Chapter 1: Technological Background

This chapter explores the scientific and technological background relevant to fusion and the technology's role in nuclear weapons. First, this chapter explains the fundamentals of nuclear physics relevant for energy production and proliferation, thereby establishing a baseline of scientific comprehension for the subsequent legal analysis (1). The chapter delves into the underlying physical principles of nuclear fusion and the commercialisation pathways of this technology for energy production (2). Subsequent to this section, a comparison is drawn between fusion and fission (3). The chapter then goes on to provide a concise overview of the relevant fundamentals of nuclear weapons (4). Following the establishment of the fundamentals, the subsequent section explores the specific applications of fusion in the context of nuclear weapons and the potential for proliferation (5).

1 Fundamentals of Nuclear Physics

This section explores the fundamentals of nuclear physics to a degree that is necessary to understand the functioning of nuclear weapons as well as the role of fusion. It explains the modern understanding of the atom and its nucleus, what isotopes are and relevant nuclear processes.

1.1 Atom and its Nucleus

Atoms are the fundamental building blocks of all matter. In its simplest model, an atom consists of a nucleus and a shell. The shell consists of negatively charged electrons, while the nucleus is made of positively charged protons, and neutrons that carry no charge. Electrons are negative, protons are positive, and neutrons are neutral. Atoms are electrically neutral, with the number of protons being equal to the number of electrons. While the atomic nucleus accounts for less than 0.01 % of the total volume of the atom, it bears almost the entire weight. The weight of an electron is negligible in comparison to that of a proton or a neutron. Conversely, the weight of a proton is approximately equivalent to that of a neutron. The number of protons in an atom is what defines it. Hydrogen has one proton, helium has two, lithium has three, and so on in the periodic table.

The constituents of the nucleus (i.e., protons and neutrons) are bound together by the so-called strong nuclear force, which is the strongest force in the universe and one of the four fundamental forces in physics.[90] The strong nuclear force is so potent that it allows for the harvesting of energy at a level several (about six) orders of magnitude higher than in chemical reactions, such as the burning of coal or the explosion of TNT, where electromagnetic energy is released.

1.2 Isotopes

In the context of atomic structure, the number of neutrons within an atom can vary. Atoms that possess the same number of protons but a different number of neutrons are called isotopes. They share the same chemical properties but they differ in mass. The mass of an atom is typically denoted by a small number as a superscript or is added to the element name by a dash. This number is the sum of protons and neutrons. For instance, hydrogen (H) comprises three isotopes: regular hydrogen ^{1}H, deuterium ^{2}H and tritium ^{3}H. Specifically for hydrogen isotopes, other abbreviations are used: D for deuterium and T for tritium. The atomic nucleus of regular hydrogen ^{1}H (sometimes also called protium) consists solely of a proton, deuterium ^{2}H consists of one proton and one neutron, and tritium ^{3}H contains one proton and two neutrons. In a smilar manner, uranium exists in different isotopes. The most abundant isotope of uranium is ^{238}U (or denoted as uranium-238 or U-238) which consists of 92 protons and 146 neutrons. The isotopes ^{235}U and ^{233}U are of particular relevance to this book; ^{235}U consists of 92 protons and 143 neutrons, ^{233}U consists of 92 protons and 141 neutrons. Another pertinent example is plutonium, which has 94 protons and, in its standard form ^{244}Pu, 150 neutrons. Of relevance for this book is the isotope ^{239}Pu with 145 neutrons and 94 protons.

1.3 Radioactivity

Some isotopes are unstable. For instance, tritium consists of two neutrons more than regular hydrogen. The nucleus of this hydrogen isotope is three

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[90] The four fundamental forces are: the strong nuclear force, the weak nuclear force, the electromagnetic force and gravity.

times its typical size and is unstable. The process of nuclear instability is characterised by the tendency of a nucleus to undergo a radioactive decay, which in turn gives rise to the phenomenon of radioactivity. Notable examples of radioactive elements include tritium, uranium, and plutonium. Following the decay process, the nucleus transforms into another nucleus. This decay is a statistical process, characterised by the half-life, which is defined as the time after which half of the nuclei have decayed. For instance, tritium has a half-life of approximately twelve years. If one were to start with one kilogram of tritium today, after a period of about twelve years there would be only 500 grams remaining. After around twenty four years, there would be 250 grammes, circa thirty six years later only 125 grammes would remain and so on. During this decay, tritium turns into helium-3, a rare yet stable isotope of helium.

1.4 Neutron Capture

Another improtant nuclear process is neutron capture. Atomic nuclei have the capacity to capture a free neutron and to integrate it into its structure. For instance, ^{235}U can capture a neutron and subsequently transform into ^{236}U. Sometimes, if a nucleus catches a neutron, a neutron transforms into a proton. In the event of this occurence, the identity of the element changes, given that the number of protons is what defines an atom. This phenomenon is called transmutation. To illustrate, in the instance of ^{238}U catching a neutron, the resultant nucleus subsequently turns into ^{239}Pu.

In addition to the process of neutron capture, atomic nuclei have the capacity to undergo fission, whereby they divide into smaller nuclei, or fusion, whereby smaller nuclei combine to form a larger atomic nucleus. The capability of a nucleus to undergo fission or fusion is contingent upon its mass. Atomic nuclei that are heavier than iron are capable of undergoing fission, whereas nuclei that are lighter than iron are capable of undergoing fusion.

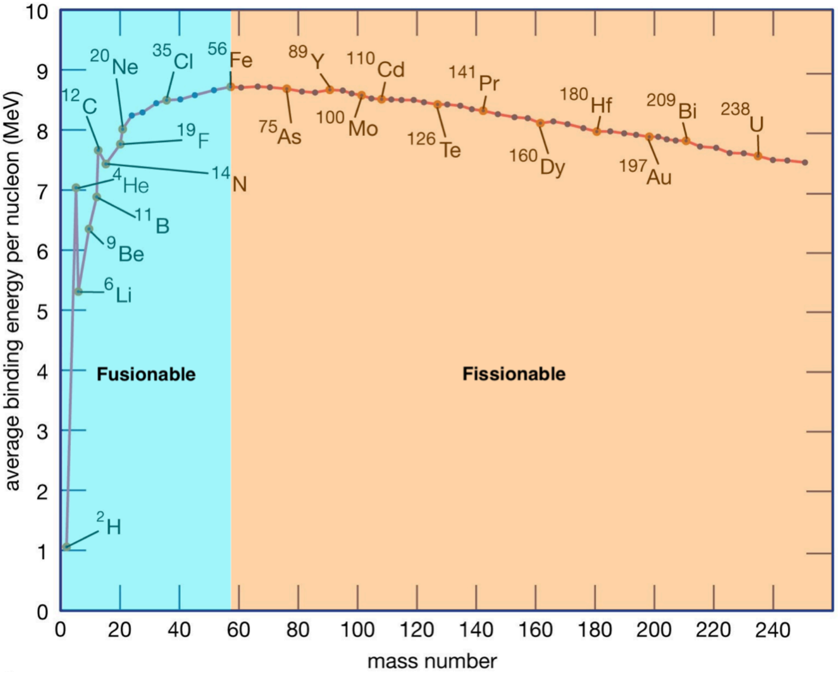

Figure 1: Comparison of the binding energy per nucleus as a function the mass number of the atomic nucleus. Due to the maximum at A=56, which is the mass of iron, iron is the defining element that separates fusionable (on the left) and fissionable (on the right) nuclei.[91]

2 Nuclear Fusion

Nuclear fusion – also referred to fusion for short – is the process that powers the stars. The harnessing of this energy has been an objective of scientists for decades. Historically, fusion research advanced more gradually than the optimistic predictions of its early decades, though it has now delivered the scientific basis for moving toward fusion pilot plants. Recent advancements in research and heightened interest from policy makers as well as private investors have led to the promises of commercial fusion within the next decade or two. Nuclear fusion has the potential to provide

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[91] Adopted and edited from https://cdn.britannica.com/46/6046-050-D533C3B3/energies-function-atomic-mass-number.jpg, last accessed 17 July 2025.

the world with a safe, greenhouse gas free and inexhaustable energy source without the downsides associated with today's nuclear energy. Fusion reactions do not produce radioactive waste that needs to be taken care of for several centuries or even millenia. Similarly, fusion reactors do not pose the risk of accidents like nuclear fission power plants. This section will explore the fundamental principles of nuclear fusion and the pathway towards its commercialisation.

2.1 Basics of Nuclear Fusion

The process of fusing atomic nuclei on Earth is an outstandingly difficult endeavour. Despite the experimental discovery of nuclear fusion[92] five years earlier than fission,[93] to date no fusion power plant exists, whereas there are hundreds of fission power plants in operation. Fusion has yet to leave the realm of fundamental research at universities and national laboratories. Today's fusion machines are among the most complex technical devices ever built. This is due to the fact that certain conditions must be met for fusion to occur. In fusion, two atomic nuclei have to be brought that closely together so the strong nuclear force attracts them. However, since atomic nuclei are positively charged, they repel each other due to the so-called Coulomb repulsion. The atomic nucleus, composed of positive protons and neutral neutrons, exhibits a net positive charge. Like charges repel each other, opposite charges attract each other. It is only when this repulsion is overcome that the strong nuclear force becomes dominant and fusion can occur. To overcome this repulsion, high temperatures in the order of tens to hundreds of millions of degrees Celsius are necessary. At these temperatures, matter exists in its fourth state, known as the plasma state. A plasma is a gas in which atoms disintegrate into their consituents, nuclei and electrons. Due to the high temperatures required for a nuclear reaction, such fusion reaction are called *thermonuclear*.

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[92] *Marcus Laurence Elwin Oliphant/Ernest Rutherford*, Experiments on the Transmutation of Elements by Protons, Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character 141 (1933), 259–281.

[93] *Otto Hahn/Fritz Strassmann*, Über den Nachweis und das Verhalten der bei der Bestrahlung des Urans mittels Neutronen entstehenden Erdalkalimetalle, Naturwissenschaften 27 (1939), 11–15.

In order for fusion reactions to be efficient, it is necessary that the so-called *Lawson criterion* is fulfilled.[94] In this context, the triple product

$$\boldsymbol{Tn\tau_E} \quad (1)$$

of temperature T, density n and energy confinement time τ_E must exceed a certain threshold. To put this formula into (a simplified) context: The higher the temperature, the more energy each atomic nucleus has, and the greater the probability is to overcome the Coulomb barrier and thus of a fusion reaction. Similarly, the closer the particles are together, i.e., the higher the density is, the more likely the nuclei are to come close enough to fuse. Moreover, the longer the energy is confined, the more reactions are likely to occur.

In stars, this criterion is met by high gravitational pressure. Stars are extremely heavy, resulting in gravitational attraction of all matter of the star to its center. On Earth, complex technology is required, making the commercialisation of fusion a lengthy process. Over the past decades of fusion research, a number of different technologies have been developed. They differ both in the type of atoms to be fused and in the technology used to confine the plasma, which is over 150 million degrees hot.

2.2 Confinement Technologies

Fusion occurs at temperatures in the millions of degrees Celsius. One cannot simply put a 150 million degree hot plasma in a pot. Since no material can withstand these temperatures, fusion requires special confinement methods, sometimes described as bottling the artificial star.

The majority of fusion research facilities and start-ups follow the concept of *magnetic confinement,* wherein a series of magnetic coils confine the plasma. Magnetic fields keep together the plasma in a vacuum chamber. Typically, these machines are toroidal in shape and are often compared to the shape of a doughnut. Different mechanisms are employed to heat the plasma to the required temperatures. One such mechanism is a complex

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[94] *J. D. Lawson*, Some Criteria for a Power Producing Thermonuclear Reactor, Proceedings of the Physical Society – Section B 70 (1957), 6. On the role of the Lawson criterion for today's research, see: *Samuel E. Wurzel/Scott C. Hsu*, Progress Toward Fusion Energy Breakeven and Gain as Measured Against the Lawson Criterion, Physics of Plasmas 29 (2022), 062103.

version of a microwave oven,[95] utilising electromagnetic waves to heat the particles of the plasma. Another mechanism involves the introduction of particles at a high velocity, leading to collisions between particles, which in turn deposits heat into the plasma. A third, comparably minor, mechanism is the application of an electric current to the plasma. As known from chargers of phones or notebooks, an electric current produces heat.

Most magnetic confinement fusion facilities fall into two configurations: *tokamaks* and *stellarators*. The primary distiction between these two types of fusion devices pertains to the configuration of magnets. Tokamaks have two different sets of magnets but a rather simple geometry, while stellarators only have a single set of magnets but a highly complex geometry. Research facilities predominantly use tokamaks. While plasma physics in tokamaks is fairly well understood, there are significant challenges associated with their operation. The use of high magnetic fields necessitates the shutdown and subequent cooling down of magnets after a certain period of time. In addition, periodic plasma eroptions expose the material to extreme heat deposition.[96] A continuous operation is not possible with tokamaks, only a pulsed one, meaning that the machine has to be switched off after a certain period of time. Conversely, stellarators offer the potential for continuous operation; however, the comprehension of plasma physics in stellarators is comparatively underdeveloped relative to that in tokamaks.[97]

To date, the only fusion experiment that has achieved $Q > 1$, meaning a net-energy output, is the National Ignition Facility (NIF). It employs a different approach to confine the plasma: intertial confinement fusion (ICF), also called laser fusion. Rather than utilising magnetic fields to confine the plasma, NIF employs extremely power lasers that are focused on a target which contains the fusion fuel. The laser pulse drives the implosion to the required density, while the fuel's own inertia confines the plasma for the brief interval before the target disassembles. The energy of the laser heats the plasma to the required temperature threshold.

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[95] To be precise, fusion machines typically use a combination of electron cyclotron resonance heating (ECRH) and ion cyclotron resonance heating (ICRH).

[96] So-called Edge-Localised Modes (ELMs). On the phenomenology of ELMs, see *Hartmut Zohm*, Edge Localized Modes (ELMs), Plasma Physics and Controlled Fusion 38 (1996), 105.

[97] *Per Helander/Craig D. Beidler/T. M. Bird et al.*, Stellarator and Tokamak Plasmas: A Comparison, Plasma Physics and Controlled Fusion 54 (2012), 124009.

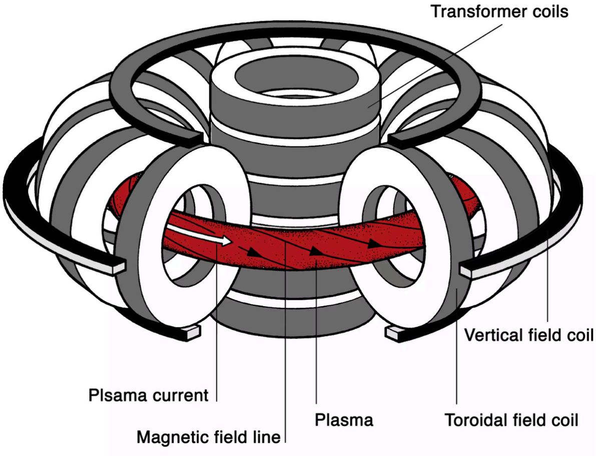

Figure 2: Schematic Depiction of a Tokamak[98]

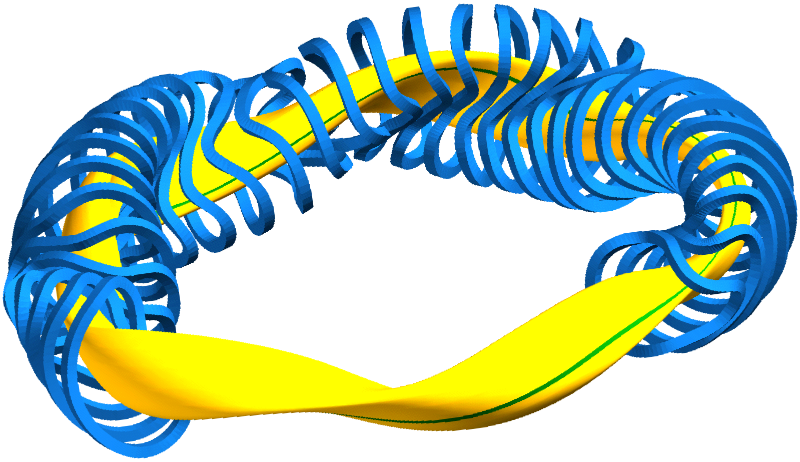

Figure 3: Schematic Depiction of a Stellarator[99]

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[98] Max-Planck-Institute for Plasma Physics, https://www.ipp.mpg.de/14869/tokamak, last accessed 17 July 2025.

[99] Max-Planck-Institute for Plasma Physics, https://www.ipp.mpg.de/4326243/original-1673955102.webp?t=eyJ3aWR0aCI6NjgyLCJmaWxlX2V4dGVuc2lvbiI6IndlYnAiLCJvYmpfaWQiOjQzMjYyNDN9--21888a527ee4a6596ff10bf4dad6b5c56b56dfc1, last accessed 17 July 2025.

2.3 Fusionable Materials

The primary fusion fuel of our Sun is the fusion of two protons – regular hydrogen nuclei. Combined with an electron, they fuse to form the hydrogen isotope deuterium ^{2}H by releasing an electron neutrino v_e (which is not of interest for this book and is just added for physical correctness) and – most importantly – energy:

$$^1\mathrm{H} + {}^1\mathrm{H} + e^- \rightarrow {}^2\mathrm{H} + \nu_e + 1.442\ \mathrm{MeV} \quad (2)$$

The energy released is measured in the unit MeV which is the most common unit of energy in the field of nuclear physics.[100] As the energy released is comparatively low, other atomic nuclei are used for fusion experiments and future fusion power plants on Earth.

Current scientific experiments such as ASDEX Upgrade, Wendelstein 7-X, JT-60SA, EAST or DIII-D fuse two deuterium nuclei ^{2}H to form the helium isotope ^{3}He, a neutron n and energy:

$$^2\mathrm{H} + {}^2\mathrm{H} \rightarrow {}^3\mathrm{He} + \mathrm{n} + 3.3\ \mathrm{MeV} \quad (3)$$

To further increase the amount of energy produced, deuterium can be fused with tritium ^{3}H to produce regular helium ^{4}He. This process, termed D-T reaction, is the reaction that will most likely power future fusion power plants.

$$^2\mathrm{H} + {}^3\mathrm{H} \rightarrow {}^4\mathrm{He} + \mathrm{n} + 17.6\ \mathrm{MeV} \quad (4)$$

In other terms:

$$\mathrm{D} + \mathrm{T} \rightarrow {}^4\mathrm{He} + \mathrm{n} + 17.6\ \mathrm{MeV} \quad (5)$$

It is important to put the amount of energy produced into context. One kilogram of coal contains approximately 20 MJ of energy. When the deuterium contained in one litre of regular water (i.e., one kilogram) is fused with tritium, approximately 30,000 MJ of energy are released.[101] To contextualise further: One kilogram of coal contains enough energy to drive a Tesla Model S for the distance of a marathon, while the deuterium in one

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[100] In nuclear physics, the typical unit for energy ins nuclear processes is MeV, short for mega electronvolt. In SI units, 1 MeV = 1.602 x 10^{-13} J.

[101] One liter of water contains roughly 10^{22} deuterium atoms.

litre of water contains enough fusion energy to circumference the entire globe one and a half times in the same car.[102]

As tritium does not occur naturally, it must be produced artificially. This process is called *breeding*. The world's current main supply source of tritium is a by-product of fission reactions, specifically from heavy-water (i.e., deuterium replacing regular hydrogen in water molecules) moderated reactors of the CANDU type.[103] Within these reactors, a neutron, produced by the fission of uranium, is periodically captured by a deuterium nucleus, resulting in the formation of tritium. This is an example of the earlier outlined process of neutron capture. The significant demand for tritium in fusion research has led to plans to breed tritium (^3H) through the irradition of lithium (^6Li)with neutrons. ^6Li is an isotope of lithium with a natural abundance of approximately 7.5 %.

$$^6Li + n \rightarrow {}^4He + {}^3H \quad (6)$$

In this reaction, a ^6Li nucleus captures a neutron and transforms into ^4He and tritium.

2.4 Fusion in a Power Plant

The basic idea behind a fusion power plant is ambitious: Liberating the strongest force in the universe and using it for humanity's energy needs, based on simple water and lithium. Such a fusion power plant will comprise two primary constituents: Firstly, a fusion reactor and secondly, the energy generation section. Within the reactor, the aforementioned nuclear reactions occur, resulting in the release of energy. This energy is not electric energy, but kinetic or thermal energy, requiring an energy conversion process. The conceptual framework of a fusion power plant bears resemblance

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[102] For these calculations it is assumed that the car consumes 130 Wh per km and that 100 % of the energy could be converted into electricity.

[103] On the tritium production in CANDU reactors, see: *Tae-Keun Park/Seon-Ki Kim*, Tritium: Its Generation and Pathways to the Environment at CANDU 6 Generating Stations, Nuclear Engineering and Design 163 (1996), 405–411. On the relevance of CANDU reactors for fusion research, see: *Richard J. Pearson/Armando B. Antoniazzi/William J. Nuttall*, Tritium Supply and Use: a Key Issue for the Development of Nuclear Fusion Energy, Fusion Engineering and Design 136 (2018), 1140–1148; *Muyi Ni/Yongliang Wang/Baoxin Yuan et al.*, Tritium Supply Assessment for ITER and DEMOnstration Power Plant, Fusion Engineering and Design 88 (2013), 2422–2426.

to that of conventional power plant technologies, such as coal, oil, gas, and nuclear fission. In essence, a fusion power plant can be conceptualised as a giant kettle. Physical and chemical processes – the burning of coal, oil, gas, the fission of an atomic nucleus, the fusion of two atomic nuclei – generate heat. Turning heat into electricity requires a steam generator and a turbine. The heat generates steam, the steam in turn powers turbine, which powers a generator that subsequently produces the actual electricity which is then transmitted to the power grid.

The operation of a fusion power plant necessitates a specific fuel cycle, providing deuterium and tritium. Deuterium gas is produced from regular water which is treated by specific chemical processes, the so-called Girdler sulfide process[104] and further distillation. On average, there is one molecule containing deuterium in 3,200 water molecules. These processes enable the separation of heavy water (first HDO, then D_2O) from regular water (H_2O). Subsequently, the heavy water undergoes electrolysis to separate deuterium from oxygen.

The supply with tritium is more complicated. In operation, a fusion power plant will produce its own tritium. For the start-up of a fusion power plant, an external supply – either from CANDU reactors or other fusion power plants – is required. The tritium produced in the fusion plant must be extracted and stored. A tritium supply cycle will be one of the most essential parts of a future fusion power plant.[105]

Inertial confinement fusion requires an additional step. This confinement technology utilizes small pellets of fuel, which are spheres containing a mixture of deuterium and tritium gas. The production of these pellets constitutes an additional step in the fuel cycle compared to magnetic confinement.

The fusion process itself does not generate waste, with the reaction product being helium, a gas that can be easily released into the atmosphere. However, waste will be produced from the fusion facility itself. The reactor components will require a specific handling after decommissioning due to their radioactivity. Neutrons produced in fusion reactions activate material, also leading to a certain degree of radioactivity. In addition, the reactor components will contain small traces of tritium which is radioactive. However, in comparison with fission power plants, the intensity and duration of

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[104] On hydrogen isotope separation, see. *Howard K. Rae*, Separation of Hydrogen Isotopes, Washington DC: American Chemical Society 1978.

[105] *Ni/Wang/Yuan et al.* (n 103); *Pearson/Antoniazzi/Nuttall* (n 103).

radioactivity is severely limited. While fission waste needs to be taken care of for thousands of years, the majority of fusion waste will be recyclable and reusable after around 100 years.[106]

2.5 The Road to Commercial Fusion Energy

Despite the considerable promise of fusion technology, decades of research have yet to yield electricity generated by fusion. Among fusion scientists, a joke is regularly told: Fusion is only thirty years away and always will be. However, tremendous progress has been made in recent years, and various actors – both public and private – are pursuing roadmaps towards the commercialisation of fusion.

Currently, there are more than sixty fusion research facilities in operation, mostly located in Europe, North America and Asia. These facilities serve as experimental platforms for the exploration of confinement technologies, sizes, configurations, and other physical parameters, facilitating a deeper understanding of plasma physics. While a proportion of these facilities are involved in military programmes, the majority are dedicated to peaceful research. The JT-60SA, situated in Naka, Japan, and operated in collaboration by Japan and EUROfusion,[107] is currently the largest tokamak. Other important tokamaks include the recently decommissioned Joint European Torus (JET) or ASDEX-Upgrade. Within the domain of stellarators, Wendelstein 7-X, located in Greifswald, Germany and operated by the Max-Planck-Institute for Plasma Physics, represents the largest and most important facility. With regard to inertial confinement fusion, the National Ignition Facility, situated in the United States and operated by the US Department of Energy, is the most important facility.

In the coming years, ITER, short for International Thermonuclear Experimental Reactor or latin for *path*, is expected to become a pivotal fusion research facility. Located in Cadarache, France, the tokamak is currently under construction and is designed to be the first magnetic confinement

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[106] On fusion waste, see *M. Zucchetti/Z. Chen/L. El-Guebaly et al.*, Progress in International Radioactive Fusion Waste Studies, Fusion Science and Technology 75 (2019), 391–398; *Sehila M. Gonzalez de Vicente/Nicholas A. Smith/Laila El-Guebaly et al.*, Overview on the Management of Radioactive Waste From Fusion Facilities: ITER, Demonstration Machines and Power Plants, Nuclear Fusion 62 (2022), 085001.

[107] EUROfusion is a consortium of fusion research institutions which is funded to 50 % by Euratom and to 50 % by the State the research institute is located in.

device to achieve the net production of energy via fusion. Originally conceptualised as a peace project in the final stages of the Cold War by uniting superpowers via the joint advancement of science, ITER is now an international consortium involving the United States, Russia, Euratom, Japan, China, South Korea and India. ITER is expected to be operational in 2034.[108]

In continental Europe, numerous fusion research facilities – funded to a significant extent by Euratom[109] – are following the roadmap developed by EUROfusion.[110] This roadmap delineates a series of milestones leading to the commericalisation of fusion. The first step is the completion of ITER in the mid 2030s. Following the successful demonstration of a net energy gain around that time, the plan is to construct a machine capable of producing not only net energy but also net electricity. This is envisioned to be achieved in DEMO, a demonstration power plant scheduled to be built in the mid-2040s. The primary objective of DEMO is to establish a foundation for the subsequent commercialisation of fusion power plants, which is anticipated to occur in the latter half of the 21st century. Given construction delays by ITER, it is unclear whether the roadmap will be pursued as anticipated.

The United Kingdom is adopting a different approach, not waiting for the completion of ITER as the UK ended its participation in the project with Brexit. The UK Atomic Energy Authority (UKAEA) is currently engaged in developing a demonstration fusion power plant, STEP, with an operational target of 2040.

In the United States, the Department of Energy is also pursuing a roadmap, with the objective to commercialise fusion in the late 2030s or early 2040s.[111] In contrast to the approach of relying on government-backed projects such as Euratom or the United Kingdom, the United States strategy places emphasis on public-private partnerships, with the private sector demonstrating notable activity. At present, approximately fifty fusion start-ups worldwide have secured several billions of USD in funding from public

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[108] *Pietro Barabaschi/Arnaud Fossen/Alberto Loarte et al.*, ITER Progresses into New Baseline, Fusion Engineering and Design 215 (2025), 114990.

[109] Euratom funds fusion research with €1.38 billion between 2021 and 2024 as part of the Horizon Europe research and development initiative.

[110] *EUROfusion*, European Research Roadmap to the Realisation of Fusion Energy (Long Version), 2018.

[111] *U.S. Department of Energy*, Fusion Energy Strategy 2024, 2024.

and private investors.[112] The private sector anticipates the availability of commercial fusion technology within the next decade.[113]

Nevertheless, there are still problems to be solved for the commercialisation of fusion. One pressing question is the start-up quantity of tritium. Current estimates suggest that ITER will consume almost all of the available tritium on the world market during its lifetime.[114] ITER itself, however, will not produce any tritium unlike future fusion plants. How will fusion power plant projects – either in research such as DEMO or commercially – be able to start their power plant if there is no tritium on the world market? Furthermore, the tritium breeding technology is still in its infancy and research in this field is ongoing.[115] In addition, plasma physics itself remains a complex topic with challenges which are object of current research, such as plasma instabilities.[116] Further challenges concern the handling of heat fluxes and the handling of materials due to neutron bombardment. Finally, there are still open questions regarding the dimension of a fusion power plant.[117]

3 Nuclear Fission

In order to comprehend the existing non-proliferation and disarmament regime, as well as the challenges posed by the commercialisation of fusion, it is imperative to understand the fundamentals of nuclear fission and the fuel cycle of a nuclear (fission) power plant. Nuclear fission is the process by which a nucleus splits into at least two smaller nuclei. Both civilian and

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[112] https://www.nuclearbusiness-platform.com/media/insights/62-billion-fusion-energy-funding-race-turning-the-dream-of-creating-a-star-on-earth-into-reality, last accessed 25 February 2025.

[113] For instance, Helion Energy envisages their first power plant in 2028. Commonwealth Fusion Systems plans to have a fusion power plant operational in the first half of the 2030s.

[114] *Pearson/Antoniazzi/Nuttall* (n 103).

[115] For an overview, see *Marek Rubel*, Fusion Neutrons: Tritium Breeding and Impact on Wall Materials and Components of Diagnostic Systems, Journal of Fusion Energy 38 (2019), 315–329.

[116] See for example *Thomas Eich/Robert J. Goldston/Arne Kallenbach et al.*, Correlation of the Tokamak H-Mode Density Limit With Ballooning Stability at the Separatrix, Nuclear Fusion 58 (2018), 034001.

[117] *Hartmut Zohm*, On the Size of Tokamak Fusion Power Plants, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 377 (2019), 20170437.

military applications utilise chain reactions of the elements uranium and plutonium. Natural uranium consists of mainly two isotopes, ^{238}U and ^{235}U. ^{235}U is a rare isotope with an abundance of only 0.72 %.[118] This means, that in 1 kg of natural uranium, only about 7 g of that uranium is ^{235}U. The remaining mass of uranium consists of the more abundant isotope of uranium ^{238}U, which has an abundance of 99.27 %.[119] Plutonium does not exist in nature; it is artificially bred in plutonium production plants.

In order to utilise the strong nuclear force of the atomic nucleus via fission in an efficient manner, it is necessary to induce a chain reaction. This means that any step produces more neutrons than it consumes. The ratio between produced and consumed neutrons needs to be greater than one. However, reactions involving ^{238}U do not release neutrons, rendering it unsuitable for sustaining chain reactions, and consequently is of no use for both nuclear reactors and nuclear weapons. In contrast, the uranium isotopes ^{233}U and ^{235}U as well as the plutonium isotope ^{239}Pu are suitable materials for nuclear chain reactions. These materials are classified as fissile material.

$$^{233}\mathrm{U} + \mathrm{n} \longrightarrow {}^{234}\mathrm{U} \rightarrow \text{Fission Fragments} + 2.50\mathrm{n} + 198\ \mathrm{MeV} \quad (7)$$

$$^{235}\mathrm{U} + \mathrm{n} \longrightarrow {}^{236}\mathrm{U} \rightarrow \text{Fission Fragments} + 2.43\mathrm{n} + 207\ \mathrm{MeV} \quad (8)$$

$$^{239}\mathrm{Pu} + \mathrm{n} \longrightarrow {}^{240}\mathrm{Pu} \rightarrow \text{Fission Fragments} + 2.87\mathrm{n} + 214\ \mathrm{MeV} \quad (9)$$

The fissile material (^{239}Pu, ^{233}U or ^{235}U) captures a neutron, thereby transmuting into an unstable atomic nucleus, either ^{240}Pu, ^{234}U or ^{236}U. This nucleus subsequently decays into fission fragments, releasing free neutrons and energy in the process. These neutrons then initiate the next fission process, thus leading to a chain reaction.

As ^{235}U is the only naturally occuring[120] uranium isotope that produces neutrons in order to keep up chain reactions, it is the main isotope of uranium used in reactors and weapons. However, at natural abundance levels of 99.27 % of unusable uranium ^{238}U compared to the fissile ^{235}U, the utilisation of uranium in sustained chain reactions necessitates the enriche-

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[118] *Zsolt Sóti/Joseph Magill/Raymond Dreher*, Karlsruhe Nuclide Chart – New 10th Edition 2018 EPJ Nuclear Sciences and Technologies 5 (2019), 6.

[119] Ibid.

[120] The uranium isotope ^{233}U is bred via neutron capture from ^{232}Th, often in molten-salt reactors.

ment of uranium in that isotope. This process is typically accomplished through the utilisation of gaseous diffusion[121] or gas centrifuges[122], and in the future maybe even with lasers[123]. While the enrichment level for power plants typically ranges from three to five per cent[124], the level for nuclear weapons required is about 90 per cent.[125] The facts that the same chemical element is used, in conjunction with the necessity for the same enrichment process, require the implementation of a safeguards regime for *fission*. Fission is a dual-use technology: The physical processes involved can be applied to both civilian and military application, including nuclear power plants and nuclear weapons respectively.

The fission fuel cycle is characterised by a greater diversity of processes when compared to the fusion fuel cycle. It commences with the mining of uranium ore. The uranium ore is subsequently processed and enriched. The enriched material is used to produce fuel rods. After operation, the fuel might get reprocessed to extract remnants of fissile material and plutonium. In the end, there is waste that needs to be disposed of.

Within the fission fuel cycle, there exists a range of facilities with varying degrees of proliferation potential. First, there is the fission reactor itself.

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[121] Enrichment is a technologically challenging process, as two isotopes are identical in their chemical properties. The only difference is the weight. ^{235}U is three atomic mass units (i.e. 3×10^{-27} g) or 1.3 % lighter than ^{238}U. Gas diffusion devices use the chemical compound uranium hexafluoride UF_6 in a gaseous state, instead of uranium ore. This gas then forced through semi-permeable membranes. Due to the difference in weight – a UF_6 molecule containing ^{238}U is heavier than a UF_6 molecule containing ^{235}U – the diffusion velocity differs between the two types of molecules, leading to an isotope separation. After the isotope separation, the fluoride is removed from UF_6 to get pure uranium.

[122] Gas centrifuges exploit both the gaseous properties of UF_6 and the weight difference of isotopes. Due to centrifugal forces, heavier molecules are pushed farther outwards than lighter molecules. On the physics behind gas centrifuges, see *Donald R. Olander*, The Theory of Uranium Enrichment by the Gas Centrifuge, Progress in Nuclear Energy 8 (1981), 1–33.

[123] Laser enrichment technology works by exciting UF_6 molecules. On its proliferation potential, see *Ryan Snyder*, A Proliferation Assessment of Third Generation Laser Uranium Enrichment Technology, Science & Global Security 24 (2016), 68–91.

[124] *Shuichi Hasegawa*, Isotope Separation Methods for Nuclear Fuel, in: Nicholas Tsoulfanidis (ed.), Nuclear Energy: Selected Entries from the Encyclopedia of Sustainability Science and Technology, New York: Springer 2013, 59–76, at 60.

[125] *Alexander Glaser*, On the Proliferation Potential of Uranium Fuel for Research Reactors at Various Enrichment Levels, Science & Global Security 14 (2006), 1–24; *Alexander Glaser*, Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation, Science & Global Security 16 (2008), 1–25.

Nuclear safeguards are implemented to verify the use of uranium and the handling of the spent fuel. Spent uranium fuel may contain plutonium, which can be utilised to construct a nuclear weapon. A significant proliferation potential exists outside the reactors, particularly within enrichment facilities and spent fuel facilities.[126] As previously mentioned, while both nuclear fission power plants and nuclear weapons require enriched uranium, the enrichment levels differ. In enrichment facility the duration of operation determines the achievable enrichment level. If such a facility is operated long enough and reconfigured, reactor-grade material can turn into weapons-grade material, thereby emphasising a focus of safeguards on material within enrichment facilities. Concerning spent fuel, the objective is to safeguard against the separation of plutonium from the spent fuel for the purpose of producing nuclear weapons. Consequently, safeguards extend to the entire fuel cycle, with a particular emphasis on nuclear material before and after its utilisation in a reactor.[127]

4 Nuclear Weapons

In order to comprehend the legal framework of nuclear weapons and the role of fusion in it, it is imperative to establish the fundamental principles of the categories and operational mechanisms of nuclear weapons. Next to biological and chemical weapons, nuclear weapons are weapons of mass destruction. Nuclear weapon is an umbrella term for different types of weapons that all utilise the energy released from nuclear reactions in an uncontrolled manner, resulting in an explosion, for military applications. Within the domain of nuclear weapons, various categorisations exist with regard to the yield or range and the nuclear processes involved.

4.1 Tactical and Strategic Nuclear Weapons

There are different approaches to categorising nuclear weapons. One category is to differentiate by yield and range between strategic and tactical nuclear weapons. In this sense, strategic weapons are defined as those used

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[126] *IAEA*, Safeguards for Reprocessing and Enrichment Plants, IAEA Bulletin 19 (1977), 30–33.

[127] For an overview of the legal framework, see Chapter 2.

for nuclear deterrence[128] due to their high yield in the range of megaton equivalents of TNT, capable of destroying entire cities, and characteristically have a high range of thousands of kilometres.[129] In contrast, tactical (also called non-strategic) nuclear weapons are characterised by a lower yield of several kilotons of TNT equivalent, and a shorter range.[130] However, this distinction has been subject of criticism. Not only is any use of nuclear weapons of strategic nature,[131] the question of range or yield is also mainly an operational question. Consequently, under such a categorisation, both nuclear weapons deployed in the atomic bombings of Hiroshima and Nagasaki on 6 and 9 August 1945 would be classified as tactical weapons; despite the fact that they resulted in the elimitation of entire cities and the death of over 200,000 people.[132] Nuclear weapons deemed strategic typically contain fusionable material.

4.2 Nuclear Weapons Delivery Systems

There are various delivery systems for nuclear weapons.[133] One option is gravity bombs, such as those deployed over Japan in 1945. In this scenario, the bomb is mounted to an airplane and released over the target. Another option is to mount a nuclear warhead onto a missile, especially intercontinental ballistic missiles (ICBMs), submarine-launched ballistic missiles (SLBMs) or cruise missiles. A ballistic missile follows the ballistic trajectory from the launch with a relatively short powering phase, while cruise missiles have an additional guiding system and can change its trajectory

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[128] On nuclear deterrence, see Chapter 2, Section 1.1.

[129] *Office of the Deputy Assistant Secretary of Defense for Nuclear Matters*, Nuclear Matters Handbook 2020, US Department of Defense 2018, at 44.

[130] Ibid, at 4; *Amy F. Woolf*, Nonstrategic Nuclear Weapons, Washington DC: CRS Report for Congress 2010, at 4 f.

[131] Former US Secretary of Defense Mattis called any use of a nuclear weapon "a strategic gamechanger", *James N Mattis*, The National Defense Strategy and the Nuclear Posture Review – Committee on Armed Services of the House of Representatives, Washington DC: U.S. Government Publishing Office 2018.

[132] *Masao Tomonaga*, The Atomic Bombings of Hiroshima and Nagasaki: A Summary of the Human Consequences, 1945–2018, and Lessons for Homo sapiens to End the Nuclear Weapon Age, Journal for Peace and Nuclear Disarmament 2 (2019), 491–517.

[133] *Jeff Richardson*, Shifting from a Nuclear Triad to a Nuclear Dyad, Bulletin of the Atomic Scientists 65 (2009), 33–42.

mid-journey.[134] As fission-only warheads are heavy (the bombs deployed on Hiroshima and Nagasaki had to be dropped from a bomber plane), mounting a nuclear weapon onto a missile usually requires miniaturisation, which is achieved by a combination of fission and fusion technology.

4.3 Fission and Fusion Bombs

A significant distinction between types of nuclear weapons is the nuclear process which powers the explosion. As nuclear weapons are weapons that use nuclear processes, they can encompass not only nuclear fission, but also nuclear fusion, a combination which is incorporated into the arsenals of all nuclear weapons States.

4.3.1 Pure Fission Bombs

The first generation of nuclear weapons, such as those deployed in Japan in 1945, utilised only fissile material in the explosion, i.e., either ^{235}U or ^{239}Pu. Within the context of a nuclear power plant, a moderator medium and associated control mechanisms are employed to ensure controlled fission chain reactions. The number of neutrons produced remains the same level as the number of neutrons captured by the reactor fuel. In contrast, a nuclear weapon does not possess moderators or other control mechanisms, as it induces uncontrolled chain reactions, leading to an explosion. Physically, both a fission reactor and a nuclear weapon are powered by the same nuclear reaction.

Pure fission nuclear weapons exist in different designs. To initiate a nuclear chain reaction, a critical mass is required. Once the material is critical, the chain reaction is initiated. However, in a weapon, (super-)criticality must only occur once the weapon is supposed to detonate. To achieve super-criticality only at detonation, different approaches were developed. Uranium-based weapons, such as *Little Boy*, the weapon that destroyed Hiroshima, used a gun-type approach. The uranium is split into two parts and placed at both ends of a tube. At detonation, a classical explosive pushes one part into the other, leading to criticality and finally the nuclear explosion. Plutonium-based weapons, such as *Fat Man*, the bomb that

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[134] *Richard K. Betts*, Cruise Missiles: Technology, Strategy, Politics, The Washington Quarterly 4 (1981), 66–80.

destroyed Nagasaki, as well as modern uranium-based weapons, use an implosion mechanism. The plutonium is shaped into a sphere. This sphere is surrounded by classical explosives. Once the classical explosives detonate, the fissile material is pushed inwards, leading to super-criticality and then an explosion. Both designs have an inherent limitation: only a fraction of the fissile material contributes to the final explosion. To increase the percentage of fissile material contributing to the explosion, fusion has to be included into the weapon design.

4.3.2 Thermonuclear Weapons

The majority of modern nuclear weapons are thermonuclear weapons, combining fission and fusion. The utilisation of fusion serves to increase the yield of the weapon and allows for lighter and more compact weapon designs (minituarisation). The influence of fusion ranges from a minor fusion component, limited to increasing the number of neutrons to boost the chain reaction, to full-scale hydrogen bombs where fusion contributes significantly to the explosion. The more neutrons there are, the more fission reaction occur, the bigger the explosion is. More advanced designs, sometimes called hydrogen bomb or just H-Bomb, use a two (or sometimes even more) staged mechanism. First, a fission primary detonates. The energy and radiation released then initiates fusion reactions within the fusion secondary. The explosion of the hydrogen bomb is then a combination of both uncontrolled fission and fusion reactions.

Such a combination of fission and fusion increases the percentage of fissile fuel burnt, thereby significantly increasing the yield of a nuclear weapon. The biggest man-made explosion ever, the *Tsar Bomba* by the Soviet Union, was such a thermonuclear weapon. It had a yield of more than 50 Mt, which is approximately 1,500 times the combined yield of both nuclear weapons deployed on Japan.[135] The development of thermonuclear weapons played a pivotal role in propelling the nuclear arms race that characterised the Cold War.

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[135] On the yield of the Tsar Bomba, Little Boy and Fat Man, see *F. A. Khan*, On Tsar Bomba – The Most Powerful Nuclear Weapon Ever Tested, Physics Education 56 (2021), 013002.

5 Fusion and the Risk of Nuclear Proliferation

Fusion energy is a dual-use technology, with the potential for proliferation, albeit to a significantly lesser extent than fission. While the development of fusion energy is driven by the demand for a clean source of energy for civilian purposes, fusion can also support nuclear weapons programmes. Fusion poses three proliferation risks. Firstly, fusion is an intense neutron source. Irradiating an atomic nucleus with neutrons can transform one element into another, thereby converting fertile[136] material into fissile[137] material. In other words, it is possible to create nuclear weapons material with fusion as an intense neutron source (5.1). Secondly, tritium – a radioactive isotope of hydrogen – plays a crucial role in fusion energy production and is also a vital component in boosted fission weapons and thermonuclear weapons (5.2). Thirdly, a specific fusion technology – inertial confinement or laser fusion – poses a proliferation risk due to potential insights gained into the functioning of thermonuclear weapons (5.3). After having explored fusion's three main proliferation concerns, this section then briefly focuses on the possibility of fission-fusion hybrid systems (5.4), before pinpointing the exact differences between the proliferation potential of fission and fusion (5.5).

5.1 Transmutation – Fusion to Produce Nuclear Weapons Material

Nuclear fusion technology has the potential be utilised in the production of nuclear weapons material. The neutrons produced in the fusion processes possess the capability to transform certain material into fissile material.[138] These materials are the key component of nuclear weapons.

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[136] Fertile material is a material that can be transformed into fissile material through neutron capture. An example for fertile materials is the uranium isotope ^{238}U.

[137] Fissile material is a material that undergoes fission by neutrons of all energies. The best example is ^{235}U. *International Atomic Energy Agency*, IAEA Safeguards Glossary, Vienna: IAEA 2022, at 36.

[138] See *Alexandre Obertelli/Hiroyuki Sagawa*, Modern Nuclear Physics – From Fundamentals to Frontiers, Singapore: Springer Singapore 2021, at 669 ff.

5.1.1 Transmutation of Uranium and Thorium

As previously stated, atomic nuclei possess a very distinctive property: When a nucleus catches a neutron, it can turn into another element. Depending on the element and the energy of the neutron, this process occurs with a certain probability that allows to artificially produce elements (so-called cross-section). This process of transmutation can play a pivotal role in nuclear weapons programmes to transform fertile material into fissile material. ^{238}U can be transformed into the fissile material ^{239}Pu.[139]

$$^{238}\mathrm{U} + \mathrm{n} \rightarrow {}^{239}\mathrm{U} \rightarrow {}^{239}\mathrm{Np} + \beta^{-} \rightarrow {}^{239}\mathrm{Pu} + \beta^{-} \quad (10)$$

The ^{238}U nucleus captures a neutron and is thereby transmuted into the unstable isotope ^{239}U. This, in turn, decays into another unstable isotope of neptunium, which decays into the weapon-grade isotope of plutonium ^{239}Pu.[140] The β^{-} denotates the decay process, referred to as beta decay, which is of no importance for this book and is only added for the purpose of physical accuracy. The important point is the observation that a neutron induces the decay of a nucleus. Irradiating uranium with neutrons can result in the production of plutonium. Plutonium is the core material of the US nuclear weapon *Fat Man* that was deployed on Nagasaki on 9 August 1945.

Similar to plutonium breeding from uranium, it also possible to breed the fissile material ^{233}U from the thorium isotope ^{232}Th via neutron capture and beta decays:

$$^{232}\mathrm{Th} + \mathrm{n} \rightarrow {}^{233}\mathrm{Th} \rightarrow {}^{233}\mathrm{Pa} + \beta^{-} \rightarrow {}^{233}\mathrm{U} + \beta^{-} \quad (11)$$

By capturing a neutron, ^{232}Th turns into ^{233}Th, which then first decays to ^{233}Pa and ultimately to ^{233}U.

It is important to note that other intense neutron source might be utilised for the purposes of breeding fissile material from fertile material.[141]

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[139] *David Hafemeister*, Physics of Societal Issues: Calculations on National Security, Environment, and Energy, Springer 2016, at 13.

[140] The decay processes are so-called beta decays, indicated by the Greek letter β. A β^{-} decay involves a neutron that decays into a proton, an electron and a neutrino.

[141] On the broader question of safeguards on intense neutron sources, see *Matthias Englert/Anne Harrington*, Next Generation Nuclear Technologies: New Challenges to the Legal Framework of the IAEA from Intense Neutron Sources, in: Jonathan L. Black-Branch/Dieter Fleck (eds.), Nuclear Non-Proliferation in International Law:

Both fission and fusion processes generate neutrons with energies, which allow for the breeding of fissile material. In addition, particle accelerators and some research institutions (such as the particle accelerators at CERN or the the high-flux reactor at the Institut Laue-Langevin) are also intense neutron sources, yet with significantly lower neutron fluxes.

5.1.2 From Fertile to Fissile Material with Fission

In order to comprehend the potential of fusion to produce fissile material, it is first necessary to understand the current methods of producing fissile material using fission technology.

As explained above in Section 4.3.1, the core of any nuclear weapon contains ^{235}U or ^{239}Pu. Current nuclear arsenals do not employ ^{233}U, but it remains a possibility for weapon designs.[142] ^{235}U is obtained from natural uranium via a lengthy enrichment process, while ^{239}Pu must be created artificially through transmutation processes. Historically, nuclear weapon States mainly used so-called graphite moderated reactors to produce fissile material.[143] Graphite, a specific form of carbon, is employed to slow down the neutrons produced in the fission process of the reactor fuel. Nuclear weapons States have also opted for the utilisation of heavy-water moderated reactors to produce their fissile material.[144] Heavy water (D_2O) is water in which the hydrogen isotope deuterium (D) replaces the regular hydrogen (H) of H_2O.

Within these reactors, natural or depleted[145] uranium is irradiated by neutrons in order to produce plutonium. However, this production methods leads to a caveat, namely the trade-off between the quality and quantity of the produced plutonium. It should be noted that the irradiation of uranium does not only lead to the desired isotope ^{239}Pu, but also to other isotopes of plutonium such as ^{238}Pu, ^{240}Pu and ^{242}Pu. While the latter three

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Volume II – Verification and Compliance, The Hague: T.M.C. Asser Press 2016, 187–212.

[142] W. K. Woods, LRL interest in U-233 (1966), Douglas United Nuclear, Inc., Richland, WA (United States).

[143] *David Albright/Frans Berkhout/William Walker*, Plutonium and Highly Enriched Uranium 1996 – World Inventories, Capabilities and Policies, Stockholm: SIPRI 1997, at 31.

[144] Ibid, at 31.

[145] Depleted means that the percentage of U-235 is below the natural weight fraction of 0.7 %.

isotopes can be utilised to a certain extent in nuclear weapons, they limit the overall usability of the produced plutonium.[146] The longer uranium gets irradiated, the more of the undesired isotopes are produced. Conversely, the shorter the irradiation time, the less amount of plutonium in total is produced.[147] This inherent limitation in the process leads to a constrained production of weapon-grade plutonium per year, amount of uranium and reactor by fission technology.

For instance, France's first plutonium producing reactor, the Marcoule G1, had a capacity of producing 12 kg of plutonium from approximately 100 t of uranium per year.[148] The Hanford-N reactor, one of the United States's two plutonium facilities during the Cold War, had a capacity of turning 380 t of uranium into 580 kg of plutonium per year.[149] What these numbers show is that tons of uranium are necessary in order to produce kilograms of plutonium from a fission facility.

Apart from military production, plutonium is also produced in a limited capacity in commercial nuclear power plants. In these facilities, the production of plutonium occurs as an by-product, which changes the energy output of the plant. Notably a single commercial pressurised water fission reactor, the most common type of nuclear reactor,[150] produces around 250 kg of plutonium each year.[151] Given the primary design objective of such a reactor is optimised for energy output rather than fissile material production, the quality of the plutonium produced is inherently limited.[152]

5.1.3 From Fertile to Fissile Material with Fusion

Fusion is a technology which – from the perspective of physics – allows to produce fissile material from fertile material significantly more efficiently than fission.

To recall, the most promising fusion reaction for commercial power plants is considered to be the D-T cycle, i.e., the fusion of the hydrogen

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[146] *Englert/Harrington* (n 141), at 193.
[147] Ibid, at 192 f.
[148] *Albright/Berkhout/Walker* (n 143), at 68 f.
[149] *Englert/Harrington* (n 141), at 194.
[150] *International Atomic Energy Agency*, Nuclear Power Reactors in the World, Vienna: IAEA 2021.
[151] *Englert/Harrington* (n 141), at 194.
[152] Ibid, at 194 f.

isotopes deuterium D and tritium T to release energy, a neutron and to form the most common helium isotope ^{4}He:

$$D + T \rightarrow {}^{4}He + n + 17.6\,MeV \quad (12)$$

Of the 17.6 MeV of energy released, the neutron carries 14.1 MeV.[153] Around these energies, the capture cross-section of fertile material to capture a neutron is in a range which allows for a significant amount of plutonium to take place, while fission events remain rare at these energies.[154] A high cross-section indicates a high probability of a reaction between these two particles. The neutron from a fusion process can be captured by an atomic nucleus of ^{238}U or ^{232}Th.

There are several options for incorporating uranium or thorium into a fusion device in order to produce fissile material. Neutron fluxes are their highest the closer one is to the reactor core. The plasma core itself is not suitable for the production of fissile material as the introduction of other materials into the plasma would prevent fusion reactions.[155] The subsequent layers of a fusion power plant are the wall and the coolant.

Consequently, one option would be to construct a wall containing uranium dioxide UO_2.[156] Neutron-wall interactions will not only be used for tritium breeding, but they might also be beneficial for proliferators. During a certain duration of operation, uranium gets transmuted into ^{239}Pu. The wall material would then be replaced and the plutonium–containing material reprocessed to extract the plutonium. Assuming a large-scale fusion reactor with a thermal power output of 3 GW in the core, such a reactor

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[153] *Thomas J. Dolan*, Nuclear Fusion, in: Nicholas Tsoulfanidis (ed.), Nuclear Energy, New York, Heidelberg: Springer 2013, 305–342, at 308; *E. Morse*, Nuclear Fusion, Heidelberg: Springer International Publishing 2018, at 29.

[154] *Bruce Cameron Reed*, Producing Fissile Material, in: Bruce Cameron Reed (ed.), The Physics of the Manhattan Project, Cham: Springer International Publishing 2021, 119–144 (120). It must be noted that at 14 MeV the capture cross-section is about two magnitudes lower than the fission cross-section. This means that the majority of neutrons would lead to a fission event of U-238 instead of transmuting the nucleus into Pu-239. However, neutrons slow down, allowing for more neutron capture events.

[155] The larger the Z of an ion, the higher the plasma energy losses by Bremsstrahlung and line radiation are. Uranium and thorium are heavy elements. On this, see *Alexander Piel*, Plasma Physics – An Introduction to Laboratory, Space, and Fusion Plasmas, Kiel, Heidelberg: Springer 2017, at 103.

[156] *F. Faghihi/H. Havasi/M. Amin-Mozafari*, Plutonium-239 Production Rate Study Using a Typical Fusion Reactor, Annals of Nuclear Energy 35 (2008), 759–766.

could produce quantities in the order of magnitude of 10 kg of plutonium annually.[157] Similar to this option, the introduction of fertile material to into the tritium breeding blanket is a theoretical possibility.[158] Depending on the configuration, simulations indicate the potential of up to several hundreds of kilograms in a large-scale facility (5.5 GW thermal power) designed for the production of fissile material or a clandestine production of about one critical mass per year.[159]

An alternative option would be to dissolve uranium within the coolant of the fusion reactor.[160] The underlying principle of D-T fusion power plants is the generation of heat, which is then transported by the coolant to power a steam turbine, which in turn produces electricity. The coolant flows in close proximity to the reactor and its first wall in order to function properly. Such an approach is limited by the low solvability of uranium.[161] However, this issue might be overcome by using a technology called TRISO, tristructural-isotropic particles. These are small particles which consist of a uranium or thorium core, which is coated by several layers of lead. These TRISO particles could be introduced into the coolant and later extracted by a filtration system.[162] Simulation studies indicate that a large-sized fusion power plant (i.e., 2.5 GW of thermal power) would be capable of producing 20 kg of ^{239}Pu or 20 kg of ^{233}U per week.[163] Another study estimates that a small sized fusion power plant (500 MW of thermal power) would be able to convert roughly one metric ton of ^{238}U into ^{239}Pu within a year.[164]

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[157] Ibid.

[158] *Fabian Sievert/Daniel Johnson*, Creating Suns on Earth, The Nonproliferation Review 17 (2010), 323–346; *Giorgio Franceschini/Matthias Englert/Wolfgang Liebert*, Nuclear Fusion Power for Weapons Purposes, The Nonproliferation Review 20 (2013), 525–544, at 542.

[159] *Franceschini/Englert/Liebert* (n 158), at 542 f.

[160] *Alexander Glaser/Robert J. Goldston*, Proliferation Risks of Magnetic Fusion Energy: Clandestine Production, Covert Production and Breakout, Nuclear Fusion 52 (2012), 043004.

[161] Ibid.

[162] *Y. Wu/S. Zheng/X. Zhu et al.*, Conceptual Design of the Fusion-Driven Subcritical System FDS-I, Fusion Engineering and Design 81 (2006), 1305–1311.

[163] *Glaser/Goldston* (n 160).

[164] *John L. Ball/Ethan E. Peterson/R. Scott Kemp et al.,* Assessing the risk of proliferation via fissile breeding in ARC-class fusion power plants, Nuclear Fusion 65 (2025), 036038.

5.1.4 Advantages of Fusion for Plutonium Breeding

There are key advantages of fusion for a nuclear weapons programme with regard to the quality and quantity of the fertile material. Primarily, the transmutation rate is significantly higher with simulations indicating that as little as 220 kg of natural uranium introduced in the blanket would be sufficient to produce 4 kg of plutonium in a single year.[165] In comparison with fission, the production of kilograms of plutonium does not require tons[166] but only hundreds of kilograms of uranium, a difference of an entire order of magnitude. Under specific conditions, a fusion reactor could be configured to convert tens of tons of uranium into several tons of plutonium, further advancing fusion's appeal for nuclear weapons applications.[167] Consequently, either less fertile material is required or more fertile material can be produced from the same amount of fissile material than with fission. The high transmutation rate further enhances the percentage of plutonium within the uranium-plutonium mixture, thereby simplifying the reprocessing procedure.[168]

To put these numbers into perspective: The IAEA defines a significant quantity (SQ) of plutonium as 8 kg.[169] A significant quantity is "the amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded."[170] Depending on the technology and the validity of the simulation studies, a single fusion power plant could produce enough plutonium for dozens of nuclear weapons each year. To provide a ballpark estimate, assuming that roughly 10% of the neutrons are used for plutonium breeding, a fusion power plant could produce one SQ per year per 10 MW of time-averaged power.

A second benefit is the quality of the plutonium.[171] While fission reactors have to find a balance between quality and quantity of plutonium, the specific spectrum of neutron fluxes from fusion reactions lead to plutonium

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[165] *Englert/Harrington* (n 141), at 198.

[166] A 1 GW_e Light Water Reactor consumes roughly 20 t of low enriched uranium and produces 250 kg of plutonium per year.

[167] Ibid, at 198.

[168] Ibid, at 198.

[169] *International Atomic Energy Agency* (n 137), at 31.

[170] Ibid, at 30.

[171] On the differentiation between MOX(mixed-oxide)-grade, reactor-grade, weapons-grade and super-grade plutonium, depending on the isotopic composition, see *J. Carson Mark/Frank von Hippel/Edward Lyman*, Explosive Properties of Reactor-Grade Plutonium, Science & Global Security 17 (2009), 170–185.

of higher quality, as plutonium isotopes other than ^{239}Pu are not often produced. As a consequence, plutonium from fusion reactors will always be weapon-grade material.[172] This characteristic renders fusion potentially attractive for proliferators as it simplifies the reprocessing process.

5.1.5 Limitations of Fusion as a Plutonium Provider

The following discussion will present several limitations of fusion as a provider of fissile material for nuclear weapons purposes. These limitations include clandestinity, reprocessing and the impact on the operation of a fusion power plant.

Clandestinity

In the context of the potential for a State to covertly utilise fusion for plutonium breeding for military purposes, two distinct scenarios can be delineated: Firstly, there is the possibility that a civilian facility may be utilised covertly to produce nuclear weapons material. Secondly, a State may undertake the clandestine construction of fusion devices for a covert nuclear weapons programme. It is important to note that safeguards are typically limited to verify the former, while the IAEA safeguards regime possesses only a very limited ability to detect clandestine facilities.[173] Historically, national intelligence services[174] or other international bodies[175] have played a significant role in detecting clandestine facilities. The issue of the application of safeguards to such fusion facilities is addressed in Chapter 3. Regarding a clandestine fusion facility producing nuclear weapons material, such a scenario is considered to be highly unlikely.[176] Primarily, fusion facilities are large facilities as witnessed by ITER with its 180-hectare site and is visible on publicly available satellite imagery. Secondly, firing

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[172] *Englert/Harrington* (n 141), at 198.

[173] This is only possible when the State has concluded an Additional Protocol. On this, see Chapter 3, Section 1.3.2.

[174] A historic overview is given by *Keith Hansen*, Intelligence and Nuclear Proliferation: Lessons Learned, Paris: Ifri 2011. See also *Thomas Fingar*, The Role of Intelligence in Countering Illicit Nuclear-Related Procurement, in: Matthew Bunn/Martin B. Malin/William C. Potter/Leonard S. Spector (eds.), Preventing Black Market Trade in Nuclear Technology, Cambridge: Cambridge University Press 2018, 48–78.

[175] In Iraq, UNSCOM, a subsidiary organ of the UN Security Council, played a major role, *Trevor Findlay*, The Lessons of UNSCOM and UNMOVIC, in: VERTIC (ed.), Verification Yearbook 2004, London: VERTIC 2004, 65–86.

[176] *Glaser/Goldston* (n 160).

up a fusion reactor requires substantial amounts of energy, including the infrastructure of supply lines and power conversion buildings to support it. These two factors serve to impede the clandestine construction and operation of a nuclear weapons programme based on fusion facilities. There is, however, the possibility that future generations of fusion power plants might become smaller and thus easier to hide.

Reprocessing

The second limitation derives from the necessity of reprocessing. High neutron fluxes, observed in both fission and modified fusion reactors, result in the transformation of a small percentage of uranium into plutonium. Consequently, the final product is a composite of different materials. To utilise the fissile material for further nuclear weapons purposes, the plutonium has to be separated from the uranium and other materials in reprocessing procedures. Reprocessing is a complicated chemical process,[177] typically requiring large-scale facilities. There are only around a dozen operational reprocessing plants located in five countries (China, France, India, Pakistan and Russia). Reprocessing plants exist for both for military and civilian applications, the latter also in non-nuclear weapon States.[178] The construction of reprocessing plants is a lengthy process, for instance, the construction of a current Japanese project is delayed by 25 years.[179] In addition, radioactive material needs to be transported to such a reprocessing facility, providing an opportunity to detect clandestine activities. However, a State committed to quickly produce nuclear weapons might opt for expedited ways to quickly build a small reprocessing plant for small quantities of plutonium separation.

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[177] The standard procedure is the so-called PUREX process. On PUREX, see *L.B. Lanham/T.C. Runion*, PUREX Process for Plutonium and Uranium Recovery (1949), Oak Ridge National Laboratory; *F. Baumgärtner/D. Ertel*, The Modern Purex Process and its Analytical Requirements, Journal of Radioanalytical and Nuclear Chemistry 58 (1980), 11–28.

[178] Germany operated a reprocessing plant from 1971 to 1990, see https://um.baden-wuerttemberg.de/de/umwelt-natur/kernenergie/kerntechnische-anlagen/sonstige-kerntechnische-anlagen/kerntechnische-entsorgung-karlsruhe-gmbh-kte/wiederaufarbeitungsanlage-karlsruhe-mit-verglasungseinrichtung, last accessed 25 February 2025. Japan currently constructs a reprocessing plant in Rokkasho, see *Tatsujiro Suzuki*, Rokkasho Redux: Japan's Never-Ending Reprocessing Saga in: Bulletin of the Atomic Scientists, https://thebulletin.org/2023/12/rokkasho-redux-japans-never-ending-reprocessing-saga/, last accessed 17 July 2025.

[179] *Suzuki* (n 178).

Impact on Tritium and Energy Production

The utilisation a fusion reactor for the purpose producing fissile material requires neutrons. Neutrons from the fusion reactions are not merely a by-product, they are used for two purposes: The deposition of energy into the coolant for energy production and the production of tritium. In the event that these neutrons are directed towards the transmutation of fertile material into fissile material, they become unavailable for their intended purpose within the facility, resulting in a change in energy output and/or tritium production. This leads to a possibility to detect the use of fusion for military purposes. Once fusion power plants are available on a commercial scale, both the standard demand of blanket material and power output should be known. However, as long as fusion remains in a research-and-development or early deployment stage, there will be a degree of uncertainty regarding precise numbers.

Fission Where No Fission Should Be

It is important to note that the neutrons produced in the fusion processes have an additional effect on uranium that extends beyond simply converting it into weapon-grade plutonium: Specifically, neutrons can induce the nuclear fission of ^{238}U. In this case, the neutron is not captured by the nucleus, but divides it into smaller nuclei. Depending on the energy of the neutron, the probability for inducing a fission reaction changes.[180] Fission events, in turn, lead to radiation and fission products in a surrounding where – under purely civilian circumstances – fission events are practically[181] non-existent. It is possible to detect these fission events, which is of particular relevance in the context of discussing potential safeguards approaches to fusion facilities.[182]

5.1.6 Safeguarding ITER

The issue of safeguarding fusion has been actively discussed when ITER was in its design process. Concerning the ITER project specifically, this risk

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[180] *Reed* (n 154).

[181] If beryllium is used as neutron multiplier of the tritium breeding wall, then there might be some traces of uranium within the wall as natural beryllium contains traces of uranium.

[182] See Chapter 5.

that the fusion machine could be used for military purposes is considered to be negligible.[183] Primarily, the dimension of the machine, the operational time and the total fusion energy produced limit the neutron flux and thus the potential amount of fissile material that could be bred. It is anticipated that it would be difficult to produce even one significant quantity of fertile material within the lifetime of ITER.[184] Secondly, the international nature of the collaboration, with the presence and supervision of representatives from all the countries involved,[185] reduces the possibility of clandestine plutonium production. However, while both the limited production of neutrons and the international oversight reduce the proliferation potential significantly, there is still the potential to gain important insights into the understanding of proliferation relevant information. For example, if an ITER Member State decided to put fertile material into test blanket modules, they could learn about breeding fissile material. While ITER is located within a nuclear weapons State (France) and other nuclear weapons States are members of the consortium (India, China, United States and Russia), the other States are non-nuclear weapon States (26 Euratom Member States excluding France, as well as South Korea and Japan). ITER itself will not be used for nuclear weapons material production. However it has been pointed out that the knowledge gained from ITER might support future developments.[186] Concerns have also been raised with regard to a potential nuclear arms race initiated by China or India where the knowledge gained from ITER might be beneficial.[187] This scenario, however, seems rather unlikely as both countries already possess the capacity to produce large amounts of fissile material from existing fission-based infrastructure.

5.1.7 Fusion without Transmutation Potential?

The D-T reaction is not the only fusion reaction feasible for fusion power plants. The European roadmap as well as the majority of fusion start-ups focus on this reaction, as it has the lowest triple product requirements and the highest power density (at a given pressure). In contrast, some start-ups

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[183] *IAEA*, Report of the Consultancy Meeting on “Non-Proliferation Challenges in Connection with Magnetic Fusion Power Plants” (2013), IAEA.

[184] Ibid; *Englert/Harrington* (n 141), at 190.

[185] They are the United States, Russia, Euratom Member States, India, Japan, South Korea, China.

[186] *Franceschini/Englert/Liebert* (n 158), at 532 f.

[187] Ibid.

pursue a different path to avoid the use of tritium given its supply problems, the need to breed it in the fusion machine's blanket and the radiological issues associated with tritium's radioactivity. Also, they try to avoid the irradiation capabilities of neutrons, potentially leading to proliferation resistant fusion facilities.

As mentioned above, any atom lighter than iron can undergo nuclear fusion. One such example is pursued by the start-up *Helion Energy*, which plans to fuse the helium isotope ^{3}He with deuterium D resulting in ^{3}He and regular hydrogen ^{1}H, while also releasing energy:

$$D + {}^3He \rightarrow {}^4He + {}^1H + 18.3\ \text{MeV}. \quad (13)$$

This reaction does not produce any neutrons and is therefore termed an *aneutronic fusion reaction*. This reaction has a key benefit as it does not require the transformation of fusion energy first into heat and then into electricity, since charged particles (protons) are released rather than neutral particles (neutrons). Electricity is nothing but a stream of charged particles.

On the downside, ^{3}He does not occur naturally on Earth, as it is an exceedingly rare isotope with a relative abundance to helium's standard isotope ^{4}He of about one in ten thousand, making natural resources on our planet inaccessible. Only the Moon has significant reserves of ^{3}He.[188] Presently, the primary source of ^{3}He is the decay of tritium with its own proliferation potential as outlined below. In theory, there are abundant resources on the Moon, yet harvesting ^{3}He on an extraterrestrial body is outstandingly difficult.[189] *Helion Energy*, next to using ^{3}He as decay product from tritium, has proposed to produce their ^{3}He from the fusion of two deuterium nuclei within a closed fuel-cycle:[190]

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[188] On the relevance of moon mining for fusion see: *L. A. Taylor/G. L. Kulcinski*, Helium-3 on the Moon for Fusion Energy: the Persian Gulf of the 21st Century, Solar System Research 33 (1999), 338; *Thomas Simko/Matthew Gray*, Lunar Helium-3 Fuel for Nuclear Fusion:Technology, Economics, and Resources, World Futures Review 6 (2014), 158–171. On the legal implications see: *Richard B. Bilder*, A Legal Regime for the Mining of Helium-3 on the Moon: U.S. Policy Options, Fordham International Law Journal 33 (2009), 243–299.

[189] Harvesting the moon would lead to different legal issues. Article 11 of the 1979 Moon Agreement declares the Moon as a common heritage of mankind and requires the establishment of an international regime to govern the exploitation of the moon. However, only a hand full of States have ratified the treaty.

[190] https://www.helionenergy.com/articles/explaining-helions-fusion-fuel-choice-d-he-3/, last accessed 25 February 2025.

$$D + D \rightarrow {}^{3}He + n + 3.3\,MeV \quad (14)$$

This reaction between two deuterium nuclei results in a ^{3}He nucleus, energy and, important for proliferation concerns, also neutrons, although with a lower energy of 2.45 MeV compared to 14 MeV from a D-T reaction. Neutrons at these energies are also capable of transmuting fertile material to fissile material.[191] In other words, there is no aneutronic fusion fuel cycle without proliferation concerns. As a consequence, fusion always poses a proliferation concern to some extent, as intense neutron source regardless of the fusion process.

5.2 Tritium and the Hydrogen Bomb

Tritium represents one of the major technological challenges to be solved in order to commercialise fusion.[192] At the same time, it also serves as a critical component in modern nuclear weapons arsenals.[193] Today, almost every nuclear weapon uses tritium.[194] Thus, the development of tritium producing technology as well as an increased availability of tritium pose key proliferation concerns of fusion.

5.2.1 Tritium Boosting of Fission Weapon

Adding tritium to a fission-based nuclear weapon significantly increases its yield. Two to three grammes of tritium are sufficient to increase the yield

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[191] *Reed* (n 154).

[192] *Pearson/Antoniazzi/Nuttall* (n 103).; *G. Federici/W. Biel/M. R. Gilbert et al.*, European DEMO Design Strategy and Consequences for Materials, Nuclear Fusion 57 (2017), 092002; *M. Kovari/M. Coleman/I. Cristescu et al.*, Tritium Resources Available for Fusion Reactors, Nuclear Fusion 58 (2018), 026010.

[193] *Martin Kalinowski*, International Control of Tritium for Nuclear Nonproliferation and Disarmament, Boca Raton: CRC Press 2004, at 8 ff.; *Andre Gsponer/Jean-Pierre Hurni*, ITER: The International Thermonuclear Experimental Reactor and the Nuclear Weapons Proliferation Implications of Thermonuclear-Fusion Energy Systems, 2004, at 24.

[194] *Robert E. Kelley*, Starve Nuclear Weapons to Death with a Tritium Freeze (*Stockholm International Peace Research Institute*, 2020), https://www.sipri.org/commentary/topical-backgrounder/2020/starve-nuclear-weapons-death-tritium-freeze, last accessed 17 July 2025.

by a factor of 10 to 100.[195] This increase in yield is due to fusion reactions increasing the percentage of fission material burnt in the bomb. Firstly, the fusion processes provide neutrons that drive the fission processes, and secondly, they compress the fission material to higher densities.[196] More neutrons result in more reactions, leading to a higher release of energy. Higher densities lead to higher probabilities that a neutron initiates a fission reaction. These two effects make the use of the fissile material more efficient and increase the yield of the bomb. By changing the amount of tritium within the primary, it is possible to have one weapon design with a variable yield. Tritium also allows for more compact weapons designs for modern delivery systems.[197]

5.2.2 Tritium in Multi-Stage Devices

Today, most modern nuclear weapons are multi-stage thermonuclear weapons, or short: hydrogen bombs since they use the fusion energy from the hydrogen isotopes deuterium and tritium. These weapons typically contain two stages, a fission primary stage and a fusion secondary stage. The energy produced by the fission bomb is transported by radiation to the fusion secondary, where it induces fusion reactions of deuterium and tritium. The energy released by these reactions further increases the yield of the weapon. A significant number of weapons designs include a third step, producing tritium in-situ from lithium-deuteride. As tritium is a radioactive gas, it decays, requiring regular maintenance as the amount of tritium within the weapon decreases. This reaction is not only of significance to nuclear weapons, but also in the production of tritium in future fusion power plants.

$$^{6}\mathrm{LiD} + \mathrm{n} \rightarrow {}^{4}\mathrm{He} + \mathrm{T} + \mathrm{D} \qquad (15)$$

Neutrons from the fission primary transform the lithium-deuteride into helium (which is irrelevant for the explosion), tritium and deuterium. In other terms: ^{6}Li is transformed into tritium. While this process takes place in the breeding blanket of a fusion reactor, it is also a stage of a mod-

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[195] *Kalinowski* (n 193), at 8 ff.; *Gsponer/Hurni* (n 193), at 24.

[196] *Andre Gsponer/Jean-Pierre Hurni*, The Physics of Thermonuclear Explosives, Inertial Confinement Fusion, and the Quest for Fourth Generation Nuclear Weapons, INESAP Tech. Rep. No. 1 1997, at 11 ff.

[197] *Sievert/Johnson* (n 158), at 338.

ern thermonuclear weapon. Given the importance of tritium, proliferators quickly jump to using tritium.

5.2.3 Tritium in Military Programmes and Civilian Nuclear Fuel Cycle

Tritium is a radioactive isotope with a half-life of 12.3 years. As a consequence, nuclear weapons programmes require the constant production of tritium to uphold their inventories as they reduce annually by about 5.5 %. Military programmes employ nuclear fission reactors to produce tritium, utilising heavy-water (D_2O) moderated reactors produce tritium when a deuterium nucleus captures a neutron. The US Stockpile Stewardship Program – the programme charged with maintaining the US nuclear arsenal – for instance, produces 2800 g of tritium within an 18-months period.[198] Civilian reactors also produce tritium, with the CANDU type reactor, which produces approximately 130 g of tritium per reactor per year.[199] The total civilian production amounts to less than 2000 g per year.[200] In CANDU reactors the tritium must be removed from the moderator to prevent its release into the environment; in military reactors tritium needs to be separated for the use in weapons. The removal process is a complex and costly process.[201] Currently, there are only two civilian tritium removal facilities, with a third under construction.[202] Even the separation capacities of nuclear weapon States are limited. For instance, the US military programme uses the Savannah River Site, which is the sole military tritium extraction facility in the United States. The small quantities produced per year result in tritium being the single most expensive material in the world with prices of around USD 30–35,000 per gram.[203]

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[198] *U.S. Department of Defense/U.S. Department of Energy*, Memorandum for Members of the Nuclear Weapons Council – Nuclear Weapons Council Strategic Plan for Fiscal Years 2017–2042 (2016).

[199] *Pearson/Antoniazzi/Nuttall* (n 103).

[200] Ibid.

[201] On the complex development process of tritium extraction technologies for fusion, see *D. Demange/R. Antunes/O. Borisevich et al.*, Tritium Extraction Technologies and DEMO Requirements, Fusion Engineering and Design 109–111 (2016), 912–916.

[202] There is the Darlington Tritium Removal Facility in Canada and the Wolsong Tritium Removal Facility in Korea. Currently, the Cernavoda Tritium Removal Facility is built in Romania.

[203] *Richard J. Pearson/Olivia Comsa/Liviu Stefan et al.*, Romanian Tritium for Nuclear Fusion, Fusion Science and Technology 71 (2017), 610–615; *Daniel Clery*, Out of Gas, Science 376 (2022), 1372–1376.

Assuming that Russian tritium production facilities are comparable to those of the United States and that the other nuclear weapon States produce tritium relative to their significantly lower nuclear arsenals, the total tritium production per year – both civilian and military combined – is in the range of five kilograms.

5.2.4 Tritium and Fusion Energy

Tritium is essential for fusion power plants, with the vast majority of concepts running on D-T fusion, but also for modern nuclear weapons.

Fusion will significantly increase the production and storage of tritium and thus also the risk of the material's diversion to use in nuclear weapons. While a single nuclear weapon requires just a few grams of tritium, one fusion facility will usually produce and consume amounts of tritium in the range of tens to hundreds of kilograms. ITER's tritium inventory is expected to be in the range of 2–3 kg,[204] and DEMO's annual tritium production is expected to be around 100 kg[205]. This underscores potential of fusion and its tritium with regard of the proliferation of nuclear weapons.

Furthermore, with respect to DEMO and other fusion power plant concepts, it is envisioned that the reactor itself both produces and consumes its own tritium.[206] Tritium is produced by a reaction between a neutron released in a D-T reaction and the lithium isotope ^{6}Li, which is placed in the wall of the reactor:

$$^{6}\text{Li} + \text{ n } \rightarrow \text{T} + {}^{4}\text{He} \quad (16)$$

This principle is also known from the second stage of thermonuclear weapons, where instead of using the gaseous and radioactive tritium in the

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[204] *M. Glugla/A. Antipenkov/S. Beloglazov et al.*, The ITER Tritium Systems, Fusion Engineering and Design 82 (2007), 472–487; *I. R. Cristescu/I. Cristescu/L. Doerr et al.*, Tritium Inventories and Tritium Safety Design Principles for the Fuel Cycle of ITER, Nuclear Fusion 47 (2007), 458.

[205] *G. Federici/C. Bachmann/L. Barucca et al.*, Overview of the DEMO Staged Design Approach in Europe, Nuclear Fusion 59 (2019), 066013; *Glugla/Antipenkov/Beloglazov et al.* (n 204).

[206] *Rachel Lawless/Barry Butler/Anthony Hollingsworth et al.*, Tritium Plant Technology Development for a DEMO Power Plant, Fusion Science and Technology 71 (2017), 679–686; *M. Coleman/Y. Hörstensmeyer/F. Cismondi*, DEMO Tritium Fuel Cycle: Performance, Parameter Explorations, and Design Space Constraints, Fusion Engineering and Design 141 (2019), 79–90.

secondary, ^{6}Li is incorporated into the weapon to produce tritium during the explosion, as seen above in Equation 15.[207]

Such an in-situ production presents two risks with regard to non-proliferation. Firstly, research on the breeding-blankets of fusion devices – which is a main area of research on the way to commercialising fusion[208] – is tightly closed to processes that take place in the second stage of thermonuclear weapons. The question of breeding tritium within the operation of a fusion device is so complex that even ITER will only be equipped with test blanket modules. Knowledge acquired from this research may hold significance for military programmes on thermonuclear weapons.

Secondly, this method is associated with a risk of diversion. Although in-situ breeding method reduces the risk of tritium diversion in the delivery process, fusion reactors have to produce more tritium than is needed for the fusion processes themselves. This is in order to account for calculation uncertainties, radioactive decay, permeation into the facility's equipment and the start-up of the next fusion reactor or power plant.[209] Current estimates indicate that the so-called tritium breeding-ratio (TBR), defined as the ratio between the amount of tritium produced and the amount of tritium consumed, is in the range of approximately 1.1 to 1.2.[210] This means that the fusion reactor needs to produce ten to twenty percent more tritium than it consumes. For instance, DEMO's excess tritium production is estimated to be in the range of ten to twenty kilograms per year.[211] This is enough to boost ten thousand nuclear weapons. To put that number into context: The *Stockholm International Peace Research Institute* (SIPRI)

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[207] *David Kramer*, DOE Prepares Major Upgrade of its Lithium-6 Operations, Physics Today 71 (2018), 29–31; *Ralph E. Lapp*, Nuclear Weapons: Past and Present, Bulletin of the Atomic Scientists 26 (1970), 103–106; *Thomas B. Cochran/William M. Arkin/ Robert S. Norris*, U.S. Nuclear Weapons Production: An Overview, Bulletin of the Atomic Scientists 44 (1988), 12–16.

[208] On the design of the tritium breeding blanket for DEMO, see *Ion Cristescu/F. Priester/D. Rapisarda et al.*, Overview of the Tritium Technologies for the EU DEMO Breeding Blanket, Fusion Science and Technology 76 (2020), 446–457.

[209] *Neill Taylor/Pierre Cortes*, Lessons Learnt From ITER Safety & Licensing for DEMO and Future Nuclear Fusion Facilities, Fusion Engineering and Design 89 (2014), 1995–2000.

[210] *Didier Perrault*, Safety Issues to Be Taken Into Account in Designing Future Nuclear Fusion Facilities, Fusion Engineering and Design 109–111 (2016), 1733–1738; *Coleman/Hörstensmeyer/Cismondi* (n 206); *J. Lion/J. C. Anglès/L. Bonauer et al.*, Stellaris: A High-Field Quasi-Isodynamic Stellarator for a Prototypical Fusion Power Plant, Fusion Engineering and Design 214 (2025), 114868.

[211] Based on DEMO's 100 kg annual tritium production, see above n 205.

estimates that there are about 12,000 nuclear weapons in the world.[212] Consequently, if each weapon contains one to three grams of tritium, the excess production from a single large fusion power plant could be sufficient to boost almost every nuclear weapon in existence.

Consequently, the excess production of tritium represents a serious risk for proliferation. As noted above, the excess is intended to address various issues, with the result that, in theory, each tritium nucleus is used only for energy production. However, these issues create the potential for proliferators to use this tritium to boost fission weapons or to use it in a hydrogen bomb.

In summary, tritium's involvement in fusion poses a risk for proliferation. It can be used to increase the sophistication of a nuclear weapon (vertical proliferation) and to support the efforts to build a hydrogen bomb (both vertical and horizontal). It should be noted that the availability of tritium alone is not sufficient to build a nuclear weapon or any other explosive device. It is only in combination with fissile material and the knowledge and mastering of the complex physics behind a hydrogen bomb that tritium poses a proliferation concern.

5.3 Inertial Confinement Fusion

Inertial confinement fusion (ICF), also referred to as laser fusion as it is the most common form of ICF, has given rise to another concern of nuclear proliferation. ICF replicates processes that are essential for hydrogen weapons. This technology involves heating small pellets made of fusionable material using extremely powerful lasers. The heat causes the outer part of the pellet to expand outwards. In accordance with Newton's Third Law *actio est reactio,* the centre of the pellet is compressed. This compression may create the physical conditions necessary for fusion to occur. To this date, only one fusion facility has produced more energy than was put into the fusion process itself:[213] The National Ignition Facility (NIF), located at the Lawrence Livermore National Laboratory in California, USA. Interestingly,

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[212] *Hans M. Kristensen/Matt Korda*, World Nuclear Forces, in: Stockholm International Peace Research Institute (ed.), SIPRI Yearbook 2022, Stockholm, Oxford: Oxford University Press 2022, 341–432, at 342.

[213] The NNSA calls this ignition. It must be noted that the fusion processes produced more energy than the laser light contained which went into cylindrical hohlraum capsule containing the fuel.

in terms of proliferation, the press release on the first ignition addresses not only on the benefits of fusion for energy production, but puts its potential for the United States's nuclear weapons arsenal at the beginning:

> *"The U.S. Department of Energy (DOE) and DOE's* ***National Nuclear Security Administration (NNSA)*** *today announced the achievement of fusion ignition at Lawrence Livermore National Laboratory (LLNL)—a major scientific breakthrough decades in the making that* ***will pave the way for advancements in national defense*** *and the future of clean power. […] This historic, first-of-its kind achievement will provide* ***unprecedented capability to support NNSA's Stockpile Stewardship Program*** *and will provide invaluable insights into the prospects of clean fusion energy."*[214]

Indeed, NIF was not constructed with the intention of paving the way to a fusion power plant, rather it was aimed to develop computer codes for hydrogen bombs in order to replace nuclear testing.[215] It thereby serves the Stockpile Stewardship Program, which aims to keep the United States's nuclear arsenal operational. The National Nuclear Security Administration (NNSA) is mandated to maintain and enhance safety, reliability and performance of the US nuclear weapons stockpile.[216]

Some even compare inertial confinement fusion with a miniature version of a hydrogen bomb.[217] While the two largest laser fusion facilities – NIF and the Laser Mégajoule in France – are located in nuclear weapons States and serve military purposes, several start-up companies are endeavouring to use inertial confinement fusion in a power plant design.[218] In addition to that, both state and non-state actors in non-nuclear weapon States such as Japan (Gekko XII – a public entity) and Germany (Marvel Fusion, Focused Energy – private entities) are also focusing on laser fusion. As the development of inertial confinement fusion accelerates, particularly among

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[214] Emphasis added. *U.S. Department of Energy*, DOE National Laboratory Makes History by Achieving Fusion Ignition (2022), https://www.energy.gov/articles/doe-national-laboratory-makes-history-achieving-fusion-ignition, last accessed 17 July 2025.

[215] *B. G. Logan*, Use of the National Ignition Facility for Defense, Energy, and Basic Research Science (1994), Lawrence Livermore National Laboratory.

[216] 50 U.S. Code § 2401.

[217] *Garry McCracken/Peter Stott*, Chapter 7 – Inertial-Confinement Fusion, in: Garry McCracken/Peter Stott (eds.), Fusion (Second Edition), Boston: Academic Press 2013, 67–81, at 67.

[218] Examples for private companies engaged in inertial confinement fusion are *tea* and *Longview Fusion* (both based in the United States), *General Fusion* (based in Canada), *Marvel Fusion* and *Focused Energy* (both based in Germany).

private entities, the risk of knowledge being diverted to the construction of hydrogen bombs increases substantially.

When NIF was constructed, the US Department of Energy reviewed the proliferation potential of ICF facilities. The study concluded that insights from the facility could provide information for advanced proliferators pursuing secondary designs, given the insights in X-ray transport, the equation of state and thermonuclear reactions. However, it was also stated that "without access to data from nuclear tests, ICF or unclassified NIF data would be of very limited utility to proliferators."[219] These appeasing remarks have been criticised.[220]

As with magnetic confinement fusion, the proliferation potential of ICF depends on the precise technology used. As mentioned above, ICF functions by heating small pellets of fusion fuel with lasers. The aspect of ICF that renders it valuable for the purposes of nuclear weapons research is the transfer of energy from the laser to the fusion fuel. While a direct transfer of energy could work for energy purposes (so-called direct-drive targets)[221], military research facilities prefer an indirect transfer (so-called indirect-drive targets). While the direct-drive fusion bears only distant resemblance to thermonuclear weapons,[222] indirect-drive fusion is of particular interest for weapons research. In this case, the lasers are first absorbed by a surrounding material (so-called *hohlraum*) which then emits X-ray radiation that drives the implosion of the fusion fuel.[223] It is this energy transfer that is of interest for the design of a hydrogen bomb as this transfer is

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[219] *U.S. Department of Energy*, The National Ignition Facility (NIF) and the Issue of Nonproliferation (NN-40), 1995, especially at 29.

[220] *Robert J. Goldston/Alexander Glaser*, Inertial Confinement Fusion Energy R&D and Nuclear Proliferation: The Need for Direct and Transparent Review, Bulletin of the Atomic Scientists 67 (2011), 59–66.

[221] For an overview of the direct-drive approach, see *R. S. Craxton/K. S. Anderson/T. R. Boehly et al.*, Direct-Drive Inertial Confinement Fusion: A Review, Physics of Plasmas 22 (2015), 110501. On its future, see *E. M. Campbell/T. C. Sangster/V. N. Goncharov et al.*, Direct-Drive Laser Fusion: Status, Plans and Future, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 379 (2021), 20200011.

[222] *National Research Council*, Assessment of Inertial Confinement Fusion Targets, Washington DC: The National Academies Press 2013, at 37.

[223] *John Lindl*, Development of the Indirect-Drive Approach to Inertial Confinement Fusion and the Target Physics Basis for Ignition and Gain, Physics of Plasmas 2 (1995), 3933–4024.

necessary in multi-stage devices.[224] Rather than materials, the proliferation concern with inertial confinement fusion lays with the potential knowledge gain. Given that literature on the physics of these weapons is classified, it is difficult to quantify the proliferation potential.

Again, it is imperative to acknowledge that the mere existence of an ICF facility does not inherently result in the development of nuclear weapons. The knowledge that could be gained from ICF fusion experiments is one of numerous factors contributing to the construction of thermonuclear weapons. Even the knowledge of indirect energy transfer is, in isolation, not sufficient to build such a weapon.

5.4 Fusion-Fission-Hybrid Systems

During the decades of fusion research, scientists have discussed the feasibility of fission-fusion hybrid systems. The idea is somewhat similar to principles behind thermonuclear weapons: The neutrons generated in the fusion reactions could be used to increase the amount of fission events.[225] The ideas went as far as using waste from regular fission power plants in such hybrid systems.[226] These States could use such hybrid systems as source of tritium and pure plutonium.

Concepts for these hybrid systems were prominently supported by the German-American physicist and Nobel Laureate Hans Bethe in the 1970s.[227] The United States also pursued a concept to use the knowledge gained from NIF to develop a hybrid fusion-fission plant called *LIFE*,[228] but

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[224] Goldston and Glaser note that a restriction to direct-driven ICF facilities could easily be overcome since the lasers could still be used for an indirect drive, *Goldston/Glaser* (n 220).

[225] *B. R. Leonard Jr*, A Review of Fusion-Fission (Hybrid) Concepts, Nuclear Technology 20 (1973), 161–178.

[226] *T. A. Mehlhorn/B. B. Cipiti/C. L. Olson et al.*, Fusion–fission Hybrids for Nuclear Waste Transmutation: A Synergistic Step Between Gen-IV Fission and Fusion Reactors, Fusion Engineering and Design 83 (2008), 948–953.

[227] *Hans Bethe*, The Fusion Hybrid, Physics Today 32 (1979), 44–51.

[228] LIFE is an abbreviation for Laser Ignition Fusion Energy. On the hybrid system see *Kevin J. Kramer/Massimiliano Fratoni/Jeffery F. Latkowski et al.*, Fusion-Fission Blanket Options for the LIFE Engine, Fusion Science and Technology 60 (2011), 72–77.

the project has since been discontinued.[229] In recent times, both Russia[230] and China[231] have pursued hybrid concepts.

However, as fusion itself is a technology that has not yet been sufficiently mastered to generate energy, it is even more difficult to realise a fusion-fission hybrid concept. The concepts currently pursued are far from a commercial dimension. Government-backed research is far from the scale of pure fusion technology, which is demonstrated for instance in ITER or the European DEMO project. Especially the private sector, which plays an important role in transforming a technology from research labs to a commercial scale, does not show any real interest in this technology. Consequently, these hybrid concepts are excluded from this research.

Furthermore, the safeguards dimension of these systems has already been discussed.[232] Such systems would be covered by the existing legal framework as they are to characterise as *nuclear facilities* that operate with *nuclear material*.[233]

5.5 Fundamental Differences Between Fusion and Fission

At this juncture, it is important to underscore the key differences between the proliferation potentials of fusion and fission.

A nuclear fission power plants operates with fissile material. A country that possesses a full nuclear fuel cycle infrastructure is a “virtual nuclear weapon State” as the former IAEA Director General ElBaradei once warned.[234] The process of enriching uranium to a level used in energy production and research is the same physical process as enriching uranium to a level necessary for nuclear weapons. The omnipresence of dual-use

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[229] *David Kramer*, Livermore Ends LIFE, Physics Today 67 (2014), 26–27.

[230] See for example *B. V. Kuteev/P. R. Goncharov*, Fusion–Fission Hybrid Systems: Yesterday, Today, and Tomorrow, Fusion Science and Technology 76 (2020), 836–847.

[231] *Maosheng Li/Rong Liu/Xueming Shi et al.*, The Project of Fusion-Fission Hybrid Energy Reactor in China, Fusion Science and Technology 61 (2012), 195–199.

[232] *Sievert/Johnson*; *Ralph W. Moir/Wally Manheimer*, Fusion–Fission Hybrid Reactors, in: Thomas J. Dolan (ed.), Magnetic Fusion Technology, London: Springer 2013, 699–742, at 733 ff.

[233] On the importance of these notions for fusion, see Chapter 3.

[234] *Julian Borger*, Mohamed ElBaradei Warns of New Nuclear Age in: https://www.theguardian.com/world/2009/may/14/elbaradei-nuclear-weapons-states-un, last accessed 17 July 2025.

material gives rise to the proliferation potential of fission, a concept that is frequently termed *nuclear latency* or *nuclear threshold States*:[235] States possessing the technological capability to develop nuclear weapons as a result of their civilian nuclear programmes. These states include Germany, Japan, Canada, Australia, South Africa, South Korea, Taiwan and Iran.[236]

In contrast, in fusion, the proliferation potential is more indirect. Tritium alone does not suffice to build a nuclear weapon. The knowledge gained from ICF alone does not suffice to build a nuclear weapon. Both options still require access to fissile material. Fissile material is not used in a fusion power plant, but could theoretically be produced by fusion reactor. Consequently, fusion can be a puzzle piece within a broader nuclear weapons programme, rather than the starting point as fission is.

5.6 Summary

Nuclear fusion carries both horizontal and vertical proliferation risks due to the release of neutrons, the use of tritium, and the research into ICF. Highly energetic neutrons, released by DT fusion, are intended to breed tritium from ^{6}Li, but can also potentially be used to breed nuclear weapons-grade plutonium or uranium. Tritium and ^{6}Li are used as boosters of fission-based nuclear weapons but are also the essential part of a fusion fuel cycle. Inertial confinement fusion research is based on understanding the physics of hydrogen bombs.

Notwithstanding, fusion has a lower proliferation potential than fission, especially when safeguards are in place: Fusion only complements fission, while fission remains the core part of a weapon, and there are significant technological limitations of fusion's contribution to a nuclear weapons programme. While any potential risk alone is not sufficient to build or increase the yield of nuclear weapons, fusion technology has the capacity to function as a component within the broader context of a nuclear weapons programme which is still based on fission. In light of the immense consequences for humanity and the planet, it is important to explore a

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[235] See e.g. Joseph Pilat (ed.), Nuclear Latency and Hedging: Concepts, History, and Issues, Washington DC: Woodrow Wilson International Center for Scholars 2019; *Maria Rost Rublee*, The Nuclear Threshold States, The Nonproliferation Review 17 (2010), 49–70.

[236] On empirical data on threshold states, see *Matthew Fuhrmann/Benjamin Tkach*, Almost Nuclear: Introducing the Nuclear Latency Dataset, Conflict Management and Peace Science 32 (2015), 443–461.

response in international law to address this non-zero probability of fusion, a technology capable to contribute in combatting the climate crisis, being misused for military purposes. Such a legal response will be explored in the next chapters.