UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, DC 20555 - 0001

October 21, 2022

The Honorable Christopher T. Hanson
Chair
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

SUBJECT: DRAFT SECY WHITE PAPER ON LICENSING AND REGULATING FUSION ENERGY SYSTEMS

Dear Chair Hanson:

During the 699th meeting of the Advisory Committee on Reactor Safeguards (ACRS), October 7-9, 2022, we completed our review of the September 2022 preliminary staff white paper, “Licensing and Regulating Fusion Energy Systems.” Our review was informed by discussions during our Regulatory Rulemaking, Policies and Practices Subcommittee meeting on September 22, 2022. During these meetings we had the benefit of discussions with representatives of the U.S. Nuclear Regulatory Commission (NRC) staff and stakeholders. We also benefited from the referenced documents.

CONCLUSIONS AND RECOMMENDATIONS

1. A license issued under Title 10 of the *Code of Federal Regulations* (10 CFR) Part 30 is appropriate for fusion facilities, provided tritium inventories are low (e.g., < 10 g active inventory) and activation is minimal (e.g., < 0.01 MW-yr/m^2 or 0.1 dpa). This will result in regulatory certainty for near-term applications.

2. The hybrid approach (Option 3 – byproduct and utilization combined framework) should be pursued for higher consequence fusion energy facilities. Our rationale is summarized below.

    a. This approach provides needed regulatory flexibility given the diverse fusion design options, their broad range of hazards, and the large uncertainties associated with their performance at engineering- or power plant-scale.

    b. This approach implicitly recognizes engineering- or power plant-scale fusion energy systems share many characteristics (e.g., decay heat, mobilizable radionuclides) that may result in hazards more like fission reactors than like accelerators and are also similar to some utilization facilities licensed by NRC.

   c. This approach would allow time for development of regulations for future higher consequence facilities as experience is gained with early applications and operation of lower consequence fusion facilities.

   d. Scaling of Option 2 (byproduct 10 CFR Part 30 framework) with additional safety requirements as the technology evolves could result in a patchwork of regulations. The resulting 10 CFR Part 30 language may look more like what exists today for a utilization facility under 10 CFR Part 50.

3. Option 3 would enable an enduring holistic framework to be established for fusion power plants in the future.

4. The white paper discussion on the hazards of fusion energy systems at engineering- or power plant-scale contains some factual inaccuracies and could benefit from additional context. This should be corrected.

BACKGROUND

The NRC has regulatory jurisdiction over fusion from the Atomic Energy Act as noted in SECY-09-0064. Furthermore, the Nuclear Energy Innovation and Modernization Act directs NRC to begin rulemaking to establish a regulatory infrastructure for advanced reactors, including fusion power plants.

The purpose of the staff white paper is to present different options for fusion energy licensing and regulation. The white paper also presents a technical assessment of fusion technologies.

DISCUSSION

The hazards for current fusion experiments or “next steps” for all fusion fuel cycles tend to be very small given the small tritium inventory anticipated to be used, the very short-pulsed nature of the machines, and the lack of significant neutron activation. However, once a self-sustaining fusion reaction (high Q) is attained (either in a long pulse, multiple short pulses, or in a continuous manner), the nature of the hazard for a Deuterium-Tritium (D-T) fusion fuel cycle at engineering- or power plant-scale changes significantly because:

a. neutron activation of the structure surrounding the vacuum vessel containing the fusion fuel occurs (creating heat, radiation, and waste concerns),

b. tritium is required to be bred in a blanket to close the fusion fuel cycle (creating radiological hazards),

c. plasma-wall interactions occur inside the vacuum vessel as charged particles in the plasma erode the plasma facing material and produce activated dust (creating mobilizable radioactive material), and

d. high temperature heat from the fusion reaction is required to provide electricity and/or process heat (challenging tritium confinement).

Other fuel cycles that do not use tritium have long been recognized as much more difficult to achieve because of the need for greater confinement and higher plasma temperatures (greater than the temperature of the sun) for the specific reactions to occur. These fuel cycles may result in the production of copious high energy neutrons that will cause activation of structures and other side nuclear effects (e.g., Bremsstrahlung and synchrotron radiation) at engineering- or power plant-scale. In addition, because most of the energy in these reactions remains with the charged particles, plasma power handling/management could be even more difficult than for systems that are designed to use the D-T fuel cycle. The impact of these differences (e.g., structural heating, shielding requirements to protect workers during operation, dose rates at shutdown for maintenance, erosion damage to plasma facing components and associated dust formation) depends on the design of the facility and the particle and neutron fluence levels experienced by the components.

For fusion energy technologies at engineering- or power plant-scale, it is incorrect to state categorically that (a) radiological hazards are much lower than those for large light water reactors (LWRs) in operation today, (b) the radiological dose levels will be only a fraction of 10 CFR Part 20 limits, and (c) these facilities will have minimal environmental impacts. There is the potential to affect public health and safety at least for systems using a D-T fuel cycle. For other fuel cycles, the risk depends on the specific characteristics (e.g., activation level, radiation damage, radiation levels, dust production) of the facility. The white paper should acknowledge these long-recognized concerns.

The claims recognized in the white paper on the risks associated with designs at power plant-scale are inconsistent with earlier studies performed by the U.S. Department of Energy (DOE) and other international entities. An extensive number of studies of both magnetic and inertial fusion systems, only a sample of which are provided in the references to this letter, explored the safety of fusion energy systems. They concluded that public health and safety risks and environmental concerns exist at engineering- or power plant-scale, as noted in the ESECOM study published in 1989 and as evidenced by the development of a DOE fusion safety standard in the 1990s. Similar detailed safety and environmental studies were performed by the European Union. There is also a long record of fusion safety reports produced by the International Atomic Energy Agency (IAEA) characterizing the nature of the hazard. In addition, the DOE established the Fusion Safety Program at the Idaho National Laboratory in the late 1970s to gather the data necessary to characterize the nature of the hazards. Main outcomes include a better understanding of how the energy sources in fusion can mobilize hazardous materials (e.g., oxidation/chemical reactivity studies of plasma facing components, mobilization from candidate fusion alloy materials under high temperature conditions); development of internationally used fusion-specific safety analysis codes (e.g., fusion adaptations of RELAP and MELCOR); and assessments of fusion environmental impacts.

The white paper discussion on the hazards of fusion energy systems at engineering- or power plant-scale could benefit from additional context to recognize the long-standing international consensus about the public health and safety aspects of fusion facilities. It contains factual inaccuracies about the magnitude of the energy sources in a fusion power plant, the radioactive inventories at risk, and the potential for those energy sources to mobilize those inventories. It also mischaracterizes the environmental/waste management and worker safety implications of such facilities. The appendix provides technical details about these items, and they should be corrected in the text of the white paper. Although the studies and analyses cited in the references are in some cases decades old, the conclusions are still valid, and the underlying data are still relevant today.

Regulatory Options

The white paper discusses options for regulating fusion energy systems as (1) a utilization facility under a 10 CFR Part 50 framework, (2) a byproduct material as is done with accelerators under the framework in 10 CFR Part 30, or (3) a hybrid using either the byproduct approach or the utilization facility approach based on the hazard. The pros and cons of each option are discussed in the paper. The key for determining the best option for fusion is understanding the nature of the hazard, which will vary widely from current research and proof-of-concept types of facilities up to larger scale engineering demonstrations or fusion power plants.

The proper regulatory approach will depend strongly on the selected fusion fuel cycle, the detailed facility design, and relevant operating experience. The lack of operating experience and detailed designs at engineering- and power plant-scale hinders the ability to make an informed decision on a complete regulatory framework. These two components are necessary to reduce uncertainties in key performance attributes and to better characterize the risk of a fusion facility.

However, at engineering- or power plant-scale, the hazards found in a fusion facility share similar characteristics to those found in fission reactors and some utilization facilities. The key safety function is radiological confinement, as noted by the staff. Degradation of confinement barriers from distributed energy sources in fusion systems (e.g., pipe breaks, decay heat, chemical reactions with air or coolant and structures, and magnet stored energy) and subsequent mobilization of tritium and activated dust is the safety challenge. This assessment has been recognized nationally and internationally for decades.

This situation is a classic decision analysis problem in the face of large uncertainties. Option 1 (utilization facility framework) could result in over-regulation for many facilities. Option 2 (byproduct framework) may be insufficient to drive the design's required depth, breadth, and rigor necessary for the staff to make a determination of adequate protection of public health and safety. In addition, scaling of Option 2 with additional safety requirements as the technology evolves could result in a patchwork of regulations. The resulting 10 CFR Part 30 language may look more like what exists today for a utilization facility under 10 CFR Part 50.

ACRS Recommended Approach

Of the three options outlined in the white paper, the hybrid approach (Option 3 – byproduct and utilization combined framework) should be pursued. It provides a graded approach commensurate with the hazard. Decision criteria will need to be developed to limit what may be licensed using 10 CFR Part 30. In addition, it allows development of regulation for higher consequence facilities as experience is gained with early applications and operation of lower consequence fusion facilities. This option is necessary and prudent given (a) the broad set of hazards anticipated for the range of fusion facilities currently under consideration, (b) the current low technology readiness of the primary concepts under development, and (c) the high uncertainties in plasma physics, plasma particle power management, self-heated plasmas, and the nuclear engineering technologies necessary to support fusion as an energy source.

Development of decision criteria will be critical to implement the hybrid approach, and this work should start now. The decision criteria should be based on anticipated inventories of radioactive materials (activation products and active tritium) in the fusion energy facility, which are a function of power level and accumulated neutron fluence. The DOE Hazard Categorization Standard and the DOE Fusion Safety Standard are useful starting points for this activity.

A license issued under 10 CFR Part 30 is appropriate for fusion facilities, provided tritium inventories are low (e.g., < 10 g active inventory) and activation is minimal (e.g., < 0.01 MW-yr/m^2 or 0.1 dpa). This will allow for innovation and maturation of proponents' concepts and will result in regulatory certainty for near term applications.

Sincerely,

Joy L Rempe Signed by Rempe, Joy
on 10/21/22

Joy L. Rempe
Chairman

Appendix:
Safety and Environmental Hazards Associated with Fusion Energy Systems

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APPENDIX

Safety and Environmental Hazards Associated with Fusion Energy Systems

The following points need to be considered in characterizing the safety and environmental hazards associated with fusion energy systems and in developing the proper regulatory approach for larger fusion power plants.

- For the D-T fusion fuel cycle, a power plant will consume ~56 kg of tritium/GW_{th}-year of operation. This consumption rate implies active tritium inventories at or near the kilogram level. The actual tritium inventory in a facility will depend on many assumptions about the physics of a burning plasma that are highly uncertain today and assumptions about tritium separation processes in the associated tritium plant of the facility. By comparison, a DOE Hazard Category II nuclear facility would contain between 1.6 and 30 g of tritium. In order to meet the U.S. Environmental Protection Agency protective action guidelines for no evacuation, releases must be less than approximately 50 g even in worst case events. Chronic tritium releases are highly regulated (< 20,000 pCi per liter for drinking water) because the tritium may enter drinking water supply systems. Thus, the tritium confinement safety function will be extremely important in the design, and segmentation of the inventory will be necessary. Moreover, because tritium permeation through materials increases exponentially with temperature, tritium confinement in a high temperature power producing fusion plant will be more challenging than in current experiments that operate at lower temperature.

- The example of tritium mobilization during a loss of vacuum event illustrates how the nature of the facility determines the hazard. For a machine such as the Joint European Torus (JET), tritium mobilization is very low because the machine is low Q, is inertially cooled, and has no significant neutron activation. However, for a fusion power plant with significant decay heat from neutron activation and high-temperature actively cooled structures in a blanket necessary to produce power, a loss of vacuum event is more severe with mobilization of tritium and activated dust and the potential for chemical interactions between the air and plasma facing components and between air and dust. Such events were studied experimentally in Japan and analyzed extensively for the International Thermonuclear Experimental Reactor (ITER).

- Decay heat levels in a D-T fusion power plant can vary between 0.01 to 1 MW/m^3. The higher values are typical of plasma facing components, such as tungsten armor that faces the plasma, and the lower values are deeper in the fusion breeding blanket. These values are very similar to the decay heat of gas reactors (~ 0.03-0.08 MW/m^3) and LWRs (~ 0.5-1 MW/m^3) indicating that actual management of this energy source is required. The actual temperature response and the ability to reach melting depends on the design of the fusion structure. A related hazard is local melting that can occur in the plasma wall due to plasma instabilities in which the stored energy of the plasma is focused on the structure. In addition, if one of the magnets (in magnetic confinement approaches) were to arc, melting of structures such as confinement boundaries in the vicinity could occur given the large, stored energy in the magnet set (10 to 100 GJ at power plant scale). In their review, staff should consider insights gained from experiments in Europe and modeling of magnet arcing in the U.S. performed to examine this safety concern.

- Both Deuterium-Deuterium (D-D) and D-T fusion reactions at power plant scale will produce fast neutrons of sufficient energy to cause radiation damage to materials at levels that will lead to deleterious changes in the materials properties of structures. For higher neutron fluxes, staff will need to ensure designers have included sufficient cooling of structures and shielding to protect workers during operation.

- When the neutron activation of components surrounding the plasma at engineering or power plant scale is significant, there will be safety and operational implications to be examined including radioactive dust produced by plasma wall interactions, remote maintenance of activated components, and ultimate disposition of the activated material as radioactive waste.

- Waste classification is strongly dependent on impurities in the materials being used. Because the material used to surround the plasma is at the discretion of the designer, the development and qualification of so-called fusion 'low activation' materials is very important to reduce the radioactive waste burden. Until these materials are available, a fusion facility will have to use existing alloys with levels of impurities whose activation at engineering or power plant neutron fluences could cause the waste to be classified as greater-than-Class C.

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