Applicability of the Export Control Regimes to Fusion
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Abstract

For many years, the international community has performed research into the applicability of fusion for the generation of power using heat from nuclear fusion reactions. To date, no design has produced energy, let alone electricity, but work done by large international projects like ITER suggests that new reactor designs are closer than ever. Consequently, it is important to consider whether and how traditional nonproliferation regimes will cover production of power from fusion reactors rather than traditional nuclear reactors that harness heat from nuclear fission.

Export control regimes are important to assuring that commodities and technologies support legitimate projects, like those needed for nuclear power production, are not diverted to weapons of mass destruction (WMD) programs. Specifically, the Nuclear Suppliers Group (NSG) covers a range of commodities for processing uranium through to fuel production (and onward). Although the NSG dual-use list covers tritium, as well as target assemblies and components needed to produce tritium, it is not clear whether other unique commodities are needed for fusion power and whether these commodities would be covered by the NSG.

To that end, this paper will examine commodities and technologies needed to research and develop systems that will produce power through fusion reactions, and crosswalk those commodities with commodities and technologies already controlled by the NSG. In general, the best place to consider export controls as a tool to address proliferation concerns associated with fusion reactors is related to next-generation lithium isotope enrichment.

Introduction

Fusion energy systems, if developed and deployed, could provide large and nearly limitless amounts of clean energy, greatly supporting domestic and international climate goals [1]. Since the first commercial fusion efforts in the 1970s, deployment of fusion for electricity generation has always been “20 years away.” However, 21st century advancements in materials, computing, laser power, and plasma generation and confinement, along with recent demonstrations, suggest that commercial fusion energy generation is closer than ever [2].

One of the benefits of fusion reactors compared to traditional fission based nuclear reactors is that they do not require the use of fissionable material. The need for fissionable materials in traditional nuclear reactors has driven more than 60 years of nuclear nonproliferation efforts based in the principles of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). Additionally, fusion reactors would not require highly radioactive material as feed material nor do they produce large quantities of highly radioactive material as waste. Although outside the

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scope of this paper, the pivot away from fissionable material will reduce, if not eliminate, concerns about diversion of material to nuclear weapons or other WMD programs. The major nonproliferation issue of concern is the extensive use of tritium and lithium enriched in ^{6}Li.

The existing international export control regime bounded by the Nuclear Suppliers Group (NSG), Australia Group, Missile Technology Control Regime, and Wassenaar Arrangement are essential to minimizing and preventing acquisition of WMD-relevant materials, commodities, and technology. The NSG already controls the trade of enriched lithium, as well as commodities associated with older methods of enriching lithium. However, less toxic methods to enrich lithium have been researched during the past 20 years. Updating export controls related to newer forms of lithium enrichment could limit help limit the diversion of lithium production from fusion energy to WMD programs.

Fusion Energy Production Considerations

Fusion energy production is fundamentally different from fission energy. Fission reactors rely on a neutron hitting an atom of ^{235}U, forcing it to excite and split in to two different atoms, or fission products, releasing energy. Fusion occurs when two small atoms fuse together to form a heavier atom [3]. This is the same process that powers the sun and releases huge amounts of energy. Researchers have generally settled on the fusion of deuterium (D) and tritium (T), two isotopes of hydrogen. The D–T fusion reaction releases four times as much energy as the fission of ^{235}U [4]. Fusion energy systems (except for fission–fusion hybrid designs) do not require the use or presence of special nuclear materials. The difficulty is to develop a device that can heat the D–T fuel to a high enough temperature and contain it for long enough so that more energy is released than the energy needed to start the reaction.

Tritium is a necessary component for any fusion system, and tritium accounting is notoriously challenging. Additionally, tritium breeding blankets and other setups require the use of beryllium, which is highly toxic and difficult to work with, or enriched ^{6}Li, which is of weapons proliferation concern.

Magnetic Confinement Fusion

In magnetic confinement fusion, hundreds of cubic meters of D–T plasma are confined to a density of less than 1 mg/m^{3}, confined by a magnetic field at high pressure, and heated to fusion temperatures. Magnetic fields are ideal for confining a plasma because electrical charges on the ions follow magnetic field lines [4]. The most well-known research in magnetic confinement fusion has been performed using tokamaks. The machines having a torus-shaped magnetic chamber was designed by the Soviets in 1951. Research involving tokamak technology continues to this day in various configurations and designs continues today [5].

Today, the most well-known and prominent tokamak machine and effort is that of ITER, a 35 country collaboration to build the world's largest tokamak in southern France. ITER will have 10 times the plasma volume of the largest operating machine today and will be capable of longer plasma durations and better confinement. Goals for ITER include achieving a D–T plasma that sustains fusion conditions mostly with internal fusion heating, generating 500 MW of fusion power in its plasma (from no more than 50 MW of input heating power), demonstrating integrated operations of technologies for a fusion power plant, test the breeding of tritium, and demonstrating safety characteristics of a fusion device [6].

Export Controls as a WMD Nonproliferation Tool

The existing export control framework is much broader than the mandate of the NPT, which is focused on not diverting nuclear materials of concern. This framework prevents the proliferation of materials, commodities, and technologies for certain end uses, namely WMD development, to certain end users much more broadly than the NPT. Export controls could more effectively support the safe deployment of fusion technologies and minimize risks for commodities to be diverted to produce materials of use in WMD programs.

Export controls are coordinated through the international regimes (NSG, AG, MTCR, and WA) so that all regime Member States can harmonize their export controls and avoid/minimize undercutting one another when proliferant States “shop around” for dual-use goods. After Member States come to a consensus on control language, each Member State implements the controls through their own domestic laws and regulations. In the United States, these are largely captured through the Export Administration Regulations (EAR).

Export Controls on Fusion Source Material Production

Initially, export controls focused solely on goods needed for the nuclear fuel cycle, and the language was based on the NPT. This included controls on the source of special fissionable material, as well as equipment or material especially designed or prepared (EDP) for the processing, use, or production of special fissionable material. This language became the basis for the NSG Trigger List. In the United States, these controls are implemented through the Nuclear Regulatory Commission (NRC) for materials and commodities, whereas the Department of Energy (DOE) implements and controls nuclear technology through its 10 CFR Part 810 regulations.

The vast majority of nuclear related exports are not especially designed or prepared and therefore are not controlled by the NRC or the DOE. These dual-use materials, commodities, and technologies are controlled by the Department of Commerce, through the EAR and include commodities that can support nuclear proliferation. A small example of commodities include pressure transducers, radiation monitors, mass spectrometers, and machine tools. Exporters apply for an export license through the Department of Commerce and the applications are reviewed by the Departments of Defense, Energy, and State to assure the end users are unlikely to divert these dual-use goods for nefarious purposes.

Tritium as a material is already controlled by the EAR through ECCN 1C235 (tritium, tritium compounds, mixtures containing tritium) and 1A231 (target assemblies and components for the production of tritium). Lithium as a material is controlled through ECCN 1C233 (lithium enriched in the ^{6}Li isotope greater than its natural abundance . . .). These are similarly controlled on the European Union list as well as in regulations of other regime Member States.

Additionally, equipment used in the enrichment of lithium are also controlled to include packed liquid–liquid exchange columns specially designed for lithium amalgams, mercury or lithium amalgam pumps, lithium amalgam electrolysis cells, and evaporators for concentrated lithium hydroxide solutions.

Note, ^{7}Li has important uses in nuclear energy because it regulates the pH in refrigerant material in the primary circuits of pressurized water reactors [7]. As the need for enriched lithium increased with more reactors coming online, and researchers recognized that traditional lithium enrichment techniques are hazardous and toxic, research has vastly increased in new and emerging lithium enrichment techniques.

Early lithium enrichment was performed in Oak Ridge, Tennessee in the 1950s and 1960s using the COLEX (column exchange) process, which uses large amount of liquid mercury [8]. This is clearly not ideal, and more environmentally friendly processes are being pursued. A review paper published in 2021 by *Physics Status Solidi A* [8] summarizes the following processes in more detail:

- **Two liquid phase chemical exchange**—The lithium compound will spread between two immiscible stages, with good results observed when the lithium (as a metal salt) is distributed between two immiscible solvents, such as an organic solution containing a macrocylic compound, like a crown ether,[1] and an aqueous solution.
- **Displacement chromatography ion-exchange resin**—Liquid chromatography includes the distribution of a target ion between a stationary phase and a moving liquid phase, with cation exchange resins showing promise for lithium enrichment.
- **Displacement chromatography resin-supported complexing agents**—The use of resin-supported complexing agents has shown promise, with crown ether immobilization on porous silicon beads showing a separation factor an order of magnitude higher than an ion-exchange resin.
- **Displacement chromatography ion-exchange membranes**—Separation techniques using an absorptive membrane can given good separation efficiency at a lower operative pressure, which makes these safer and easier to operate, with separation aided by surface diffusion, multilayer adsorption, and ion-pore electrostatic contact between lithium ion and molecules like crown ethers.
- **Thermal diffusion**—With a temperature differential between two gases, lighter isotopes tend to migrate toward the hotter zone at a faster rate when a thermal gradient is present.
- **Distillation and fractional crystallization**—This traditional organic chemistry technique is used to separate and purify compounds based on changes in solubility.
- **Laser methods**— Because various isotopies of the same element absorb laser light at different wavelengths, laser methods are noted for their enhanced selectivity and purity. Lasers can be fine-tuned to ionize only the isotope atoms of interest.

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[1] Crown ethers have been investigated for isotopic enrichment, and some show promise for lithium isotope enrichment. The precursors of these crown ethers could be considered for export control.

- **Diffusion and electromigration**—Electrochemistry-based techniques are a growing area of interest for metallic processing. Major methods being research for lithium enrichment include exchange electrolysis, direct electrolysis, and ionic migration.

Identifying key choke-point commodities for these newer lithium enrichment techniques could be a vital step for preventing proliferation of the nefarious aspects of fusion research. Crown ethers may be key to several of these processes, and their precursors could be a key consideration for export control, similar to the way the AG controls precursor chemicals that could be used to synthesize chemical warfare agents.

Lastly, a very key component in some types of fusion is the design, implementation, and use of high-power laser. A select subset of lasers are already export controlled because they can be used to enrich uranium through laser isotope enrichment processes, such as AVLIS (atomic vapor laser isotope separation). This process was largely only examined at R&D scale because although it results in very high separation coefficients, the throughput is miniscule. Controls for nuclear proliferation lasers are based on laser type (copper vapor, neodymium-doped, pulsed carbon dioxide, etc.), wavelength, and power. If the international nonproliferation community decides that fusion, and specifically inertial confinement fusion, is of proliferation concern, lasers are a second area that should be explored for potential export controls. However, the lasers needed for inertial confinement are highly specialized and designed with likely little-to-no export market, especially to proliferant States, so this may be a less fruitful path than others.

Export Controls on Technology

Although fusion technologies are generally in the realm of R&D, the know-how may need to be more widely distributed if this technology were to enter commercialization [9]. Currently, many relevant software codes are export controlled and require a license from the developing government. From a technology standpoint, some codes present a high proliferation risk and likely require the most forward thinking.

Conclusion

Overall, fusion reactors present far fewer proliferation and export control concerns compared to traditional fission reactors. However, the best way to leverage export controls to address nonproliferation concerns associated with fusion reactors is likely through controlling commodities and technology associated with lithium enrichment, with particular focus on new and emerging lithium enrichment techniques that do not currently fall under any export control regimes. Some relevant software codes are already export controlled and will continue to be tightly controlled to further limit proliferation.

It is not yet clear which of the international regimes would or could take consider fusion-related commodities, materials, and technologies. The NSG is tied to the NPT and several assessments of the NPT have noted that the treaty, as it stands now, would not cover fusion reactors. Because lithium enrichment is tied to traditional proliferation as well as fusion, the NSG could consider emerging lithium enrichment technologies. The WA controls high power lasers with dual-uses such as directed energy weapons. Developing new export control language is often a tedious, years-long process, but working through international regimes is key to assuring that U.S. nonproliferation efforts are not undercut by assuring that major suppliers and exporters are in line with their controls.

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