Do proposed regulatory approaches for commercial fusion energy jeopardize successful technology deployment?

R. Patrick White^{1,*} and Liam S. Hines¹

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HIGHLIGHTS

- Renewed interest in fusion technology as a possible clean energy source is driving investment in the development, design, and deployment of commercial fusion power plants.
- The regulatory pathway in the United States for commercial fusion is unclear due to the lack of operating experience.
- Industry proposals to use risk-informed regulatory approaches for initial commercial fusion projects could complicate the licensing process for a first-of-a-kind fusion facility and delay near-term commercial deployment.
- A hybrid deterministic and risk-informed regulatory process that incorporates seven decades of lessons learned in commercial fission could enable the implementation of regulatory requirements that evolve in parallel with the development of commercial fusion facilities.
- This new regulatory approach could enable more rapid deployment of commercial fusion technology and facilitate long-term regulatory stability as fusion energy develops from a first-of-a-kind demonstration technology to a mature low-carbon energy source.

Fusion energy has long been touted as an energy source capable of producing large amounts of clean energy without the fuel, pollution, siting, and safety constraints of other energy sources. Despite this promise, fusion energy has not come to fruition after six decades of research and development due to continuing scientific and technical challenges. Significant private investment in commercial fusion start-ups signals a renewed interest in the prospects of near-term development of fusion technology. Successful deployment of fusion energy, however, will

require an appropriate regulatory framework to ensure public safety and economic viability. Initial discussions and proposals from fusion start-ups (e.g., Commonwealth Fusion Systems, General Fusion, TAE Technologies) and industry associations (e.g., Fusion Industry Association) have advocated the use of risk-informed regulations as the basis for the licensing of commercial fusion technology in the United States. These proposals are based, in part, on regulatory methods used for licensing commercial fission technology that developed in parallel with the commercial fission industry.

Risk-informed regulations incorporate risk information from probabilistic safety analyses to ensure that regulations are appropriate for the actual risk of an activity. Proponents of risk-informed regulation believe that these methods can improve the economics and operation of nuclear facilities by focusing regulatory resources on addressing credible accident scenarios that are most likely to pose threats to worker and public safety. In addition to interest from industry, the U.S. Nuclear Regulatory Commission (NRC) has begun an initiative to develop a new risk-informed regulatory framework for the licensing of advanced nuclear fission power plants, but it is unclear if this framework would be applied to fusion. Despite the benefits of adopting a risk-informed framework for a mature fission industry, use of risk-informed regulations for the licensing of first-generation commercial fusion technology could be detrimental to the goal of economic near-term deployment of fusion. Commercial fusion technology has an insufficient operational and regulatory experience base to support the rapid and effective use of risk-informed regulations. More conservative regulatory analyses could instead be used for first-generation fusion facilities to facilitate more rapid deployment, and enable collection of operating experience to support future use of risk-informed regulations. A hybrid regulatory pathway that incorporates seven decades of lessons learned in commercial fission would enable the implementation of regulatory requirements that evolve with the development of commercial fusion technology, from a first-of-a-kind demonstration plant to a mature low-carbon energy source.

Fusion energy has been the “holy grail” of energy production since its conception nearly 70 years ago. Fusion energy has been touted as an inexhaustible source of clean energy that could be readily scaled to meet humanity’s continuously growing energy demands. The new technology would eliminate many of the constraints of other existing

¹Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA

*Email: rpwhite@mit.edu

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energy sources:

- No fuel constraints: unlike fossil fuels, the different fuels for fusion energy are more abundant – normally consisting of readily available hydrogen isotopes
- No geographic siting constraints: unlike renewable energy, fusion facility siting is not limited based on site conditions such as available wind, solar, hydro, or geothermal resources
- No pollution constraints: unlike fossil fuels or nuclear fission, the main byproducts of fusion reaction are stable, non-toxic gasses such as helium
- No safety constraints: unlike nuclear fission, fusion reactions do not produce long-lived nuclear fission products and would not be vulnerable to nuclear meltdown accidents

Eliminating these constraints makes fusion energy extremely attractive, and the technology could be poised to ascend as humanity's final energy source.

As scientists and engineers began developing fusion technology, however, technical challenges began to emerge. Creating, sustaining, controlling, and containing high temperature fusion reactions required development of new scientific theories and invention of new engineering systems. Development of a net energy positive fusion device has remained elusive to fusion energy developers for decades as each scientific advancement has revealed new physics or engineering challenges. Public enthusiasm waned as fusion energy appeared to always be "30 years away."

The past 10 years, however, have seen a renewed interest in fusion energy development. The urgent need to decarbonize has revitalized interest in development of novel clean energy sources like fusion, and technical advancements such as the maturation of high temperature superconducting magnet technology have spurred private investment in the development of commercial fusion energy technology [1]. Private fusion energy developers have proposed a wide variety of technologies for commercial fusion energy facilities but most have one goal in common: they seek to develop and demonstrate a commercial scale net energy fusion device within a decade. Commercial fusion energy developers are now poised to attempt to overcome the final technical challenges facing fusion energy.

Regulatory Challenges for Fusion

As commercial developers seek to make fusion energy a reality, they must also begin to address the operational challenges associated with any new energy source. One significant challenge for fusion energy will be the regulation and licensing of commercial fusion energy facilities. The promise of fusion energy is based on the elimination of fuel, siting, pollution, and safety challenges that constrain other energy technologies. While there are fusion technologies that can theoretically eliminate all of the constraints, the physics and engineering realities associated with most approaches to commercial scale fusion have introduced new challenges. The most technically achievable fusion energy reaction (highest

Figure 1: Regulatory hazards of particular concern for commercial fusion facilities.

reaction rate at achievable operating temperature and most abundant fuel) combines two isotopes of hydrogen (^2H - deuterium and ^3H - tritium) to form a helium atom and a neutron. Most developers seeking to demonstrate net-energy gain will utilize this deuterium-tritium fusion reaction for their fusion energy facilities.

This reaction, however, has safety challenges related to both the fuel and the reaction products. The tritium fuel is radioactive (emitting low energy beta radiation) and is chemically identical to hydrogen, so it is susceptible to fire, explosions, and leakage from storage vessels unless properly contained. The structural materials in the fusion device absorb neutrons produced by the fusion reactions and become radioactive. Thus, during operation, neutron-activated radioactive material will be produced inside of the fusion facility. This radioactive waste will need to be carefully managed both during and after commercial operations. These radiological hazards and other industrial hazards can likely be managed through engineering and operational controls, but regulation will be needed to ensure the safe operation of commercial fusion facilities. The regulatory rules for commercial fusion facilities have not yet been established and regulators are working to establish appropriate regulatory frameworks and pathways for commercial fusion.

Figure 1 summarizes the high level hazards that could be expected at a commercial fusion facility utilizing the deuterium-tritium fuel cycle. Given the potential radiological hazards associated with commercial fusion energy, the regulator for fusion facilities in the United States would be the Nuclear Regulatory Commission (NRC). The NRC has previously asserted authority to develop fusion regulations, but elected to wait for further commercial development to issue formal fusion regulations [2]. The 2018 Nuclear Energy Innovation and Modernization Act required the NRC to address the licensing challenges of advanced nuclear systems including fusion and prompted the NRC to begin discussions with stakeholders on the regulation of fusion energy [3]. Fusion energy proponents (specifically the Fusion Industry Association) have offered several pathways to fusion licensing under existing regulatory frameworks in initial public meetings with regulators [4]. It is not yet clear what approach the NRC will take to license and regulate fusion technology [5].

Uncertainty in the licensing process for commercial fusion may lead to schedule delays and cost increases, hampering the economic viability of fusion facilities and dissuading fusion stakeholders from initiating future projects. Without a clear long-term plan for commercial fusion licensing, the regulatory decisions made in licensing the first-generation of fusion facilities could make or break the viability of fusion energy. Overburdening regulations that target safety concerns irrelevant to fusion systems, or technology-specific regulations that allow for only specific fusion devices to be licensed, could pose obstacles for a burgeoning fusion industry. Regulators and developers must seek to develop regulatory frameworks that properly address the safety hazards of fusion facilities without hindering the innovation of new technologies [6]. A licensing framework that enables the safe and efficient regulation of the novel technology is necessary for fusion energy to succeed.

Characterizing Regulatory Frameworks is Critical

The development of appropriate regulations that facilitate fusion energy innovation requires an understanding of the different approaches to regulating technologies, and the different methods for ensuring that safety concerns are properly addressed. The most important trade-offs in licensing fusion energy will be between *deterministic* and *probabilistic* regulations and between *prescriptive* and *performance-based* regulations.

The first dichotomy, deterministic vs. probabilistic, characterizes how regulations assess safety and risk. Risk analyses, as they apply to regulation, primarily focus on three factors known together as the ‘risk triplet’: the specific sequence of events that define a particular accident, the probability of that event sequence occurring, and the consequences should that event sequence occur [7]. The main difference between deterministic and probabilistic frameworks is how each factor in the risk triplet is considered when evaluating risk. Deterministic analyses focus on engineering analyses and their consequences, without explicit regard to probability [7]. Deterministic analyses will tend to emphasize designing for high-consequence, low-probability event sequences with the assumption that design for the highest-consequence events will ensure safety for any lower-consequence events [8].

Probabilistic analyses, by contrast, prioritize the likelihood of a specific accident sequence occurring when evaluating risk. Regulations based on probabilistic analyses consider all three factors of the risk triplet and focus on event sequences with the greatest consequences and the greatest probability of occurring [7]. The philosophy of regulation based on probabilistic analyses maintains that the bounding-case assumptions of deterministic analyses are not comprehensive, and that emphasizing highly unlikely but catastrophic accident scenarios can fail to encapsulate lower consequence events that are much more likely to pose real threats to public safety. Selection of deterministic or probabilistic regulatory frameworks for fusion technologies could reflect how the

risk associated with fusion facility accidents would be most efficiently and effectively analyzed to protect public safety.

The second dichotomy, prescriptive vs. performance-based frameworks, describes how facilities must address and protect against specific accidents. A prescriptive framework demands facilities take a specific set of actions or require specific equipment to meet a particular safety objective [7]. In the case of fission facilities, a prescriptive requirement could require a facility to have emergency diesel generators to provide emergency power to safety systems that cool the nuclear reactor core in order to meet the safety objective of ensuring that the reactor fuel does not overheat during a loss of off-site power [9]. Fission reactor designers are required to have these emergency diesel generators included in their design as part of the regulatory requirements. Under a prescriptive framework, facilities must address safety objectives exactly as instructed by regulators. While a prescriptive framework provides regulatory certainty, there is little room for flexibility and innovation.

A performance-based framework, by contrast, provides this flexibility. Performance-based regulations instead only specify what measurable safety objectives must be met, but allows the licensees flexibility in how they meet this metric [7]. In the aforementioned case of facility blackouts, a performance-based framework may require facilities to demonstrate that their design ensures the reactor core does not overheat during blackouts but would allow the applicant to choose how their design achieves this objective [9]. This flexibility, however, comes at the cost of regulatory certainty [8]. Compared to the prescriptive framework, in which developers know exactly what a facility needs in order to meet the conditions of licensing, performance-based frameworks allow developers to meet safety objectives through novel approaches. Novel safety approaches can require additional analyses and safety reviews from regulators to ensure that new methods to meet performance metrics soundly address safety objectives. Given the different benefits of prescriptive and performance-based frameworks, there is no “one-size-fits-all” regulatory framework; each framework will produce optimal licensing pathways for different situations. For the future of fusion energy, a licensing framework that balances both flexibility and certainty will be essential to creating a regulatory framework for fusion.

Current Proposed Frameworks for Commercial Fusion Regulation

Nuclear energy regulation in the United States as it exists today is a deterministic and prescriptive framework focused on the safety concerns of fission light water reactors (LWRs) [10]. Existing regulations target the safety concerns of fission LWRs, such as the control of fission chain reactions in water-cooled systems, or the release of radioactive fission products from reactor fuel. The safety concerns for fission facilities are not applicable to fusion energy and the unique hazards of fusion (including tritium and fusion neutron

activated materials) would need to be separately evaluated. The historical difficulties of licensing fusion devices under existing fission regulations has spurred interest from the fusion industry to develop entirely new regulatory frameworks for fusion technology that target the specific safety concerns of fusion systems [4].

A separate licensing framework for fusion energy would ease many of the complications of adapting regulations designed for fission to fusion. Proposals for new fusion regulatory frameworks include not only tailoring new regulations to the specific safety concerns of fusion technologies, but also departing from existing deterministic, prescriptive frameworks to address safety concerns with probabilistic, performance-based regulations [11]. Proponents of these approaches believe adopting a probabilistic performance-based framework can enable regulatory focus on accident scenarios of greatest concern to public safety and provide commercial fusion developers flexibility in pursuing a variety of innovative approaches to achieve commercially viable fusion energy [11]. A probabilistic performance-based framework initially appears to provide the conducive regulatory environment necessary for the growth of a fusion energy industry. However, the regulatory and commercial benefits of probabilistic, performance-based frameworks actually culminate from the maturation of and development of extensive experience with a technology.

The Challenge of Regulating Fusion with Risk-Informed Frameworks

The risk-informed regulatory frameworks currently under development for advanced commercial fission systems are the result of seven decades of technology development and accumulation of operational experience. The first generation of commercial fission facilities in the United States was largely regulated with deterministic and performance-based regulatory frameworks due to the limited operational experience with the technology and wide variety of technologies under development [12]. Emergence of LWR technology as the dominant reactor technology encouraged development of prescriptive requirements to create a more predictable licensing process [13]. The accumulation of operating experience facilitated the use of risk-informed methods to reduce the excess engineering conservatism associated with deterministic regulation.

The evolution from simplified deterministic methods to risk-informed methods reflects increasing industry and regulator understanding of nuclear technology and maturation of design and analysis processes. These risk-informed frameworks require a detailed mechanistic understanding of plant operation and failure modes to develop accurate failure event sequences and substantial statistical information from component, system, and facility operation to adequately model and predict the failure frequencies and probabilities. Documentation and study of thousands of cumulative years of commercial fission reactor operation have opened the door for the effective use of risk-informed frameworks for commercial

fission technology. This experience is what provides the technical basis for risk-informed models and insights for fission.

Initial commercial fusion facilities will be groundbreaking engineering devices, demonstrating at an industrial scale new engineering and scientific principles. This type of innovation is exciting for technological progress but will pose a significant challenge for risk-informed regulatory frameworks. Commercial fusion facilities will require the use of many novel technologies and engineering systems that do not have significant operating experience. The net energy gain or burning plasma conditions inside of a commercial fusion device have never been controlled on Earth, and the scientific basis for the control of these reactions is still incomplete. No fusion facility has ever produced more than a small amount of thermal energy and no facility has ever achieved net energy production. Development of net-energy fusion facilities that produce hundreds or thousands of megawatts of energy is a dramatic extrapolation from current experience. There will be many unknowns as developers seek to control fusion energy devices in new operational regimes.

Novel technologies can be operated safely, but their development is an inherently iterative process as scientists and engineers incorporate lessons learned from the design, manufacturing, and operation of multiple generations of devices. The main challenge of using risk-informed methods for the safety analysis and regulation of commercial fusion facilities is that these methods require significant data on component, system, and facility-level operation to support regulatory decision-making. Developing an understanding of these operational characteristics to support risk-informed decision-making would require substantial testing of components, systems, and facilities [8]. While this information could likely be gained without the thousands of reactor-years of operation through thoughtfully-designed testing programs for fusion technology, the information would not likely be available for first-generation fusion commercial fusion technology without significantly delaying deployment and increasing costs associated with the testing and regulatory process.

A Hybrid Deterministic and Risk-Informed Regulatory Method Could Enable Rapid Early Deployment and Long Term Regulatory Refinement

Commercial fusion should use the lessons learned from commercial fission to both enable the rapid deployment of first-generation fusion technology but embrace the use of risk information as it becomes available to develop more effective regulation. The use of simplified deterministic regulatory methods for first-generation fusion technology would increase engineering conservatism of initial facilities but reduce the uncertainties associated with facility design and licensing. The reduction in regulatory process uncertainty associated with the use of deterministic analysis reduces upfront regulatory costs for technology developers, provides greater assurance of project completion, and reduces the risk of regulation-related

delays that can dramatically increase costs. The resulting stable, predictable regulatory framework could enable initial commercial maturation of the fusion industry and allow for reductions in cost via gradual design standardization and industry learning-by-doing [14].

Regulatory challenges for some advanced fission reactors highlights the limitations associated with using fully risk-informed methods for the regulation of novel energy technologies. The NRC has shifted towards use of risk-informed regulation in recent years and continued this practice in the development of initial regulation of advanced fission reactors [15]. Initiatives such as the Licensing Modernization Program intended to increase advanced reactor regulation effectiveness have run into challenges as some novel reactor developers would like to use deterministic analysis for first-of-a-kind reactors [16]. Despite the NRC's experience with transitioning from deterministic to probabilistic analyses, a focus on risk-informed regulation may complicate the near term regulation and deployment of novel fission technology.

If first-generation commercial fusion facilities can be successfully deployed, commercial fusion developers could leverage accumulated operating experience to develop more mature models of fusion facility risk. These models could then be used to reduce engineering conservatism and costs through risk-informed regulation. A clear regulatory pathway should be established from the outset for fusion facilities that allows incorporation of this design and operational experience into risk analyses for subsequent commercial fusion designs and facilities. These ongoing risk analyses can then serve as the technical basis to meet additional risk-informed regulatory requirements for subsequent commercial facilities. This process would allow designers to leverage operational experience to support use of more realistic regulatory requirements and enable learning-by-doing on both subsequent builds and licensing proceedings.

A regulatory framework that fosters the evolution from deterministic to risk-informed methods for regulating fusion may enable developers and regulators to utilize operating experience from first-generation facilities to support licensing of subsequent facilities. This regulatory framework could help maximize the efficiency of the development and design process, and ensure that facilities have sufficient information to justify their operation. An explicit hybrid pathway incorporates seven decades of lessons learned in commercial fission and enables the implementation of regulatory requirements that evolve with the development of commercial fusion technology from a first-of-a-kind demonstration plant to a mature low-carbon energy source.

Policymakers and regulators should work to develop appropriate policies that enable safe, economic, and rapid commercialization of the technology while promoting long-term industry success. Proponents of the fusion industry should be cognizant of the immaturity of commercial fusion

technology and ensure that they advocate for licensing pathways that are appropriate for the developing industry. Regulators should evaluate a variety of regulatory models and work with applicants to develop a regulatory framework that protects public safety while facilitating economically competitive technology innovation. Deliberate development of a regulatory framework that supports both the initial deployment of fusion technology in the next 15 years and subsequent commercial deployments is critical to support industry development.

Conclusions

Commercial fusion technology has potential as a future source of low carbon energy that compliments other low carbon energy sources, but regulatory questions must be resolved to enable successful development and deployment. Initial proposals for regulation of commercial fusion technology have highlighted industry interest in risk-informed regulations, but inappropriate use of risk-informed frameworks could be detrimental to the goal of economic near-term deployment due to limited design and operational experience with fusion technology. Lessons learned from the regulation of commercial fission technology suggest that an evolutionary regulatory approach using deterministic requirements for first-generation technology and implementing risk-informed requirements once the technology matures could minimize the regulatory burden for commercial fusion technology. Industry, regulators, and policymakers should carefully consider the potential implications of regulatory frameworks on the development and deployment of fusion technology before inadvertently creating requirements that could inhibit the development of commercial fusion technology.

Citation

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