Comparative maps of safety features for fission and fusion reactors

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ABSTRACT

The differences between nuclear fission and fusion have been discussed widely in the literature. However, little has been done to investigate the key differences in safety designs and regulatory requirements between the nuclear reactor types. In this study, an innovative methodology was successfully developed to map nuclear safety features to the fundamental safety principles set out by the nuclear regulators. Three safety cases were assessed in the mapping study, a research fusion reactor (Joint European Torus), a research fission reactor (Tsing Hua Open-pool Reactor) and a commercial fission reactor (Hinkley Point C). The graphical representation allowed a comparative analysis of the safety features and fundamental principles which revealed differences between the hazard profiles of fission and fusion reactors and provided important insights for the creation of a similar map for a future commercial fusion device.

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INTRODUCTION

The potential of fusion energy has been recognised in recent years as an alternative energy source to support the commitment in reducing CO_2 and protecting the environment. Several developments have been made in the delivery of fusion, such as the construction of the International Thermonuclear Experimental Reactor (ITER) in southern France and the Spherical Tokamak for Energy Production (STEP) programme in the UK. However, Herb et al. [1] highlighted the urgent need for developing safety frameworks alongside designing fusion concepts. They reported that there was no official regulatory framework for a fusion powerplant to date† [2–4]. Furthermore, several studies pointed out the need for specific requirements due to the inherent differences in the technologies and physics between fusion and fission [5–7]. Inabe et al. [6] also emphasised the extensive use of non-radioactive but hazardous materials in the fusion environment as an added safety consideration. However, most previous studies primarily focused on the key physics phenomena and safety requirements, while very little research has been performed to establish the connection between them. Hence, the aim of this study was to identify and illustrate the connections between the safety features and the fundamental safety principles (FPs) historically used in regulating nuclear plants using a mapping process that could be extended to identify the appropriate connections for innovations in nuclear powerplants in the future, such as Gen IV or V fission reactors or a commercial fusion powerplant. To enable the latter and since no commercial fusion

† The UK has proposed a regulatory framework in the recent published white paper, which can be found in the following link:

https://www.gov.uk/government/consultations/towards-fusion-energy-proposals-for-a-regulatory-framework reactor exists, the safety case of a research fusion reactor (Joint European Torus) was investigated. In contrast, for fission reactors, the study was able to assess the safety cases of both a research reactor (Tsing Hua Open-pool Reactor) and a commercial fission reactor (Hinkley Point C).

The paper is structured as follows. Section 2 will describe the method used for the mapping process and for presentation of the results. Section 3 will present the mapping results. A comprehensive analysis of the maps will be discussed in section 4 and some conclusions are drawn in the closing section of the paper.

METHODOLOGY

The priority of the study was to identify the link between safety features and the associated fundamental safety principles (FPs) of nuclear reactors including both fission and fusion reactor types, i.e., the light water reactor at Hinkley Point C (HPC), the Tsing Hua Open-pool Reactor (THOR), and the fusion research reactor designated the Joint European Torus (JET). A schematic of the full process is shown in Figure 1.

The fundamental principles, shown in Table 1, were extracted from the United Kingdom (UK) nuclear Safety Assessment Principles (SAPs) [8], which use a goal-setting approach. The existing nuclear safety requirements are often criticised for being too focussed on fission [1,7,9], and consequently inappropriate to apply to fusion. Herb et al. [1] investigated the key safety principles in some design areas, such as containment systems and defence in depth based on the existing German nuclear regulations, they concluded that the current requirement could be applied in principle to a fusion reactor, but a detailed assessment would need to be discussed further. In this study, an assessment in

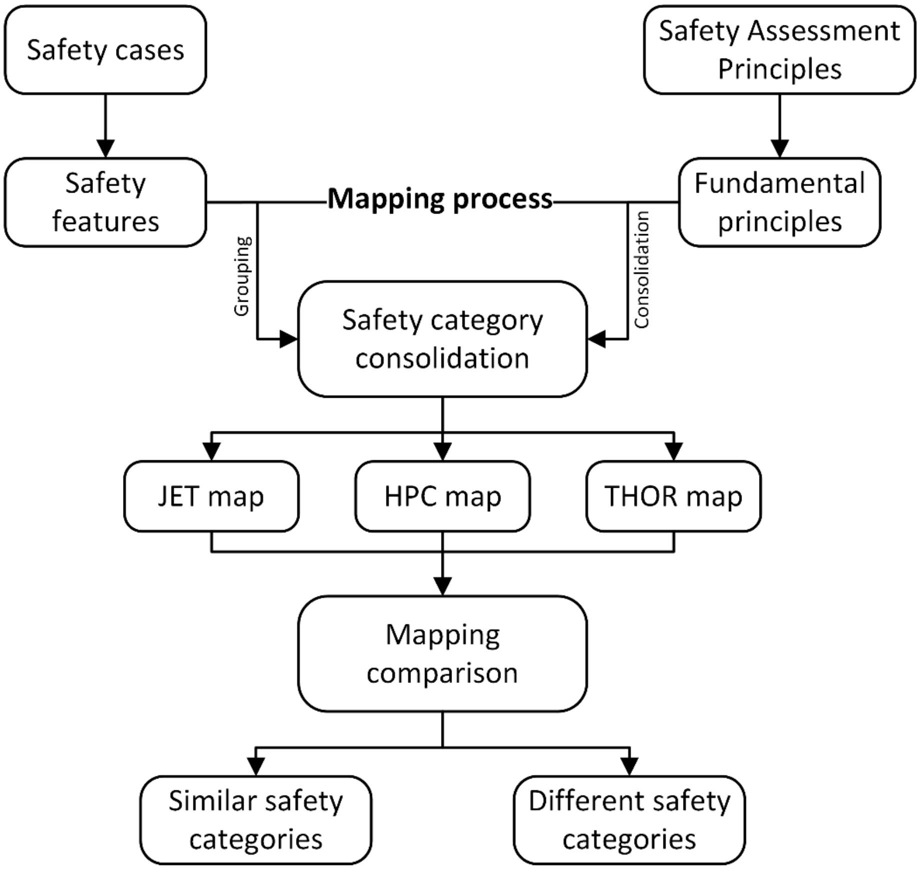

Figure 1. A schematic diagram of the mapping process and analysis.

the UK regulatory context has been conducted based on the Safety Assessment Principles [8], in which the fundamental principles have been extracted and used in a mapping process to provide a fair evaluation and comparison between the safety cases for fission and fusion reactors.

Safety features were extracted from the safety cases presented in the HPC Pre-Construction Safety Report (PCSR) [10], THOR Safety Analysis Report (SAR) [11] and the JET safety case [12]. There are multiple elements of the safety characteristics that are described in these documents, including the general engineering safety design and nuclear safety functions. General engineering design, such as site development and non-nuclear pipework, would be applicable to the construction of any complex engineering structure. Thus, it would be difficult to use them to address the key differences between fission and fusion. Therefore, only those safety features that were clearly nuclear-specific were extracted.

Table 1. UK fundamental principles (FPs) (extracted from the Safety Assessment Principles (SAPs) [8])

FP.1	**Responsibility for safety**	The prime responsibility for the safety must rest with the person or organisation responsible for the facilities and activities that give rise to radiation risks.
FP.2	**Leadership and management for safety**	Effective leadership and management for safety must be established and sustained in organisations concerned with, and facilities and activities that give rise to, radiation risks
FP.3	**Optimisation of protection**	Protection must be optimised to provide the highest level of safety that is reasonably practicable
FP.4	**Safety assessment**	Duty holders must demonstrate effective understanding and control of the hazards posed by a site or facility through a comprehensive and systematic process of safety assessment
FP.5	**Limitation of risks to individuals**	Measures for controlling radiation risks must ensure that no individual bears an unacceptable risk of harm
FP.6	**Prevention of accidents**	All reasonably practicable steps must be taken to prevent and mitigate nuclear or radiation accidents
FP.7	**Emergency preparedness and response**	Arrangements must be made for emergency preparedness and response in case of nuclear or radiation incidents
FP.8	**Protection of present and future generation**	People, present and future, must be adequately protected against radiation risks

The mapping process was achieved by following the decision tree shown in Figure 2. Firstly, each safety feature was assessed for its ability to demonstrate each of the fundamental principles. If the assessment was positive, a relationship was recorded. The feature was then returned for assessment against the remaining principles by following the loop at the top of Figure 2. If it was rejected, additional information, such as its relation to other components or systems, was extracted from the safety cases to support our understanding of the safety function and to confirm that it was insufficient to demonstrate the fundamental principle. If the result of this further assessment was returned as positive, then the relationship was recorded, and the process continued to follow the top loop for this safety feature. However, if it was still a negative outcome, the rejection decision was recorded, and the process proceeded to the assessment of the safety feature against other fundamental principles following the loop on the left in Figure 2.

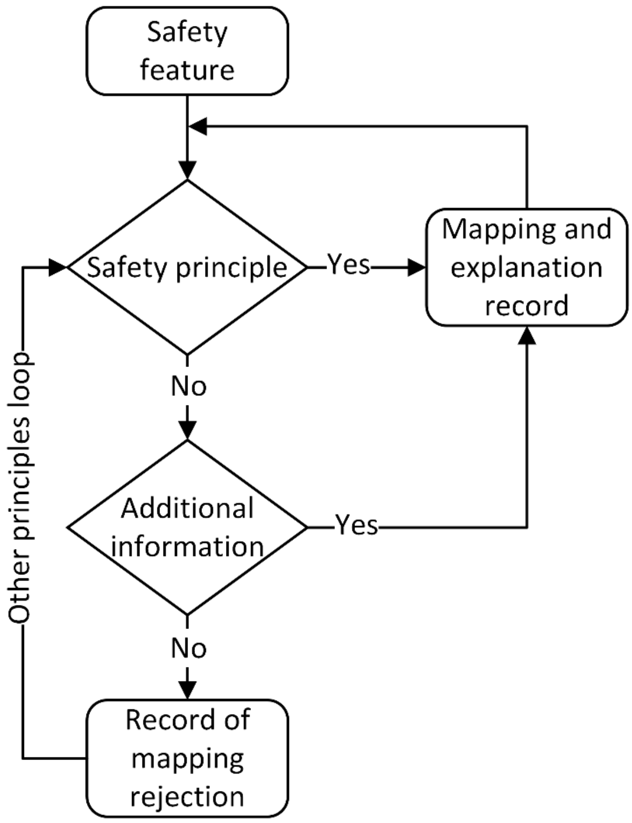

Figure 2. Decision tree used to assess the demonstration of each fundamental principle by a safety feature.

At the end of the mapping process, the safety features, which shared a common safety function, were grouped under the safety categories as shown in the first columns of the maps in Figure 3. For example, in HPC, waste treatment and interim storage share the same function that primarily deals with nuclear waste. Thus, they were classified under the category of "discharges and waste". Categories were set at a high level to allow appropriate comparison between the reactors. Further consolidation was achieved by counting the number of relationships generated between the safety features in the group and the fundamental principles, as described above. A colour coding system, shown in Figure 5, was used to illustrate this relationship. In this figure, the jet colour map in the vertical direction represented the proportion of total safety features that were grouped into the category. This was used to generate a colour map ranging from dark blue to dark red. In the horizontal direction, a colour scale was used to represent the proportion of safety features in the category linked to the fundamental principles. For example, in the map for the JET reactor in Figure 3, the safety category entitled 'human factors and operational aspects' is in the top row and possesses 13 out of 42 safety features (31%); hence the colour associated with 31% in the 5th row from the top in Figure 5 has been used for the top row in Figure 3. In this safety category, 9 out of 13 safety features (0.69) were mapped to fundamental principle 4 (FP4); hence, the intensity corresponding to the column headed (0.61-0.70) in Figure 5 has been used for the corresponding cell in Figure 3.

Finally, the three maps were reorganised in a way that aligned the categories for comparison and analysis. Similar categories were identified and rearranged as shown in Figure 3. There were also categories that appeared only in the map of a single reactor, such as inventory limit and dose constraints for JET, or coolant system for HPC and THOR. These categories were consolidated separately in Figure 4.

RESULT

The completion of the mapping process resulted in three maps for JET, HPC and THOR based on the fundamental principles defined in the current UK nuclear safety assessment principles (SAPs). There were 42, 83 and 35 safety features extracted from the JET safety case summary, HPC pre-construction safety report (PCSR) and THOR safety analysis reports, respectively. The safety features were grouped into seven safety categories for the JET map, eight categories for the HPC map and seven categories for the THOR map. Figure 3 consolidates the six categories which appear in all three maps. Conversely, the remaining categories from each map are collated in Figure 4.

The colour coding has revealed several characteristics, which will be discussed in detail in the following section. The graphical depiction of the results allows a comparison using the intensity of the colours, which highlights the key safety categories for each nuclear reactor in the vertical direction and the emphasised fundamental principles in the horizontal direction.

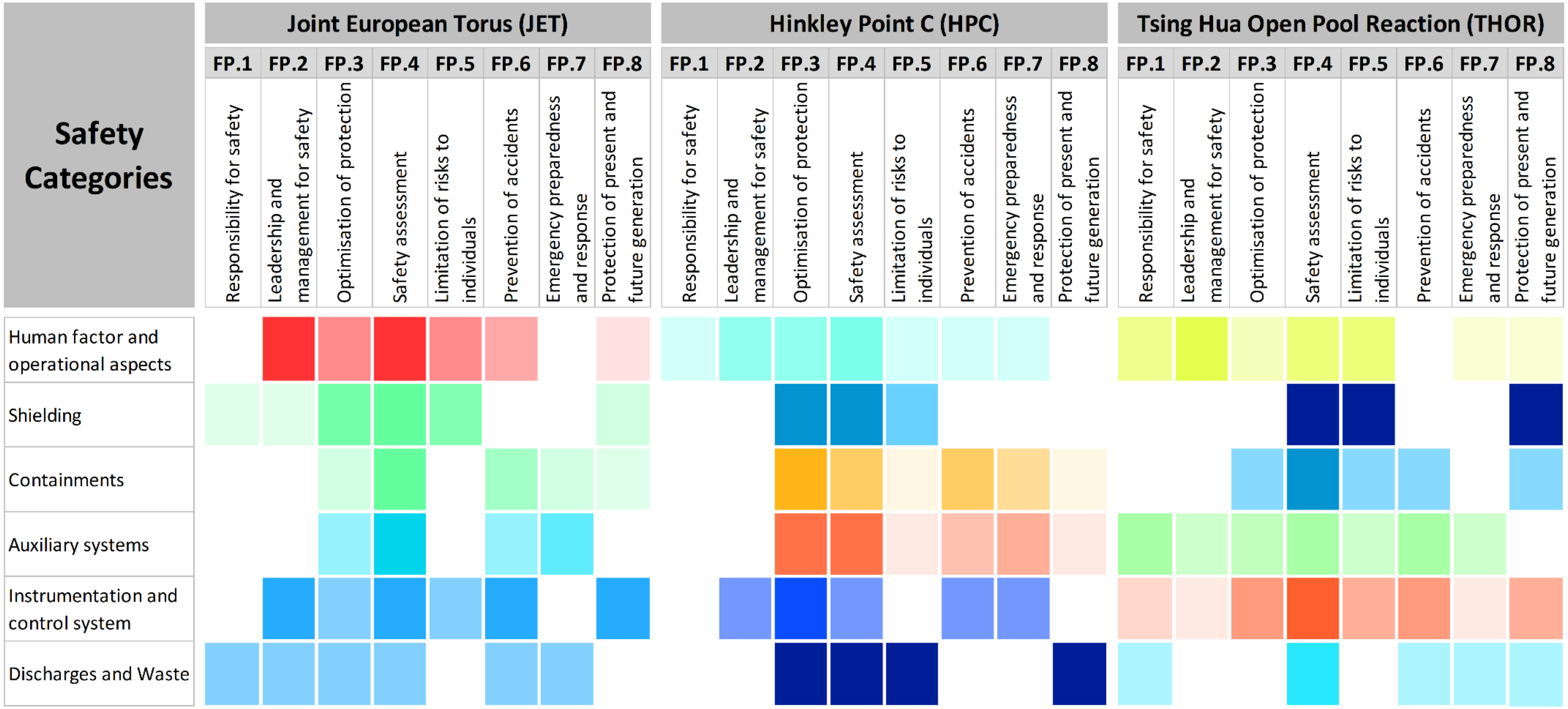

Figure 3. A comparison of identical safety categories between JET, HPC and THOR maps based on the UK fundamental principles. The safety categories comprised of several safety features extracted from the JET safety case, HPC Pre-construction Safety Report and THOR safety analysis report. The fundamental principles were extracted from the safety assessment principles (SAPs (UK)). The colour legend for the map is shown in Figure 5.

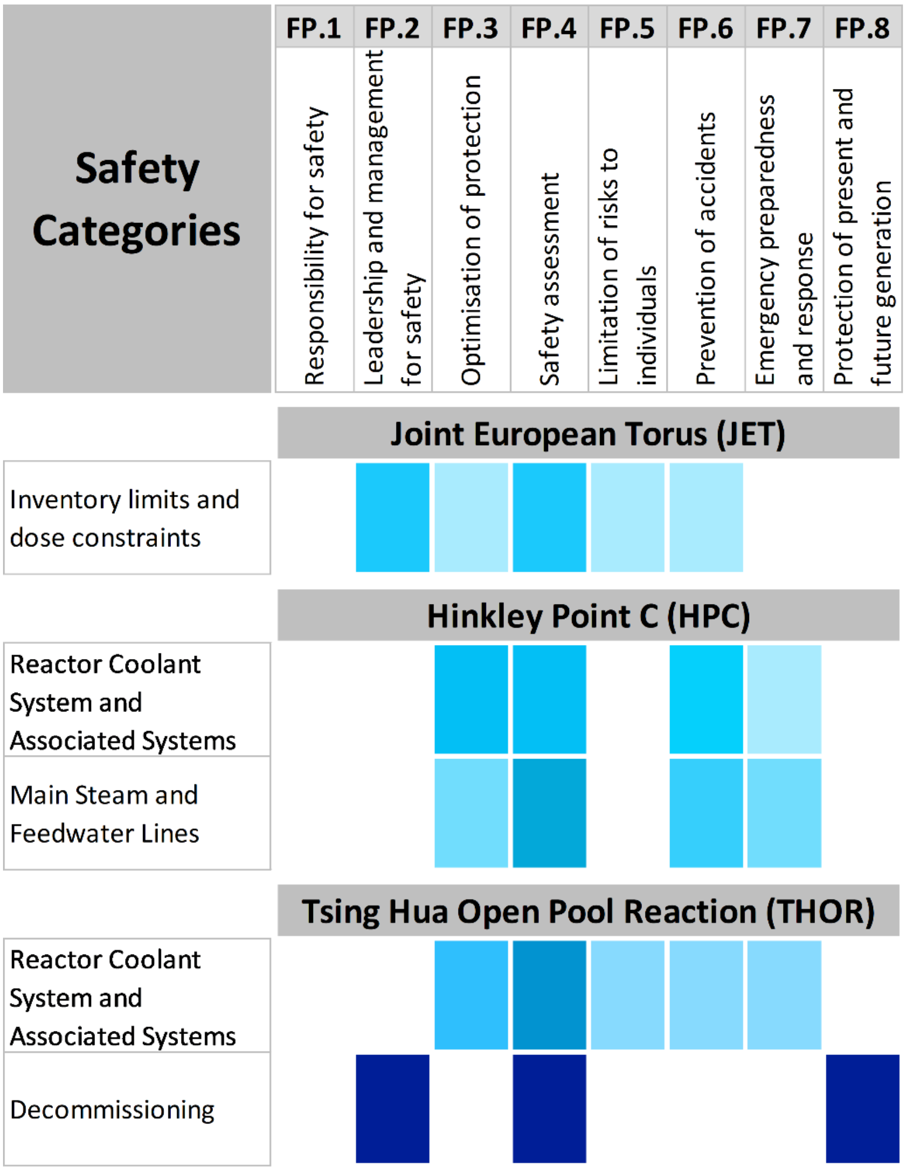

Figure 4. Map of categories that only occur in the safety case of a single reactor.

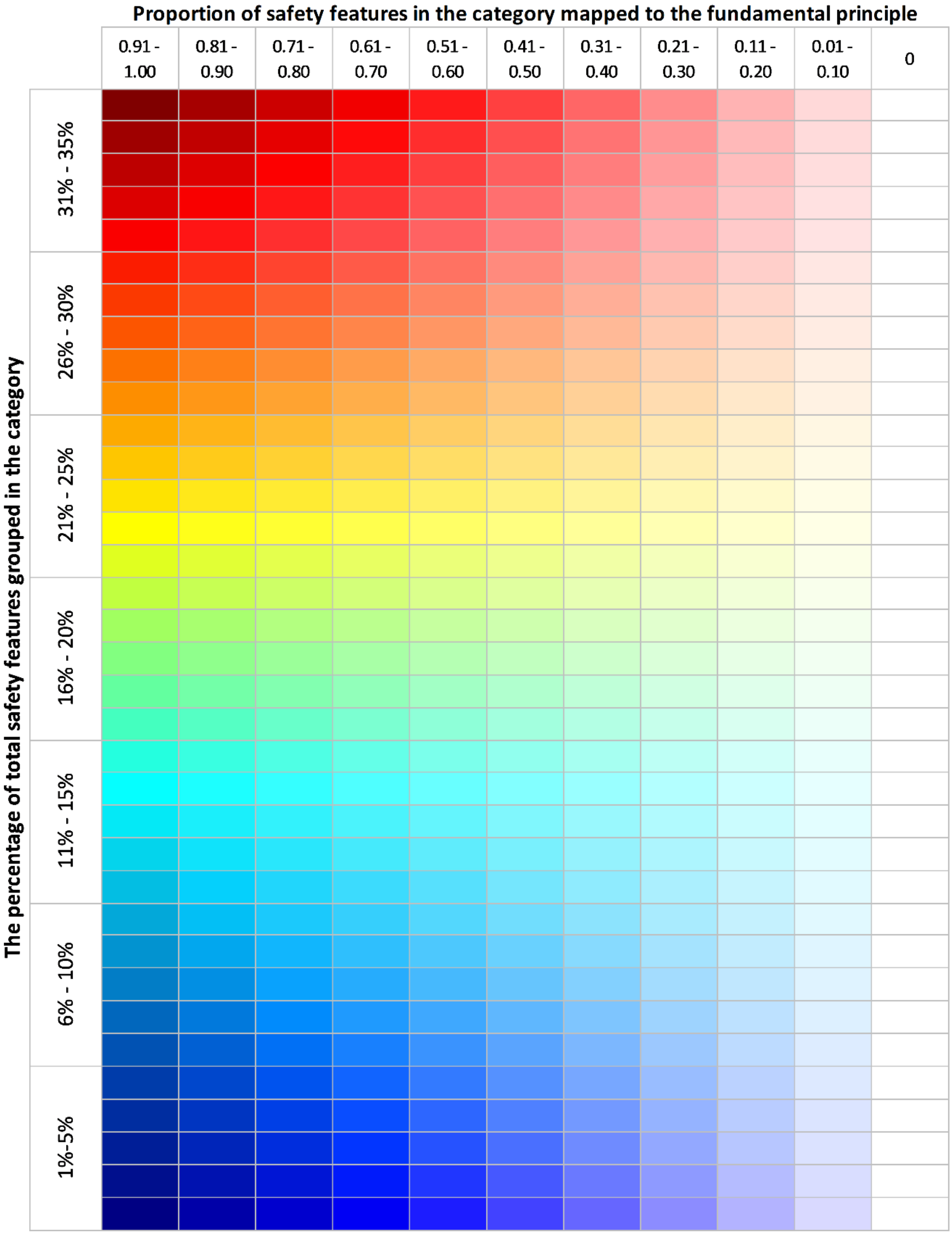

Figure 5. Map colour system: in the vertical direction, the heat colour selection was based on the number of safety features in the category; in the horizontal direction, the colour intensity depends on the proportion of the safety features in the category mapped to the fundamental principles.

DISCUSSION

The mapping process attempted to draw the connections between key safety features in reactor designs and requirements for both fission and fusion reactors. While the maps were developed at a high level, the results reveal patterns which could be helpful in understanding the relationships between the safety approaches and regulatory requirements. This section will be presented in the following order. Firstly, an analysis of the resultant maps in which the key differences between fission and fusion reactors are identified. Previous studies compared the risk profile between fission and fusion reactions based on their differences in physics and technology; however, the mapping results both contradict and support some of these comparisons. Secondly, the safety management approaches will be compared with the regulatory principles. This supports an understanding of the current methodologies employed to demonstrate the safety requirements. Finally, the possibility of establishing a map for a future commercial fusion device will be explored based on the knowledge gained from this study.

1. Differences in hazard profile between fission and fusion reactors

The key differences between fission and fusion reactors lie in their principal nuclear reactions, which Wu et al. [13] summarised as: a fusion reaction would inherently terminate itself in the case of an accident while a fission reaction intrinsically carries the possibility of a nuclear chain reaction. Thus, they claimed that a fusion reactor is fundamentally safer than a fission one. In our study, the maps for fission reactors (HPC and THOR) revealed a clear focus on preventing and mitigating the potential runaway chain reactions of a fission device. Categories such as auxiliary and reactor cooling systems, which have primary functions of controlling reactivity and the removal of heat from the fuel to ensure the integrity of the core loop, demonstrated the efforts in preventing and mitigating chain reactions in fission reactors. Auxiliary systems were the most important in the HPC map containing 28% of the total number of safety features in the safety case. The category was the third most important in the THOR map with 17% of the safety features. Conversely in both maps, the reactor coolant system contains approximately the same proportion of safety features and only appears in the safety cases of fission devices (10% and 9% of safety features in HPC and THOR respectively).

On the other hand, in the case of fusion reactors, Wu et al. [13] highlighted the complexity of radiation exposure and the mobility of the tritium inventory from the ITER preliminary safety report. In our study, the map for JET supported their conclusion with clear emphases on the categories of shielding, containment, and tritium inventory limits. Like the map for THOR, the JET map also has a large number of safety features in the operational categories (31%). Thus, this category was the most important while the above-mentioned categories were ranked second, third and fifth respectively in the JET map in terms of importance. The shielding category contained 17% of JET safety features but only 8% of HPC safety features and as few as 3% of THOR safety features. Wu et al. [13] explained that the sources of radiation exposure in fusion devices are the high energy (14MeV) fusion neutrons, activation products and tritium itself; while, for fission, the sources are mainly gamma-radiation and activation products. Furthermore, the lack of knowledge and operational data for high energy neutrons (14MeV), which interact with electronics and structural components such as breeding blanket, toroidal and poloidal field coils or vacuum vessel, present a challenge that requires multiple layers of shielding [7]. This is not only to ensure the safety of personnel but also to protect important and expensive monitoring instruments, which play a critical role in plasma and radiation control.

Additionally, the use of tritium as fuel in fusion presents a major challenge. Despite its half-life of 12.32 years and relatively weak beta radiation, the high permeation power of tritium is particularly dangerous [14]. It could diffuse through materials and escape during reactor operation or maintenance. Furthermore, tritium shares some characteristics with hydrogen which allow it to replace hydrogen atoms in materials, especially water. Leaked tritiated water could readily traverse the environment and cause exposure to humans through various pathways such as direct inhalation, ingestion or in the food chain. The presence of tritium in the human body could cause serious harm to tissues and organs. Therefore, it is critical to monitor and contain tritium during both operation and maintenance. This is evidenced in Figure 4, where the category of inventory limit and dose constraint, that primarily concern the tritium inventory, contained 10% of the safety features in the JET safety case, which covered a wide range of different areas in reactor operation including beryllium recycling and the quantity of tritium in cryopanels. Herb et al. [1] pointed out that the tritium inventory would not be stored locally unlike for fission fuel which is contained in the reactor core. Thus, multiple parts of the reactor will be affected and need to be secured [7,15].

The comparison of the safety categories has shown key differences between the reactors. It is clear that the regulatory assessment of safety in fusion should reflect its hazard profile by addressing the categories in their appropriate priority.

2. Approaches in demonstrating safety regulatory requirements

The general patterns in two groups of fundamental principles, namely FP3 & 4 and FP6 & 7, stand out in particular. Firstly, 'Safety Assessment' (FP4) requires an understanding and control of hazards while 'Optimisation of Protection' (FP3) needs to satisfy the ALARP principle (As Low As Reasonably Practicable)‡. In other words, FP4 forms the basic safety requirements for each identified hazard to be addressed while FP3 builds upon on the evaluation of the need for further defensive layers. In the map for HPC, the majority of categories (6 out of 8) showed either an equal or slightly higher concentration of safety features for FP3 than FP4. On the contrary, categories in the map for JET (6 out of 7) and the THOR map (8 out of 8) showed a stronger emphasis on FP4 than FP3. The lack of emphasis on FP3 in the maps of JET and THOR is logical since both reactors pose a lower level of risk than the two commercial HPC reactors, which also showed that the effort to meet the safety requirements is proportional to the level of underlying risk.

In the context of research reactors, JET and THOR, previous studies have described the hazard profile of the fusion technology as being of a lower level of risk compared to fission technology [3,15,16]. However, in our study, both maps showed less emphasis on most safety categories for the fundamental principle most closely associated with the technology, i.e., FP3 – Optimisation of protection, than the other fundamental principles. The proportion of changes between the fundamental principles was observed to be almost identical, which could suggest that the overall level of risk between the two reactors is the same while the focus is in different areas. Furthermore, in shielding and waste control, the JET safety case showed the same proportion between FP3 and FP4, which implies that the JET device poses a higher risk than the THOR reactor in these categories. Therefore, our results relating to FP3 and 4 do not support the above claim that the hazard profile for fusion is always lower than for fission, particularly in the case of JET and THOR. The passive nature of the fusion reaction, as discussed by Wu et al. [13], would provide an inherent safety feature for fusion reactors.

‡ The details of each principle can be found in Table 1

However, its level of risk should take into account different and unknown parameters, for example, Sandri et al. [17] raised concerns about the exposure to workers and staff due to radiation from tritium and activated products. The authors highlighted the need for the specific design of a fusion facility to allow a thorough process and procedure to be established.

'Prevention of Accidents' (FP6) and 'Emergency procedures and response' (FP7) represent different approaches to safety management. The sixth fundamental principle emphasises the prevention of accidents and mitigation of consequences; while the seventh principle accentuates preparedness and responses to reactor accident scenarios. In our results, a higher emphasis on FP6 than FP7 was observed in 50% or more of the categories across the maps (4 out of 6 for JET, 3 out of 6 for HPC and THOR). These results suggest that prevention and mitigation is currently the main safety approach in these categories, which requires a knowledge of the probability of accident events and analysis of the consequences. Any uncertainty in these analyses would lead to "appropriate conservatism" [8]. In the case of fusion, Lomonaco et al. [18] highlighted that a lack of knowledge and experience in unknown initiating events would lead to a high level of conservatism in design. They argued that this might put an unnecessary burden on the design of, and investment in, fusion reactors. Furthermore, any commercial fusion reactor would serve as a first of a kind, in which the lower level of technological readiness and lack of operating experience would be major challenges to demonstrating its safe operation despite its advantage in the inherent safe nature of fusion [1]. Therefore, it is critical that the approach to safety in future fusion plants should overcome these challenges without diminishing the advantages of fusion reactors discussed above. The information contained in the maps in Figures 3 and 4 provide some insights that could be useful in the construction of a safety case for commercial fusion devices.

For example, in Figure 3, our results showed that a higher intensity for FP7 (preparedness and response) appeared in one category throughout the three maps. This insight could imply an alternative approach focusing on monitoring and planning for emergency rather than prevention and mitigation. In the safety assessment principles (SAPs), paragraph 609 suggests that this could be a reasonable approach, given justification by a thorough analysis. For example, in the containment category, the safety features in the HPC and THOR safety cases were mainly to contain fission products in the reactor core. The open-pool design of THOR relies heavily on cladding to contain the radioactive fission products which is evidenced by the substantial number of analyses to demonstrate the integrity of fuel cladding during any uncovered core accident. In the HPC case, fuel cladding and several additional physical layers, such as the reactor vessel, containment building, corium recovery area, were designed to prevent the release of radiation. However, in the case of fusion, the complexity in the design of reactor components and the management of the tritium inventory in various systems of the plant (including the vacuum vessel, fuel injection system, tritium processing facility), makes it challenging to design containment for the whole system [15]. Additionally, Löffler and Nie et al. [19,20] investigated hypothetical accident consequences of fusion and demonstrated that the severity of radiation consequences in fusion accidents is less than that in fission accidents. It was highlighted by Nie et al. [20] that the consequence of a hypothetical fusion accident could only reach level 6 on the International Nuclear Event Scale (INES) while Chernobyl and Fukushima accidents reached level 7. The authors also investigated the potential individual dose and the restoration time of the affected environment following a fusion accident and concluded that they are of several orders lower than that in fission accidents. Furthermore, the UKAEA's Fusion Safety Authority has previously reported on two worst-case accidental scenarios (loss of vacuum vessel (LOVA) in the first scenario and LOVA with additional breach of further confinement layer in the second scenario) and a hypothetical scenario (breach of all confinement layers) with the aim of establishing the potential consequence of fusion accidents [21]. Based on the risk matrix of the UK Radiation Emergency Preparedness and Public information Regulation 2019 (REPPIR 2019), the first accidental scenario poses a very low likelihood and limited consequence while the second scenario presents “minor to low moderate” impact range with likelihood of “events not considered in the design”. The hypothetical accident could result in individual (at 1km away from the source) receiving dose of up to 1 Sievert. However, the likelihood of such event is lower than the minimum threshold considered in the REPPIR matrix. In the UK’s proposed regulatory framework [22], it was highlighted that the likelihood and impact range of the first accidental scenario would require no emergency planning under the REPPIR 2019. On the other hand, some considerations would be needed in the arrangement of emergency preparedness and response for accidents corresponding to the second or the hypothetical scenarios. Therefore, a combination of a good monitoring strategy and planning for emergency preparedness could be a sound approach in the design of a fusion device.

A careful integrated use of prevention and preparedness could ease the current challenges in fusion, which concurs with Lomonaco et al. [18] who suggested that the regulation of nuclear devices should strike a balance between safety requirements and economic value. This is particularly applicable to hazards with very low to low consequences which often require an extensive probabilistic risk assessment to demonstrate the prevention strategy. A recognition of the low level of consequences of these hazards could result in a reduction in the extent of the risk analysis and a simpler safety system, which could be countered by more comprehensive preparedness measures.

3. Potential use of JET map in the mapping of future fusion devices

A comparison of the maps for THOR and HPC shows that the latter involves substantially more safety features than the former, perhaps this is to be expected given the larger scale of HPC; nevertheless, there is a recognisable common pattern. Several activities carried out at THOR, such as training and education, medical treatments (boron neutron capture therapy), manufacture of irradiated materials, gave rise to a number of safety features in the human factors and operational categories. Taking this into account, the order of almost all remaining categories (auxiliary systems, containments, reactor coolants and associate systems, and shielding) in the THOR map shows a direct resemblance to the HPC map, except for the category of discharges and waste. Since the safety report for the HPC was produced at the pre-construction stage, this could be considered as an outlier. Thus, one could conclude that the common pattern is characteristic of fission devices and the difference in the number of safety features characterises the differences between a research and a commercial reactor, some of which are associated with their scales and should be recognised in transitioning from the design of one to the other. For example, in shielding, a higher proportion of safety features are present for HPC compared to THOR, which shows the scaling effect from the small-scale research reactor to the large-scale of a commercial one. Similarly, in containment, the significant rise in scale and power output resulted in an exponential increase in the number of safety features. Thus, these scaling effects will need to be considered in developing a corresponding map for a commercial fusion reactor from one for a research reactor, such as JET. For instance, it would be expected to have a significant number of safety features in the instrumentation and control systems to ensure the safe operation of the reactor. In terms of waste management, Ciampichetti et al. [16] highlighted that the radiological risks of fusion waste are lower than fission, which suggests the design of a fusion device should place more emphasis on monitoring tritium discharges in the category of discharges and waste.

Since a commercial fusion device would be the first of a kind (FOAK) with the associated unknowns of a FOAK, it is essential that the lessons learnt from experience with commercial fission devices and fusion research devices should be fully utilised in its design. This mapping methodology and the graphical results presented here provide a framework for identifying the lessons and discussing their implementation in a FOAK fusion reactor and also allow a comparative analysis of the safety features and fundamental principles of the three devices as a preliminary to generating an equivalent map for a future commercial fusion device.

CONCLUSION

In conclusion, this study has developed a methodology for the mapping of nuclear safety features and regulatory fundamental principles. The graphical presentation using maps has revealed the interaction between regulatory requirements and safety approaches. This has enabled a straightforward comparative analysis that has highlighted a number of strends. Firstly, fusion and fission reactors require very different priorities for their safety categories. Fusion safety cases focus on shielding and inventory limits while fission safety cases emphasise auxiliary systems and reactor cooling systems. Secondly, the strong emphasis on safety assessment (FP4) compared to protection optimisation (FP3) could be observed in almost every category in the maps for the Joint Europe Torus (JET) and Tsing Hua Open pool Reactor (THOR), while the opposite is present in the Hinkley Point C (HPC) map, perhaps as a result of the differences in scale and purpose. However, all of the maps show a heavier emphasis on prevention and mitigation approaches (FP6) than on emergency preparedness and response approaches (FP7). The graphical representation allowed a comparative analysis of the safety features and fundamental principles of the three devices which revealed differences between the hazard profiles of fission and fusion reactors and provided important insights for the creation of a similar map for a future commercial fusion device.

AUTHORS’ CONTRIBUTION

EAP & RJT conceived the study, TN performed the analyses with inputs from CW & YST under the supervision of CW, EAP & RJT. First draft prepared by TN, edited by EAP & RJT and reviewed by CW & YST. All authors have read and agreed to the final version of the manuscript.

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