, systematic and effective manner. Therefore, it is recommended to carry on the current works conceiving, standardizing and building a systematic approach to collect, share and employ safety related data from operating experience.

3.2 DEMO

Possible radiation risks – Contemplating that the radiological consequences is a top-level safety objective of DEMO the following gaps and recommendations are listed with respect to the licensing process: (a) the design extension conditions are to be considered while the corresponding postulated initiating multiple failure events need to be defined and (b) the radiological risk that depends on design finalization has to be assessed.

Safety functions – The decay heat appears only in activated confinement materials and it is considered within the supporting safety function of the control of thermal energy in support of the confinement fundamental safety function. For the licensing process, the need for the decay heat removal as a fundamental safety function should be examined.

Site characteristics – Upon site selection, the national legislation of the hosting State will be taken into consideration.

Provisions for radiation protection – IAEA GSR Part 4 Requirement 9 (*Assessment of the provisions for radiation protection*) [3] applies to the DEMO safety case, where radiation protection principles and measures are regarded. However, due to the pre-conceptual maturity level of the design the complete application and formalization of the ALARA process has yet to be defined.

Engineering aspects – A technical report dedicated to the safety assessment implementation of the DiD principle into the safety architecture may be important for facilitating the licensing process and systematically demonstrating a reduced probability for design back fitting. Furthermore, the need is recognized for additional codes and standards as well as modifications of the existing inventory.

Human factors – The best practices from the ITER instrumentation and control as well as control room designs are to be considered in DEMO.

Safety over the lifetime of a facility or activity – In accordance to the information presented in the GSSR, the radiation risk assessment is under consideration during all stages of the DEMO lifetime.

Defence-in-depth – The requirement assessment exhibited that both the lines of protection and objective provision tree methods could assess the implementation of the DiD principle in the DEMO safety architecture.

Scope of the safety analysis – Both the GSSR and DEMO licensability stand to be enhanced by encompassing an assessment of the plant normal operation (including start up and shutdown) along with its AOOs. A preliminary assessment of the post-operational phase could be introduced in the GSSR ahead of the preliminary safety analysis report.

Deterministic and probabilistic approaches – While accident analysis (design basis accidents (DBAs), design extension conditions (DECs) and beyond design basis accidents (BDBAs)) is referenced in the GSSR, AOOs are not discussed whereas they are incorporated in the accidents. In addition, adoption of plant state categorization in accordance to the IAEA conventions could expedite licensing and PSA could assist the impact evaluation of events and support event selection for deterministic analysis.

Criteria for judging safety – The GSSR lists criteria for judging safety of AOOs, DBAs and BDBAs related to radiological/toxic hazards. Nevertheless, as for the case of ITER in the previous section, it is recommended to develop criteria for judging risk and likelihood of AOOs and accidents. PSA shall be developed. The estimated frequencies as well as consequences of incidents and accidents would expedite licensing and contribute in devising emergency operation procedures.

Uncertainty and sensitivity analysis – The DEMO pre-conceptual and conceptual designs incorporate R&D activities in uncertainty quantification and sensitivity analysis. Thus, sensitivity, perturbation and uncertainty quantification frameworks as well as tools are coupled with nuclear safety codes. Future implementations need to consolidate sensitivity and uncertainty quantification and propagation practices as a substitute to the shortage of experimental data.

Use of computer codes – An experimental R&D roadmap should be drawn in support of computer code development and validation since only codes subjected to proper V&V could be employed in the licensing process. Code-to-code benchmarking is not deemed sufficient for the licensing process and should not be used as a substitute to the shortage of experimental data.

Use of operating experience data – While EUROfusion supports ongoing activities for collecting operating experience, the large amount of safety related data required for DEMO operation necessitates systematic, standardized and effective data collection, integration and storage. R&D efforts ought to be devoted in collecting pertinent data in accordance to standardized manners adopted by States and organizations.

4 RECOMMENDATIONS

The review output has been synthesized into a number of recommendations for the licensing process of future FPPs which are summoned into three groups, i.e.: generic, those contributing to a harmonised view on the safety approach as well as those in support of licensing for first-of-a-kind fusion technologies. The list of recommendations is summarized in the following subsections while full-length descriptions have been recorded in deliverable D1.6 “Assessment of the safety cases of large fusion facilities” that will be openly accessible.

4.1 Generic recommendations

With a reference to the first question posed in the Introduction section, the responses are delineated as:

Harmonisation of safety fundamentals and safety requirements – In brief, it is proposed to investigate the possibility of harmonizing fission and fusion requirements using the technology neutral formulation of the IAEA safety fundamentals and safety requirements. Furthermore, the fusion technology should be addressed by universally accepted technology specific requirements and recommendations facilitating the development of national legislations for FPPs.

Internationally harmonized licensing process – In order to facilitate the licensing process of future FPPs, the best licensing practices from nuclear power plants and existing fusion facilities should be compared.

Internationally harmonized safety case structure and content – The formulation of an internationally harmonized proposal of a safety case structure and content could optimize the preparation of the entering licensing documentation, while facilitate licensing at regulator level in States considering or embarking on an FPP program.

Internationally harmonized general design certification – An internationally accepted design approval independent of site selection could facilitate global deployment of FPPs in States considering or embarking on an FPP program.

4.2 Harmonized view on the safety approach

A precis of proposals deemed suitable to the second question posed in the Introduction section is:

Harmonise fundamental safety function definitions – Although fusion technology does not, in principle, create a need for new fundamental safety functions, their definitions could be reformulated to enable a harmonised applicability to both fission and fusion technologies.

Plant states – Categorizing the plant states within a safety case according to the IAEA conventions to operational states (normal operation and AOOs) and accident conditions would simplify licensing. There is also need for adapting the DEC subdivision and considering of conditions to be practically eliminated.

Communication on defence-in-depth principle implementation – A comprehensive representation of the safety architecture would enable a transparent and systematic assessment of the DiD principle communicating which, why and how each provision is available during every plant condition and throughout the facility lifetime. A technical report focused on the safety assessment of the DiD principle implementation into the safety architecture may be important for accommodating the licensing process and systematically demonstrating reduced probability for design back fitting, while the integrated safety assessment methodology may be employed.

Single failure criterion – Additional guidance on requirements addressing the single failure criterion would be needed.

Minimize dose to workers, public and environment – R&D in mitigation strategies and systems ought to be pursued to minimize the dose to workers, the public and the environment.

Approach for classification – A standardized approach for the classification of all provisions contributing to the installation safety might be considered. In addition, system and component classification should contemplate the need for optimization to avoid unnecessary constraints with negative consequences in terms of e.g., construction, implementation, maintenance and availability.

4.3 Recommendations in support of licensing for first-of-a-kind fusion technologies

A synopsis of suitable responses to the third question posed in the Introduction section is:

Communication on fusion power plant particularities – The applicants of first-of-a-kind FPPs should enter the licensing process with fully developed designs supported by systematic technical reports on the proof-of-concept. The technical reports should be communicated to regulators early in the technology development.

Codes and standards – In parallel to safety important component classification and qualification, relevant codes and standards should be identified at the earliest, while a technical report justifying the selected codes and standards could expedite the licensing process. R&D activities are needed to develop new, adopt existing or propose technology neutral codes and standards at the earliest, since the current codes and standards may not be applicable to a number of safety important components of FPPs.

Database with operational experiences – It is imperative to establish a database hosting operational experience on safety related data in a structured, systematic and effective way. R&D resources should be invested in collecting operational experience data and storing it in standardized manners adopted by States and organizations.

Validated computer codes – The prerequisite to employ in the licensing process computer codes submitted to a V&V procedure mandates drawing a detailed roadmap for experimental R&D in support of computer code development and validation.

Independence of computer codes – Different sets of independent technology specific, computer codes ought to be used by the technology developer/licensee and the regulator, respectively.

Uncertainty quantification of input data – R&D activities are recommended to improve uncertainty quantification of input data and perform result sensitivity analysis. It is suggested to identify key safety parameters for sensitivity analysis and uncertainty quantification to improve the completeness and accuracy of the input data uncertainty and perform sensitivity analysis especially where code validation is scarce.

Implementation of a systematic activity based on the phenomena identification and ranking table approach – Safety related phenomena featuring large uncertainty and high importance in ensuring compliance with the radiological safety objectives should be identified. The application of a systematic approach for independent, agreed and comprehensive phenomena identification and assessment resulting in a ranked determination of their uncertainty and importance (through qualitative or quantitative methods) will mainstream future R&D efforts in fusion safety.

5 CONCLUSIONS

The safety cases of the ITER and DEMO facilities have been reviewed with respect to the framework defined in IAEA GSR Part 4 [3]. The task focused on recognizing opportunities for an efficient and harmonized licensing process of future FPPs, while the actions are primarily based on, as well as limited by, the information available within the safety cases. As a result, several observations along with seventeen recommendations have been formulated. These outcomes could potentially find a use in bridging the harmonisation gaps in the licensing process of future FPPs.

ACKNOWLEDGMENTS

This project has received funding from the European Commission – Euratom under Grant Agreement No 101061643. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or European Commission – Euratom. Neither the European Union nor the granting authority can be held responsible for them.

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