# Article 5: Fusion and Fission

Nuclear fission power has been under serious scrutiny throughout the decades-long history of civilian fission reactors. A complex regulatory system has emerged, accompanied by sizeable public distrust in four areas: nuclear weapons proliferation, the disposal of radioactive waste, reactor accidents, and terrorist or military attack. Fusion power will probably need to deal with the same challenges and fears. But to what extent are the risks from fusion and fission power similar? In order to answer this question, we explore the qualitative and quantitative differences between fusion and fission technology for these four issues. For the most part, we restrict the discussion to magnetic confinement fusion.

## Nuclear weapons proliferation

There are two types of nuclear weapons: Fission bombs ("atomic bombs") harness the energy released in fission reactions; the Hiroshima and Nagasaki bombs were fission weapons. A few years after fission bombs were developed, the energy from fusion reactions was harnessed for weapons by using the energy from a fission bomb to set off secondary fusion reactions. These "hydrogen bombs" were even more destructive than fission-only weapons. At the moment, nine countries possess atomic bombs: the U.S., Russia, China, the United Kingdom, France, Israel, India, Pakistan, and North Korea. The first five – and probably Israel and India as well – also have hydrogen bombs, while Pakistan and North Korea probably do not.

Nuclear proliferation refers to the development of nuclear weapons capabilities in new countries. It requires access to special nuclear materials, which the expansion of nuclear power plants could potentially provide. It also requires specialized training in nuclear technology, some of which would be gained through experience with nuclear power.

Civilian fission power is tightly linked to fission weapons through two special materials: plutonium and highly enriched uranium. Either can sustain an explosive chain reaction. The uranium found in nature cannot be used for weapons without expensive manipulation, called isotope enrichment. Isotope enrichment, in which the ratio of uranium-235 to uranium-238 is increased relative to the ratio found in nature, is part of the preparation of uranium for most kinds of nuclear power plants. "Weapons-grade" uranium is produced by further enrichment. Plutonium is found in nature only in trace amounts so it needs to be made in nuclear facilities. Plutonium is a by-product of the reactions in fission power plants, but it is unavailable for weapons use unless steps are taken to separate it from the highly radioactive "spent fuel" in which it resides.

Thus, fission power represents a step toward the nuclear materials for an atomic bomb, but the next steps are not inevitable. There is technological space for civilian fission power without nuclear weapons, and many countries have chosen to be in that space. Because of the requirements for nuclear power, they have nuclear scientists and nuclear equipment, but they do not have and do not seek to have the required separated plutonium or enriched uranium these weapons require. Without these materials no bomb can be built.

The relationship between civilian fusion power and hydrogen bombs is more complicated. First, a country that chooses not to develop fission weapons cannot develop fusion weapons because hydrogen bombs require fission as well as fusion. Second, however, both uranium and plutonium for weapons can be produced at a fusion plant using the abundant neutrons generated in the reactor. Plutonium can be produced at a fusion plant by placing natural uranium just outside the reactor core and bombarding it with neutrons from the fusion reactions. In the same way, uranium-233 of high isotopic purity, a weapons material, can be generated from neutrons bombarding thorium. No uranium enrichment plant would be necessary. Diverting some of its neutrons, a 1,000 megawatt fusion plant could conceivably create enough uranium-233 or plutonium for one fission bomb within a week, not including the time needed to put the necessary hardware in place, which could add a few additional weeks to this proliferation scenario *[1]*.

It would be difficult to disguise the generation of plutonium or uranium-233 if an international safeguards regime with inspections were operating, because a country which operates only fusion plants would have no valid reason to have uranium or thorium on hand. This has been called "the major nonproliferation advantage" of fusion power plants *[2]*. This advantage would not apply to any "fusion-fission hybrid" – a power plant designed to combine elements of fusion and fission reactors.

Having a fusion reactor could conceivably abet a country's transition from fission weapons to follow-on fusion weapons because the fusion reactor could produce tritium for such weapons. Tritium is a heavy isotope of hydrogen that scarcely exists in nature because its half-life is 12 years. Fusion power plants both consume and produce tritium, and if tritium were to become a more common article of commerce thanks to the fusion power industry, this might slightly lower the barriers to fusion weapons.

A larger barrier than tritium availability is the highly guarded secrets related to hydrogen bomb design. But the prospect of fusion power raises concerns here too, at least with regard to inertial confinement fusion, where there is a significant overlap between the technology for pellet compression and ignition and hydrogen bomb design. It is telling that the primary objective of the National Ignition Facility, the main focus of U.S. research in inertial confinement fusion, is to better understand the physics behind thermonuclear weapons without testing them. A particular concern is that scientific data from inertial confinement fusion research could be used in the development of nuclear weapons *[3]*, although the civilian fusion power plants themselves are unlikely to be useful in this regard *[2]*. Magnetic confinement fusion, by contrast, has been the poster child of international collaboration in scientific research, dating back to Soviet collaboration with Western countries in the 1950s – in part because there is no credible pathway from magnetic confinement fusion to nuclear weapons.

## Waste disposal

In nuclear fission reactions the uranium nucleus splits into two other nuclei. These nuclei include radioactive isotopes with half-lives ranging from fractions of a second to millions of years. One important radioactive byproduct from the perspective of public health is iodine-131 (half-life, eight days). The human body concentrates any iodine intake in the thyroid gland, and when the iodine is radioactive (which it normally is not) the result, especially in children, can be thyroid cancer. Other damaging isotopes have half-lives of years to decades (cesium-134, cesium-137, and strontium-90); these isotopes dominate the environment months to decades after any fission-reactor accident. The accident at Fukushima Daiichi in Japan in March 2011 led to land contamination by radioactive cesium and the relocation of more than 100,000 people, some of them permanently.

Fission plants also inevitably produce radioactive “transuranic” elements (elements heavier than uranium). Transuranic elements are found in nature only in trace amounts, but they are produced in reactors by a succession of nuclear reactions initiated by the absorption of a neutron by uranium. (When a neutron strikes a nucleus of uranium, the result can be either fission or absorption.) Several transuranic isotopes have half-lives of centuries to millions of years, and these represent one of the most challenging aspects of radioactive waste management for fission power.

Current national regulations for nuclear power require that human beings living thousands of years from now should experience only minimal damage from any radiation created by nuclear energy today. The United States, for example, has targeted 10,000 years or even longer as the minimum duration for geological storage of what is called “high-level” nuclear radioactive waste at the proposed storage facility at Yucca Mountain, Nevada. Such regulations raise deep questions. The regulations governing the Yucca Mountain facility note that “except for a few archaeologic and natural analogs, there is a limited experience base for the performance of complex, engineered structures over periods longer than a few hundred years” (10 C.F.R. § 63.102(h) *[4]*). To date, despite a number of test projects, no permanent facility for civilian high-level waste has become operational. All civilian high-level fission waste is being held in temporary storage, awaiting a long-term solution. A waste facility for military waste is operating in the United States in New Mexico – the Waste Isolation Pilot Plant. Advanced reactors are being considered which may be able to destroy most of the long-lived transuranic isotopes – but, in exchange, radioactive isotopes with shorter half-lives would be generated in abundance and would present their own management issues.

Irradiation of the structural materials of a nuclear fission reactor adds to the radioactivity it produces. Most of this waste is “low-level” radioactive waste, whose storage management is less daunting. United States nuclear regulations allow low-level waste to be buried in relatively shallow trenches. Required storage times for low-level waste can still be as long as 100 years. As a result, even wastes classified as “low-level” present substantial institutional challenges.

A fusion power plant is a radioactive environment for two principal reasons: 1) tritium is inserted into the plasma, regenerated in the blanket, and held in storage before being reinserted into the plasma, inevitably with some losses along the way that end up in waste streams; and 2) materials surrounding the plasma are made radioactive by bombardment by fusion neutrons.

The physical half-life of tritium is 12.3 years, meaning that after 12.3 years half of any tritium initially present has transformed itself into innocuous, non-radioactive helium-3. This twelve-year half-life is short enough that tritium management does not require costly and politically complex long-term storage; 99 percent is gone in 82 years. Moreover, the energy released when a tritium nucleus decays is small relative to most radioactive nuclei. Nonetheless, tritium is subject to intense regulation, because being a heavy isotope of hydrogen, it acts chemically like ordinary hydrogen. In particular, it is readily incorporated into water and can thus be ingested by organisms. Tritium's biological half-life – the time it takes for half the tritium to be eliminated from the human body after ingestion – is about ten days, the same as for water, because essentially all of the tritium is in the form of tritiated water, HTO. Thus, it would take just over two months for a person to eliminate 99 percent of the tritium ingested. (The biological half-life, to be sure, varies from person to person; it can be shortened by drinking large amounts of water.) Releases to the environment and worker exposure are highly regulated; for example, the maximum concentration of tritium in drinking water supplies allowed by the U.S. Environmental Protection Agency (EPA) is just 2 trillionths of a gram per liter of water. Accordingly, the management of on-site tritium is already a preoccupation of operators of fusion research facilities. It will be a central concern at any commercial fusion reactor.

The world's largest civilian facility for tritium processing is the Ontario Hydro's Tritium Removal Facility in Darlington, Ontario, Canada (see Section 3). The facility is on the shore of Lake Ontario and about one hour from Toronto. It processes tritiated water (HTO) whose initial concentration of tritium was 750 million times larger than EPA's allowed concentration in drinking water supplies and whose final concentration after treatment (97 percent tritium removal) was 20 million times larger *[5]*.

As for the generation of radioactivity by neutron bombardment of structural materials, this may well be a larger issue for a fusion plant than for a fission plant. About five times as many neutrons are created in a deuterium-tritium fusion reactor as in a fission reactor producing the same amount of energy, and the neutrons made in the deuterium-tritium reaction carry about seven times as much energy as the neutrons (on average) created in a fission event. The search for better structural materials for fusion reactors, although principally concerned with finding materials that retain their strength under neutron bombardment, also seeks materials whose demands on waste disposal are reduced *[6]*.

It may be possible, at some additional cost, to lessen waste disposal costs by avoiding steels that contain niobium and molybdenum. Neutron bombardment of niobium will create niobium-94 ($^{94}$Nb), a radioactive isotope with a half-life of about 20,300 years. This half-life is approximately the same as the half-life of plutonium-239 (24,100 years), which is the isotope whose half-life set the scale for the storage of high-level waste from nuclear fission reactors half a century ago. On the other hand, niobium is one of the elements in superconducting magnets (see Article 3), and this raises the question of the extent to which neutrons can make their way beyond the vacuum vessel to the surrounding magnets to generate $^{94}$Nb in significant quantities.

As for molybdenum, neutron bombardment creates radioactive molybdenum-93 ($^{93}$Mo) from molybdenum-92 ($^{92}$Mo), a stable isotope of molybdenum constituting 15 percent of the molybdenum in the Earth's crust. The half-life of $^{93}$Mo is 3,500 years, not a desirable half-life from the perspective of waste disposal. Molybdenum provides resistance to wear and extra strength at high temperatures, so metallurgists would rather not remove molybdenum from steel. Under consideration is the use of an isotope-separation process to provide specialty molybdenum for fusion reactors that contains negligible amounts of $^{92}$Mo, thereby essentially eliminating $^{93}$Mo from the reactor's structural materials at time of disposal while enjoying the improvements in performance that molybdenum brings to steel *[7]*.

The volume of activated material generated at a fusion power plant would be very large. In the European Union's Power Plant Conceptual Study, it was estimated that over 70,000 metric tons of waste would be generated during the 25-year lifetime of a 1,500 megawatt plant, with another 50,000 metric tons coming at decommissioning *[8]*. If all this waste were considered low-level waste, it would need to be stored for about 100 years *[8]* – a substantial advantage when contrasted with the much longer period required for high-level fission waste. Estimates of the cost for storing low-level waste range from $100 to $10,000 per cubic meter and depend strongly on the radioactivity level. Moreover, the direct payment for storage is estimated to represent only about 15 percent of the total disposal cost; other expenses include evaluation, packaging, and transportation *[9]*.

An alternative to storage as low-level waste, called "clearance and recycling," is being explored *[10,11,12]*. This system would begin with the separation of tritium from irradiated structural components removed from a fusion plant either at the end of their useful lives or when the plant itself is decommissioned. The waste would then be stored for a "decay period," after which materials would have lost enough of their radioactivity through decay to be fit for release and sale into the general economy. For example, concrete from the structure could be crushed and used in road construction. Materials whose radioactivity remains above legal limits would be refabricated into new parts for use within the nuclear industry. Only 10 percent of the waste from the plant would be ineligible for clearance and recycling *[8]*. With further work to identify materials that do not become highly activated or that quickly shed their radioactivity, even further reduction in the burden of fusion waste management might result.

There are already a few examples of clearance and recycling for activated waste from fission reactors. In one instance, 100 tons of lead casks from the Idaho National Engineering & Environmental Laboratory were recycled into bricks for a radioactivity-shielding wall at Idaho State University. The laboratory gave the bricks to the university for free and realized savings of $0.70 per pound by recycling instead of disposing of the waste; moreover, the university avoided buying lead bricks at a cost of about $1.75 per pound *[13]*. However, as of 2008, one review found there had been only five instances of clearance/recycling from fission reactors *[14]*.

The implementation of a clearance and recycling system for fusion power plants would confront serious obstacles. For example, the waste would need to be remotely dismantled, handled, and remanufactured; some of the needed techniques could be borrowed from the fission power industry, but new methods would need to be developed. There would also need to be a market for cleared materials. As one analysis observes: “the American scrap metal industry is highly concerned about radioactivity in their products as consumers may refuse to purchase products they believe are tainted” *[9]*. Even if cleared materials are not avoided out of fear, they will not be accepted if they are more expensive than alternative products that already exist. Finally, the possibility that regulations about radioactivity management could become stricter over time introduces further uncertainty into the clearance and recycling process *[9]*.

In summary, fusion’s principal advantage over fission from the perspective of radioactive waste management is the absence of the long-lived radioactive isotopes that are inherent in the fission process. Tritium is the most important radioactive isotope intrinsic to deuterium-tritium fusion, and its in-plant management and releases to air and water are subject to demanding regulations. Tritium has a half-life of only 12 years, so it is not subject to the rules for millennial-scale storage of high-level radioactive waste that currently hobbles fission power. Moreover, there may be opportunities to develop fusion reactor materials that reduce the waste management challenges associated with activated products, thereby compensating for the greater energy of fusion neutrons relative to fission neutrons. (More energetic neutrons create greater transformation of the nuclei in structural materials into radioactive forms.) Nonetheless, the management of radioactive fusion wastes will not be a trivial matter by any means.

## Reactor accidents

A “meltdown” occurs at a fission reactor when the reactor’s cooling system fails and the core’s highly radioactive contents provide, after several hours, sufficient heat to melt the core’s containment vessel, whereupon the radioactive contents can move to the floor of the reactor and beyond. The Fukushima Daiichi accident in Japan, following a large earthquake and tsunami, produced a meltdown at several of the reactors. Seconds after the earthquake, the systems designed to shut down the reactors worked as intended and halted fission reactions. However, the reactor’s backup cooling systems – needed to control the residual decay heat from the fission products in each reactor’s core – failed when a tsunami a few minutes later sent seawater over the protective sea wall at the coast. Through containment breaches and fires, these fission products were dispersed over hundreds of kilometers. As noted above, more than 100,000 people were evacuated and relocated to escape from exposure to radioactive fission fragments. The social disruption and psychological distress has been enormous.

A meltdown had occurred earlier, in 1979, at the Three Mile Island nuclear power plant in Pennsylvania, U.S. Although the reactor was destroyed, very little of the radioactivity released within the facility left the reactor site.

A “criticality accident” can also disperse radioactivity from a fission plant. A criticality accident occurred at Ukraine’s Chernobyl plant in 1986. The chain reaction at a nuclear reactor is controlled so that fission events occur at a steady rate, but operators at Chernobyl managed to put the reactor into a “runaway” condition where this control was lost. A brief nuclear explosion ensued that breached the reactor containment, resulting in widespread contamination of food, soils, and buildings by the radioactive fission products that had been in the reactor core. Contamination forced the abandonment of large amounts of land and infrastructure and the displacement of even more people than at Fukushima.

At fusion reactors, runaway chain reactions cannot happen. When a fusion power plant experiences a malfunction, the conditions in the reaction chamber change, and fusion inevitably stops. The energy present in a fusion reactor is sufficient to melt individual internal components, but not to breach the containment vessel – where, in any case, far less radioactivity is present than in a fission reactor’s core. However, accidents that release radioactivity are still possible. For example, a dramatic failure of a superconducting magnet could cause the vacuum vessel to rupture. This could release tritium and radioactive dust from the vacuum vessel walls, potentially dispersing radioactivity beyond the walls of the facility. Given appropriate plant design, such accidents might not require evacuation of the surrounding area. In one "worst-case" simulation, the "most exposed individual" at a distance of one kilometer from a fusion plant received a dose of radiation less than that experienced during a mammogram *[15,16,17]*. Only in the event of an unprecedented earthquake or similarly energetic event could all safety measures be breached and result in the mobilization of enough radioactive material to require evacuation of the surrounding population *[18]*.

## Terrorism and war

The fission power industry is a potential target of attacks by terrorist organizations or military forces. In addition to the loss of electricity production capacity and the proliferation concerns discussed above, the fear is that an attack on a reactor or waste storage site could lead to widespread radiation poisoning. The most commonly feared possibilities are inducement of a meltdown or the deliberate dispersal of radioactive material.

For bad actors to induce a meltdown intentionally at a fission reactor, they would need to disable numerous redundant safety systems. Spent fuel storage buildings, by contrast, are today much less well-protected and therefore more vulnerable to the deliberate disabling of their primary and backup cooling systems *[19,20]*. Fortunately, the radioactivity at spent fuel storage facilities produces heat far more slowly than in reactor cores right after shutdown. As a result, deliberately creating a leak to drain the pool of water in which the high-level waste is stored is less certain to induce a meltdown.

However, a highly energetic external event could mobilize dangerous levels of radioactivity. Detailed studies have not been performed, but it is possible that a bomb or airplane crash could qualify. The amount of radioactivity that could be dispersed is vastly larger for fission plants than fusion plants. In particular, used nuclear fuel from many years of operation of a nuclear fission power plant, full of radioactive fission fragments, is often retained at a fission reactor site, either relatively immobile in dry casks or easily dispersed from pools of water.

Creating and detonating a "dirty bomb" – conventional explosives wrapped in radioactive material – might be less difficult than inducing a meltdown. Attackers could steal or be provided with radioactive material from either fission plants or spent-fuel processing facilities *[20]*. Or they could steal similar material from research reactors, medical therapy machines, food irradiators, and other devices where large amounts of radioactivity are found *[20]*. The U.S. National Research Council (2002) considered the eventual use of a dirty bomb or other radioactivity-dispersing device to be highly probable, with "materials and means… readily available" and "few preventative measures in place" *[19]*.

The tritium and activated materials on the reactor walls at a fusion power plant could be used in a dirty bomb. One study found that the accidental release of 150 grams of tritium or 6 kilograms of tungsten dust from one conceptual reactor would require evacuation of the facility and surrounding areas *[21]*. It follows that such quantities incorporated into a dirty bomb could cause significant contamination. However, it seems unlikely that tritium would be used in a dirty bomb, given that it currently costs about $30,000 per gram; a less expensive, more easily attainable radionuclide would probably be preferred.

The impacts on human health resulting from radiation released by an induced reactor accident or dirty bomb would probably develop slowly. Few people would die from acute radiation poisoning, and the exposure of the surrounding population to a radioactive plume might result in only a small increase in cancer occurrence *[20]*. However, in the event of such an incident, this information might still create panic and lead to serious economic consequences *[19,20]*. The radioactive contamination from an induced meltdown could force the abandonment of large amounts of land and infrastructure, displacing populations for years and creating a level of social distress comparable to what happened at Fukushima. Conceivably, by contrast, a dirty bomb might result in less dislocation and distress, if the bomb contaminated only a few square kilometers and the dispersed radioactivity was promptly cleaned up *[19,22]*.

Overall, the fusion power system presents far smaller risks than the fission power system from the point of view of becoming associated with the malevolent dispersal of radioactivity. Neither the risk of an attack on fusion power infrastructure nor the risk of using fusion waste in a dirty bomb would seem to be significant, though the risk is present. By contrast, despite the numerous safety measures in place, the comparable risks from the fission power system are far higher, both because of the possibility of meltdown and because of the much greater quantities of highly radioactive materials involved.

Table 5.1 summarizes this article through six comparisons of fission and fusion energy systems.

| | Fission | Fusion |
|---|---|---|
| **Primary reaction** | Uranium fission | Deuterium-tritium fusion |
| **Radioactive materials of concern: Short-lived** | $^{131}$I, $^{137}$Cs, $^{90}$Sr | Tritium |
| **Radioactive materials of concern: Long-lived** | Activation products, transuranics | Activation products |
| **Risk: Proliferation** | Inherent in fuel cycle | Not inherent, but requires safeguards |
| **Risk: Meltdown** | Possible | Impossible |
| **Risk: Terrorist attack** | Focus of current concern | Minimal |

Table 5.1: Summary of the fission-fusion comparisons in this article.

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