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Technical White Paper: State Regulation of Fusion Machines

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EXECUTIVE SUMMARY

Overview

Fusion energy holds the potential to revolutionize the energy sector by generating vast amounts of power from minimal fuel. While fusion machines have a fundamentally lower hazard profile than fission reactors, they may nonetheless contain several hazards of concern to state radiation control agencies, including x-rays, radioactive material, and air effluents, as well as industrial hazards that warrant attention from other occupational safety agencies. State regulatory frameworks must evolve to address the unique challenges posed by this emerging technology. As state agencies develop expertise with regulating fusion machines, there are a number of technical and organizational growth opportunities.

This paper will review some of the key regulatory issues related to the commercial deployment of fusion machines, discuss available guidance, recommend radiation safety considerations, and (where available) describe best practices for regulating these technologies. This paper is intended to supplement guidance provided by the Nuclear Regulatory Commission (NRC) for the regulation of byproduct material used or produced by fusion machines. It is vital that states and partner federal agencies continue to share information and learn from each other as fusion machine technology grows and matures.

Key Regulatory Considerations

Regulating fusion machines requires addressing complex physical, radiological, and environmental factors. The interplay of neutron fluxes, tritium management, and the potential for emergency planning necessitates a robust and coordinated approach across state and federal regulatory bodies. Key areas of focus include:

Fuel Management

- **Tritium Monitoring:** Fusion machines utilizing tritium must establish monitoring systems for effluents and, in some cases, environmental impacts. Depending on the potential-to-emit quantities of tritium, licensees can deploy tools like groundwater wells and rainwater collectors to track tritium dispersion and demonstrate compliance with regulatory dose and concentration limits.
- **Environmental Monitoring:** Larger facilities may require assessments of hydrology impacts and public dose risks, ensuring alignment with federal and state standards.

Radiological Dose Compliance

- **ALARA Principles:** Adherence to the "As Low As is Reasonably Achievable" (ALARA) standards requires effective ventilation, decontamination procedures, and bioassay programs to monitor internal worker doses.

- **Monitoring Systems:** Air and effluent monitoring through ion chambers and bubblers, supplemented by surface contamination checks and sampling, are essential for compliance.

Neutron Management

- **Shielding and Material Selection:** High neutron fluxes necessitate appropriate shielding plans and construction materials (e.g., plastic and concrete) designed to control activation products and promote regulatory compliance safety.
- **Component Durability:** Neutron-induced degradation of components that could impact radiation safety should be addressed through maintenance protocols.
- **Public Dose Limits:** Facilities must demonstrate compliance with dose limits of 1 mSv/year (100 mrem/year) for areas accessible to the public.

Activation Products

Licensees should maintain accurate inventories of activated materials, develop handling protocols, and ensure proper storage and disposal processes to minimize worker and environmental exposure.

Emergency Planning

Facilities with significant tritium inventories (greater than 7.4×10^{14} Bq (20,000 Ci)) require an evaluation showing acceptable offsite doses (< 10 mSv or < 1 rem) or an emergency plan to ensure public safety. Smaller facilities should collaborate with local responders to establish robust onsite emergency policies.

Inspection and Training

- Inspectors need appropriate equipment, such as neutron dosimeters, to verify compliance with safety standards. States may benefit from engaging external experts to address neutron- and tritium-specific equipment if they do not otherwise have experience regulating neutron and tritium facilities.
- Operators should undergo phased training programs emphasizing fusion machine operations and radioactive material handling, adhering to established safety standards.

Regulatory Challenges

The regulation of fusion machines must consider the diversity of technologies and the need for coordination between state and federal authorities as rulemaking concludes. Key growth areas include:

- **Diverse Technologies:** The variety of fusion approaches may require licensing staff and regulators to learn how to apply general regulations to the specifics of each approach.
- **Emergency Planning Integration:** States must incorporate non-radiological hazards which could impact radiation safety, such as hydrogen fires, into emergency response strategies.
- **Material Control:** Effective inventory control and safety measures for tritium and activation products are critical.
- **Dose Assessment:** General criteria for maximum offsite dose assessments, including emergencies, need to be established.

- **Decommissioning Planning:** Lifecycle planning and financial assurance for facility decommissioning will need to be developed in partnership with licensees as shared operational experience is gained.
- **Emergent Issues:** As fusion machines advance, unanticipated regulatory complexities may arise, requiring continuous growth, collaboration, and adaptation.

Recommended Best Practices

To navigate the complexities of licensing and registering fusion activities, regulators should adopt the following best practices:

- **Phased Licensing:** For new applicants, begin with limited operational scopes, expanding as licensees demonstrate compliance and safety performance. Enhanced monitoring can help ensure safety where it is inappropriate or would cause undue delay to establish up-front design requirements.
- **Stakeholder Engagement:** Early and frequent interactions with applicants ensure a thorough understanding of the technology and its implications.
- **Cross-Program Collaboration:** States should unify strategies across radiation control programs to streamline licensing and compliance processes.
- **Use of External Expertise:** Engage third-party experts to evaluate complex aspects like shielding plans and accident scenarios, with costs covered by applicants.
- **Emergency Coordination:** Encourage partnerships between fusion facilities and local emergency responders to enhance preparedness and response capabilities.

Regulatory Coordination

Effective regulation of fusion machines requires collaboration between state and federal authorities, particularly the NRC. Key considerations include:

- **Collaboration:** In programs where responsibility for accelerators and other machine generated radiation is separate from the radioactive materials program, staff responsible for licensing and inspections should share insights, address gaps in expertise, and align regulatory practices.
- **Clarity in Jurisdiction:** Non-Agreement States must work with the NRC to clearly define regulatory responsibilities.
- **Training and Resource Sharing:** States should leverage training programs and shared resources to build competencies in neutron shielding and other technical areas.

Conclusion

Fusion energy represents a critical step toward achieving net-zero emissions, enhancing energy security, and maintaining technological leadership. As fusion machines emerge across the United States, regulatory bodies must adopt risk-informed, adaptive approaches to licensing. By fostering collaboration, leveraging expertise, and prioritizing safety, regulators can support the integration of fusion machines into the broader energy landscape, ensuring a sustainable and secure future for this transformative technology.

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INTRODUCTION

Fusion uses a small amount of fuel to generate a large amount of energy, and so fusion has been of interest to academics, private industry, the military, and national laboratories since the dawn of the atomic age. For several decades, small fusion machines have been available commercially as neutron generators in the well logging industry and for benchtop research and development applications. In the past ten years, larger vault-sized fusion machines have become available that produce neutron fluxes several orders of magnitude greater than earlier commercial fusion machines. Ultimately, researchers and industry partners hope to use fusion technology to generate electricity. To date, fusion machines[1] have not been able to demonstrate net engineering energy gain; however, the technology is rapidly advancing, and prototype fusion energy plants are planned in the U.S. within the next five years.

At its most simple level, a fusion machine accelerates a charged particle of a low atomic number (usually hydrogen or helium) towards other similar particles, therein causing atoms to fuse and release energy and new particles and then directly captures and uses the resultant products, including particles, heat, or other electromagnetic radiation. The physical conditions necessary for fusion involve potential hazards, including electric, magnetic, explosive, chemical, and radiation. This paper focuses on regulatory oversight of the radiation hazards.

Particle accelerators have been regulated by State radiation control programs for decades, and fusion machines are a subset of particle accelerators. Agreement States also license the radioactive material associated with fusion machines as targets and other activated materials. Historically, the U.S. Nuclear Regulatory Commission (NRC) only regulated fusion machines that used a tritium target (neutron generators) and, to date, the NRC has not regulated fusion machines with targets other than tritium.

In 2019, the U.S. Congress passed the Nuclear Energy Innovation and Modernization Act (NEIMA; Public Law 115-439). Section 103 of NEIMA specifically requires the NRC to "complete a rulemaking to establish a technology-inclusive, regulatory framework for optional use by commercial advanced nuclear reactor applicants for new reactor license applications" by December 31, 2027. NEIMA's definition of an advanced nuclear reactor included both fission and fusion technologies.

On April 13, 2023, the U.S. Nuclear Regulatory Commission issued SRM-SECY-23-001 "Options for Licensing and Regulating Fusion Energy Systems" which directed NRC staff to license near term fusion machines by building on the existing process for licensing the use of byproduct

[1] Different terms are used for devices that use fusion as the source of energy. This paper will use the term "fusion machine" consistent with the definition introduced into the Atomic Energy Act by the ADVANCE Act of 2024. This term is considered synonymous with terms such as "fusion device," "fusion reactor," "fusion facility," and other terms used to describe uses of fusion energy in other sources.

materials. Underlying this analysis was a conclusion that fusion machines "operate in a manner consistent with the regulatory definition of particle accelerator" (SECY-23-001, at 10).

As such, Agreement States will continue to regulate fusion machines of all sizes. As fusion machines become larger, with greater outputs, the radiation safety requirements to license such facilities may exceed the limitations of existing guidance for near-term fusion machines. Near-term fusion machines include designs currently under development for deployment in the U.S., e.g. ARC, etc. In the Commission's April 2023 decision, NRC staff were also directed to provide recommendations to the Commission, in consultation with the Agreement States, if proposed fusion machine designs exceeded those currently envisioned.

Although the NRC Commission decided to regulate fusion machines under the byproduct material framework in 10 CFR Part 30, the definition of byproduct material in the Atomic Energy Act of 1954, as amended (AEA) did not mention fusion. This gap was addressed by the U.S. Congress, in 2024, with the passage of the "Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy Act" (ADVANCE Act of 2024), which, in part, included amending the AEA to introduce and define the term "fusion machine" and revise the definition of "byproduct material" to add material produced by a fusion machine (discussed further below) as well as amending NEIMA to separate fusion machines from other advanced nuclear reactors.

This paper will review some of the key regulatory issues for fusion machines and, for each issue, discuss available guidance (U.S Department of Energy, NRC, and others), recommend radiation safety considerations, and (where available) describe best practices for regulating these technologies.

Historical Background

The early beginnings of research on fusion energy can be traced to the 1920s when British astrophysicist Arthur Eddington (1882-1944) published a theory that stars draw their energy from the fusion of hydrogen into helium. As this idea spread around the world, many scientists researched fusion energy and worked to confirm Eddington's theory. Physicist Ernest Rutherford (1871-1937) and his team began to conduct experiments with a heavy isotope of hydrogen in the 1930s. They produced the first man-made fusion reaction in 1933. Mark Oliphant (1901-2000), one of Rutherford's assistants, discovered new forms of hydrogen and helium: deuterium, tritium and helium-3. He found that when they reacted with each other, the particles that were released had far more energy than that with which they started.

During the 1940s and 1950s research programs were set up in many countries to gain a better understanding of the physics of fusion, the fusion process for energy production, and to develop thermonuclear weapons. The tokamak, a type of magnetic confinement fusion machine, was proposed by Soviet scientists in 1950. In 1958, most American, British, and Soviet fusion research programs were declassified and made public at the Second Geneva Conference on the Peaceful Uses of Atomic Energy. Since then, fusion research has been characterized by international collaboration. An example of this is the International Thermonuclear Experimental Reactor (ITER) which is the world's largest fusion research and engineering experiment where 35 countries are working together aimed at creating energy through a fusion process.

An early approach to fusion machines involved magnetic fields to confine fusion fuel in the form of a plasma, called magnetic confinement fusion. An alternative early approach was based on heating and compressing a fuel pellet with intense lasers, called inertial-confinement fusion. Recently many other fusion technologies using alternative fuels and confinement strategies are being considered for potential fusion machines.

In 2022, a team at Lawrence Livermore National Laboratory's (LLNL) National Ignition Facility (NIF) reached a scientific energy breakeven and produced more energy from fusion than the laser energy used to drive it.

Progress in fusion energy and technology continues to be accelerated because it is a potential source of plentiful and safe energy. The state of the science, technological breakthroughs, and component manufacturing improvements have led to a need for a regulatory framework for fusion machines.

FUSION DEFINITION

Following the passage of NEIMA, the NRC formed a working group in 2020 to develop a clear and predictable regulatory framework for fusion machines and held more than ten public meetings[2]. That technical effort leveraged expertise from States, universities, the private fusion industry, the Department of Energy, Non-Governmental Organizations (NGOs), international partners, and advisory committees and culminated in the NRC staff submitting SECY-23-0001, "Options for Licensing and Regulating Fusion Energy Systems," on January 3, 2023.[3] In response, the Commission unanimously agreed to regulate fusion machines under the 10CFR Part 30 byproduct materials framework.[4]

In 2024, Congress further codified the Commission's technical assessment and decision to regulate fusion as byproduct material in law via the ADVANCE Act.[5] Section 205 of the ADVANCE Act defines fusion machine and added it to section 11 of the AEA.

> "The term 'fusion machine' means a machine that is capable of – "(1) transforming atomic nuclei, through fusion processes, into other elements, isotopes, or particles; and (2) directly capturing and using the resultant products, including particles, heat, and other electromagnetic radiation."

In addition, subsection 205(a) of the ADVANCE Act amends the definition of byproduct material in AEA section 11e.(3)(B) to read as follows:

> any material that – (i) has been made radioactive by use of a particle accelerator, *including by use of a fusion machine;* and (ii) *if made radioactive by use of a particle accelerator that is not a fusion machine,* is produced, extracted, or converted after extraction, before, on, or after August 8, 2005, for use for a commercial, medical, or research activity;

The ADVANCE Act changed NEIMA's term "fusion reactor" to "fusion machine" and introduced a new definition of "fusion machine" in the AEA, separating fusion machines from fission reactors. The definition of fusion machine was also incorporated in the definition of "byproduct material" in the same subpart as particle accelerators (Section 11e.(3)(B) of the byproduct material definition). This resulted in two types of devices that produced radioactive material under the same section of the AEA definition of "byproduct material" and made "fusion machine" a subset to the term "particle accelerator".

CRCPD recommends that any states who are evaluating regulation of fusion machines by programs which regulate accelerators or lasers use legislative and regulatory definitions for

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[2] https://www.nrc.gov/materials/fusion-machine.html

[3] This options paper may be accessed at https://www.nrc.gov/docs/ML2227/ML22273A178.html

[4] The NRC Commission decision (SRM-SECY-23-001) may be accessed at https://www.nrc.gov/docs/ML2310/ML23103A449.pdf

[5] https://www.congress.gov/118/plaws/publ67/PLAW-118publ67.pdf

fusion machines and byproduct material which are compatible with U.S. Nuclear Regulatory Commission definitions.

LICENSING

Licensing the use of byproduct material by fusion machines can present growth opportunities to states and to the NRC due to the nascent nature of the technology and still-developing operational experience. States may need to determine the jurisdictional split between their radioactive materials, X-ray, and any other radiation control programs; those programs should work together throughout the licensing process.

LICENSING CHALLENGES

1. The variety of fusion machines under development will add complexity to license review as conditions will be different for different technologies. States and NRC must ensure extensive training is provided to staff.
2. States must decide how to incorporate non-radiological hazards which could impact radiation safety into emergency planning.
3. States must consider appropriate expectations for the precision of radioactive material inventory control, particularly as it pertains to tritium and activation products.
4. The National Materials Program should develop general criteria for assessing evaluations of maximum dose to offsite persons, including for emergency planning. This guidance should include the flexibility for license applicants to utilize the latest codes and assumptions most appropriate for their technology.
5. Financial assurance and decommissioning planning (e.g., waste volumes) will need to be iteratively developed for first-of-a-kind facilities.
6. As more facilities become licensed and begin operation, additional growth opportunities are likely to be identified. Collaboration between states and the NRC will be vital for information sharing, alignment, and assistance.

RECOMMENDED BEST PRACTICES:

1. Be aware of companies in your State that are pursuing fusion research. Meet with company leadership to learn about their technology and any proposed timeline for licensure.
2. Meet with the applicant early and often. Have the applicant provide presentations to state regulatory staff on the various components of the fusion machine, and how they work, as

early as possible before a license application is submitted. Continue to meet regularly with the applicant during the application review. Involve all relevant radiation programs in routine meetings with the applicant so that all programs maintain general awareness of the applicant's current and future licensing needs.

3. Perform site visits as construction milestones are reached to maintain situational awareness.
4. Consult with other states or the NRC who have issued fusion-related licenses or developed guidance for advice, recommendations, and lessons learned.
5. Consider using a phased licensing approach for the use of byproduct material by fusion machines. For example, a licensee may need to receive tritium well in advance of actually conducting tritium operations in the fusion machine because the various tritium handling systems need to be commissioned and tested. Likewise, the licensee may request use of instrument calibration sources only. Depending on the maturity of the applicant's design, the state may need to work with applicants to authorize commissioning of the fusion machine in a phased approach that allows material licensees to test processes and equipment at increasing device power and output. For example, an applicant who plans to use tritium fuel in a fusion machine should consider first testing their system using deuterium fuel.
6. Ensure authorized activities are consistent with the facility's design and safety systems.
7. Ensure applicants make available for review necessary modeling data and the name of software/codes (including assumptions) as part of the licensing process.
8. Consider hiring a third-party consultant for assistance in complex areas of licensing review. Consultant fees incurred by States should be paid by license applicants. The role of the consultant should be to provide expertise in evaluating complex areas for compliance with regulatory requirements. For example, if a state assesses the level of modeling software expertise needed to evaluate a fusion machine application and determine in-house staff do not have the depth of expertise required to evaluate an applicant's modeling data, the state may choose to supplement their knowledge by hiring a third-party consultant to evaluate modeling data.
9. Evaluate the plausibility and potential impact of industrial hazards (such as a hydrogen fire) to result in exposure to ionizing radiation.
10. Evaluate whether the facility considered other catastrophic environmental events (e.g. state standard seismic acceleration for industrial facilities, etc.), appropriate for the region being built in, when addressing potential exposure scenarios.
11. Various codes are typically used by licensees in applications.
    a. Shielding is typically evaluated in Monte Carlo codes. The most popular is MCNP6, but others can include OpenMC, FLUKA, and Geant4. Some states,

such as Washington, require licenses to include sign-off by approved third-party expert reviewers.

b. Shielding can also be evaluated analytically, e.g., using standards like the NCRP documents listed below.
    i. NCRP 49, 1976: Structural Shielding Design and Evaluation for Medical Use of X-Rays and Gamma Rays of Energies up to 10 MeV National Council on Radiation Protection and Measurements
    ii. NCRP 147, 2004: Structural Shielding Design for Medical X-Ray Imaging Facilities.
    iii. NCRP 144, 2003: Radiation Protection for Particle Accelerator Facilities. National Council on Radiation Protection and Measurements.

c. Traditionally, the COMPLY Code has been used to evaluate the dose due to radioactive air emissions (e.g., tritium). More recently, the CAP88 code has been recommended and sample instructions on how to use CAP88 is linked here.

REGULATORY AUTHORITY

Particle accelerators, which are electronic sources of radiation, and fusion machines (a type of particle accelerator) produce radioactive material during operations. Particle accelerators have been regulated by states for many decades. The NRC and Agreement State programs have jurisdiction over the byproduct material used or produced by a fusion machine, but not the fusion machine itself. Like general particle accelerators, a fusion machine can be registered or licensed by a state that has that authority. Within the state, multiple programs or agencies may have jurisdiction over different regulatory aspects of fusion machines. Although fusion machines are related to particle accelerators, larger fusion machines may have a different risk profile than the particle accelerators currently regulated for medical and other industrial purposes. This will require a regulatory approach that ensures the risks and hazards are appropriately regulated. Licensing and regulatory activities should be risk informed. (See Appendix A, "Typical Tritium Fuel Cycle Considerations for a D-T Fusion Machine with Blanket Integration")

In Non-Agreement States, the accelerator is regulated by the State and any byproduct material is regulated by the NRC. CRCPD recommends the following best practices for regulating fusion machines in Non-Agreement States:

- State should ensure they have expertise for evaluating shielding plans for high neutron fluxes or use contract experts.
- Coordinate with NRC to determine jurisdictional boundary for regulating fusion machines.

In Agreement States, both the particle accelerator component of the fusion machine and any radioactive material (tritium, activation products) are regulated by the State. In Agreement States, CRCPD recommends the following best practices for facilities with fusion machines:

- Shielding plan reviews must consider all radiation hazards associated with the fusion machine. Ensure shielding plan reviewers have competency with neutron shielding, or partner with staff who do.
- Inspections should be performed jointly for all radiation control programs (X-ray, radioactive materials, air emissions), whenever possible.

Radiation control programs should review the types of activities and uses being requested and thoughtfully consider how to regulate the project. Radiation control programs should have a means to identify, assess, and resolve conflicts between requirements of the State radiation control programs (e.g., operator training).

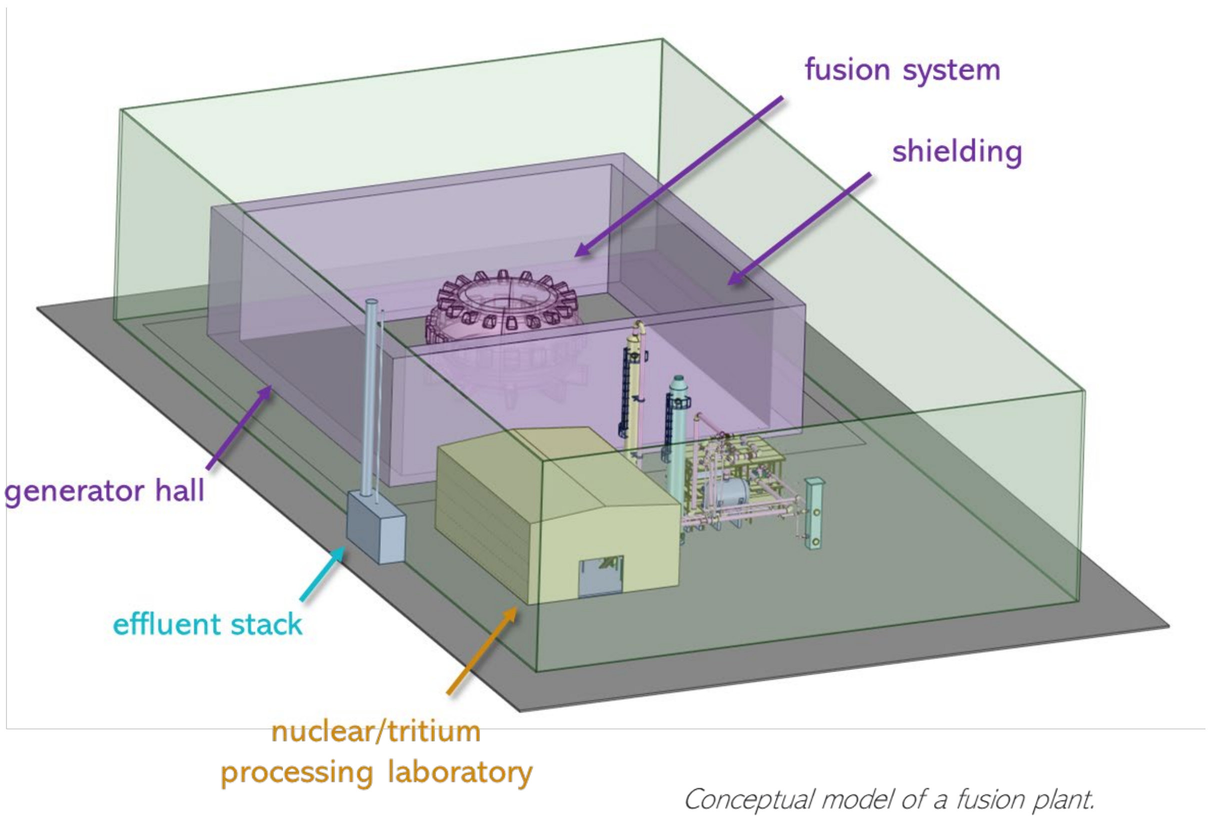
The following table provides a possible licensing approach. The level of risk will depend on the complexity and scale of the proposed facility.

Table 1: Licensing needs in phases of fusion licensing

Phase	Sample licensing needs
Calibration	• Californium-252 or Americium-Beryllium neutron source

	• Portable neutron generator
Research and Development	• Multiple reviews for increased shielding as commissioning progresses • Tritium, depleted uranium (Getter bed) • Potential exemptions for air emissions in early stages • Financial assurance for decommissioning
Demonstration/ Pilot	• Normal emissions of 3.7×10^{12} to 3.7×10^{13} Bq 100 to 100,000 Ci) of tritium • Tritium monitoring and handling equipment • Activation products • Emergency planning (if/as needed) • Environmental monitoring
Commercial	• Full-scope licensing

Figure 1 Conceptual Model of Fusion Machine



Conceptual model of a fusion plant.

LICENSING CONSIDERATIONS SPECIFIC TO FUSION MACHINES

Fuel

The following images demonstrate the reactions of the four most common types of fuel for fusion machines.

Figure 2. Deuterium-Deuterium fusion

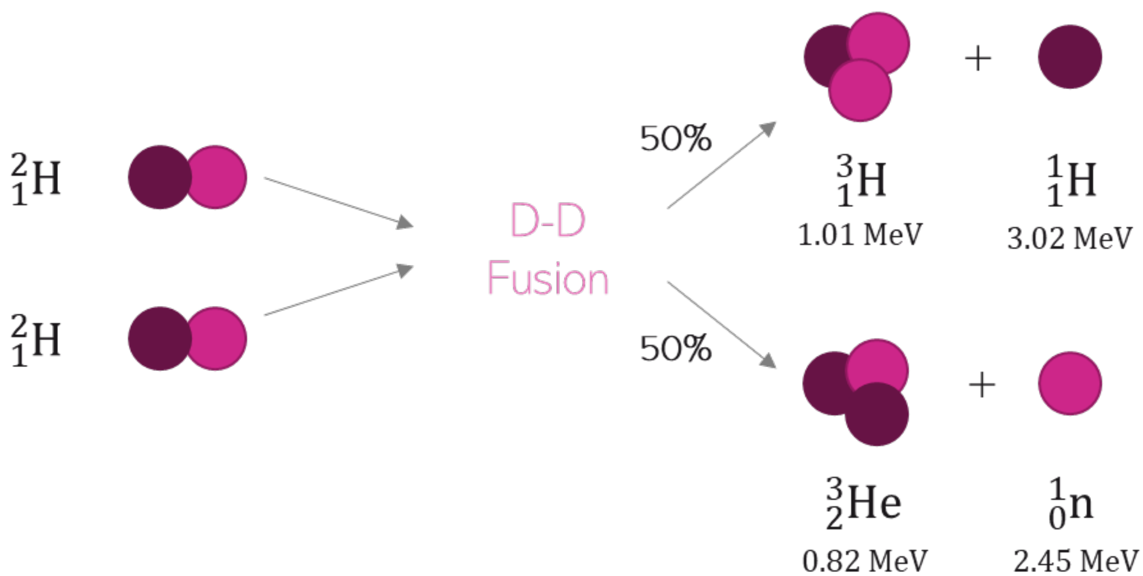


Figure 3. Deuterium-Tritium fusion.

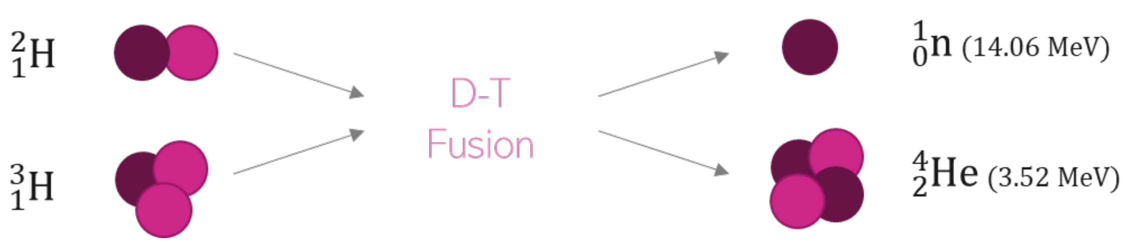


Figure 4. Deuterium Helium-3 fusion

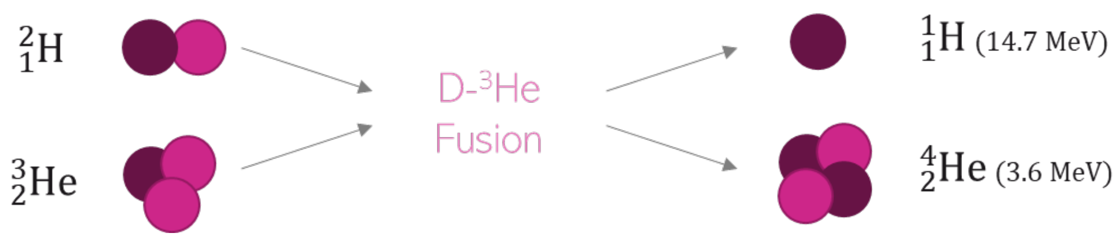
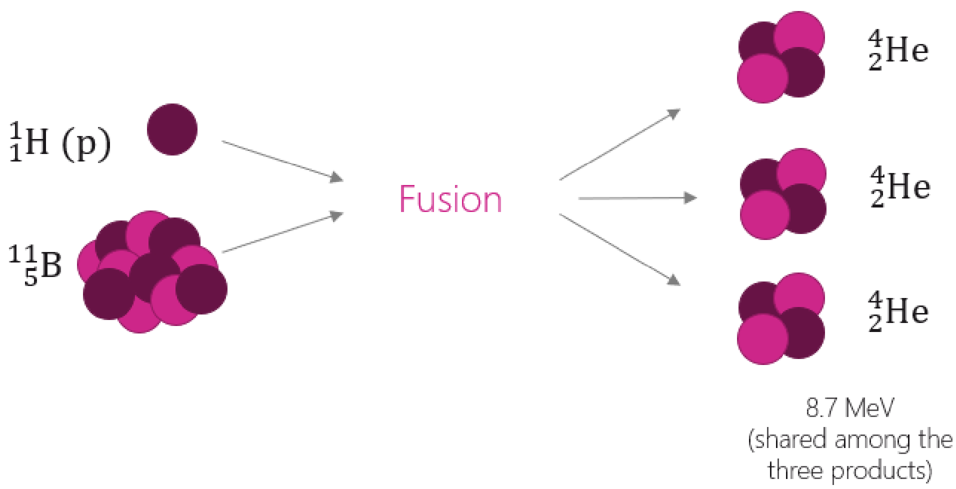


Figure 5. Proton-Boron-11 fusion



Tritium

Facilities operating a fusion machine must monitor the release of tritium. It is expected that some tritium will be released as airborne effluent as part of normal operations. Regulations in 10 CFR 20.1302 require licensees to "make or cause to be made, as appropriate, surveys of radiation levels in unrestricted and controlled areas and radioactive materials in effluents released to unrestricted and controlled areas to demonstrate compliance with the dose limits for individual members of the public." Monitoring these releases is accomplished by effluent monitoring, and compliance can be shown by either monitoring or calculation. Effluent releases must also meet the constraint rule in 10 CFR 20.1101(d) which constrains air emissions of radioactive material to the environment such that the individual member of the public likely to receive the highest dose will not be expected to receive a total effective dose equivalent in excess of 0.1 mSv (10 mrem) per year. If a licensee subject to this requirement exceeds this dose constraint, they are required to report the exceedance and promptly take appropriate corrective action to ensure against recurrence.

Effluent monitoring is measuring the release of radioactive material through the facility stack. License conditions typically follow ANSI/HPS N13.1: Sampling and Monitoring Releases of Airborne Radioactive Substances From the Stacks and Ducts of Nuclear Facilities. Absolute emission quantities (measured in Becquerels or Curies) are typically monitored via bubblers. Air exiting the stack is sampled for tritium by bubbling it through a fluid (e.g., glycol) and counting samples of the fluid in a liquid scintillation counter on a weekly basis. Additionally, the flow rate of air going through the stack is monitored (and is required to interpret the absolute emission based on the bubbler results). Although not typically required as a license condition, licensees will likely also have real-time stack monitoring that measures tritium concentration (in units of $\mu Ci/m^3$) in a flow-through ion chamber. Such bubblers, stack monitors, and ion chambers are off-the-shelf items.

Case Study: Washington State Department of Health (WADOH) - Office of Radiation Protection

Best Practices for Environmental Radiation Monitoring

Environmental radiation monitoring plays a crucial role in protecting public health by ensuring that radiation levels remain below regulatory limits and by keeping radiation exposure as low as reasonably achievable (ALARA). It also helps assess the overall impact of radiation on the environment.

The data collected through monitoring programs can be used to:

- Identify and measure unexpected releases or exposures,
- Track the buildup of contaminants over time,
- Show that safety technologies and procedures are working as intended.

It's essential for licensees and registrants to fully comply with the WADOH limits on releases and radiation exposure to the public and employes. Environmental monitoring and laboratory procedures shall be tailored to the specific radiological processes used at the facility and meet regulatory standards for data quality. These procedures should be sensitive enough to detect radioactivity early, before limits are exceeded.

Larger facilities may be required to prepare an annual report outlining environmental releases. Additionally, the WADOH may establish an independent Quality Assurance/Quality Control (QA/QC) program to ensure these standards are met and to provide the public trust in the monitoring programs held by the licenses and registrants in Washington State.

Environmental monitoring measures the release of radioactive material into the environment. Often, this can be accomplished by measuring the total emission when the total emission is 3.7×10^{12} Becquerels (100 Ci) or less. Monitoring may also be accomplished by setting up groundwater wells, rainwater collectors, or other water collection methods. These devices are set up on facility property and may be set up outside the property within the community. Hydrology studies must be conducted to evaluate the flow of groundwater to determine the best placement of wells. This is especially important if the facility is near a river or body of water. Rainwater collectors can effectively be placed anywhere unobstructed to the sky. A less invasive, cheaper instrument that can be implemented are micro diffusion cells (the size of a thumb) that passively monitor for tritium. Prior to operations, it is important to establish the baseline environmental conditions at the selected site, which can later be used to measure the incremental environmental impacts of the facility during operation and decommissioning. Environmental monitoring may or may not be required once operations begin. However, as a voluntary best practice, all facilities possessing large amounts of tritium should conduct environmental monitoring to increase public trust.

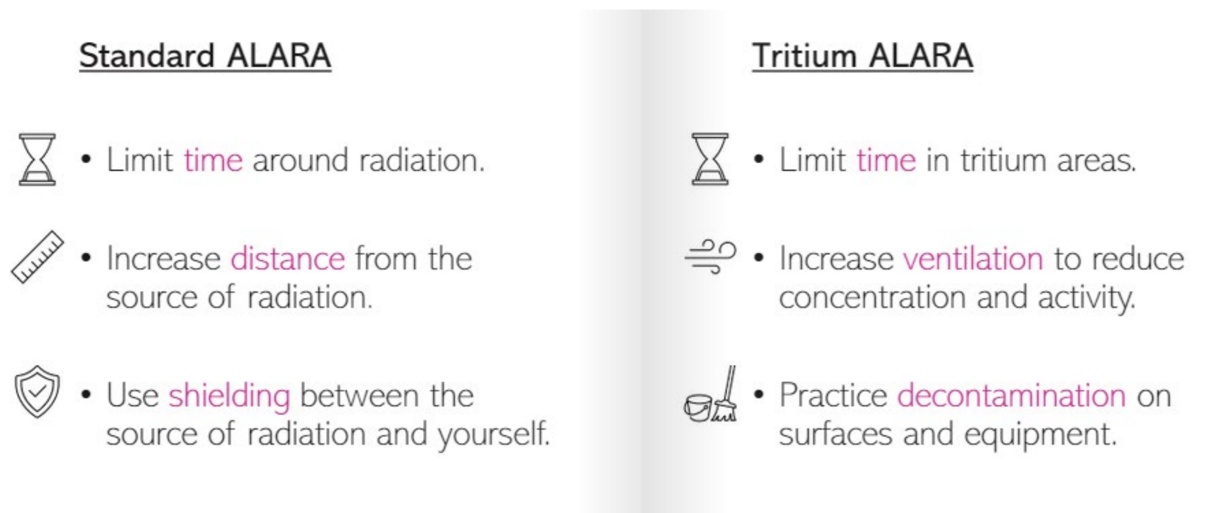
Environmental Review

For Agreement States, the requirements for environmental review may vary depending on the specific state environmental protection act. In some cases, environmental review may be performed by other state agencies. Radiation control programs should be familiar with state environmental requirements for general industry and for power-production facilities and be aware of other state requirements for environmental reviews. Environmental review may not be required for all facilities with fusion machines. For example, the scope of operations for small research facilities may not trigger an environmental review. Best practice is to identify the requirements for environmental review early and engage with key stakeholders.

Dose

For traditional uses of radioactive material, ALARA is practiced with time-distance-shielding. For tritium, ALARA is practiced with time-ventilation-decontamination. In order to support dose reduction, fusion machine licenses should support adequate ventilation, tritium measurement, and decontamination processes.

Figure 6. ALARA: As Low As is Reasonably Achievable



Ultimately, a licensee must also incorporate routine bioassays for staff who are involved in higher risk tritium activities (e.g., if the potential exposure is > 3.7×10^{9} Becquerel (100 mCi) in one month). A bioassay is a method used in dosimetry to measure the amount of tritium that has been absorbed into the body. Tritium exposure is typically assessed by analyzing bodily fluids, such as urine, to determine the concentration of tritiated water (HTO) or organically bound tritium (OBT). Since tritium emits low-energy beta particles that are difficult to detect externally, bioassay provides a direct measurement of the internal dose, helping to estimate the radiation exposure and guide appropriate health and safety measures for individuals working with or around tritium. Licensing authorities must review and assess the licensee's proposed bioassay program.

Monitoring

The air in tritium use areas is monitored using ion chambers that flow air through them – these are off-the-shelf items. These detectors measure tritium concentration to give indicators to radiation workers. The effluent concentration limit is 3700 Bq/m^3 (0.1 $\mu Ci/m^{3)}$ (and tritium work areas typically strive to be at or below this limit), and 7.4×10^5 Bq/m^3 (20 $\mu Ci/m^{3)}$ corresponds to the radiation worker dose limit if a worker were to work in such an area for 2000 hours per year[6]. Similar monitors are used to measure the concentration of tritium leaving the stack. The stack should also be equipped with bubblers that sample air through e.g., glycol vials. Bubbler samples are typically counted once per week in a liquid scintillation counter and give an absolute measurement of Becquerels emitted per week. Additionally, surfaces must be monitored routinely for removable tritium.

Waste

Experience to date has shown that waste can be effectively managed using existing waste disposal pathways (for example, hospitals and cyclotron facilities). While current estimates for costs are comparable to other facilities with similar waste streams, until more experience is gained with operational fusion machines, there remains uncertainty with the volume and costs. Fusion machines may generate other waste streams including activated dust from plasma facing components and tritium contaminated components. States should continue to monitor facilities and ensure decommissioning plans accurately reflect the scope and costs.

[6] https://www.nrc.gov/reading-rm/doc-collections/cfr/part020/part020-appb.html and https://www.nrc.gov/reading-rm/doc-collections/cfr/part020/appb/hydrogen-3.html

Neutron and Charged Particles

All fusion systems produce neutrons and other charged particles, from either primary or secondary reactions. Neutrons present regulatory challenges both from direct energy deposition by the neutrons themselves and from radioactive decay of activated components. In addition to neutron activation, protons can also activate components.

In research and development near-term, material susceptibility to neutron damage may not be fully understood under prolonged fusion environmental conditions. Adequate safety measures must be in place to identify, assess, and mitigate safety consequences of neutron-induced material failures.

The risk from neutrons is proportional to the flux and energies of neutrons produced.

Licensing challenges may include:

1. **Construction materials**: Attention must be paid during the design and construction phase of fusion machines to maintain the creation of activation products that may pose challenges for decommissioning as low as reasonably achievable.

2. **Neutron embrittlement**: In fusion machines with large neutron outputs, licenses should have quality control and maintenance plans for managing neutron damage to components important to confining byproduct material. Materials science research for fusion-compatible materials remains in progress. License reviewers should be aware which components can be replaced (and at what frequency) and what components cannot be replaced (and therefore limit the operating lifetime of the fusion machine).

3. **Public Dose Limit**: If a fusion machine is installed close to unrestricted areas, neutron emission from the system may be the primary radiation hazard to members of the public due to the distances neutron radiation can travel, if unshielded. All licensees must demonstrate compliance with public dose limits of 1 mSv (100 mrem) per year from licensed operations (10 CFR 20.1301). If licensees use environmental dosimeters to demonstrate compliance with public dose limits, be aware of the dosimeter's lower threshold of detection. For example, monthly exchange of an environmental dosimeter with a minimum dose measurement of 100 μSv (10 mrem) will not demonstrate compliance with public dose limits (12 months × 100 μSv (10 mrem) minimum is greater than 1 mSv (100 mrem). In this example, quarterly dosimeter exchange would be simpler and resolve concerns with threshold of detection.

4. **Neutron shielding plans:** MCNP N-Particle Monte Carlo code and other software may be used by applicants to model neutron doses and shielding from fusion machines. Regulatory agencies should consider which simulation methods (and assumptions) are

acceptable and how the simulations can be confirmed by license reviewers.

5. **Activation products:** Licensees must consider how to inventory and manage activation products. Licensees should develop a system to account for discrete activated items that are removed from the fusion machine or vault by identifying radioactive items and applying inventory control practices to these items. In addition, licensees must apply either procedural or engineering controls to limit radiation worker exposure to activation products.

Recommended best practices:

1. For research and development applications, ensure licensees have decommissioning financial assurance and safety processes in place to address any activated material created during commissioning or operation.
2. The absolute quantity of activation products (typically licensed as “elements 3-83") can be difficult to predict a priori, particularly due to material impurities (e.g., trace cobalt concentration in steel). The challenge is exacerbated by isotopes with short half-lives (< 5 min), where activities can be very high for very short periods of time. Some states license elements 3-83 as two line items: one for half-lives less than or equal to 120 days, and one for greater than 120 days. Some states have elected to license “as needed” quantities of elements 3-83 due to activation (with plans to revise the number as impurities become known through operational experience). Some states have opted for a beam time limit in lieu of a Becquerel/Curie limit (that directly corresponds to how much activated material is created).
3. During pre-licensing meetings with the applicant, determine what modeling software the applicant intends to use to demonstrate radiation safety compliance. Ensure reviewers understand the assumptions and limitations of the software.

INSPECTIONS

In general, inspections of licenses with fusion machines are expected to be more time-intensive than inspections of typical radioactive materials licensees. Inspectors should expect to spend significant effort on inspection planning to effectively assess operations on site.

For inspections, inspectors should be provided with dosimetry and detectors, appropriate to the types of radiation and energy ranges encountered at the licensed site. For example, for fusion technologies that generate neutrons, inspectors should have neutron dosimetry and detection capability. Inspectors must have knowledge of the physical and radiation properties of the specific radiologic hazards specific to the site (such as tritium or neutrons), and of the fusion machines involved, along with awareness of other hazards. Radiation control programs should determine if inspectors will independently verify contamination levels and effluent monitoring or perform a compliance review of facility records. If inspections include independent verification of contamination and effluent, this may require new program equipment or new methods of laboratory analysis and coordination with other state programs which perform air emission monitoring. Radiation control programs should also consider sampling tritium in ground water. Due to the complexity of inspection issues and the required experience with neutron shielding and tritium, the use of an outside qualified expert may be needed to assist or provide training. Licensees must also develop methods for identifying when activated items become “waste” and how to manage inventory for items which will be returned to service (possibly following decay, detritification, or decontamination). In addition, licensees must apply either procedural or engineering controls to limit radiation worker exposure to activated air and dust.

Recommended best practices:

- Units within a State radiation control program (x-ray, radioactive materials, etc.) should develop a unified inspection strategy for assessing a fusion licensee’s compliance with radiation control regulations.
- Perform smaller inspections more frequently by focusing on a different subset of program areas on each inspection.
- Rotate inspector responsibilities so that radiation control programs maintain depth of expertise for fusion licensees.
- Tailor early inspection of fusion machines to the phase of commissioning and operation of the facility.

EMERGENCY PLANNING

10 CFR Part 30 contains emergency planning requirements for licensees who are authorized to possess large amounts of unsealed radioactive material. These requirements have isotope-specific thresholds and require calculation of the unity rule. Per 10 CFR 30.32(i), applicants who seek to possess more than 7.4×10^{14} Becquerels (20,000 Ci) of tritium (assuming a 50% release fraction) must consider the need for an emergency plan or demonstrate why a plan is not required because any theoretical public dose will be below regulatory threshold. Some fusion machine applicants may also need to consider irradiated material in their evaluation for the need of an emergency plan since 10 CFR 30.72 Schedule C includes emergency planning thresholds for solid combustible and solid noncombustible irradiated material. If an applicant's requested possession limits exceed the thresholds in 10 CFR 30.72 Schedule C, applicants must provide either an emergency plan or an evaluation showing that the maximum dose a person offsite due to a release of radioactive materials would not exceed 10 mSv (1 rem) effective dose equivalent.

The Department of Energy Standard for Safety of Magnetic Fusion Facilities (DOE-STD-6002-96) has an emergency planning standard that requires "fusion facilities be designed and operated in such a way that no public evacuation will be necessary, even in the event of a severe off-normal event." One primary challenge in this area is the lack of operational experience with large-scale, commercial, fusion machines. Because there are no commercial fusion machines for energy production currently in operation, emergency planning for fusion machines is largely based on theoretical analyses and simulations, which may not fully capture the complex and dynamic nature of a real-world emergency. In addition, plasma energy, coolant energy (e.g., pressurized water, cryogens), chemical energy sources, and magnetic energy involved in fusion reactions pose a risk of explosions and fires, which could release other non-radioactive hazardous materials.

NRC Regulatory Guide 3.67 "Standard Format and Content for Emergency Plans for Fuel Cycle and Materials Facilities" describes an acceptable method for providing emergency plans and implementing procedures. Fusion machine license applicants who provide an emergency plan may follow this guidance. However, the NRC has not published guidance for performing or reviewing a dose evaluation to demonstrate that a release of radioactive materials would not exceed 10 mSv (1 rem) effective dose equivalent. To date, such evaluations are reviewed on a case-by-case basis by license reviewers. Some states provide licensees with guidance on how to calculate offsite dose consequences using programs such as CAP88 and COMPLY.

States and the NRC should consider what capabilities are needed for offsite emergency response or investigation activities related to a fusion machine. Who would lead an investigation or response? What type of environmental sampling would be needed, especially to address tritium concerns? What type of public messaging may be needed? An emergency plan would answer most, if not all of these questions, but many facilities with fusion machines will likely not be required to have an emergency plan due to possessing less than 7.4×10^{14} Becquerels (20,000 curies) of tritium or being able to demonstrate that the public dose will be less than 10 mSv (1 rem) to a maximally exposed individual. Facilities that fall within this scope should be encouraged to coordinate with local emergency response agencies and develop a policy and/or procedure with them anyway. All fusion machine licensees need to be prepared to handle substantive on-site emergencies that require off-site resources and coordination.

USER/OPERATOR TRAINING

Individuals who operate fusion machines must be familiar with all device hazards. Historically, training requirements for particle accelerator operators have been qualitative. Although the requirements vary from State to State, particle accelerator operators typically must be instructed in radiation safety and demonstrate competence to use the accelerator, related equipment, and radiation survey instrumentation[7].

For fusion machines that produce or use radioactive material, training requirements for operators may need to be more detailed based on the amount and hazard posed by the material that they use.

Section 8.7.2 of Nuclear Regulatory Commission document NUREG-1556, Vol. 21 "Program-Specific Guidance About Possession Licenses for Production of Radioactive Material Using an Accelerator" states that training for individuals who handle radioactive material from an accelerator should include: 1) a college degree or equivalent experience, 2) 40 hours of radiation safety training specific to the individual's job duties, and 3) six months of experience with similar types and quantities of radioactive material.[8]

The Department of Energy describes tritium training topics in its Standards Document DOE-STD-1129-2015 "Tritium Handling and Safe Storage," for tritium handlers (in Appendix F) and for operations and maintenance personnel (in Appendix G).[9] These training topics would be broadly applicable to any facility operating a fusion machine that uses or produces tritium.

It is typically up to Agreement States to determine which individuals should be named on a radioactive materials license as an authorized user and which individuals may work under an authorized user's supervision.

CRCPD recommends the following best practices:

- Individuals that operate fusion machines should receive training in system operation as well as training for handling radioactive material used as fuel or produced by a fusion machine.
- When a fusion machine uses radioactive fuel (e.g., tritium), at least one operator should be named on a radioactive materials license.

CRCPD notes that it may be difficult for licensees building first-of-kind fusion machines to acquire hands-on training with the tritium quantities requested for the fusion machine. In this

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[7] CRCPD Suggested State Regulations, Part I, Section I.6

[8] NUREG-1556, Volume 21, "Program-Specific Guidance About Possession Licenses for Production of Radioactive Material Using an Accelerator", Revision 1, May 2018. https://www.nrc.gov/docs/ML1814/ML18143A670.pdf

[9] DOE Standard DOE-STD-1129-2015 "Tritium Handling and Safe Storage", September 2015, Appendix F. https://www.standards.doe.gov/standards-documents/1100/1129-AStd-2015/@@images/file

scenario, CRCPD recommends a phased licensing approach that expands as the licensee gains experience.

CYBERSECURITY

While the NRC has previously reviewed the need for cybersecurity controls to protect byproduct material, they have not specifically reviewed the potential consequences if the availability, integrity, or confidentiality of data or systems associated with fusion machines were adversely impacted. As fusion machine technologies advance, their reliance on digital control systems could present unique cybersecurity challenges. Given the critical nature of systems managing the magnetic fields, particle accelerators, cryogenic systems, vacuum systems, tritium handling, radiation monitoring, and other essential operations, facilities should continue to assess the impact of computer system failures. Each of these components, depending on the design of the fusion machine, should be reviewed to determine how their failures could impact integrity and safety of the fusion process. If a successful cyberattack could result in failures of systems or initiate events ranging from operational disruptions to environmental hazards, then facilities should incorporate cybersecurity best practices.

Best Practices

State radiation control programs may not have statutory authority to regulate cybersecurity for fusion machines. Depending on the specific authority, state programs could work with facilities to implement voluntary compliance guidelines, not tied to a materials license, as best practices to ensure the security, safety, and operational continuity of fusion machines such as:

- Conduct Risk Assessment & Threat Modeling
- Develop a comprehensive Cybersecurity Plan
- Develop an Incident Response Plan (IRP)
- Conduct Routine Audits
- Train Employes

Cybersecurity References

Consider existing recognized standards and frameworks in developing Cybersecurity plans, such as:

- **ISA/IEC 62443**: Security for industrial automation and control systems.
- **NIST Cybersecurity Framework**: Guidelines for critical infrastructure protection. https://www.nist.gov/cyberframework

CONCLUSION

As of 2024, there are multiple states which have licensed fusion machines, and additional facilities are proposed across the nation. Within state radiation control, the radioactive materials and x-ray programs are working together to develop a licensing path which is focused on safe and effective control and monitoring of the radioactive materials and other radiation hazards. The fusion machines vary in many ways and the complexities of licensing and inspecting these facilities continue to grow.

It is vital that states and the NRC continue to share information and learn from each other as licenses for fusion machines are issued. This paper has outlined many of the complex scientific and technological factors which will require consideration and refinement as experience is gained.

CRCPD supports the concept of and growth in fusion energy and stands ready to coordinate information and resource sharing.

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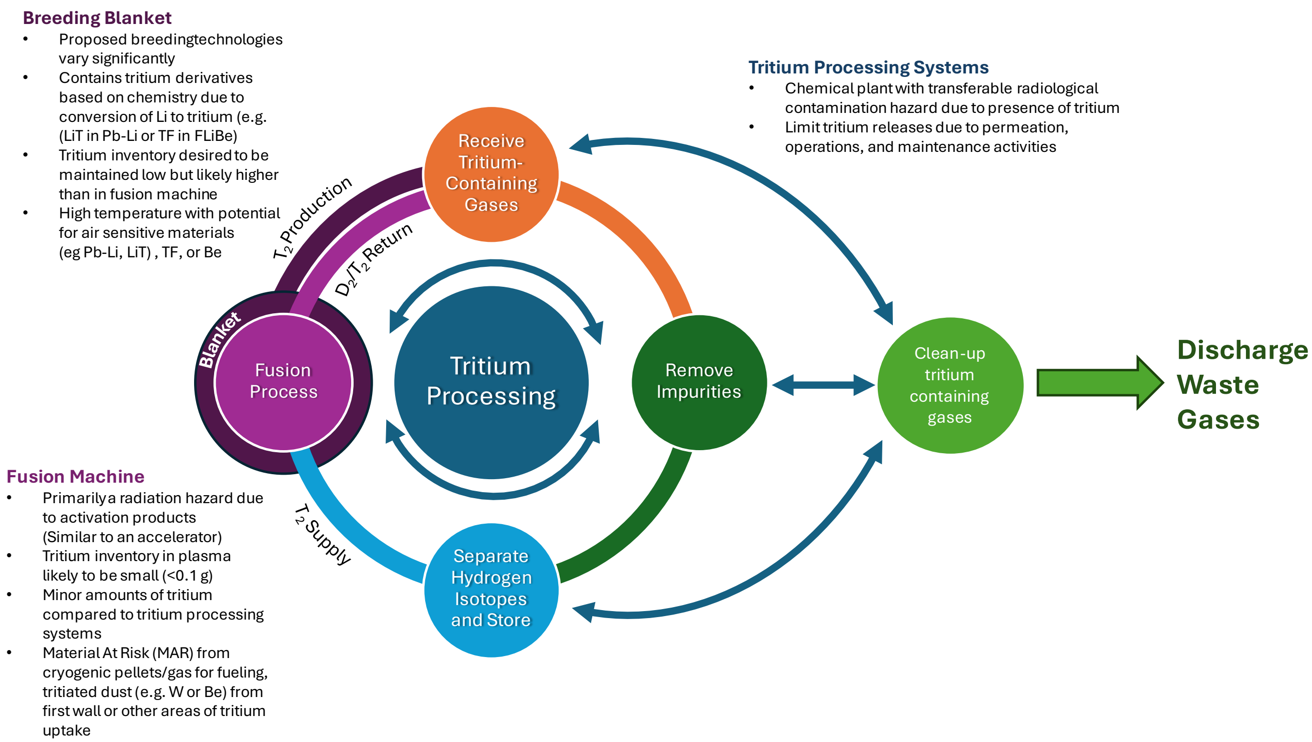
Appendix A
Typical Tritium Fuel Cycle Considerations for a D-T Fusion Machine with Blanket Integration[10]



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[10] Figure adapted from Dave Babineau, Brenda Garcia-Diaz, Jim Klein, Bob Sindelar, Marlene Moore, and George Larsen. Savannah River National Laboratory presentation, “Fusion and Tritium Accident Risks and Analysis” presented at NRC Public Meeting June 7, 2022. Available at https://www.nrc.gov/docs/ML2215/ML22159A269.pdf.