Discussion Paper DIS-16-04

Small Modular Reactors: Regulatory Strategy, Approaches and Challenges

Section 3. Fusion Technologies

CNSC would like to know:

1. *What are the types and magnitudes of risks and hazards that would be posed by different fusion technologies (conventional and radiation hazards)?*
2. *With this in mind, how would the risks posed by activities involving fusion reactors differ from current nuclear fission reactors?*
3. *Should fusion reactors be regulated differently than fission reactors?*

1. Risks and hazards posed by different fusion technologies

Summary Response

Fusion facilities, both research and development stage, and future commercial power producing systems, will have radiation hazards driven by three factors:

- Inventory of volatile radioactive substances, primarily tritium
- Prompt exposure to neutron or high energy photon flux from a fusion reaction
- Radioactivity from decay of materials activated by fusion neutron flux

The magnitudes of these radiation hazards will depend on the specific fusion technology and the nature of the system. Large volume magnetic fusion systems, for example, may have higher tritium inventories than pulsed approaches. Similarly, neutron and photon energy flux will depend on the design of blanket and shielding systems that may be technology specific.

While total tritium inventory at any one time is unlikely to create a high accidental release risk to the public, total annual tritium throughput in a fusion power plant will be relatively high (a 500 MWt fusion plant will need to produce and consume ~30 kg of tritium per year). The management and containment of tritium flows during regular operation is therefore likely to be the most important area of interest for regulators.

Components replaced during a fusion power plant's operating lifetime, as well as materials at the time of decommissioning may need to be treated as low or intermediate level radioactive waste, with appropriate precautions.

Research and development fusion facilities may have minimal or little activation hazards and avoid the use of tritium fuel entirely.

The specific nature and level of conventional hazards will also depend on the underlying technology, however, it can be expected that fusion systems will have some or all of the following hazards:

- High voltage, including very high energy pulsed power systems
- High magnetic fields and potentially large superconducting magnet systems
- High power laser systems and/or particle beams
- Molten metal or molten salt systems for breeding blankets and heat removal. These systems may include the use of reactive metals, particularly lithium
- Conventional power plant hazards such as hot, high pressure gas (steam, possibly helium or supercritical CO2)
- Common industrial hazards – use of large equipment, heavy machinery, hot surfaces etc.

Detail

Depending on designs, a commercial fusion power plant may have inventory of a few grams to a few tens of kilograms of tritium, in addition to an inventory of activated materials. These radioactive hazards do not have the potential to cause an accident directly, but other emergency situations, such as fires, could be exacerbated due to the presence of tritium. Commercial fusion power plants will need to have defense-in-depth systems to prevent the release of tritium to the environment in emergency situations, and minimizing the volatile tritium inventory (tritium not bound in getter bed systems) will be an important design objective, and will drive risk assessments and appropriate regulatory requirements.

During normal operations as well, the prevention, control and monitoring of the permeation of tritium into the plant environment (presenting a workplace hazard), and into the external environment will likely require a multi-level, redundant approach. Preventing the permeation of tritium into steam power conversion cycle and freshwater systems (through heat exchangers, for example), will require particularly careful analysis and engineering.

In contrast, fusion R&D systems can be constructed with greatly reduced radiation hazards by minimizing or eliminating the tritium inventories, for example, through operating with deuterium or hydrogen only or by limiting the operating times.

In R&D fusion systems the goal is to validate reactor physics and components and generate a burst of neutrons from fusion reactions which when scaled can achieve break-even. The amount of nuclear yield in fusion reactions is controllable by adjustment of fuel (deuterium–hydrogen (D-H) vs deuterium-deuterium (D-D) vs deuterium-tritium (D-T)) and materials' choice. Any R&D fusion system is expected to have low repetition rate, or low duty-cycle operation and will probably generate only limited number of successful shots. Most shots in R&D systems will be fueled with deuterium only or D-H and may only have limited number of D-T shots. Due to small neutron yield in successful shots, limited number of such successful shots, low repetition rate of operation and small quantity of nuclear substances, the expected radiation exposure to the public from the year-operation of an R&D fusion system would be far below the annual average effective dose from natural background radiation of about 1.8 mSv in Canada and 2.4 mSv worldwide.

Quantity of nuclear substance in fusion system is small comparing with fission systems. For example, about 27 tonnes of fresh enriched fission fuel is required each year for a 1000 MWe fission reactor comparing with, for example 250 kg fuel per year (half deuterium, half tritium) estimated for comparably sized fusion systems. That being said, having total annual tritium throughput of tens of kilograms is high and tritium management and containment of tritium flows in fusion reactor needs to be addressed and regulated. However, most of the R&D fusion systems use only D-D fuel or very limited use of D-T fuel (few D-T shots per year). So, the total inventory of tritium in R&D fusion systems will be significantly reduced and most probably below 1 PBq exemption limit for Class II equipment.

Additional radiation hazard may be activation of the eutectic liquid lithium-lead (PbLi) which is considered in many liquid blanket concepts of fusion systems, and activation of wall and other structural components. The PbLi blanket is considered as a medium for heat exchange and as tritium-generating material. The long-term radiotoxicity of PbLi under fusion irradiation depends on impurities in lead (e.g. Eu, Bi). A study conducted in Europe with respect to tokamak fusion concept has found that if all PbLi is disposed after one cycle it can be disposed as simple recycling material (SRM) or the same PbLi can be used during the entire lifetime of the plant but the longer irradiation will transform PbLi into complex recycling material (CRM) [1]. The strategy of handling PbLi will depend on the economic and other criteria and regulation at the time. Various radiation protection methods will be employed to allow work on the components after irradiation such as for example instituting access time limits, providing shielding to attenuate the gamma radiation associated with decay of some isotopes, and considering materials (where possible) with lower activation and/or faster decay time.

R&D fusion systems will probably omit use of breeding blankets (such as PbLi) while validating physics and developing reactor components. Neutron yield can be lowered during the development stage by using D-D fuel and limiting the use of D-T fuel. Depending on the fusion approach and material's choice, the activation of the neutron exposed materials in any R&D system can be minimized due to small neutron yield, limited number of successful shots and low repetition rate of operation.

For example, in General Fusion's "Plasma Compression" (PC) R&D systems, a magnetized plasma is compressed to fusion conditions by a moving metal liner. No PbLi shielding blanket is used. The fuel in most experiments will be D-D (about 10 µg D-D) producing a yield of 10^{10} D-D fusion neutrons per shot. In the later phase of the R&D, few shots (<10 shots) would be taken using D-T fuel (about 1 mg D-T). The expected neutron yield per successful D-T shot is up to 10^{20} fusion neutrons.

An extensive analysis has been conducted to estimate neutron yields and induced activations in various components of General Fusion's PC systems. It was found that neutron yield of 10^{10} D-D fusion neutrons will result in negligible activation of irradiated materials. The total activity from a successful shot decays from an initial total activity of 40000 Bq to less than 1000 Bq within an hour with no long lived isotopes present. Use of D-T fuel increases the expected activation doses but due to only limited number of D-T shots the activity is relatively low and decays within few hours to few days depending on the materials used. Material activation will be further reduced by shielding the components or by using material with lower activation or higher decay rate. For example, mild steel have significantly lower activation than stainless steel and will be used instead of stainless steel where appropriate. Also, using aluminum, where appropriate, instead of steel, produces more rapidly decaying isotopes. Aluminum radioisotopes have half-lives under 7 minutes, and most under a second.

The prompt exposure dose depends on the neutrons energy and secondary gamma release. It was calculated that for D-D fusion experiments with expected neutron yield of 10^{10} neutron yield (2.45 MeV + 14.1 MeV), the total expected exposure dose (neutrons + gamma) to an unshielded subject at 150 m is 6.2×10^{-7} mSv and at 3 km is 4.06×10^{-14} mSv. So, the expected radiation exposure for D-D fusion shots is well below the exemption limitations of 1 mSv for public even at distances where no public or even personnel is expected during operation due to exposure to conventional hazards.

The total exposure dose from 10^{20} D-T neutron pulse (14.1 MeV) to unshielded subject is significantly higher but no fusion system (R&D or commercial) will ever operate without being enclosed within shielding enclosure or using shielding blanket. Such shielding enclosure/blanket would absorb most of the fast neutrons. For example, use of PbLi liquid blanket with thickness of about 1.5 m would absorb about 97% of the fast neutrons. As the amount of D-D fuel increases, or if D-T fuel is used instead, both the prompt exposure and material activation increases. However, the neutron yield will be limited by the lack of criticality in the fusion reaction, and bracketed by the amount of fuel that is present in the reaction. Shielding and distance requirements for worker safety can therefore be accurately designed, and materials can be chosen to prevent the activation of long lived isotopes.

For R&D fusion systems, due to the low repetition rate of operation and limiting number of successful pulses per year, the inventory of nuclear substance (tritium) can be kept below 10^{15} Bq, and the maximum energy per particle is less than 50 MeV (2.45 MeV and 14.1 MeV), limits that are prescribed for Class II equipment under current regulations.

Most of the conventional hazards are already regulated under Canadian Standard Authority (CSA) or International Standard Authority or Work Safety Authority. For example, ANSI safety standard Z136 regulates high power lasers, or CSA B51 regulates Pressure vessels. Work Safely Authority usually governs other conventional hazards such as for example high energy pulsed power supply and exposure to chemical or physical agents.

For example, the static magnetic fields in fusion systems will most probably be in the same range as in magnetic resonance imaging machine (0.5 T – 9 T) and nuclear magnetic resonance spectrometer (11 T – 23T), which are already regulated by work safety authority. The magnetic field strength decreases rapidly as the distance from the source increases. Large superconducting magnet systems used in steady magnetic fusion systems would require quench protection system to mitigate against potentially destructive quenches.

The risks and hazards expected in fusion reactors do not affect health and safety of the public at the same or similar significance as the fission reactors. As indicated herein above the risks and hazards expected in fusion reactors, especially R&D fusion systems, are closer to risks and hazards regulated under Class II Nuclear Facilities rather than Class I Nuclear Facilities.

2. Risks and hazards in Fusion vs Fission

Summary Response

This nature of radiation hazards in fusion is fundamentally different from fission energy systems, where the primary risks are much more severe:

- Critical fission reaction with large stored energy and the potential for dangerous runaway if control is lost
- Highly radioactive spent fuel requiring continuous cooling to avoid containment failure

The radiation hazards in fusion (tritium, activation) would be considered secondary hazards in fission systems, because the severity of any accident would be much lower than the primary fission risks above, and unlikely to cause any risk to the public.

Fusion reactions are driven reactions, where heating and control systems (both in the case of pulsed and continuous operation) are required for fusion reactions to occur. Any form of system failure severe enough to compromise fusion system operation will also immediately therefore stop any fusion reaction.

Even the largest fusion systems will contain no more than a few seconds of fuel (stored energy), meaning that no runaway reaction is possible – a fusion reaction will run out of fuel and extinguish itself immediately if not replenished with fuel.

Fission reactors, by comparison, contain 6-24 months of fuel in the reactor core, operating in a critical fission chain reaction. This is the energy equivalent to several supertankers worth of oil, and because the reaction proceeds spontaneously, the loss of control of a fission reaction can result in large uncontrolled energy releases.

Unlike fission, fusion is therefore inherently fail-safe.

The differences between fission and fusion also extend to the process of research and development of the technologies. Since it is by definition impossible to build a non-critical fission reactor, even a research and development or prototype system must include all the safeguards of a commercial fission power plant. Consequently, treating any fission reactor, whether research or commercial, similarly for regulatory purposes is logical.

Research and development fusion systems, on the other hand, can be constructed with greatly reduced radiation hazards compared to a commercial fusion power plant. Fusion R&D systems can minimize or eliminate the tritium inventories, for example, through limited operating times or operating with deuterium or hydrogen only. The risk of exposure to neutron or high energy photon radiation, and the potential for activated materials can also be directly reduced.

Detail

1. **No stored energy**. Fusion reactions are driven reactions, in case of failure, reaction cease to exist.
2. **No risk of runaway reaction** - no need for evacuation plans.
3. **No fissile materials** (D & T fuel) – no nuclear proliferation issue.
4. **No reaction without shielding** - Liquid PBLi blanket.
5. **No spent nuclear fuel**.
6. **No decay heat**.
7. **Short-term radionuclides**, decay within couple of decades (at the end of operational life) vs radionuclides with millions of years decay time.

3. Should fusion reactors be regulated differently than fission reactors?

Summary Response

Yes.

The current legislation, which blankets all fission and fusion reactors as Class 1A facilities and treats them similarly from a regulatory perspective cannot be justified based on the risks inherent in each case.

If using tritium fuel, fusion power plants will contain significant levels of tritium inventory, and produce and consume even greater quantities of tritium on an annual basis. Components may become activated, and workers will need to be protected from potential exposure to radiation hazards.

None of these, however, compare to the primary radiation hazards inherent in fission reactors, namely critical fission reactions and massive stored energy, and highly radioactive spent fuel. Accident scenarios in fission reactors, both commercial power plants and research reactors, in worst case can release massive amounts of radioactivity and quickly endanger the surrounding public, and as a consequence a rigorous regulatory framework equivalent to the risk is appropriate.

Fusion reactors have a very different risk profile, particularly when considering the public surrounding a fusion facility. For example, US Department of Energy Standard, DOE-STD-6002-96, provides guidance for safety requirements of magnetic fusion facilities [2]. Moreover, the risk profile for a fusion system can be very different for research systems vs. fusion power plants.

This scalability of fusion systems is implicitly recognized today by the CNSC. Deuterium-tritium neutron sources, which use fusion reactions to produce those neutrons (hence they could be called fusion reactors), are licensed as Class II prescribed equipment, and used in many industrial applications.

Fusion reactors therefore need a graduated regulatory framework. It is in Canada's, and the public's interest that fusion research be able to be pursued actively in Canada, within a regulatory framework appropriate to the level of risk inherent in each fusion system.

Once commercial fusion reactors become possible, the regulatory framework for them should be appropriate to the hazards inherent in the technology. Those hazards are fundamentally different than in the case of fission reactors, and hence fusion systems should be regulated under a distinct, and appropriate framework, not treated under the same category as fission reactors.

When considering an appropriate framework for fusion, the CNSC has, in its regulatory framework today, good examples to build from. The regulatory framework for accelerators allows for different classifications, based on scientific grounds, with thresholds based on beam energies and total inventory of radioactive materials.

References

[1] R. Pamin, "Long-Term Activation and Tritium Generation of Flowing Lithium-Lead under Prolong Irradiation in Fusion Power Plants," *Fusion Science and Technology,* Vol. 50, 2006.

[2] "Safety of Magnetic Fusion Facilities: Requirements," U.S. Department of Energy DOE-STD-6002-96, Washington, 1996.