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THE LICENSING OF NUCLEAR FUSION POWER PLANTS – A PROPORTIONATE APPROACH

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Abstract

The commercial exploitation of nuclear fusion energy for electricity production is now nearer than previously imagined. Several organisations are developing fusion reactors with the aim of demonstrating electricity production in the 2030s. These timescales suggest that conceptual designs are being worked on now and the detailed design, construction and commissioning of these demonstration power plants will be taking place over the next 10 to 15 years. At present nuclear fusion is not covered by the comprehensive set of international Conventions and standards covering nuclear safety and nuclear security that apply to nuclear fission power plants. Also, national laws and regulatory frameworks for nuclear energy focus on nuclear fission and often their licensing provisions do not apply to nuclear fusion facilities. It is recognised that the hazard potential of a fusion power plant is significantly less than that of a fission power plant; however, the public and politicians will expect this new form of electricity production from nuclear fusion to be regulated to ensure the safety of workers and the public and the protection of the environment. The paper explores the issues surrounding a licensing framework for nuclear fusion and argues for a licensing framework to be proportionate to the hazard potential of fusion power. It will also consider the regulatory challenges associated with the introduction of fusion power, the likely steps in the licensing process and the appropriate regulatory oversight.

Introduction

1. Fusion is a nuclear process and as such the public and politicians will expect the commercial exploitation of the technology to be adequately controlled. Until recently the exploitation of fusion technology for power generation was considered to be a long-term prospect 30 to 40 years into the future. However, the commercial exploitation of nuclear fusion for power generation is rapidly becoming a realisation with several countries and organisations embarking on ambitious plans to develop fusion power plants within the next 10 to 20 years. At present, however, the design, construction, commissioning, operation, decommissioning, or regulation of nuclear fusion power plants are not covered by the comprehensive set of nuclear safety and nuclear security international Conventions, standards and guides that apply to nuclear fission power plants (NPPs). Also, in general, national laws and regulatory frameworks for nuclear power plants focus on nuclear fission and often their licensing provisions do not apply to nuclear fusion facilities. Whilst it is recognised that the hazard potential of a fusion power plant is significantly less than that of a fission power plant (FPP), the public and politicians will expect this new form of electricity production from nuclear fusion to be regulated to ensure the safety of workers and the public and the protection of the environment.

2. The timescales for some of the FPP projects are such that conceptual designs are being thought of now, but, unlike for nuclear fission technologies, there are no specific nuclear safety, nuclear security or environmental protection standards for FPPs and no agreed approach to how such plants should be regulated. This lack of fusion specific regulatory focus has led to a vacuum and this vacuum has led some to consider applying the fission approach to fusion power plant design and regulation. The problem with this approach is that the application of NPP standards would be too onerous because of the much lower hazard potential associated with fusion reactors. The application of fission standards could unnecessarily increase costs, deployment times and public concern. It could also give the impression that nuclear fission related international treaties relating to transboundary accidents and third-party insurance are also applicable.

3. The paper explores the issues surrounding a licensing framework for nuclear fusion and argues for a licensing framework to be developed that is proportionate to the hazard potential of fusion power. It will also consider the regulatory challenges associated with the introduction of fusion power, the likely steps in the licensing process and the appropriate regulatory oversight.

Fusion Power Plant Safety Issues

4. The hazard potential of a fusion power plant is significantly less that that of a fission power plant. To understand the reasons for this it is worth exploring the key differences between the fission and fusion processes.

Key Safety Issues	Fission	Fusion
Production of radioactive “fission” products	**YES** Wide variety of radioactive “fission” products produced in the fuel	N**O** No radioactive fission products produced
Inventory resident in the reactor core	**YES** Considerable standing inventory of fission products and actinides	**Limited** Very small quantities of tritium in the plasma Some absorbed tritium in the components inside the vacuum vessel Some radioactive dust
Decay heat in fuel following shut-down	**YES** Approximately 8% of full power heat at shut-down, weeks to reduce	**Limited** No decay heat in fuel Some decay heat associated with neutron activation of breeder blanket structures
Decay heat removal requirements	**YES** Defence in depth required for decay heat removal systems	**Limited** Decay heat removal may be required for breeder blankets
Criticality potential	**YES** +ve power, +ve void coefficient potentials	**NO**
Power-coolant mismatch	**YES** LOCA ATWS	**YES** Loss of cooling Vacuum vessel Loss of cooling to breeder blankets
Emergency core cooling	**YES** Defence in depth required for ECCS	**Limited** Emergency cooling requirements to maintain confinement barrier integrity
Core/power protection systems	**YES** Multiple shutdown systems (defence in depth) required to prevent fuel and core damage	**YES** To terminate plasma, consequences of failure not as severe as in fission reactors.
Potential for significant offsite release	**YES** Potential for catastrophic releases	**NO** Some potential for tritium and activated

	e.g. Chernobyl, Fukushima, TMI	dust release but not catastrophic

Table 1 Comparison of Key Safety Issues for Fission and Fusion Power Plants

5. Table 1 above provides a brief summary of the key safety issues for fission and fusion power plants. It can be seen that in the case of NPPs there is the potential for the release of large quantities of radioactive materials. This is because the fission of either uranium 235 or plutonium 239 produces a wide variety of radioactive “fission products”. These fission products accumulate and together with the build-up of plutonium to provide a potentially catastrophic source term should they be released into the environment. A considerable amount of engineering is required, including several lines of defence, to prevent the uncontrolled release of radioactive materials, and hence keep the risks to workers and the public low.

6. In the case of FPPs, there are no radioactive “fission products” and no standing inventory of radioactive materials in the plasma that produces the fusion power. There is a small quantity of tritium in the plasma, and there are quantities of activated dust particles retained in the vacuum vessel. The residual tritium in the plasma and the activated dust, together with the release of tritium that had been absorbed in the components inside the vacuum vessel, have the potential to be released into the atmosphere in the event of an accident. However, this potential source term, whilst not trivial, is significantly less harmful that that associated with NPPs. Lukacs [1] summarise the main safety issues associated with fusion power plants.

7. For FPPs the consequences of accidents, plant malfunctions, human error or sabotage are not as severe as would be the case for NPPs. Nevertheless, the consequences of failure of an FPP protection and containment systems are not trivial and engineered protection systems are required to limit the likelihood of radioactive material releases and hence limit the risk to workers and the public.

Regulation

8. For centuries society has demanded that if an industrial activity has the potential to cause harm it should be regulated to ensure that people are safe from such activities. The regulation of the nuclear industry is often more onerous than many hazardous industries. This

is because nuclear energy is considered by some to be controversial and hence it receives additional attention from the press and politicians. Nuclear power is seen as being different form other industrial activities, not only because of the perceived association with nuclear weapons, but also because of impact of the catastrophic accidents that occurred at the Chernobyl and Fukushima nuclear power plants.

9. The current national and international nuclear regulatory landscapes have been shaped by the special characteristics associated with nuclear fission. These include: the high energy density locked in the atom, the potential for criticality and associated exponential increases in power generation, the radioactive decay of fission products in the core of a nuclear reactor that requires cooling long after the fission process has been terminated, and the production of radioactive waste. The high energy density, the need to provide exceptional levels of control of the fission process and the radioactivity of products produced by the fission process led to demands for stringent controls and very high levels of protection. The international community, led by the IAEA, responded to these demands and implemented a comprehensive international framework for nuclear safety and nuclear security that national governments could use to develop their own national laws that were needed to control the design, construction, commissioning, operation and decommissioning of NPPs.

10. These special characteristics of nuclear fission brought about a bespoke legal and regulatory framework for NPPs, and though counties have different legal systems and regulatory approaches, there is generally a consistency of approach to regulation of NPPs. The IAEA handbook on nuclear law [2] sets out the principles of nuclear law. Safety and security rightly feature highly in these principles, but another important principle is that of "permissioning". The permissioning principle recognises that because of the special characteristic of nuclear technology, prior permission should be obtained for activities involving nuclear fission. Permission is often granted vis a "licence" granted by government or the regulatory authorities. Licensing is therefore an important feature of the regulatory framework for the control of NPPs. Having a robust nuclear licensing process, administered by a competent, effective and independent regulatory body provides the politicians with the reassurance that the technology is being managed properly, and it gives the public confidence that it is safe and secure, and that the risks to their health and safety from the operation of NPPs are acceptably low.

Regulatory options

11. Whilst the current regulatory framework has been built around fission based technologies, the fundamental principle that a technology that has the potential to cause harm should have some form of regulatory control that ensures that it cannot be used until it has been shown that it is safe, and that the user of the technology should seek permission before using it, is relevant to fusion based technologies. The key issue is the extent to which the "permissioning principle" should be applied to FPPs. It is generally recognised that if the hazards associated with an industrial application are judged to be low and hence below regulatory concern, specific permission from the regulatory body may not be necessary. It is accepted that general national health and safety laws will be applicable and provide the appropriate level of public protection.

12. FPPs, as shown above, do not have the same hazard potential as NPPs and hence the key question is: is the hazard potential sufficiently low as not to require regulatory body permission to design, construct, commission, operate or decommission. Whilst the hazard potential is significantly lower than that of an NPP, it is not trivial and hence some form of regulatory oversight will be required for public and political reassurance.

13. There are currently no fusion power plants under construction or operating and hence there is no direct experience of appropriate regulatory approaches. However, a number of fusion power plant proposals are either at, or approaching, the concept design stage and hence the nature of an appropriate regulatory framework, especially one that would require permissioning / licensing from a regulatory body, is of considerable interest. The options that are worthy of consideration are:

- licensing in line with that applied to NPPs;
- regulation in line with nuclear fuel cycle and radioactive waste management facilities;
- regulation in line with non-nuclear radiation facilities; and
- licensing tailored to the hazard potential of FPPs (proportionate regulation).

Application of NPP Licensing Approach

14. As discussed above, licensing an FPP in the same way as an NPP would be unduly onerous given that the uncontrolled radiological release following a major uncontained accident is significantly less than that of an NPP. Applying fission regulation would require unnecessarily complex safety case documentation, unnecessary defence-in-depth features to protect against internal and external hazards, lead to more complex engineering solutions and longer construction times, all of which would lead to additional unnecessary cost. The application of a fission licensing regime would also send the wrong messages to the public and the politicians, that this technology was unduly hazardous and hence reinforce the controversy surrounding nuclear technologies.

Application of Nuclear Fuel Cycle Facility Approach

15. The regulation of nuclear fuel cycle and radioactive waste management facilities varies. Some countries, including the UK, have adopted a nuclear licensing regime similar to that used for NPPs, but the levels of protection required for internal and external hazards take into account the consequences of failure. In the UK the licensee is responsible for safety and hence the licensee can put forward its arrangements for managing safety in order to comply with the goal setting conditions that are attached to the nuclear site licence [3]. This regulatory approach is similar to that used in France and Canada. In the UK, whilst there are the same set of conditions attached to a fuel cycle facility licence as are attached to an NPP licence, the licensee has the ability to produce arrangements that reflect the hazard potential of the facility. The licensee can also agree with the regulator the "hold points" where regulatory permission is needed. Fuel cycle facilities do not have the same hazard potential of NPPs and hence the level of regulatory oversight, including permissioning "hold points" are not as onerous. A nuclear fuel manufacturing facility would not be expected to have the same regulatory requirements and oversight as a reprocessing facility handling spent fuel with large fission product inventories. Also, the level of regulatory inspections is again commensurate with the hazard potential of the facility. In the UK, France and Canada, for example, fuel cycle facilities are regulated by the nuclear safety regulators (ONR, ASN, and CNSC respectively)

16. In the USA for example, fuel cycle facilities are in general regulated by the NRC under 10CFR70 regulations. These regulations are not as strict/onerous as the 10CFR50 regulations used to regulate nuclear power plants. Thus, the NRC has the flexibility to tailor its activities in relation to the hazard.

17. It could be argued that the regulatory approach for fuel cycle facilities provides an example of proportionate regulation where regulatory permissions are required for certain activities, and where regulatory requirements reflect the hazard presented by the facility.

Regulation in line with non-nuclear radiation facilities

18. In the USA it has been argued [4] that demonstration fusion power plants should be treated as low risk facilities and regulated under 10CFR30 regulations. The implication is that this approach would enable NRC to apply light touch regulation that would not impede fusion innovation. For the longer-term deployment of fusion power, Roma and Desai [4] suggest that 10CFR30 could again be used as the basis for a regulatory framework. Their approach is based on the assertion that fusion is a low hazard / low risk technology that does not warrant rigorous regulatory oversight.

19. The problem with this approach is that an FPP is a power station with the potential (albeit small) for the offsite release of radioactive materials under certain accident conditions. It is hard to see the public accepting that an FPP with a primary heat source that is produced by a nuclear process could be simply classed a radiation facility with light touch regulatory oversight.

20. It is interesting to note that in the US the NRC has indicated that an FPP should be considered as a "utilisation facility" and hence come under NRC regulation. It is also interesting to note that the US Government's recently enacted Nuclear Energy Innovation and Modernisation Act [5] includes fusion reactors in its definition of advanced nuclear reactors. In this Act (SEC. 103 Advanced Nuclear Reactor Programme) the USNRC is charged with completing rulemaking to establish a technology inclusive regulatory framework for commercial advanced nuclear reactors (including fusion reactors) by no later than 31 December 2027. When completed the regulatory framework for FPPs will part of 10 CFR 53 "Licensing and Regulation of Advanced Nuclear Reactors".

Proportionate Regulation

21. It is clear that fusion power stations have the potential to release radioactive materials into the environment under certain accident conditions and as such should be regulated in order

to assure the public that the technology is safe and the environment is protected. It is equally clear that the hazard potential of an FPP is many orders of magnitude below that of an NPP. Given this disparity, it is unreasonable to apply the extremely strict regulatory framework, that rightly exists for NPPs, to fusion based power plants. The key question therefore is: what type of regulation is appropriate for FPPs?

22. The successful deployment of fusion power will require public acceptance and in order to gain this, the public will need to be reassured that this new technology will be properly managed to ensure worker and public safety, and the protection of the environment. Effective regulation is key to ensuring public acceptance. It is also important for regulatory certainty so that investors, owners and operators can have confidence in the expected regulatory requirements,

23. The fundamentals of nuclear safety regulation are:

- no one should be allowed to construct or operate a fusion nuclear power plant without a licence;
- a licensee must be a fit and proper organisation with the necessary financial and technical (understands the technology) resources;
- the licensee is responsible for safety;
- permission from a regulator is required in advance of undertaking major activities that affect safety (such as commencement of construction, commencement of commissioning or commencement of operation);
- permission to undertake a major safety related activity is based on the adequacy of safety documentation (safety cases) submitted by the licensee;
- the regulator has appropriate enforcement powers including the power to halt activities if safety case requirements are not complied with;
- appropriate penalties are available for non-compliance.

24. In the case of FPPs for regulation to be effective and efficient it should be proportionate to the hazard and not place unnecessary burdens (including financial burdens) on the licensee. The UK, US, Canada and other countries have demonstrated that it is possible to develop and implement proportionate nuclear regulatory regimes. In the UK the goal setting approach to

nuclear licensing offers an ideal mechanism for the development of a proportionate regulatory regime.

25. The key to a proportionate regulatory regime is that the regulatory framework is rigorous to give the public and politicians the confidence that the technology is being adequately controlled and at the same time does not put unnecessary obstacles in the delivery of the licensee's programme. A licensing regime is the obvious choice to demonstrate to the public that the FPPS are being managed properly and to provide regulatory certainty. In the UK context a set of licence conditions could be developed (in consultation with the industry) to reflect what is important to the management of safety and, where appropriate, security in the fusion context. These conditions would be goal setting and require the licensee to make and implement the arrangements that would be necessary to deliver the goals. In this way the range of licence conditions would focus on the things that are important to safety and security, and the arrangements would focus on appropriate processes and activities needed to deliver the safety goals. This approach would allow the licensee to develop arrangements and safety documentation that is proportionate to the hazard.

26. Regulation is of course law enforcement and as there is no global legal framework, countries will have different regulatory systems. However, whatever the national regulatory system, there is no reason why a proportionate approach based upon the accepted licensing principles cannot be developed. It would help if the international community could get together to develop an agreed set of safety and security standards and guidelines for fusion power plants. This would enable vendors and licensees to develop globally applicable power plant designs, and regulators to develop consistent, regulatory approaches that reflect the hazards associated with fusion power.

27. The regulatory framework focusses on safety and security but it does not apply to asset protection for commercial reasons. It is entirely possible that for commercial and operability reasons the owner / licensee may wish to introduce additional design and operational features over and above those needed for safety and security. Where this was the case, the additional features to be applied could be included in the safety and security documentation in order to demonstrate that they did not adversely affect safety or security. However, the regulatory system would not require these additional features to be included in regulatory processes and they would not be subject to regulatory requirements or scrutiny.

Regulatory Challenges and the Way Forward

28. The advent of fusion power for commercial power generation is no longer a dream and several organisations are at the concept design stage for power plants. As discussed in this paper, this new technology will need to be regulated in an effective, efficient and proportionate way. However, to achieve this several challenges will need to be overcome.

29. The first is to convince the fusion industry that regulation via a licensing regime is not something to be concerned about. The fusion industry's perception seems to be licensing means nuclear fission licensing with lengthy regulatory timescales, substantial additional costs and intrusive regulatory oversight. This paper has shown that this is not the case and a bespoke, proportionate licensing regime is not only deliverable but also essential. Subjecting fusion power to a proportionate licensing regime should not be seen as an unwelcome link with fission power. With good communication to highlight the differences, an effective and proportionate fusion power licensing regime will give confidence that this new technology is being effectively managed.

30. The second challenge is to squash the myth that controlling fusion power via a licensing regime will make it more difficult to attract investment and inhibit innovation. A proportionate licensing regime that reflects the hazards associated with fusion power will embed safety and security in the design process. Good safety is clearly good business and with safety being an integral part of the design process, innovation should be more effective.

31. The third challenge is design standards. At present there are no specific national or international safety or security standards that are specific to fusion power plants. This has left a vacuum that needs to be filled to avoid a default precedent of making use of fission standards. Given the state of development of some fusion power plant programmes, there is an urgent need for the international community to get together to address this issue. The IAEA / NEA, in conjunction with the fusion industry and regulators should commence the development of a comprehensive suite of high-level safety and security standards and guides for commercial fusion power plants. These standards should not be confused with industrial codes and standards for FPP components. The initial focus should be on design standards and this should be followed by construction, commissioning, operation and decommissioning standards and guides.

32. There is clearly a different hazard potential for FPPs when compared with NPPs and hence a different approach to regulation will be needed. The international community (IAEA / NEA) should give consideration to the development of guidance for Regulatory Bodies to ensure a consistent and effective regulatory approach that will enable the global deployment of fusion power plants.

33. The fourth regulatory challenge is the need to upskill the regulators in fusion technology. As discussed above some fusion power programmes envisage demonstration power plants operating in the next 10 to 15 years. This means that detailed designs will need to be in place in the next 5 years to allow construction to commence if these operational timescales are to be achieved. Regulators have a role to play in assessing and permissioning fusion power plant designs prior to construction, commissioning and operation. To enable regulators to undertake these tasks they will need to recruit new staff and or retrain existing staff to ensure that they have the capability to regulate fusion power station technologies. The fusion industry (in the UK, the UKAEA's centre for fusion energy) and academia will have a role to play in the training of regulators to enable inspectors and assessors to gain the necessary understanding of fusion technology and its associated safety and security features.

34. A fifth challenge comes from the potential need for asset protection. An investor / owner may have more stringent design requirements to protect its asset (fusion power plant) following accidents or external events such as an earthquake or tsunami that are more extreme than those that are required to be covered safety or security reasons. These asset protections requirements which ensure that an FPP can continue to operate after the event should not be confused with safety or security requirements. If the safety / security case demonstrates that these commercial requirements are not needed on safety or security grounds the regulators should not consider them in their regulatory processes. Any requirements that go beyond those for safety and security should be treated as commercial risk requirements and not subject to regulation.

Conclusions

35. The hazards associated with fusion power plants are many orders of magnitude lower than those of NPPs, but they are not trivial. Fusion power plants have the potential to cause

harm and as such a considerable amount of engineering is required to manage the hazards and ensure that the risks to workers and the public are as low as reasonably practicable, and the environment is adequately protected. Although the engineering challenges and defence in depth requirements for safety and security for FPPs are not as demanding as those for NPPs, effective regulatory oversight is necessary to assure the public and politicians that the introduction of fusion technology for commercial power generation is safe and secure; and to provide regulatory certainty for investors, owners and licensees.

36. The application of the same regulatory approaches as are used for NPPs is not justified and would be too onerous given the much lower hazard potential of FPPs. Equally, the application of regulatory regimes used for experimental, medical or sterilisation facilities via non-intrusive licensing systems would also not be appropriate. Nuclear safety regulators in many countries have shown that it is possible to apply different regulatory approaches to different facilities, e.g. nuclear fuel cycle facilities are not regulated to the same requirements as NPPs. Hence it is entirely feasible that an effective proportionate regulatory regime for fusion power can be developed and implemented in a way that does not lead to the imposition of unnecessary burdens, whether in relation to the time needed to licence or construct, or in terms of unnecessary costs associated with safety documentation and permissioning.

37. Existing nuclear regulatory authorities have the capability, experience and flexibility to deliver this task but additional skill sets and training in fusion reactor technologies will be required. There are no international nuclear safety or nuclear security standards or guides specifically for fusion power plant design or operation and hence it would also useful for the international community to get together to develop an agreed set of safety and security standards and guidelines for fusion power plants.

38. Any requirements that go beyond those for safety and security should be treated as commercial risk requirements and not subject to regulation. The difference between safety and security risk, and commercial risk should be made very clear to the public and politicians.

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