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Conference Report

Recommendations for the future regulation of fusion power plants

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Abstract

The discussion in the international community on how fusion power plants (FPPs) will be licenced and regulated is ongoing. As such, there is a concerted drive from the European stakeholders to understand the requirements from such a framework and how to best establish it with the aim of easing the licensing process of FPPs. Initiated by the EUROfusion consortium, a group of European experts were convened to produce a set of recommendations on the regulatory framework for the safety and licensing of FPPs. To do so effectively, the group assessed lessons learned from existing fusion facilities, reports by International Atomic Energy Agency and European Commission on FPP safety and the on-going work by the UK government, US Nuclear Regulatory Commission and Canadian Nuclear Safety Commission, as well as the licensing process of ITER. As a result, commonalities between fusion and fission were identified in terms of fundamental safety objectives which could facilitate parity in certain framework aspects. However, significant differences to any such implementation were also identified, particularly with respect to the lower hazard potential inherent to FPPs and how to remain proportionate to the associated safety challenges and the physical principles behind these two types of reactors together with their associated technologies. The recognition of the differences in the safety challenges in FPPs and fission-based nuclear power plants (NPPs) is paramount to future regulatory framework development. Ultimately, regulatory frameworks depend upon a country's legal framework, therefore it is apparent that a common global regulatory framework for FPPs is not possible. However, as with present-day NPP regulation, efforts could be made to develop harmonised approaches to FPP regulation to provide common

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levels of protection. In view of this objective, 12 recommendations are presented across 4 topics: regulations, international databases, codes and standards, safety demonstration rules and regulatory approaches. These recommendations are provided to inform and advise potential future actions on FPP regulatory framework and licencing process principles.

Keywords: fusion power plants, DEMO, licencing, safety, regulatory framework

1. Introduction

There is an ongoing discussion in the international community on how fusion power plants (FPPs) will be licenced and regulated. At the time of writing, there is no consensus on how FPPs should be regulated to ensure safety for both the workers and the public, together with the protection of the environment. As such, there is a concerted drive from the European stakeholders to understand the requirements and formulation of such a framework and how to best establish it with the aim of easing the licensing process of FPPs.

A robust fusion licencing and regulatory framework has a critical role to play in not only the aforementioned areas of safety and protection, but also in focussing technological development according to clear requirements and guidelines whilst promoting the public acceptance of fusion.

In view of expediting the subject with respect to the needs of the European Roadmap and the DEMO project, EUROfusion established a working group to draw up the considerations to be addressed when developing a regulatory framework that is specifically tailored to fusion safety. This group, which involved nuclear safety experts in the fusion and fission fields, assessed the challenges faced in the FPP licencing process and consolidated the key regulatory aspects that need addressing on the path to the successful licencing and safe operation of FPPs.

Such a framework would need to recognise the differing safety challenges that nuclear fission-based power plants (NPPs) and FPPs face. The working group's recommendations reflect the need for the regulatory framework to acknowledge the lower hazard potential of an FPP when compared with an NPP. Nevertheless, this methodology should be based upon a simplification or adaptation of the current and well-established fission-oriented nuclear regulation. The resulting recommendations are therefore a set of high-level principles for FPP regulation to ensure a proportionate approach is taken to licensing requirements and regulatory oversight.

The methodology undertaken by the group is described in section 2, with the findings from the discussions detailed in section 3 and the recommendations presented per topic in section 4.

2. Methodology

To identify the areas of a future framework that need adapting for an FPP, the group applied a systematic approach based on two steps: the analysis of the lessons learnt from existing fusion facilities and the review of reports launched by International Atomic Energy Agency (IAEA) and European Commission on FPP safety. The specific steps to this approach consisted of addressing each of the following subject matters:

- Review of the experience of licensing the ITER project (2009–2012),
- Review of the regulation applied to ITER design and safety demonstration (including the interpretation of the regulation issued initially for fission plants),
- Discussion from the regulator position on the application of the French regulation to ITER specificities vs fission plants,
- Review of the EC-funded study on the applicability of the regulatory framework for nuclear facilities to fusion facilities—towards a specific regulatory framework for fusion facilities,
- Review of the IAEA technical document (IAEA TECDOC) on FPP regulation,
- Review of the public expectations of safety risks in experience to-date.

Each subject was presented to the group by the respective expert and discussed to extract the core considerations. Four topics on the FPP safety challenges were identified in this process to form the foundations for the recommendations:

- Regulations,
- International databases, codes and standards,
- Safety demonstration and rules,
- Regulatory Approaches for the licensing process.

3. Findings

3.1. Commonalities between fusion and fission

The main safety principles, as developed in the IAEA Fundamental Safety Principles [1] apply to NPPs, regardless of whether they are based on fission or fusion technology. Principles one to nine (responsibility for safety, role of government, leadership and management for safety, justification of facilities and activities, optimization of protection, limitation of risks to individuals, protection of present and future generations, prevention of accidents and emergency preparedness and response) are applicable to both fission and fusion. Principle ten, related to protective actions to reduce existing or unregulated radiation risks, is not applicable to fusion device of either technology as it concerns radiation of essentially natural origins and exposure that arises from human activities conducted in the past. The IAEA Fundamental Safety Principles [1] indicate that 'safety has to be assessed for all facilities and activities, consistent with a graded approach'.

This graded approach allows for the same principles to be followed for fission and fusion, applied proportionately to the safety challenges.

Through the IAEA Fundamental Safety Principles, the fundamental safety objectives can be reached, i.e. to protect people and the environment from harmful effects of ionizing radiation. In pursuing this objective for both fission and fusion, well-established safety principles are used including Defence in Depth, as low as is reasonably achievable (ALARA), and passive safety principles.

Additionally, FPPs are not creating the need for specific fundamental safety functions. Confinement of radioactive and hazardous materials, limitation of internal and external exposure and potentially decay heat removal are commonalities between fusion and fission.

It is therefore apparent that the same methodology applies to both fusion and fission. There are, however, differences in the implementation due to differences in hazard potential (i.e. unmitigated risks) and in the physical principles behind these two types of reactors together with their associated technologies (i.e. use of vacuum systems vs use of pressurised circuits). These aspects are covered in the next section related to the lessons learnt from fusion facilities.

3.2. Lessons learnt from fusion facilities

3.2.1. Lessons learned from ITER. The total radioactive inventory of ITER is about more than one order of magnitude lower than in Pressurized Water Reactor 900 MWe plants. Additionally, the radiological consequences of the main radionuclide used in ITER, tritium, leads to a limited impact on the public and the environment, particularly in the long term, given its 12.3-year half-life and its low radiotoxicity.

Considering the lower impact of the ITER worst case safety scenarios, the approach defined the safety requirements in proportion to the safety challenges of ITER. This is due to the goal-orientated nature of the French regulatory framework.

Based upon the ITER experience, there are several identified potential domains to be adapted:

- **Uncertainties/safety margins**: some of the ITER loads, such as the electromagnetic and cryogenic loads, are specific to a fusion facility. Calculating these loads includes significant uncertainties that are compensated for through margins. The demonstration of the robustness of the ITER design against its loads is a key element in the licensing process. The uncertainties led to the definition of conservative requirements and design for first confinement system components. The progressive start-up of the operation of ITER, based on a step-by-step approach, is also used to define the set of operational parameters acceptable from a safety point of view and a condition of the license granting.
- **Definition of safety requirements**: the goal-oriented regulatory approach facilitated the definition of safety requirements proportionate to the radiotoxic potential of ITER. One advantage of FPPs is the rapidly extinguish of the fusion reaction after any undesired event. This is different from NPPs where the insertion of neutron absorbers is needed to terminate the chain reaction. The lower hazard potential and the inherent safety characteristics of the fusion process allows for a graded approach, proportionate to the challenges, to be applied in the licensing process. This has been used for ITER licensing process.
- **Robustness of the confinement barriers**: the confinement barriers are designed in accordance with the codes and standards originally prepared for fission facilities. The design and manufacturing difficulties encountered with first-of-a-kind components and structures were raised during the application of certain codes and standards. Subsequently, adaptations were required to address the ITER requirements, e.g. with the vacuum vessel. The last confinement barrier plays a very special role in the safety demonstration for ITER, particularly the basement ensuring the machine is supported in all scenarios (design basis accident (DBA) and design extension conditions (DECs)).
- **Rules for safety analysis**: Due to the experimental nature of ITER, a deterministic approach is applied. For certain aggravating failures, the application of the common mode failures can be relaxed in some areas where the releases are relatively constant regardless of the evolution of the initial conditions.

3.2.2. Review of (previous) EU studies and identification of proposed key features for FPP regulation. In 2021, the European Commission published a *Study on the Applicability of the Regulatory Framework for Nuclear Facilities to Fusion Facilities—Towards a specific regulatory framework for fusion facilities* [2], carried out by German Technical Safety Organization and the Karlsruhe Institute of Technology.

The study collects international information by identifying countries which either are constructing or operating fusion facilities, together with those that have done assessments of their current regulation status and its applicability to fusion facilities. The focus is on facilities including tritium as fuel for the fusion process. The most relevant countries were identified as France (with ITER to use tritium) and United Kingdom (with JET experience and new plans on using tritium). Germany has no plans for such a fusion facility, but the main results from a related German review were summarized. For other investigated countries—Russia, China, Korea, and Japan—no detailed documentation was found in the open literature. The conclusion was that no country has implemented a dedicated and specific regulatory framework for fusion facilities to-date. Nevertheless, it was observed that the competent regulatory authorities in more and more countries are paying attention to this issue.

The EC-funded Study contains a relatively detailed technical review of main differences between fusion and fission facilities, describing 17 fusion specific systems using the example of the DEMO configuration. The study also extends the previous work done by the IAEA in identifying safety requirements specifically needed for FPPs. The performed work comprises an in-depth technical analysis of systems, structures, and components and their associated importance for safety and a screening of existing international regulatory documents which may be considered for developing a specific regulatory framework for future fusion facilities utilizing tritium with magnetic confinement. A screening of IAEA Safety guides leads to the conclusion that existing guides directly applicable to fusion facilities would primarily be those relating to radiation protection; leadership and management for safety; and predisposal management of radioactive waste.

The EC-funded Study also delivered an *Action plan for the development of a targeted and proportionate regulatory framework*, identifying 13 steps, together with the involved stakeholders, including:

- establishing a common European legal framework,
- agreeing on fusion specific implementation of the defence in depth concept and a graded approach,
- developing safety requirements for fusion facilities using D–T plasmas and magnetic confinement,
- establishing a system for operating experience feedback,
- developing safety guides for different aspects of fusion specific technical aspects,
- developing fusion specific codes and standards.

Since the EU Study publication, the UK Government has carried out a consultation on its proposals for a regulatory framework for fusion energy. In the response to this consultation, noting also some opposition to the proposals, the UK Government presented the decision that future fusion energy facilities will be regulated under the legal framework already in place for regulating fusion research (i.e. by the Health & Safety Executive and Environment Agency, or equivalent devolved regulator, as is currently the case for JET) [3]. The decision was based on proportionality with regards to the level of hazards involved in fusion [4]. This considered the knowledge of hazards from JET and a range of independent published accident studies for conceptual designs of FPPs, such as the earlier European fusion programme studies, the Safety and Environmental Assessment of Fusion Power series and the Power Plant Conceptual Study. As part of the next steps, it is recognised that the health and safety and environmental regulators should continue to build their technical capability and capacity to regulate fusion energy facilities and consider developing fusion-specific processes and guidance.

3.2.3. Other recent international developments. In the USA, the Nuclear Energy Innovation and Modernization Act obliges the Nuclear Regulatory Commission (NRC) to establish a technology-inclusive regulatory framework by the end of 2027. The status of this development until 2021 was also summarized in the aforementioned EC-funded Study. Since the reporting in this Study publication, a policy issue was submitted in early 2023 on *'Options for Licensing and Regulating Fusion Energy Systems*', providing three options for NRC consideration [5], including:

1. Categorization of fusion energy systems as utilization facilities[9] with the staff developing a new framework to address the associated specific hazards.
2. A by-product material[10] approach augmenting the framework for radioactive material licenses.
3. A hybrid framework with decision criteria, based on the potential risks and hazards of a specific fusion energy system, to determine whether a by-product material or a utilization facility approach is appropriate for that system.

In April 2023, the NRC approved Option 2 with 'limited-scope rulemaking', meaning that the regulator's staff should take into account the existence of fusion systems that already have been licensed and are being regulated, as well as those that may be licensed prior to the completion of the rulemaking. In parallel, the regulator shall continue to develop dedicated regulation for fusion energy systems. If future anticipated fusion designs are identified to present hazards significantly beyond those of near-term fusion technologies, the validity of the approach must be re-evaluated [6, 7].

In Canada, the nuclear regulatory system is based on goal setting. The Canadian Nuclear Safety Commission (CSNC) has reviewed the country's regulatory framework for readiness to regulate fusion technologies [8]. In the study, three hypothetical preliminary descriptions of fusion facilities were developed to cover a range of approaches to test the regulatory framework. The three hypothetical concepts were (i) a full-scale hypothetical commercial tokamak, (ii) a full-scale commercial projectile induced fusion facility[11], and (iii) a research hybrid magneto-inertial facility. Using these concepts, it was possible to screen and classify the applicability of Canada's existing regulatory documents against the three cases and account for the relatively large technological differences in different approaches. This recognises the fact that there are private enterprises in Canada developing non-tokamak based FPPs concepts. Otherwise, the high-level findings of the study are similar to what has been concluded elsewhere.

3.3. Development of high-level goals for FPP regulation

3.3.1. International safety standards. As FPPs produce ionising radiation and, they fall within the remit of the IAEA's Fundamental Safety Principles, discussed in section 3.1 [1]. These form the overarching document of the IAEA's Safety Standards. Currently the extent of the application of the IAEA Safety Standards (Requirements and Guides) to FPPs has yet to be determined but it is widely accepted that the Fundamental Safety Principles apply to FPPs.

[9] *Utilization facility* in [5], the definition would be a facility 'peculiarly adapted for making use of atomic energy in such quantity as to be of significance to the common defence and security, or in such manner as to affect the health and safety of the public'.

[10] *By-product material* is essentially artificially made radioactive material other than fissile materials.

[11] Hypothetical Commercial, Projectile Induced Fusion (HCPIF): Full scale, commercial, inertial confinement, projectile induced pressure wave and cavity collapse representative of pulsed, inertial confinement technologies.

The fundamental safety objective is to protect people and the environment from the harmful effects of ionising radiation. However, this objective is expected to be achieved '*without unduly limiting the operation of facilities or the conduct of activities that give rise to radiation risks*'. To achieve this objective requires control measures to manage radiation exposure to people and the release of radioactive material to the environment; restrict the likelihood of accidents that could lead to a loss of control over sources of radiation; and to mitigate the consequences of such events if they occur.

To deliver the safety principles requires some form of regulation to identify the duty holders responsible for safety, provide a legal framework to identify the appropriate safety requirements, provide a Regulatory Body with sufficient powers to enforce compliance with the safety responsibilities and ensure that there are arrangements in place to protect the public should there be an accidental release of radioactivity to the environment outside the facility.

3.3.2. Regulatory approaches. Society expects that industries with the potential to cause harm to people and the environment are regulated to ensure that the public and workers are properly protected. When deciding upon what is an appropriate level of regulation, governments must consider the hazard potential of the activity, i.e. what is the unmitigated risk to the public from accidents that could occur. Regulatory frameworks are not based on the individual risk to a worker or members of the public, as facilities must be designed to ensure that such risks have been reduced to ALARA or as low as is reasonably practicable (ALARP). The required mitigation, whether through design or operational requirements, is dependent upon the hazard potential. Therefore, the degree of regulatory oversight set out in the regulatory framework will depend upon the hazard potential and the complexity of the required mitigation measures.

The current national and international nuclear regulatory landscapes have been shaped by the special characteristics associated with nuclear fission. In the case of NPPs, the hazard potential is very high due to the nature of the fission process, as demonstrated with the Chernobyl accident. The hazard potential of FPPs is expected to be much lower than that of a NPP because of the different nature of the fusion process. Nevertheless, the hazard potential of FPPs, especially those using magnetically confined D–T reactions, is not insignificant.

Regulation is a legal construct and in essence it is law enforcement. Therefore, a regulatory framework will depend upon a country's legal framework. As such it is not possible to have a common global regulatory framework for FPPs. However, great efforts are being made with NPP regulation to develop harmonised approaches to provide common levels of protection. To facilitate the global deployment of FPPs, similar efforts should be made to develop agreed principles for FPPs to harmonise regulatory approaches. Ultimately, the approach taken by countries to regulate FPPs will reflect the country's legal framework for safety.

Consequently, two main approaches exist: goal setting and prescriptive. The goal setting approach enables regulatory requirements to be tailored to the hazard potential of a facility. In the case of prescriptive regulatory regimes, regulatory requirements and supporting regulations relating to the safety of FPPs should be based on a graded approach and be proportionate to the hazard potential of FPPs.

3.3.3. Licensing. The public expects hazardous activities to be controlled such that they cannot be undertaken without permission from the government or its safety regulator. In the case of NPPs, the required permission is provided by nuclear licensing regimes. Here the licensee is required to seek permission from the regulator before commencing certain activities such as start of construction or commencement of reactor operation. The public and politicians expect the nuclear safety regulators to be technically competent and appropriately resourced. Nuclear site licensing has proven to be an effective regulatory tool. Whilst the hazard potential for FPPs is lower than that of NPPs, it is not insignificant and hence some form of licensing/permissioning regime should be implemented to provide the public with the assurance that their safety is not being put at risk from FPP operations.

3.3.4. Derivation of FPP licensing and regulation goals from the IAEA fundamental safety principles. Through the discussion and adaptation of the IAEA Fundamental Safety Principles, 10 high-level goals were derived to deliver the effective regulation and licensing of FPPs:

- Goal 1 Before the deployment of FPPs in a country, there must be an appropriate regulatory framework for safety, security and safeguards (from IAEA SF1-Principle 2 [1]).
- Goal 2 The regulatory framework must be proportionate to the Hazard Potential of FPPs (from IAEA SF1-Principles 3 and 5 [1]).
- Goal 3 The regulatory framework must include a Regulatory Body to oversee the design, construction, commissioning operation and decommissioning of FPPs (from IAEA SF1-Principle 2 [1]).
- Goal 4 The regulatory framework must ensure that the Regulatory Body is independent of the fusion industry and independent of those in Government who are responsible for the promotion of FPPs (from IAEA SF1-Principle 2 [1]).
- Goal 5 The regulatory framework must provide for a licensing or other form of effective permissioning regime (from IAEA SF1-Principles 1 and 2 [1]).
- Goal 6 The regulatory framework must ensure that the Regulatory Body has the necessary powers to enforce FPP regulatory requirements (from IAEA SF1-Principle 2 [1]).

Goal 7 The regulatory framework should ensure that there are appropriate and effective emergency preparedness arrangements in place in locations used for the siting of FPPs (from IAEA SF1-Principle 9 [1]).

Goal 8 The regulatory framework must put the responsibility for safety on the FPP operator/licensee (from IAEA SF1-Principle 1 [1]).

Goal 9 The regulatory framework must ensure that the licensee/operator is required to verify safety via the production safety documentation (safety case) to support the design, construction, operation and decommissioning of FPPs (from IAEA SF1-Principles 1, 3, 5, 6, 7 and 8 [1]).

Goal 10 The regulatory framework must ensure the minimisation and the effective management of radioactive waste arising from FPP operations (from IAEA SF1-Principles 1 and 7 [1]).

3.4. Outstanding challenges facing the licensing and regulation of FPPs

The differing hazard potential between NPPs and FPPs stems from the fact that the fuel used in fusion facilities, tritium, is considered one of the least harmful radionuclides. The long-term consequences of fusion facility accident scenarios are, therefore, lower when compared to the long-term consequences associated with NPP accident. However, tritium is not the only radioactive material in an FPP that could be released in the event of an accident. Radioactive dust coming from the activation of first wall materials also forms part of radioactive source terms. A further difference between FPPs and NPPs is the fact that FPPs do not produce high level waste as is the case with NPPs. FPPs also benefit from the self-extinguishing nature of the fusion reaction, which contrasts with the potential for an uncontrolled chain reaction in NPPs.

The hazard potential of an FPP is less than that of an NPP, but it is not insignificant and the design, construction, commissioning, and operation must be effectively regulated to ensure the safety of workers, and the public and the protection of the environment. The current set of NPP safety standards and regulatory approaches already allow for a graded approach i.e. the safety approach should be proportionate to the hazard potential. However, the application of current NPP safety standards and regulatory approaches to FPPs is not appropriate, and a review of the IAEA nuclear safety standards will need to be performed for judging the adequacy and applicability of these safety standards and regulatory approaches to FPPs both at national and international levels.

The first challenge is therefore the re-assessment of whether the current regulations and safety standards are appropriate with regards to the lower of hazard potential FPPs.

At the same time, fusion technologies are still evolving and need flexibility in design or operation requirements, whilst maintaining the safety goal of protecting workers, the environment, and members of the public. Certain relatively new technologies, e.g. nuclear mechanical components under vacuum, superconducting magnets, advanced cooling technologies and detritiation systems, will need to be developed according to the implementation of international codes and standards (e.g. ISO, IEC…) agreed on by designers, operators and regulators. These technologies, particularly the highly innovative cases (sometimes first-of-a-kind) will incorporate uncertainties and therefore require robust margins. At the same time, many safety requirements exist for confinement or monitoring radioactive materials (containment barriers, dynamic confinement systems, etc). The codes and standards will need re-visiting and not only modified, but also adapted.

The safety rules applicable to NPPs may also need to be revisited since most of these rules were established because of the characteristics of NPPs including for long-term consequences in severe NPP accidents. Among these safety rules, the need for redundancy and diversity for safety related systems and components, or a large list of aggravating failures will be revisited at the light of the reduced long-term consequences of severe accident scenarios.

The second challenge is therefore the adaption of existing NPP codes and standards and safety rules, ensuring they offer flexibility to allow FPPs to be safe when incorporating adequate margins, whilst still based on a proportionate approach.

These challenges go along with the need to communicate with all stakeholders, particularly the regulators and designers, on:

- The FPP hazards and associated risks to workers and the public from normal operation and plant accidents including the impact of external hazards,
- The new technologies applicable to FPPs including vacuum vessels, breeding blanket, divertor, detritiation systems, superconducting magnets, cryogenic systems all of which will exist in radioactive and high energy neutrons environment,
- The different approaches needed for safety and security culture.

This requires knowledgeable experts in safety risks to effectively communicate these topics. To overcome FPP licensing and regulatory challenges, stakeholders will need to be convinced of:

- The lower long-term risks of FPPs in postulated accidents (DBA and DEC),
- The absence of final disposal needs for high level waste, and
- The need to reduce the environmental footprint of FPPs in during normal operation.

The third challenge is therefore the adequate and effective communication of fusion risk specificities and the propagation of fusion safety culture to all stakeholders, both internal and external.

4. Recommendations

4.1. Regulations

FPP design is in its infancy with several design options under consideration, hence there is a need for flexibility in the requirements and regulatory approach to be applied whilst maintaining the fundamental safety goals of protecting workers, the environment, and members of the public. FPP regulations should consider whenever possible a goal-setting regulatory approach, recognise the need for emergency preparedness, consider the importance of transparency, education, and information of the public especially in relation to routine tritium discharges, consider the importance of radioactive waste minimisation and optimized management [9–11] and the need for standards and requirements for pressurized equipment to be consistent with FPP specificities.

Recommendation 1—goal setting regulation

Based on the experience of ITER and JET and the current need for flexibility to accommodate emerging technologies, a goal—setting regulatory approach should be adopted whenever possible for FPP design, construction, commissioning, operation, and decommissioning, to allow the operator to apply a proportionate approach to reflect the FPP hazard potential.

Recommendation 2—criteria for emergency reference levels in regulations

A design objective for FPPs should be that no accident or event within the design basis should result in the release of radioactive materials that would require offsite emergency countermeasures or further restrictions of the civilian population outside the plant.

For DECs, countermeasures may be temporarily accepted for short-term periods (for the closest reference groups), limited in time and space.

Recommendation 3—environmental criteria for larger public acceptance

To encourage public acceptance of future FPPs, transparency, education, and information of the public with respect to tritium discharges is necessary for the deployment of FPPs.

Recommendation 4—radioactive waste production

For the future global deployment of FPPs, the fusion community should make every effort to get Governments to seek international agreement on the need for uniformity of waste acceptance, storage and disposal criteria and understanding of fusion specificities. Minimization of radioactive waste shall be of primary consideration. Any material, and their impurity, that would lead to highly activated long lived materials from neutron activation in FPPs should be avoided.

Recommendation 5—regulation of FPP pressurized systems

Specific European regulations on pressurized equipment shall be written for FPPs or adapted from the existing set of the European Directives to consider fusion specificities.

4.2. International databases, codes and standards

International databases, codes and standards will be needed to support FPP designers, regulators, and operators. The applicability of such databases, codes and standards initially developed for fission need to be further assessed and could lead to the identification of areas where adaptation may help in considering the specificity of FPPs.

Recommendation 6—international database

Internationally verified and validated analysis codes should be developed to ease the acceptability of simulation by local authorities.

A list of topics for which international databases are needed to consider the specificity of FPPs shall be assessed, with regards to data on fusion technologies and operating modes as well as to fusion material nuclides effects and complex maintenance activities.

Recommendation 7—FPP codes and standards

Codes and standards, developed for fission facilities, are used by designers, regulators, and operators of nuclear plants. These codes and standards (e.g. ISO, IEC) should consider fusion specificities.

A list of these fusion specificities should be established, topic by topic, to identify the nuclear and/or industrial codes and standards that are applicable, non-applicable, to be newly created and necessitating adaptations. This must be conducted with regards to materials specific to fusion, fusion technologies, and safety methodologies.

4.3. Safety demonstration and rules

Safety demonstration and rules should be developed and adapted for FPPs to allow more flexibility to reflect the hazard potential of FPPs and should be based on a Graded Approach.

Given the current stage in FPP development, safety demonstration shall be based on an initial deterministic approach complemented by the application of a probabilistic approach, limited at the categorization of postulated initiating events and the identification of the hierarchy between events.

Recommendation 8—graded approach to safety demonstration

The safety demonstration rules that are applied at an international level for FPPs should be developed and adapted to allow more flexibility with regards to the risks associated with routine or accidental releases. This graded approach applies as follows:

- no systematic application of the single failure criterion when the short- and long-term consequences of accident scenarios are low,
- acceptance of potential common mode failures when the short- and long-term consequences of accident scenarios are low,
- no systematic combination of loads when the consequences of accident scenarios are low,
- adaptation of DECs to the FPPs.

Recommendation 9—deterministic and probabilistic approaches

Given the current stage in FPP development safety demonstration shall be based on an initial deterministic approach (using conservative assumptions), with appropriate lines of defence that are proportionate to the hazard potential. This approach should be complemented by the application of a probabilistic approach, limited at the categorization of postulated initiating events and the identification of the hierarchy between events. The failure rates are not sufficiently well known; therefore, sensitivity analyses need to be conducted to refine the safety requirements definition.

4.4. International regulatory approaches for the licensing process

International Regulatory Approaches for the licensing process need to reflect the FPP hazard potential and be consistent with the IAEA Fundamental Safety Principles [1] and, preferably, technology neutral. There is a need for international agreement on what constitutes an appropriate legal and safety regulatory approach for FPPs.

Recommendation 10—consensus on a regulatory framework for FPPs

To enable the global deployment of FPPs, the fusion community should make every effort to get IAEA and members states to seek international agreement on what constitutes the basis of an appropriate legal and safety regulatory framework for FPPs that should be delivered by the national regulator.

Since, at present, FPPs are not within the scope of the Council Directive 2009/71/Euratom [12] 'Establishing a community framework for the nuclear safety of nuclear installation', options for the regulation of future FPPs should be defined and assessed to develop an appropriate regulatory framework.

Recommendation 11—implementing a legal and regulatory framework for FPPs

A new regulatory framework for future FPPs should be consistent with the IAEA Fundamental Safety Principles [1] and, preferably, technology neutral.

Recommendation 12—prescriptive regulatory frameworks

For countries using a prescriptive approach to regulation, any regulatory requirements and regulations relating to the safety of FPPs should be based on a graded approach and be proportionate to the hazard potential of a FPP.

5. Conclusions

The analysis of the lessons learnt from existing fusion facilities, the review of reports by IAEA and European Commission on FPP safety and the on-going work by UK government, US NRC and Canadian CSNC has led to the identification of commonalities between fusion and fission in terms of fundamental safety objectives, even though they were initially shaped for nuclear fission characteristics. Nevertheless, there are differences in the implementation of a common methodology due to differences in hazard potential (i.e. unmitigated risks) and in the physical principles behind these two types of reactors, together with their associated technologies.

The regulation and licensing of FPPs requires an assessment of whether the current set of national or international safety standards for NPPs are FPP appropriate given the inherent lower hazard potential to remain proportionate with the associated safety challenges.

Regulatory frameworks depend upon a country's legal framework, therefore it is apparent that a common global regulatory framework for FPPs is not possible. However, as with present-day NPP regulation, efforts could be made to develop harmonised approaches to FPP regulation to provide common levels of protection.

In view of this objective, 12 recommendations have been presented relating to 4 areas of adaptation to the FPP challenges:

- **Regulations—**considering whenever possible a goal-setting regulatory approach; recognising the need for emergency preparedness; considering the importance of transparency, education, and information of the public especially in relation to routine tritium discharges; the importance of radioactive waste minimisation and optimized management; and the need for standards and requirements for pressurized equipment to be consistent with FPP specificities.
- **International databases, codes and standards** will be needed to support FPP designers, regulators, and operators. The applicability of such databases, codes and standards initially developed for fission need to be further assessed and could lead to the identification of areas where adaptation may help in considering the specificity of FPPs.
- **Safety demonstration and rules** should be developed and adapted for FPPs to allow more flexibility to reflect the hazard potential of FPPs and should be based on a Graded Approach. Given the current stage in FPP development safety demonstration shall be based on an initial deterministic approach complemented by the application of a probabilistic approach, limited at the categorization of postulated initiating events and the identification of the hierarchy between events.
- **International regulatory approaches for the licensing process** need to reflect the FPP hazard potential and be consistent with the IAEA Fundamental Safety Principles [1] and, preferably, technology neutral. There is a need for international agreement on what constitutes an appropriate legal and safety regulatory approach for FPPs.

Further activities are now required to address this topic. The next step is to establish a list of fusion specificities to identify their impact on safety and therefore the applicability of certain nuclear and/or industrial codes and standards, together with codes and standards that are not applicable, and the areas where new codes and standards need to be developed. At this stage, we have not given a recommendation concerning the external liability of the FPP operator, but liability issues should also be considered. In particular, new criteria related to fusion activities could be introduced in the Paris Convention or in an analogous liability framework most applicable for fusion [13].

The development of FPP specific codes and standards, safety goals and a technology neutral safety regulatory framework will need to be supported by a consistent communication strategy. For fusion success, it is critical to educate and inform the public and politicians about the safety of FPPs including their hazard potential, their safety characteristics, the safety measures that ensure that risks to workers and the public are ALARP/ALARA, the impact on the public of design basis and design extension accidents, the scale and management of radioactive waste and the precautions that are taken to protect the environment.

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References

[1] IAEA 2006 *Fundamental Safety Principles, IAEA Safety Standards Series No. SF-1* (IAEA)
[2] European Commission Directorate General for Energy 2022 Study on the applicability of the regulatory framework for nuclear facilities to fusion facilities: towards a specific regulatory framework for fusion facilities: final report (Publications Office of the European Union) (available at: https://data.europa.eu/doi/10.2833/787609)
[3] UK Department for Business, Energy & Industrial Strategy 2022 Towards fusion energy: the UK Government's response to the consultation on its proposals for a regulatory framework for fusion energy (available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1084472/towards-fusion-energy-uk-government-response.pdf)
[4] UK Atomic Energy Authority 2021 Technology report—safety and waste aspects for fusion power plants (available at: https://scientific-publications.ukaea.uk/wp-content/uploads/UKAEA-RE2101-Fusion-Technology-Report-Issue-1.pdf)
[5] United States Nuclear Regulatory Commission 2023 Options for licensing and regulating fusion energy systems, policy issue SECY-23-0001 (available at: www.nrc.gov/docs/ML2227/ML22273A178.html)
[6] Clark B.P. 2023 Memorandum: staff requirements—secy-23-0001—options for licensing and regulating fusion energy systems (available at: www.nrc.gov/docs/ML2310/ML23103A449.pdf) (Accessed 21 June 2023)
[7] U.S.NRC 2023 Fusion energy systems (available at: www.nrc.gov/materials/fusion-energy-systems.html) (Accessed 3 July 2023)
[8] Canadian Nuclear Safety Commission2022 Review of the Canadian Nuclear Safety Commission's regulatory framework for readiness to regulate fusion technologies, task #5: final overview report K-640209/RP/004 R01 (CNSC Reference: RSP-762.1)

[9] The Council of the European Union 2011 COUNCIL DIRECTIVE 2011/70/EURATOM: establishing a community framework for the responsible and safe management of spent fuel and radioactive waste (19 July) (available at: http://data.europa.eu/eli/dir/2011/70/oj)
[10] European Commission 2019 REPORT FROM THE COMMISSION TO THE COUNCIL AND THE EUROPEAN PARLIAMENT on progress of implementation of Council Directive 2011/70/EURATOM and an inventory of radioactive waste and spent fuel present in the Community's territory and the future prospects (17 December) (available at: https://eur-lex.europa.eu/legal-content/EN/TXT/%20PDF/?uri=CELEX:52019DC0632&from=EN)
[11] The Council of the European Union 2009 COUNCIL DIRECTIVE 2009/71/EURATOM: establishing a community framework for the nuclear safety of nuclear installations (25 June) (available at: http://data.europa.eu/eli/dir/2009/71/oj)
[12] United Nations 1988 No. 13706 convention on third party liability in the field of nuclear energy, concluded at Paris on 29 July 1960 (available at: https://treaties.un.org/doc/Publication/UNTS/Volume%201519/volume-1519-I-13706-English.pdf) (Accessed 16 November 2023)
[13] The Council of the European Union 2006 COUNCIL DIRECTIVE 2006/117/EURATOM: on the supervision and control of shipments of radioactive waste and spent fuel (20 November) (available at: http://data.europa.eu/eli/dir/2006/117/oj)