Securing The Future: *Nuclear Security Challenges in Fusion Energy*

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Abstract

The pursuit of nuclear fusion as a sustainable energy source has numerous advantages, including minimal greenhouse gas emissions, abundant fuel supply, and the potential to provide a safe and reliable energy alternative. However, the transition from theoretical concepts to practical applications presents significant challenges, especially as it relates to nuclear security. This paper explores the intersection of fusion and security considerations, defining nuclear security, and highlighting the distinct challenges associated with fusion energy. Key security issues include the control and accountability of tritium, a critical fuel component, as well as facility security against sabotage and the risk of cyberattacks on fusion systems. Furthermore, this paper examines the legal and regulatory gaps that may hinder effective governance and the complexities of knowledge management within the context of dual-use technology. International coordination is also a vital factor to advance fusion development in a safe and secure manner.

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To mitigate these security risks, this paper proposes comprehensive strategies for securing fusion energy initiatives and discusses the potential of fusion to contribute to geopolitical stability. As nations strive to harness the power of fusion, careful consideration and proactive measures are essential in order to integrate security frameworks that protect against emerging threats. Overall, the development of fusion energy offers a pathway toward sustainable energy and demands a rigorous approach to address its associated security challenges. Through collaboration and creating resilient regulatory mechanisms, the international community can work to ensure that fusion contributes positively to global energy needs without compromising security.

INTRODUCTION

The quest for nuclear fusion as a sustainable energy source holds great promise in its many advantages, including miniscule greenhouse gas emissions, limitless supply of fuel, and the potential to offer a safe and reliable alternative to traditional energy sources. Despite these benefits, the journey from theoretical frameworks to practical implementation is fraught with significant hurdles, specifically as it relates to nuclear security. This paper explores the critical intersection of fusion technology and security considerations, elucidating the definition of nuclear security and identifying distinct challenges that fusion energy presents for nuclear security governance. It addresses key security concerns, including the management and accountability of tritium, essential for fusion processes; facility security; and cybersecurity risks and concerns for national governments developing fusion programs, as well as international organizations responsible for nuclear oversight, and regulatory authorities tasked facilitating the secure use of nuclear and other radioactive materials. Additionally, this paper addresses legal and regulatory gaps that may obstruct effective governance and the complexities surrounding knowledge management within the context of dual-use technologies. In a landscape where international cooperation is essential, this paper also proposes comprehensive strategies to mitigate security risks and improve global safety in asserting that a proactive and collaborative approach is imperative as nations strive to unlock the full potential of fusion energy without compromising security.

I. OVERVIEW OF THE ADVANTAGES AND CHALLENGES OF FUSION ENERGY

Fusion is at the forefront of cutting-edge scientific innovation because of its potential to revolutionize the global energy landscape. As a process that replicates the energy-producing mechanism of the sun, fusion contains profound advantages, including environmental sustainability, a virtually inexhaustible fuel supply, and a high safety margin compared to traditional nuclear fission. Its appeal as a clean, efficient, and secure energy source has driven international research collaborations and significant public and private investment. Despite its promise, the path to practical fusion energy is complex, and it is riddled with technical, economic, and regulatory challenges. Achieving and sustaining the extreme conditions necessary for fusion, ensuring the integrity of reactor materials, addressing high development costs, and navigating legal and security frameworks all represent substantial obstacles. This section examines both the compelling advantages of fusion energy and the formidable challenges that must be overcome in order to make fusion energy a viable solution to the world's growing energy needs.

A. Advantages of Fusion Energy

Fusion energy has consistently been marketed as the future of sustainable power generation. One of its most significant advantages lies in its nature as a "clean" energy source that produces minimal greenhouse gas emissions during operation. Unlike fossil fuels, which release carbon dioxide and other pollutants that contribute to global warming and environmental degradation more generally, fusion reactors do not emit harmful gases. Consequently, fusion aligns with international climate goals and represents a viable long-term solution for mitigating climate change. This directly supports several UN Sustainable Development Goals ("SDGs"), most notably SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).[1] SDG 7 emphasizes ensuring access to affordable, reliable, sustainable, and modern energy for all, a goal that fusion facilitates by offering a safe, long-term, and scalable energy solution.[2] Similarly, SDG 13 calls for urgent action to combat climate change and its impact, which fusion addresses through its near-zero carbon emissions and potential to displace fossil fuels.[3] Although there are no SDGs associated directly with fusion, the implementation and safe practices of fusion can directly contribute to the UN SDGs in the long term. Additionally, fusion utilizes abundant and cost-effective fuel sources. The two primary fuels for fusion are deuterium and tritium, which are derived from materials that are widely available.[4] Deuterium, which is a stable isotope of hydrogen, can be extracted from seawater, and tritium can be bred from lithium, which is plentiful in the Earth's crust and oceans.[5] This abundance reduces dependence on geopolitically sensitive fossil fuel markets and minimizes the risks associated with resource scarcity. Furthermore, the energy yield from fusion is extremely high. A single kilogram of fusion fuel can produce as much energy as millions of kilograms of fossil fuels, which makes it a prime energy source for the future.[6]

Unlike nuclear fission reactors, which can suffer core damage in the event of design flaws or loss of cooling (as seen in the Chernobyl and Fukushima

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[1] *The 17 Goals*, U.N. DEP'T OF ECON. & SOC. AFFS., https://perma.cc/UR2X-QZ8K.

[2] *Id.*

[3] *Id.*

[4] *DOE Explains . . . Deuterium-Tritium Fusion Fuel*, U.S. DEP'T OF ENERGY, https://perma.cc/6ALU-JSSZ.

[5] *Fusion: Energy of the Future*, INT'L ATOMIC ENERGY AGENCY (Aug. 1, 2001), https://perma.cc/JZ94-3HCJ.

[6] Mustakimah Mohamed, Nur Zakuan, Tengku Hassan, Serene Lock & Azmi Shariff, *Global Development and Readiness of Nuclear Fusion Technology as the Alternative Source for Clean Energy Supply*, SUSTAINABILITY, 2024, at 1, 6.

accidents), fusion systems are self-limiting in the sense that they do not rely on a self-sustaining chain reaction and inherently shut down if confinement conditions are lost.[7] This means that if there is any disturbance in the reactor conditions, such as a loss of temperature or confinement, then the reaction naturally ceases.[8] As such, this inherent safety feature drastically reduces the potential for catastrophic accidents and widespread environmental damage.

Another critical benefit of fusion energy is the reduction in long-lived radioactive waste. Traditional nuclear fission reactors produce nuclear waste that remains hazardous for thousands of years and requires complex and long-term storage solutions.[9] Fusion, on the other hand, produces very little radioactive waste, and any waste generated has a significantly shorter half-life, meaning that it poses less risk to future generations and the environment.[10]

Finally, fusion contributes minimal carbon emissions in the direct energy production process, as well as across the entire lifecycle of fuel acquisition and facility operations.[11] This makes it an integral component of future low-carbon energy portfolios. Moreover, advanced innovations in fusion technology continue to improve efficiency, safety, and growth capacity, thus positioning it as a central pillar in the next generation of clean energy infrastructure.

Collectively, these advantages establish fusion as a powerful and sustainable energy source with significant implications for national energy strategies and international energy security. Its potential to generate large amounts of energy from small amounts of fuel, combined with a favorable safety profile and minimal environmental impact makes fusion a key player in the future of global energy systems. Although the path to commercial deployment is complex, the long-term benefits of fusion are substantial in that it offers the possibility of a cleaner, safer, and more equitable energy future. As states and international organizations consider integrating fusion into their respective future energy portfolios, its deployment must be accompanied by appropriate regulatory and nuclear security frameworks. This requires proactive planning by regulators, policymakers, and international oversight bodies to verify that fusion technologies are governed in a manner consistent with global security and nonproliferation objectives.

B. Challenges of Fusion Energy

Despite its considerable potential, fusion has substantial technical and economic challenges that must be addressed before it can become an extensively deployed and practical source of energy. The most immediate technical obstacle

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[7] *Advantages of Fusion*, ITER, https://perma.cc/X46K-SP63.

[8] *Id.*

[9] *Nuclear Explained, Nuclear Power and the Environment*, U.S. ENERGY INFO. ADMIN. (Nov. 27, 2022), https://perma.cc/Y4P3-SQAU.

[10] Pietro Barabaschi & Laban Coblentz, *The Potential of Nuclear Fusion as a Sustainable Solution for Global Energy Security*, EUR. FILES (Apr. 3, 2025), https://perma.cc/E5RF-DTLC.

[11] Keii Gi, Fuminori Sano, Keigo Akimoto, Ryoju Hiwatari & Kenji Tobita, *Potential Contribution of Fusion Power Generation to Low-carbon Development Under the Paris Agreement and Associated Uncertainties*, ENERGY STRATEGY REVS., Jan. 2020, at 1, 1.

is the necessity of achieving and maintaining extreme temperatures and pressures.[12] Fusion reactions require temperatures exceeding 100 million degrees Celsius (conditions hotter than the core of the sun) to force hydrogen nuclei to overcome their electrostatic repulsion and fuse.[13] Achieving these conditions in a controlled and sustained manner on Earth requires highly advanced confinement systems, such as magnetic confinement (tokamaks) or inertial confinement (laser-driven), each of which introduces engineering challenges that require resolution.[14]

Closely tied to this is the issue of materials science hurdles. The extreme environment inside a fusion reactor subjects materials to intense heat, neutron bombardment, and magnetic stresses.[15] Current material technologies are not fully capable of withstanding these conditions over extended operational periods. Therefore, developing new materials that can tolerate these environments without degradation is a key research component and additionally, a critical barrier to scaling fusion reactors for industrial use. This challenge is part of a broader engineering effort that includes stabilizing ultra-hot plasma, designing magnetic confinement systems, managing neutron impacts, and converting fusion energy into usable heat, which requires precise and resilient technologies that can operate under extreme conditions.[16] These interconnected demands make fusion development an extremely complex technological undertaking in modern energy research.

Another major disadvantage is the high cost of development.[17] Fusion research requires significant financial resources, both in terms of the initial investment, ongoing research, and maintenance costs. Building and operating experimental reactors, such as the International Thermonuclear Experimental Reactor ("ITER"), involves global cooperation and multi-billion-dollar investments.[18] ITER, a multinational fusion research project currently under construction in France, currently involves thirty-five partner nations, and it is intended to demonstrate the technical feasibility of sustained fusion power at scale.[19] Estimates suggest that developing a single commercial-scale fusion power plant could require investments reaching into

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[12] *See generally* Hiroshi Yamada, *Fusion Energy*, *in* 4 HANDBOOK OF CLIMATE CHANGE MITIGATION AND ADAPTATION 3139 (Wei-Yin Chen, Toshio Suzuki & Maximilian Lackner eds., 2012).

[13] *Id.* at 3169.

[14] *See, e.g.*, Ojong Enow, Ebimor Gbabo, Andrew Ofoedu, Possible Chima & Oluwapelumi Adibowale, *The Role of Nuclear Fusion in Future Energy Supply: A Review of Technological Progress and Challenges*, 4 INT'L J. MULTIDISCIPLINARY RSCH. & GROWTH EVALUATION, no. 2, 2023, at 829; Wolfgang Picot, *Magnetic Fusion Confinement with Tokamaks and Stellarators*, IAEA BULL., May 2021, at 6; J.H. Nuckolls, *Grand Challenges of Inertial Fusion Energy*, 244 J. PHYSICS: CONF. SERIES 2010, at 1.

[15] Grant Currin, *Will Fusion Solve Our Energy Problems?*, COLUM. ENG'G (Apr. 16, 2025), https://perma.cc/WR7Q-842K.

[16] *Id.*

[17] FUSION INDUS. ASSOC., THE FUSION INDUSTRY SUPPLY CHAIN: OPPORTUNITIES AND CHALLENGES 24 (2023), https://perma.cc/3JUE-9EQM.

[18] *In a Few Lines*, ITER, https://perma.cc/3CNN-JFZD (describing ITER as a multinational experimental fusion reactor under construction in France designed to demonstrate the scientific and technical feasibility of large-scale fusion energy); FUSION INDUS. ASSOC., THE GLOBAL FUSION INDUSTRY IN 2024 ¶ 4 (2024) (identifying ITER as the world's largest fusion research collaboration and a central milestone in the transition toward commercial fusion energy).

[19] *In a Few Lines*, *supra* note 18.

the billions.[20] More specifically, the development of a singular powerplant is estimated to be as high as nine billion U.S. dollars.[21] The high cost of development requires substantial support from both private and public investment to continue research efforts in advancing and implementing fusion energy on an industrial scale. These costs are a significant risk for investors and policymakers, especially in the absence of immediate economic returns.

The long timeline to commercialization further complicates fusion's viability as an energy solution. Despite decades of research, a commercially viable fusion power plant is not expected to be operational until at least the 2040s.[22] This protracted timeline makes it difficult to align fusion development with urgent climate action goals that require near-term reductions in emissions. The extended timeline also complicates planning and investment cycles for both public and private stakeholders.

Continued investment from both public and private sectors shows how important political support and international collaboration are for advancing fusion. Without consistent funding in place, then research programs may stall, which could lead to delays and possibly technological stagnation. Absent policy intervention and international backing, fusion development could encounter significant financing challenges as public budgets are limited and private investors weigh long-term returns against technical risk. However, recent trends suggest growing optimism: since 2019, the number of private fusion companies has more than doubled, with more than $6 billion in private investment flowing into the sector.[23] This surge is driven by advancements in enabling technologies, successful milestones at public fusion labs, lessons learned from major international projects like ITER, and an increasing global urgency to find scalable clean energy solutions.[24] This momentum also reflects a shifting landscape where fusion is viewed as an emerging frontier for both public good and commercial opportunity.

In summary, although fusion has great potential, it is currently hindered by significant scientific, technical, and economic challenges. Overcoming these obstacles will require long-term vision, cross-sector collaboration, and sustained commitment at both the national and international levels. Absent these efforts, fusion energy may remain an aspirational goal rather than a practical solution in time to address global energy and climate challenges.

II. NUCLEAR SECURITY

Nuclear security is defined by the International Atomic Energy Agency ("IAEA") as "the prevention of, detection of, and response to, criminal or

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[20] *Making it Work*, ITER, https://perma.cc/72F4-QSKL.

[21] CLEO B. CHOU, JANAM JHAVERI, JANE W. BALDWIN, PHILLIP M. HANNAM, KYLE KELLER, WEI PENG, SAM RABIN, ARVIND P. RAVIKUMAR, ANNETTE M. TRIERWEILER, XINGCHEN T. WANG & ROBERT SOCOLOW, AN ENERGY TECHNOLOGY DISTILLATE FROM THE ANDLINGER CENTER FOR ENERGY AND THE ENVIRONMENT AT PRINCETON UNIVERSITY 16–21 (2016), https://perma.cc/CMT5-KFJJ.

[22] Yamada, *supra* note 12, at 3140.

[23] Jack Moore, *Toward Public-Private Synergies*, ITER (Nov. 20, 2023), https://perma.cc/JC3D-HTNG.

[24] *Id.*

intentional unauthorized acts involving or directed at nuclear material, other radioactive material, associated facilities, or associated activities.’”[25] At its core, nuclear security encompasses a broad spectrum of protective actions, including physical protection measures, material accounting and control, personnel reliability programs, and cybersecurity measures, among others. These measures collectively form the backbone of a nuclear security regime aimed at securing nuclear and other radioactive materials as well as facilities from threats such as theft and sabotage.[26]

Physical protection is a foundational element of nuclear security and involves the implementation of systems and measures to deter, detect, delay, and respond to unauthorized intrusions or malicious acts against nuclear facilities and materials.[27] Physical protection measures include access controls, surveillance systems, intrusion detection technologies, and rapid response protocols.[28] In the context of nuclear security, physical protection measures serve as the frontline defense by preventing adversaries from gaining access to sensitive materials or disrupting operations. Traditionally, physical protection measures have been designed for nuclear fission infrastructure; however, these principles are applicable to fusion facilities, especially those handling large inventories of tritium, which is a radioactive isotope of concern.

Several international legal instruments form the bedrock of the global nuclear security framework. Key conventions include:

- The Convention on the Physical Protection of Nuclear Material (“CPPNM”) (1980) obligates state parties to protect nuclear material during international transport; and criminalize certain offenses involving nuclear material, such as theft, or sabotage.[29]
- The Amendment to the CPPNM (2005) significantly expands upon the original treaty to require the protection of nuclear material in domestic use, storage, and transport; and introduces provisions for the physical protection of nuclear facilities.[30]
- The International Convention for the Suppression of Acts of Nuclear Terrorism (“ICSANT”) (2005) criminalizes acts involving radioactive materials or nuclear facilities carried out with the intent to

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[25] Int’l Atomic Energy Agency, IAEA Nuclear Sec. Series No. 20, Objective and Essential Elements of a State’s Nuclear Security Regime 1 (2013) (italics omitted).

[26] Int’l Atomic Energy Agency, IAEA Nuclear Sec. Series No. 13, Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFIRC/225/Revision 5) 4 (2011).

[27] *Id.* at 5.

[28] *Id.* at 32, 45.

[29] *See generally* International Atomic Energy Agency [IAEA], *The Convention on the Physical Protection of Nuclear Material*, IAEA Doc. INFIRC/274/Rev. 1 (May 1980) [hereinafter CPPNM].

[30] *See generally* International Atomic Energy Agency [IAEA], *Amendment to the Convention on the Physical Protection of Nuclear Material*, IAEA Doc. INFIRC/274 (July 8, 2005) [hereinafter CPPNM Amendment].

cause death, serious injury, or major economic damage.[31] ICSANT promotes international cooperation in investigation, extradition, and prosecution and explicitly applies to acts involving nuclear installations, regardless of whether they use fissile material.[32] This could extend to fusion facilities, especially those involving tritium, a radioactive isotope of concern, even though fusion is not explicitly referenced in the Convention. Therefore, ICSANT does not regulate fusion energy *per se*, but it can apply to acts of sabotage or terrorism targeting fusion sites or tritium inventories.[33]

- The Treaty on the Non-Proliferation of Nuclear Weapons ("NPT") (1970) governs the spread and control of nuclear weapons and nuclear materials.[34] Its three pillars, nonproliferation, disarmament, and peaceful use of nuclear energy, broadly support global governance of nuclear technology.[35] However, the NPT is primarily focused on fissile material and technologies directly relevant to nuclear weapons programs.[36] Since fusion energy does not rely on uranium-235 nor plutonium-239 and does not produce them, it currently falls outside the conventional scope of the NPT. Nonetheless, tritium's military relevance, suggests that over time, fusion-related activities may warrant expanded consideration within the nonproliferation framework. This is particularly the case if tritium production, use, and distribution increase globally.

Among these instruments, the CPPNM and its 2005 Amendment are the most comprehensive legal frameworks addressing nuclear security.[37] The Amendment, specifically, establishes detailed obligations for state parties to develop and maintain a sound physical protection regime, criminalize unauthorized acts involving nuclear material, and facilitate international cooperation and information exchange.[38] It is binding under international law and provides a clear standard for securing nuclear materials and associated facilities.[39]

These conventions share several overarching elements that collectively strengthen the global nuclear security framework. First, they emphasize international cooperation by encouraging collaborative efforts among states to prevent and respond to nuclear threats through information sharing, joint exercises, and

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[31] *See generally* U.N. International Convention for the Suppression of Acts of Nuclear Terrorism, Apr. 13, 2005, 2445 U.N.T.S. 89 [hereinafter ICSANT].

[32] ICSANT, *supra* note 31, arts. 7–10, 13–14.

[33] ICSANT, *supra* note 31, arts. 1(1), 1(3), 2(1)(b)–(c), 2(3)(b).

[34] *See generally* International Atomic Energy Agency [IAEA], *Treaty on the Non-Proliferation of Nuclear Weapons*, IAEA Doc. INFCIRC/140 (Apr. 22, 1970) [hereinafter NPT].

[35] *Id.* at arts. I–IV, VI.

[36] *Id.* at arts. I–III.

[37] *See generally* CPPNM, *supra* note 29; CPPNM Amendment, *supra* note 30.

[38] CPPNM Amendment, *supra* note 30, at arts. 2A(1)–(3), 5–7.

[39] CPPNM, *supra* note 29, arts. 3–4, 7; CPPNM Amendment, *supra* note 30, arts. 2A(1)–(3), 7, annex I.

mutual assistance.[40] Second, they establish the criminalization of nuclear-related offenses by requiring states to prosecute acts such as theft, sabotage, and nuclear terrorism under their national laws.[41] Third, the conventions outline physical protection obligations by setting standards for the secure handling, transport, and storage of nuclear materials and the protection of associated facilities.[42] Fourth, they require well-designed material accounting and control systems to monitor nuclear materials throughout their lifecycle, which reduces the risk of diversion or misuse.[43] Lastly, the NPT specifically promotes compliance through its integration with the IAEA's verification regime to ensure that nuclear materials are used solely for peaceful purposes.[44]

The applicability of these frameworks to fusion is limited, but increasingly salient. The CPPNM and its Amendment, as currently written, primarily address fissile materials, specifically uranium-235, uranium-233, and plutonium-239, which are not used in fusion energy.[45] Fusion reactors, by contrast, will use isotopes such as deuterium and tritium.[46] Although deuterium is nonradioactive, tritium is a radioactive isotope and a dual-use material with implications for nuclear weapons design.[47]

The CPPNM does not explicitly cover tritium nor the specific configurations of fusion technology. However, the general principles of nuclear security, such as material control, facility protection, and incident response are applicable and urgently needed in the fusion context. With that said, there is growing recognition that these conventions must evolve or be supplemented with fusion-specific guidance to address emerging threats in this domain.

ICSANT and the NPT, while not written with fusion energy in mind, also hold partial relevance. ICSANT can apply in cases of malicious acts involving radioactive material, such as tritium or attacks on fusion facilities.[48] The NPT, while centered on fissile material, may eventually need to be amended to address the potential proliferation risks associated with fusion's dual-use components especially if tritium usage becomes widespread across civilian and commercial sectors.

It is clear that the legal and institutional architecture of nuclear security was designed around the risks inherent to fission energy, including the protection of nuclear materials, facilities, and sensitive information, however, its underlying

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[40] CPPNM, *supra* note 29, at 5–6; CPPNM Amendment, *supra* note 30, at art. 5(1)–(3); ICSANT, *supra* note 31, at 7, 13–14; NPT, *supra* note 34, at III, IV, VIII.

[41] CPPNM, *supra* note 29, at 7(1); CPPNM Amendment, *supra* note 30, at 7(1); ICSANT, *supra* note 31, at 2(1)–(3), 5(1).

[42] CPPNM, *supra* note 29, at arts. 3–4, annex I; CPPNM Amendment, *supra* note 30, at 2A(1)–(3), 3–4, annex I.

[43] CPPNM Amendment, *supra* note 30, at 2A(1)–(3); NPT, *supra* note 34, at III(1)–(2).

[44] NPT, *supra* note 34, at III (1)–(4).

[45] CPPNM, *supra* note 29, at 1(a); CPPNM Amendment, *supra* note 30, at art. 1(a), annex II.

[46] *Fuelling*, ITER, https://perma.cc/9GF5-3X6L.

[47] *See generally* Jiyoung Kim, Yeongchan Kim, Changwoo Kang, Danwoo Ko, Hyolee Kim & Seung Woo, *Safeguardability Evaluation for a Conceptual Tritium Production Facility*, NUCLEAR ENG'G & TECH. (March 2025), https://perma.cc/Z5S2-KWZQ.

[48] *See generally* ICSANT, *supra* note 31.

structures and obligations are relevant for the governance of fusion energy. These frameworks are directly relevant to fusion energy because fusion facilities also involve radioactive materials, here tritium, complex nuclear infrastructure, and dual-use technologies that have comparable security and nonproliferation concerns. The emergence of tritium-intensive fusion systems, along with the associated risks (associated material control, physical protection, and cybersecurity risks, among others), necessitates a forward-looking adaptation of existing legal and regulatory frameworks. As fusion energy progresses toward commercialization, it must be accompanied by a nuclear security paradigm that accounts for its distinct technical characteristics while building upon established international principles for material protection, threat prevention, and institutional oversight. The following section explores the specific nuclear security challenges posed by fusion energy in greater detail, including tritium accountability, facility protection, cybersecurity risks, legal and regulatory concerns, knowledge management concerns, and international coordination.

III. NUCLEAR SECURITY CHALLENGES IN FUSION ENERGY

As fusion advances from experimental stages toward commercial implementation, the associated security landscape grows more complex. Although fusion lacks traditional fissile materials like uranium-235 and plutonium-239, it introduces new categories of risk that must be addressed proactively in order to mitigate the risk of theft and sabotage. Among the most pressing concerns is the management of tritium, a radioactive hydrogen isotope essential to many fusion reactions and a component in some weapons; it is also a high-value dual-use material that is difficult to detect and contain.[49] Alongside material control, facility security and the threat of sabotage also present major challenges as fusion reactors will become high-interest targets due to their valuable assets and symbolic significance. These facilities must be protected against physical threats as well as cyber intrusions, which could disrupt operations, compromise safety and security systems, and expose sensitive data to unauthorized actors.[50] Further compounding these risks are persistent legal and regulatory gaps. Existing nuclear security frameworks primarily focus on fission materials and do not adequately encompass the distinct requirements of fusion technologies nor the evolving digital infrastructure upon which they rely. Additionally, knowledge management and the dual-use nature of fusion-related technology introduces another layer of complexity as open scientific collaboration must be balanced with security against proliferation-sensitive innovations. Finally, the inherently international nature of fusion research and development requires coordination and governance, as inconsistent standards or weak regulatory oversight in one nation could have cascading

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[49] *Id.* at arts. 1(1), 2(1)(a), (b).

[50] *See generally* MICHELLE NALABANDIAN, ALEXANDRA VAN DINE & PAGE STOUTLAND, NUCLEAR THREAT INITIATIVE, GLOBAL ACTION ON CYBERSECURITY AT NUCLEAR FACILITIES: MOVING BEYOND THE STATUS QUO (2019), https://perma.cc/QHD5-Z7N2.

effects on neighboring states and global security more broadly. Collectively, these interconnected challenges highlight the urgent need for an integrated and forward-looking nuclear security strategy tailored to the fusion era.

A. Tritium Control and Accountability

Tritium, a radioactive isotope of hydrogen, plays a central role in many proposed fusion reactor designs, specifically those using deuterium–tritium ("D-T") fuel cycles, which appears to be the most promising approach for early commercial fusion energy.[51] As fusion research accelerates toward industrial-scale implementation, the production, storage, and use of tritium presents serious nuclear security and nonproliferation challenges. Owing to its dual-use nature and physical properties, it is imperative to maintain effective control and accountability of tritium to prevent its misuse in ways that could compromise international security.[52]

Tritium is classified as dual-use material, meaning that it has both civilian and military applications.[53] In civilian settings, tritium is essential for energy generation in D-T fusion reactions, in which deuterium and tritium nuclei combine to produce helium and a high-energy neutron.[54] This reaction releases substantial energy and is widely considered the most achievable form of controlled fusion in the near term. As fusion technologies mature, the increasing availability and circulation of tritium could inadvertently expand proliferation risks, if it is not closely regulated. Although tritium also has recognized military relevance, discussion of those applications is beyond the scope of this analysis due to professional restrictions. The focus here is on its role in civilian fusion energy systems and associated governance challenges.

Unlike small laboratory experiments that use trace amounts of tritium under highly controlled conditions, full-scale fusion power plants would likely require the handling and management of kilograms of tritium annually.[55] This amount vastly exceeds what is currently used in civilian applications, including in watch dials and exit signs.[56] The presence of kilogram-scale inventories also introduces new security challenges, as these quantities are valuable, portable, and potentially vulnerable to theft by malicious actors.[57]

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[51] *Fuelling, supra* note 46.

[52] *See generally* Taylor Loy, Tritium Matters: Constructing Nuclearity and Navigating Ambivalence of a Unique Material (June 25, 2024) (Ph.D. dissertation, Virginia Tech) (on file with the Virginia Tech University Libraries Electronic Theses and Dissertations).

[53] 10 C.F.R. §110.2 (2025).

[54] *DOE Explains . . . Deuterium-Tritium Fusion Fuel*, *supra* note 4.

[55] *See generally* Ziling Zhao, Chuan Li, Nan Gui, Feng Xi, Yanwi Wen, Bin Shan, Jia Fu & Qunchao Fan, *Research on Tritium Behavior Issues in High-temperature Gas-cooled Reactors*, PROCS. 2021 28TH INT'L CONF. ON NUCLEAR ENG'G (Aug. 4–6, 2021), https://perma.cc/XQ3X-MG8N.

[56] Taylor Loy, *Promoting Fusion Energy Leadership with U.S. Tritium Production Capacity*, FED'N OF AM. SCIENTISTS (Nov. 26, 2024), https://perma.cc/3UHJ-HNEY; *Tritium: Facts and Safety*, DEF. HEALTH AGENCY (Dec. 26, 2024), https://perma.cc/4V2P-FBKC.

[57] Taylor Loy, *How Military Tritium Production in Civilian Reactors Can Further Nonproliferation Goals*, CTR. FOR ARMS CONTROL & NONPROLIFERATION (Feb. 12, 2025), https://perma.cc/24XX-L9Q7.

Adding to the difficulty is the nature of tritium itself. As a low-mass, radioactive gas, tritium is inherently difficult to track, contain, and detect.[58] It can diffuse through many metals at elevated temperatures over time, which makes containment and inventory monitoring a persistent technical challenge. Unlike solid nuclear materials, tritium's gaseous form allows it to diffuse readily, making small losses difficult to measure with high precision. This leads to a fundamental accountability issue (i.e., facilities handling tritium may experience routine, minor losses that are hard to quantify), which complicates efforts to distinguish between benign operational releases and illicit diversion.

From a security perspective, this creates vulnerabilities at multiple stages, including during production, storage, transport, and use. Effective material control will require specialized containment infrastructure, such as tritium-compatible vessels with high-integrity seals, real-time monitoring systems, and advanced sensors capable of detecting minute leaks or unauthorized transfers. Accountability will depend on physical protection and comprehensive administrative systems, including accurate recordkeeping, routine audits, anomaly investigations, and personnel reliability programs.

To this point, the regulatory landscape surrounding tritium is incomplete. Although international agreements such as the CPPNM and its Amendment, as well as the NPT, establish frameworks for securing and safeguarding fissile materials respectively, they do not yet fully address the distinct characteristics of fusion-related isotopes such as tritium. As such, as fusion energy development scales up, there is a pressing need for national regulators and international bodies like the IAEA to update or extend existing protocols to explicitly include tritium. This may involve new inspection procedures, in addition to the development of standardized containment criteria and formal requirements for tritium accounting and reporting.

Moreover, international collaboration will be critical. As tritium is used and potentially traded across borders for reactor fuel, for example, or for scientific research, cooperative control mechanisms must be established to track its movement and verify secure handling across the fusion landscape. Overall, information-sharing among states, combined with technical guidance from the IAEA and peer review mechanisms, can promote harmonized standards and reduce the risk of oversight gaps that could be exploited by malicious actors.

Tritium is both a linchpin of fusion energy and a material of concern. Its role as a dual-use good, coupled with its challenging physical properties and increasing demand necessitates an urgent reevaluation of current security and accountability measures. Moreover, as fusion moves from the lab to large-scale energy infrastructure, establishing enforceable systems for tritium control will be essential to securing its promise while mitigating its security risks.

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[58] *See, e.g.*, HEALTH PHYSICS SOC'Y SPECIALISTS IN RADIATION SAFETY, TRITIUM (2020), https://perma.cc/7FRQ-BRBY; Junxiang Mao, Ling Chen, Wengming Xia, Junjun Gong, Junjun Chen & Chengqiang Liang, *Measurement Techniques for Low-Concentration Tritium Radiation in Water: Review and Prospects*, SENSORS, Sep. 2024, https://perma.cc/SV6P-ZDCQ.

B. Facility Security and Sabotage Risk

As fusion energy systems progress into large-scale infrastructure, their complexity and criticality make them correspondingly vulnerable to physical threats. Fusion reactors and their supporting facilities house sophisticated technology and sensitive materials, such as tritium and advanced control systems, which will become high-value assets both symbolically and strategically. Energy infrastructure has historically been targeted to disrupt essential services and to achieve ideological, political, or other calculated objectives by undermining public confidence, creating economic disruption, or demonstrating the vulnerability of critical national systems. Therefore, their visibility and technological significance may make them attractive targets for theft and sabotage as well for adversaries seeking to cause disruption, gain leverage, or generate psychological and political impact disproportionate to the immediate physical damage.[59] As such, a comprehensive approach to facility security is vital to preserve the integrity and continuity of fusion operations.

Fusion facilities are characterized by highly intricate systems, including powerful magnets, plasma containment chambers, cryogenic infrastructure, and tritium-handling units.[60] These components require technical precision and physical protection from external threats. Because of the specialized nature of these systems, damage from a deliberate attack (such as by an insider or external actor) could result in operational disruptions, limited radiological release, and significant delays in development timelines. Furthermore, as repositories of cutting-edge intellectual property and scientific innovation, fusion facilities may also be targeted by adversaries seeking to steal sensitive data or exploit vulnerabilities in its cyber-physical systems as well.

An important reminder of the risk of insider threats comes from the 2009 incident at the Kaiga Nuclear Facility in India where an aggrieved employee deliberately contaminated the staff drinking water supply with tritium.[61] As a result, fifty-five employees required medical treatment.[62] Although the event did not lead to any fatalities, it demonstrates how even relatively small quantities of tritium can be misused by trusted insiders to cause disruption, erode confidence in facility safety and security, and generate public concern.[63] For fusion facilities, which will are expected to manage kilogram-scale tritium inventories, such risks warrant careful consideration, as the potential consequences could be more significant if not properly mitigated. This case emphasizes the need for personnel

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[59] *See generally* INT'L ATOMIC ENERGY AGENCY, *supra* note 26; U.S. DEP'T OF ENERGY, ENSURING ELECTRICITY SYSTEM RELIABILITY, SECURITY, AND RESILIENCE (2017) (discussing the 2013 Metcalf substation attack in California); Rebecca Smith, *Assault on California Power Station Raises Alarm on Potential for Terrorism*, WALL ST. J., Feb. 4, 2014, at A1; U.N. OFF. OF COUNTER-TERRORISM & U.N. SEC. COUNCIL COUNTER-TERRORISM COMM. EXEC. DIRECTORATE, THE PROTECTION OF CRITICAL INFRASTRUCTURE AGAINST TERRORIST ATTACKS: COMPENDIUM OF GOOD PRACTICES (2019).

[60] *Fusion Systems*, FUSION ENERGY PARTNERS, https://perma.cc/N2KS-8LGS.

[61] Randeep Ramesh, *Worker Blamed for Nuclear Leak at Indian Plant*, GUARDIAN (Nov. 30, 2009), https://perma.cc/3RSD-ZQVC.

[62] *Id.*

[63] *Id.*

reliability programs, continuous monitoring, and insider threat mitigation strategies as integral components of fusion facility security frameworks.

To mitigate such risks, physical security measures must be structured around the internationally recognized physical protection pillars of deterrence, detection, delay, and response.[64] Deterrence begins with visible and well-communicated security protocols, including perimeter fencing, surveillance systems, controlled entry points, and personnel vetting, which serve to dissuade potential attackers.[65] Detection involves the use of sensors, alarms, motion detectors, and continuous monitoring to identify unauthorized access or suspicious activities in real time.[66] Delay measures are designed to slow intruders long enough for response teams to act and may include hardened barriers, secure interior zones, and layered access controls.[67] Finally, a rapid and coordinated response capability should comprise trained personnel, law enforcement liaisons, and emergency procedures; these elements are essential to neutralize threats before significant harm can occur.[68]

Given the long construction timelines and substantial multinational investments in fusion energy projects, such as ITER or DEMO,[69] any disruption from sabotage, insider threats, or cyberattacks could result in significant physical damage and financial loss, as well as lead to diplomatic tensions and geopolitical instability. These facilities often represent decades of scientific collaboration, cross-border funding, and shared goals. An attack on one fusion project could potentially be perceived as a national security breach and an act against an international partnership, which could potentially escalate diplomatic consequences.

For this reason, security should not be treated as a peripheral concern nor an add-on once construction is completed. Instead, it must be embedded from the earliest stages of planning and design through a comprehensive "security-by-design" approach.[70] This guarantees that security is not just an afterthought, but a foundational element of project development. As such, physical protection systems, personnel access controls, cybersecurity defenses, emergency response protocols, and insider threat mitigation measures must be integrated into the architectural, engineering, and operational blueprints of these facilities from the outset of its development.[71]

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[64] INT'L ATOMIC ENERGY AGENCY, *supra* note 25, at 5.

[65] *Id.* at 23–24.

[66] *Id.*

[67] *Id.*

[68] *Id.* at 17–18.

[69] *After ITER*, ITER, https://perma.cc/Z4FD-3Y8U.

[70] MARK K. SNELL, CALVIN D. JAEGER, SABINA E. JORDAN, CAROL SCHARMER, KOJI TANUMA, KAZUYA OCHIAI & TORU IIDA, SANDIA NAT'L LABS & JAPAN ATOMIC ENERGY AGENCY, SECURITY-BY-DESIGN HANDBOOK 13 (2013).

[71] *Id.* at 3, 13–16, 20–22.

The security-by-design methodology provides that:

- security features are built-in, not retrofitted, thereby reducing vulnerabilities and long-term costs;
- design constraints are aligned with security requirements, avoiding conflicts between operational efficiency and protective measures;
- early risk assessments inform layout decisions, access zoning, and material flow;
- redundancies and defense-in-depth strategies are systematically incorporated; and
- cyber-physical interfaces (such as control systems and diagnostics) are secured as core elements, not as isolated IT concerns.[72]

Moreover, embedding security mechanisms early in the process allows for interoperability with international safety and security standards, aids in the facilitation of regulatory approvals, and improves stakeholder confidence, including among international partners and funding contributors. This is especially vital for fusion, which is a field where public perception and global cooperation are vital to long-term viability.

As fusion facilities transition from the experimental phase to full-scale power plants, physical security will become just as critical as technological performance. As such, proactive planning, durable architecture, and international collaboration on protective measures will be essential to secure these vital installations from the evolving threat landscape.

C. Cybersecurity in Fusion Systems

Additionally, as fusion energy research advances toward commercialization, cybersecurity concerns also emerge as an essential component of the broader nuclear security framework. Fusion reactors rely on highly automated, computer-controlled systems to manage and monitor complex operations such as plasma containment, cryogenic control, fuel handling, and diagnostic instrumentation, among other areas.[73] These systems provide the precision and responsiveness needed for stable reactor performance, and they also introduce a significant attack surface that could be exploited by adversaries.[74] Therefore, adequate cybersecurity measures must be in place to prevent the digital infrastructure that supports fusion technology from becoming a key vulnerability that could undermine reactor safety and security, reliability, national security, and global technological leadership.

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[72] *Id.* at 20, 77, 93, 126, 138.

[73] *See, e.g.*, *Fusion Control Systems*, SUSTAINABILITY DIRECTORY, https://perma.cc/UK3B-BWZF; Matthew Horner, *SCADA Fusion with Commercial Fission*, HOMELAND SEC. AFFS., Apr. 2018, at 2.

[74] Page Stoutland, *Addressing Cyber-Nuclear Security Threats*, NUCLEAR THREAT INITIATIVE, https://perma.cc/4BNA-28H9.

Modern fusion facilities, especially experimental and next-generation demonstration reactors,[75] integrate advanced computing platforms and networked control systems to enable real-time adjustments and remote diagnostics.[76] However, this integration of digital automation also increases susceptibility to cyber intrusions. Malicious actors could exploit software vulnerabilities, misconfigured networks, or weak access controls to infiltrate cyber systems, disrupt operations, manipulate data, or even cause physical damage to equipment.[77] For instance, cyberattacks targeting magnetic confinement control could destabilize the plasma, potentially damaging the reactor's inner components or halting operations altogether.

Moreover, fusion facilities are rich in intellectual property, including proprietary algorithms, reactor design data, and materials research.[78] Therefore, sophisticated cyberespionage campaigns may aim to exfiltrate this sensitive information to gain competitive or economic advantages. The theft of such data poses a threat in terms of hindering innovation, and it could also lead to the proliferation of dual-use technologies if transferred to unauthorized entities.

Cybersecurity concerns related to fusion are further complicated by the rapid emergence of private fusion startups, many of which are focused on innovation, speed-to-market, and research breakthroughs.[79] Although this entrepreneurial

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[75] Irena Chatzis & Matteo Barbarino, *Demonstration Fusion Plants*, IAEA BULL., May 2021, at 12, 13. Chatzis and Barbarino discuss the following facility developments:

- Europe (EUROfusion DEMO): Aiming for operation by 2050, this project is in the conceptual design phase and seeks to demonstrate the technological and economic viability of fusion by producing several hundred MWs of net electricity.
- China (CFETR and DEMO): The China Fusion Engineering Test Reactor ("CFETR") is planned to start construction in the 2020s and will help bridge the gap between ITER and a subsequent DEMO reactor, which is planned for the 2030s.
- India (SST-2 and DEMO): India plans to build the SST-2 device around 2027 to qualify reactor concepts and components for a DEMO, with DEMO construction starting in 2037.
- Japan (JA DEMO): Japan's conceptual study for a steady-state DEMO (JA DEMO) is underway, with construction planned for around 2035.
- South Korea (K-DEMO): In its first phase (2037–2050), K-DEMO will focus on component development and testing, with the hope of demonstrating net electricity generation after 2050.
- Russia (DEMO-FNS): Russia is planning a fusion-fission hybrid facility (DEMO Fusion Neutron Source) to be built by 2023.

[76] *See generally* Bruno Soares Gonçalves, J. Sousa, Carlos A.F. Varandas & IPFN Control and Data Acquisition Team, *Real-time Control of Fusion Reactors*, 51 ENERGY CONVERSION & MGMT. 1751 (2010).

[77] RAHAT MASOOD, ASSESSMENT OF CYBER SECURITY CHALLENGES IN NUCLEAR POWER PLANTS: SECURITY INCIDENTS, THREATS, AND INITIATIVES 25–26 (Cyber Sec. & Priv. Rsch. Inst., George Washington Univ., GW-CSPRI-2016-03, 2016).

[78] *Fusion Licensing*, SUSTAINABILITY DIRECTORY (May 5, 2025), https://perma.cc/2LLA-Y9LR.

[79] Richard J. Pearson, Alan E. Costley, Robert Phaal & William J. Nuttall, *Technology Roadmapping for Mission-led Agile Hardware Development: A Case Study of a Commercial Fusion Energy Start-up*, 158 TECH. FORECASTING & SOC. CHANGE 1, 1 (2020).

spirit is essential for progress, it also means that cybersecurity may not be institutionalized in the same way that it is within traditional nuclear facilities, which operate under well-established regulatory oversight and deeply embedded safety and security cultures.[80] In contrast to these facilities, startups may lack dedicated security personnel, comprehensive incident response protocols, and regular auditing practices, which could render them more vulnerable to both targeted attacks and opportunistic threats.

Therefore, addressing cybersecurity in fusion systems requires a multilayered and proactive approach. This includes implementing industry-standard security practices, such as network segmentation, multifactor authentication, encryption, continuous monitoring, and software patch management.[81] Equally important, but often overlooked, is cultivating security culture (defined as shared values, attitudes, and behaviors that prioritize security) across all levels of personnel, from engineers and system designers to executives and administrative staff.[82] Regulatory bodies and international organizations must also expand their purview to include fusion-specific cybersecurity guidance and audits to help promote consistent standards across public and private sector operators.[83]

As the energy landscape becomes more interconnected and competitive, the ability to secure the digital infrastructure of fusion technologies will be as vital as managing the physical and material risks. Additionally, as fusion energy transitions from a laboratory concept to commercial reality, incorporating cybersecurity into the design, operation, and governance of fusion systems will be essential to protecting this transformative technology from exploitation or disruption.

D. Legal and Regulatory Gaps

The legal and regulatory landscape surrounding fusion energy's development is incomplete and outdated. Unlike nuclear fission, which has been subject to decades of detailed international agreements and related guidance, among other international documents, fusion energy has yet to benefit from a mature and harmonized set of legal standards. This legal and regulatory vacuum presents a serious security challenge as fusion systems scale up and begin handling materials and technologies with potential dual-use applications. Therefore, the onus is on the international community to implement a proactive, rather than reactive, approach to addressing the legal and regulatory gaps before fusion energy is fully realized.

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[80] Susan Y. Pickering & Peter B. Davies, *Cyber Security of Nuclear Power Plants: US and Global Perspectives*, GEO. J. INT'L AFFS. (Jan. 22, 2021), https://perma.cc/3NUK-XD3T.

[81] *What is Advanced Persistent Threat (APT)?*, SOPHOS, https://perma.cc/3EZ6-HUKF.

[82] INT'L ATOMIC ENERGY AGENCY, IAEA NUCLEAR SEC. SERIES NO. 7, NUCLEAR SECURITY CULTURE 5–6 (2008), https://perma.cc/H7NJ-DXQR.

[83] Tighe Smith, *How International Collaboration Keeps the World Safe from Cyberthreats*, IAEA BULL., June 2023, at 26, 26–27.

Most existing nuclear regulatory frameworks were developed in the context of fission reactors and nuclear weapons proliferation.[84] These frameworks, including the NPT, the CPPNM and its Amendment, and the safeguards framework administered by the IAEA, are primarily concerned with special nuclear materials like uranium-235 and plutonium-239, which are both directly usable in nuclear weapons.[85] Accordingly, this framework focuses on the control of fissile materials.[86] Fusion does not rely on fissile material in the same manner. The most common fusion reaction under development, D-T fusion, produces no plutonium, does not require enriched uranium, and generates less long-lived radioactive waste.[87] These differences render many of the fission-based regulations inapplicable or insufficient for addressing fusion technology.

One of the most pressing issues is that regulatory frameworks for fusion are not yet standardized internationally. Countries currently pursuing fusion research, such as the United States, United Kingdom, China, France, and Japan, are either in the process of developing or have developed national laws and policies.[88] Some of these nations treat fusion facilities under the same regulatory umbrella as fission reactors, while others apply modified standards or operate under *ad hoc* arrangements.[89] For example, in the United Kingdom, fusion energy is regulated separately from fission under the Health and Safety Executive for Great Britain, which classifies fusion facilities as industrial sites rather than nuclear installations.[90] In the United States, the Nuclear Regulatory Commission ("NRC") decided in 2021 to regulate fusion under a different framework from nuclear fission by opting for a risk-informed approach that aligned more closely with particle accelerators.[91] Japan's Fusion Energy Council has proposed regulating fusion energy under its Act on the Regulation of Radioisotopes, thus creating a risk-based and proportional regulatory model that differs from traditional nuclear

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[84] *Understanding the Difference Between Nuclear Fission and Fusion Technologies*, U.S. NUCLEAR REGUL. COMM'N, https://perma.cc/EF63-AYZR.

[85] CPPNM Amendment, *supra* note 30, at art. 1(a), annex I; NPT, *supra* note 34, at art. III(1); *Safeguards Agreements*, IAEA, https://perma.cc/6ZXG-LZPV [hereinafter *Safeguards Agreements*].

[86] CPPNM Amendment, *supra* note 30, at art. 1(a), annex I; NPT, *supra* note 34, at II–III(1); *Safeguards Agreements*, *supra* note 85; *Fissile Material*, OFF. FOR DISARMAMENT AFFS., https://perma.cc/3SS7-UTHP.

[87] *DOE Explains . . . Fusion Reactions*, U.S. DEP'T OF ENERGY, https://perma.cc/86NQ-H6EZ; *Advantages of Fusion*, *supra* note 7.

[88] *Which Countries Are Leading Fusion Research?*, SUSTAINABILITY DIRECTORY (Apr. 22, 2025), https://perma.cc/L4YA-2LXU.

[89] *Status of the Organization*, ITER, https://perma.cc/527T-QSVP.

[90] Oliver Le May, *The Future for Fusion: Government Consults on National Policy Statement EN-8 for Nuclear Fusion Energy*, CMS LAW-NOW (May 29, 2024), https://perma.cc/NT7E-NCYZ (summarizing Energy Act 2023); *see generally* INT'L ATOMIC ENERGY AGENCY, INTERNATIONAL EXPERIENCE IN THE REGULATION OF FUSION FACILITIES, IAEA-TECDOC-2115 (2026), https://perma.cc/H6G8-B6DU.

[91] Jeffrey S. Merrifield, William E. Fork & Sid Fowler, *NRC's Unanimous Vote to Separate Fusion Energy Regulation from Nuclear Fission*, PILLSBURY (Apr. 19, 2023), https://perma.cc/YG5Z-CALU; INT'L ATOMIC ENERGY AGENCY, *supra* note 90, at 9.

fission regulations.[92] These varying approaches create the risk of regulatory arbitrage, where malicious actors could exploit weak or inconsistent legal environments to take advantage of different markets by acquiring sensitive materials, evading oversight, or transferring dual-use technologies without adequate scrutiny.

Further complicating the issue is the private sector's growing role in fusion development. Unlike traditional nuclear programs, which are typically state-operated and closely monitored by the state, the field of fusion energy is populated by private startups, international joint ventures, and cross-border collaborations.[93] These developments make it even more important to have clear legal definitions, compliance standards, and licensing procedures that are consistent across jurisdictions. Without a cohesive international regulatory framework, it becomes challenging to enforce accountability and uphold the universal application of safety and security standards.

Another important consideration is the regulation of dual-use technology innovations developed for peaceful fusion energy applications that could also have military or illicit utility. These technologies include high-powered lasers, advanced superconductors, plasma confinement systems, and tritium handling techniques.[94] Without targeted export controls or international oversight, such technologies could be repurposed for illicit activities. In sum, current legal instruments are not adequately tailored to address the fusion-specific manifestations of dual-use risk.

International coordination is essential to address these legal and regulatory gaps. The IAEA, as the arbiter of peaceful uses of nuclear technology, should be supported by its Member States to take a leading role in developing fusion-specific guidelines. By working in partnership with national regulators, private sector actors, and scientific institutions, the IAEA can facilitate the development of technical guidance documents, establish best practices for tritium control, clarify nuclear security expectations, and create model regulations for states pursuing fusion energy. Given the IAEA's statutory mandate and technical expertise, it is well-positioned to promote harmonized international standards and assist Member States in adapting their regulatory and security infrastructures to address the emerging risks associated with fusion technologies.

To conclude, the evolving fusion energy landscape requires a modern and comprehensive legal and regulatory response. The legacy frameworks that govern nuclear energy today are not sufficient to ensure the safe, secure, and peaceful development of fusion technologies. Without standardized international legal and regulatory frameworks, gaps and inconsistencies may be exploited, thus potentially undermining nonproliferation objectives and increasing global security risks. Therefore, bridging these legal gaps through coordinated and proactive legal and policy development will be essential to harmonizing the advancement of fusion energy with the imperatives of international security and global stability.

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[92] *Japan Fusion Energy Council Publishes Paper on Fusion Regulations*, FUSION INDUS. ASS'N, https://perma.cc/TY7Y-3ATS; INT'L ATOMIC ENERGY AGENCY, *supra* note 90, at 6.

[93] *Fusion Funding*, SUSTAINABILITY DIRECTORY (Jan. 12, 2025), https://perma.cc/J7H2-32TG.

[94] U.S. DEP'T OF STATE, TECHNOLOGY ALERT LIST (2002), https://perma.cc/58L8-ZC8X.

E. Knowledge Management: Managing the Balance of Transparency and Security

The pursuit of fusion is driven by peaceful objectives, including clean energy production and scientific advancement, but it also carries significant risks related to the dual-use nature of certain fusion-related knowledge and technologies. As fusion research continues to expand through international collaboration, open-access publications, and the expansion of academic and private sector initiatives, managing the balance between transparency and security becomes progressively complex and important.

Several core elements of fusion science were initially designed for civilian use, but have potential military applications as well. Tritium handling techniques, for instance, are essential for fueling D-T fusion reactions, yet the expertise and infrastructure required to manage tritium can also have broader security implications due to its potential military applications as well.[95] Similarly, high-powered lasers, such as those used in inertial confinement fusion, are capable of delivering concentrated pulses of energy within nanoseconds to replicate the extreme temperatures and pressures found inside stars.[96] Plasma confinement systems, which are essential for magnetic fusion and advanced computing tools used for modeling fusion plasmas could also advance the broader understanding of weapons physics.[97]

With that said, the implication is clear: although most fusion research is conducted for peaceful purposes, some of its underlying technologies could inadvertently contribute to the advancement of nuclear weapon capabilities if openly shared without adequate oversight.[98] This concern is particularly salient given the emphasis on open scientific collaboration, which is foundational to the fusion community.[99] Projects like ITER, which involves dozens of countries, are structured around transparent data-sharing processes to accelerate development. Similarly, academic institutions often rely on unrestricted access to scientific papers, datasets, and conferences to fuel innovation and maintain progress.[100]

This culture of openness creates a significant dilemma. Export controls and classification policies, which are critical for nonproliferation, are difficult to

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[95] *See, e.g.*, HEALTH PHYSICS SOC'Y SPECIALISTS IN RADIATION SAFETY, *supra* note 58; Mao et al., *supra* note 58; *DOE Explains . . . Deuterium-Tritium Fusion Fuel*, *supra* note 4.

[96] Lindsey Valich, *Scientists Hit Key Milestone in Fusion Energy Quest*, UNIV. OF ROCHESTER (Dec. 13, 2022), https://perma.cc/L2Y7-9V7Y.

[97] *DOE Explains . . . Plasma Confinement*, U.S. DEP'T OF ENERGY, https://perma.cc/V8R8-6ET8; Allyn Katherine Milojevich, Oak Ridge Nat'l Lab'y, Applicability of the Export Control Regimes to Fusion (May 2023) (unpublished manuscript) (on file with the Institute for Nuclear Materials Management, https://perma.cc/3A2Q-QFLJ).

[98] John Carlson, Nuclear Threat Initiative, "Peaceful" Nuclear Programs and the Problem of Nuclear Latency (Nov. 19, 2015) (unpublished manuscript) (on file with the Nuclear Threat Initiative, https://perma.cc/L6TS-QR4J).

[99] *What is ITER?*, ITER, https://perma.cc/Y99L-8D4V; *The Demonstration Power Plant: DEMO*, EUROFUSION, https://perma.cc/Z2DM-UV7W.

[100] NAT'L ACAD. OF SCIS., NAT'L ACAD. OF ENG'G & INST. OF MED., ENSURING THE INTEGRITY, ACCESSIBILITY, AND STEWARDSHIP OF RESEARCH DATA IN THE DIGITAL AGE 33–35 (2009), https://perma.cc/BU9J-YBDL.

reconcile with the general free flow of information inherent to academic and research environments. Therefore, a delicate balance must be struck, as excessively restrictive policies could stifle innovation, yet insufficient controls may allow adversaries and unauthorized actors to exploit published findings for competitive advantage or malicious use. To address this concern, a nuanced knowledge management approach is required to secure proliferation-sensitive information without undermining scientific progress. Such an approach involves identifying which technologies and data are most susceptible to misuse, improving international cooperation on dual-use risk assessments, and promoting secure channels for sensitive collaborations. Striking this balance is essential to protect fusion's peaceful promise and minimize its potential contribution to global security threats.

F. International Coordination and Governance

There is an impending need for strong international coordination and governance as fusion technology progresses toward global commercialization. Fusion's inherently multinational nature, which is reflected in major collaborative projects such as ITER and the proliferation of fusion research across both established and emerging states, requires the following: (1) scientific cooperation and shared security protocols; (2) regulatory standards; and (3) nonproliferation commitments.[101] The disparities in national oversight could lead to significant vulnerabilities in the global nuclear security architecture without such alignment across these domains.

It is well established that fusion energy presents a fundamentally different set of challenges than traditional fission-based nuclear technologies.[102] However, existing international frameworks are not yet fully adapted to account for these distinctions. Most current treaties and agreements, including the NPT and the CPPNM and its Amendment, are rooted in concerns about fissile materials, such as enriched uranium and plutonium. Fusion systems, which typically do not use nor produce these materials, fall into what could be considered a regulatory gray area, especially as it relates to tritium control, cyber-physical security, and dual-use technology oversight.[103]

There is also a growing risk of jurisdictional inconsistency as fusion reactors begin to transition from research projects to commercial power generation. Countries vary widely in terms of their regulatory maturity, technical capacity, and enforcement mechanisms. Advanced nuclear states may have sophisticated regulatory agencies and established security procedures, while other states may lack the institutional infrastructure to manage the distinct challenges of fusion. This variation could foster weak security spots in regions where fusion facilities operate under minimal oversight or outdated legal frameworks, which could lead

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[101] *Why Is International Collaboration Essential in Fusion?*, SUSTAINABILITY DIRECTORY (Nov. 28, 2025), https://perma.cc/LD8K-WHBV.

[102] *See generally* Carley Willis & Joanne Liou, *Safety in Fusion*, IAEA BULL., May 2021, at 14.

[103] INT'L ATOMIC ENERGY AGENCY, IAEA WORLD FUSION OUTLOOK 2023, FUSION ENERGY: PRESENT AND FUTURE (1st ed. 2023).

to exploitation of these gaps by adversaries seeking to gain access to sensitive materials, technologies, or data.[104]

To mitigate these risks, the global community must work to develop international norms and harmonized governance structures specific to fusion energy. This includes establishing conventions governing this technology, in addition to agreed-upon definitions for fusion-relevant materials, developing minimum security requirements for facilities, and coordinating export controls on sensitive components and knowledge.[105] The IAEA is well-positioned to lead such efforts given its existing mandate and expertise in nuclear technology, but it may require expanded authority under its statute or new guidance instruments tailored to fusion.[106]

In addition to formal regulatory alignment in a global context, informal channels such as technical exchanges, peer review missions, and joint training exercises can strengthen cooperation and build trust between states. As more private companies enter the fusion landscape, states must also work preemptively and collaboratively with industry to ensure that commercial innovation does not outpace regulatory and security requirements. To summarize this sentiment, the global commercialization of fusion energy will only be as secure as its weakest link. Therefore, a coordinated international approach that is grounded in common security standards, transparent practices, and shared responsibility is crucial so that fusion energy contributes to global stability rather than introducing new pathways for risk or conflict.

IV. MITIGATING SECURITY RISKS IN FUSION

Establishing a comprehensive security framework is also imperative to prevent its development from inadvertently introducing new risks to international stability as fusion technology moves toward commercial realization. Although fusion does not involve traditional fissile materials like uranium-235 or plutonium-239, it does utilize radioactive substances, specifically tritium, that have both civilian and military applications.[107] These unique aspects of fusion require a tailored approach to nuclear security with an emphasis on prevention, protection, and international accountability.

International bodies like the IAEA, which sets global standards for nuclear safety and security, play a central role in ensuring the secure development of fusion technologies. As discussed earlier, existing nuclear treaties were largely built around fission energy and must evolve to reflect the distinct characteristics of fusion systems.[108] While tritium and deuterium are not classified as special nuclear materials under the CPPNM and its Amendment, their potential misuse requires updated legal frameworks and, additionally, expanded guidance which

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[104] J. Elbez-Uzan, L. Williams, S. Forbes, A. Dodaro, R. Stieglitz, M.I. Airila, J. Holden & S. Rosanvallon, *Recommendations for the Future Regulation of Fusion Power Plants*, NUCLEAR FUSION, Mar. 2024, at 1, 1, 3–4, 8–9.

[105] *Id.* at 9–11.

[106] David de Caires Watson, *IAEA Hosts the First Meeting Focusing on Safety and Regulation of Fusion*, INT'L ATOMIC ENERGY AGENCY (Nov. 15, 2023), https://perma.cc/68Y5-6Y79.

[107] MARTIN B. KALINOWSKI, INTERNATIONAL CONTROL OF TRITIUM FOR NUCLEAR NONPROLIFERATION AND DISARMAMENT (2004).

[108] *Understanding the Difference Between Nuclear Fission and Fusion Technologies*, *supra* note 84.

could be issued via the IAEA's Nuclear Security Series.[109] IAEA guidance is often referenced in the development of national legal and regulatory frameworks.[110] Given the IAEA's influence, expanding its guidance to explicitly address fusion could help promote greater harmonization across national regulatory regimes.

One of the core components of fusion security is tracking and controlling sensitive materials to prevent theft and sabotage. Therefore, material accounting systems must be implemented at the facility level and aligned with national and international protocols. As previously noted, these systems should include real-time monitoring, anomaly detection, and thorough auditing procedures. Secure access control is also vital to verify that only authorized personnel are able to interact with critical systems and radioactive inventory, with physical, digital, and procedural measures in place to mitigate the risk of insider threats or external intrusions.

Fusion energy would also benefit from the integration of security-by-design principles from the outset of conceptualization and development. Unlike legacy fission facilities, many fusion systems are still in the early phases of conceptualization and construction. Therefore, security measures can be built into the design rather than added reactively and retroactively. Such measures include incorporating secure zones, automated surveillance, access-limited control areas, and robust cybersecurity architecture, which can drastically reduce vulnerabilities. By designing reactors with security in mind, it helps to improve overall resilience to physical sabotage and cyberattacks, and it also simplifies compliance with future regulatory requirements.

Additionally, sharing strategies across states and industry is essential to strengthening global fusion security.[111] The success of international projects like ITER demonstrates the value of cooperative research and the transparent exchange of technical knowledge.[112] A coordinated effort to share best practices ranging from facility protection standards to cyber-hygiene protocols can also help to create a unified front against emerging threats. To this point, national laboratories and industry stakeholders must collaborate on the development of universal benchmarks and jointly evaluate security innovations. National laboratories play specialized roles across distinct areas of nuclear research and security. This specialization creates a strategic advantage in developing universal benchmarks and advancing security innovations. It also allows for collaborative efforts between laboratories and industry to pursue shared objectives. Such collaboration can result in an integrated approach in physical protection and cybersecurity measures that can be fortified against malicious threats. Furthermore, given their respective broad technical expertise and mission diversity, U.S. national laboratories are well-equipped to lead in this area. Laboratories such as

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[109] Adolf von Baekmann, *Modern Fuel Cycle Technologies and IAEA Safeguards*, IAEA BULL., Oct. 1990, at 11, 11–13.

[110] *Id.*

[111] *Fusion*, INT'L ATOMIC ENERGY AGENCY, https://perma.cc/8RPX-S5W7.

[112] *See, e.g.*, Wolfgang Picot, *ITER: The World's Largest Fusion Experiment*, IAEA BULL., May 2021, at 10.

Sandia National Laboratories focus on physical security and systems engineering, whereas Oak Ridge National Laboratory ("ORNL") offers expertise in fusion energy, nuclear materials research, and cybersecurity, among other domains.[113] ORNL, in particular, contributes through its Fusion Energy Division and collaboration with federal agencies to advance innovation and integrated security and safeguards approaches in this domain.[114] These diverse capabilities allow the national laboratories to pilot, validate, and adapt security solutions that are scalable at the international level. Moreover, national laboratories often serve as natural conveners by promoting collaboration among government, industry, and international partners to align security goals with scientific advancement. Such cross-sector partnerships promote interoperability, efficiency, and mutual trust, thus helping to close vulnerabilities in weaker national systems that could be exploited on a global scale.

Facilities and regulatory bodies should also commit to regular threat evaluations that reflect the dynamic nature of global risk environments to maintain effective protection protocols of fusion technology. The rise of cybercrime, the evolution of non-state actors, and advancements in dual-use technologies require continuous vigilance. Threat assessments should be updated frequently and conducted by multidisciplinary teams, including cybersecurity experts, nuclear engineers, and intelligence professionals to develop security postures that are aligned with the latest intelligence and technological developments. These assessments must shape national defense strategies and facility-level operational protocols so that appropriate protections are in place as risks to this emerging technology evolve.

In sum, the secure advancement of fusion energy depends on an integrated approach grounded in international cooperation, technical precision, and proactive security planning. Institutions like the IAEA must adapt their oversight mechanisms, and fusion developers and operators must adopt rigorous standards for material control, facility design, and cross-border collaboration. As the global community seeks to harness the immense potential of fusion, security must be treated as a foundational element of responsible innovation and not merely as an afterthought.

A. Other Considerations: Fusion's Role in Geopolitical Stability

As the development of fusion accelerates, its implications extend well beyond science and energy production. Fusion energy, which is often described as a clean, abundant, and valuable energy source, has the potential to reshape the global balance of power. Theoretically, this technology can either serve as a tool for global peace and cooperation or become a source of tension and inequality. Understanding its broader geopolitical context is crucial as nations pursue this transformative energy source.

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[113] *About Sandia*, SANDIA NAT'L LABS, https://perma.cc/H7WQ-3ZB6; *About ORNL*, OAK RIDGE NAT'L LAB'Y, https://perma.cc/2R68-E28C.

[114] *About ORNL*, *supra* note 113.

One of the most profound implications of fusion energy is the potential for energy independence. Fusion allows countries to produce substantial amounts of electricity from widely available fuels such as deuterium, found in seawater, and tritium, which can be bred from lithium during reactor operation. Unlike oil, gas, and uranium, these inputs are not concentrated in a few politically sensitive regions, meaning that states would no longer be at the mercy of energy exporters or vulnerable to supply disruptions caused by conflict or market manipulation, among other events. This reduction in reliance on fossil fuels and imported energy could lead to greater national autonomy and a rebalancing of power in global energy markets.

Further, the dominance of fossil fuels is gradually diminishing due to several factors including the global transition toward decarbonization, in addition to the expansion of renewable energy technologies, climate-related regulatory pressures, and advances in energy storage as well as grid modernization. As states continue to diversify their energy portfolios and reduce reliance on imported oil and gas, the geopolitical leverage historically associated with fossil fuel control will then weaken. Over time, this shift is likely to reduce the influence and dominance of hydrocarbon-rich states in shaping global energy markets and security dynamics.

As fossil fuels decline in global significance importance, then power dynamics may shift substantially. Countries currently dependent on fuel exports could face economic instability, and those investing heavily in fusion research may rise in global influence. Energy exporters like Russia and Persian Gulf states may see diminished geopolitical leverage, whereas countries leading in fusion technology, such as the United States, China, Japan, and members of the European Union, could gain new forms of soft power. This redistribution of influence would likely introduce new tensions and reduce the likelihood of resource-based conflicts, including those historically centered around oil and gas.[115]

Fusion's collaborative nature also opens avenues for new forms of technological diplomacy. Unlike fission, which was often developed in secrecy and driven by military interests, fusion research has largely been conducted through multilateral, peaceful efforts.[116] The ITER project is a flagship example of this cooperation in that it has brought together countries across political divides, including the United States, China, Japan, Russia, and the European Union, to jointly advance fusion science.[117] Such collaboration builds scientific trust, promotes peaceful innovation, and models a framework for diplomatic engagement rooted in shared global goals. In this context, fusion becomes an energy solution and a vehicle for sustaining peaceful international relations.

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[115] Sage Miller, *Fusing Particles and Interests: The Geopolitics of Nuclear Fusion*, GEO. SEC. STUD. REV. (Jan. 5, 2023), https://perma.cc/P9YU-DHQY.

[116] *See, e.g.*, *Security and Secrecy*, ATOMIC HERITAGE FOUND. (June 5, 2014), https://perma.cc/7K45-B7VH; Irena Chatzis & Matteo Barbarino, *What Is Fusion, and Why Is It So Difficult to Achieve?*, IAEA BULL., May 2021, at 4; *Making It Work*, *supra* note 20.

[117] *The ITER Organization*, ITER, https://perma.cc/YKP8-8NK4.

With that said, the benefits of fusion are not guaranteed to be distributed equally. A significant concern regarding fusion involves the risk of unequal access to this technology, specifically between technologically advanced nations and the Global South. Currently, only a limited number of countries possess the infrastructure, funding, and human capital necessary to participate in fusion research. If access to fusion continues to be concentrated in wealthy or powerful nations, then energy gaps may continue to widen, thereby exacerbating global inequalities. This could lead to a two-tiered energy world in which some countries benefit from clean, stable power, and others remain dependent on polluting or unreliable energy sources.

These disparities carry serious implications. Countries excluded from the fusion transition may face growing economic disadvantages, environmental vulnerability, and even geopolitical marginalization. In turn, frustration over exclusion could lead to instability, competition, or attempts to acquire fusion capabilities outside of established regulatory frameworks. Conversely, equitable access to fusion technology facilitated through international organizations like the IAEA as well as cooperative technology-sharing agreements could elevate fusion as a tool for peace and global equity, which would strengthen rather than undermine geopolitical stability.

International efforts must prioritize inclusive participation across nations in order to fully realize fusion's global benefits. This includes providing technical assistance, training, and infrastructure support to developing countries; creating secure open-source fusion research platforms; and establishing frameworks for secure and responsible technology transfer. A global fusion governance structure that is complementary to existing nonproliferation and energy cooperation mechanisms could also promote transparency, manage intellectual property, and uphold security standards across all adopting nations.

Security is another critical dimension of fusion's geopolitical impact. Although fusion does not rely on traditional fissile materials, it still involves sensitive materials such as tritium, which have potential military applications. The manner in which fusion technology is shared, governed, and secured will therefore shape its role in international peace and security. Comprehensive material accounting measures and regulatory frameworks are essential to prevent misuse and proliferation risks. In parallel, assurances of fusion's exclusively peaceful purpose should be supported by international institutions and bolstered through effective oversight and enforcement mechanisms.

In summary, fusion energy stands at a crossroads between technological breakthrough and geopolitical transformation. It offers the promise of greater energy independence, the prospect of reduced global reliance on fossil fuels, and a new avenue for diplomatic innovation through science-based collaboration. Yet without careful management, it could also deepen inequalities and fuel new geopolitical rifts. The future of fusion will depend on scientific milestones in addition to the values, policies, and partnerships that influence its development. If the global community embraces a shared vision of security, equity, and cooperation, then fusion could become a stabilizing force in a rapidly changing world.

V. CONCLUSION

The development of fusion as a sustainable energy source could fundamentally reshape the future of global power generation. Because of fusion energy's ability to produce an abundant amount of energy while emitting minimal greenhouse gases and relying on widely available fuels like deuterium and lithium-derived tritium, fusion stands as a promising alternative to traditional fossil fuels and nuclear fission. Additionally, fusion energy's potential for high energy output, inherent safety features, and significantly reduced radioactive waste makes it a compelling candidate in the global transition to clean energy. However, the path from theoretical models to practical implementation is fraught with significant challenges, chief among them being the need to address the complex and evolving nuclear security concerns surrounding fusion technology.

This paper has examined the intersection of fusion energy development and nuclear security, outlining the need to adapt fission-based frameworks to address fusion-specific risks. Key among these risks is the control and accountability of tritium, a radioactive isotope central to the most promising fusion reactions. The qualities of tritium, including its dual-use nature, difficulty to detect and contain, and potential use in nuclear weapons development raises urgent security concerns that cannot be ignored as fusion scales toward commercial viability. Also concerning is the physical and cyber vulnerability of fusion facilities. As fusion facilities evolve from research laboratories to commercial-scale reactors, these installations will become high-value assets that may attract adversarial interest for acts of theft and sabotage. The increasing integration of digital control systems in fusion facilities also introduces a new threat vector where a cyber intrusion could potentially disrupt operations, damage infrastructure, and result in the unauthorized access of sensitive scientific data.

In addition to material and facility security, the legal and regulatory architecture surrounding fusion energy is underdeveloped. While existing conventions, including the CPPNM and its Amendment, ICSANT, and the NPT, provide some foundational principles, they all fall short of encompassing the full scope of fusion-specific concerns. These instruments were crafted with fission in mind and lack explicit provisions for tritium control, fusion reactors, and the unique dual-use technologies associated with plasma physics, superconducting magnets, and high-energy lasers. Moreover, as scientific knowledge is more widely shared across borders in pursuit of collaborative breakthroughs, the issue of knowledge management becomes more urgent. Fusion science thrives on transparency and open exchange, but this openness must be balanced against the risk of proliferation for the development of nuclear weapons. Therefore, managing access to sensitive data and controlling the dissemination of dual-use-related data are essential tasks that require the development of international consensus and shared norms.

One of the most critical conclusions of this paper is the necessity for improved international coordination and governance. Fusion is inherently multinational, which is exemplified by large-scale collaborative projects like ITER, and as such, its global nature requires global security protocols. However, disparities in regulatory maturity, enforcement capacity, and political will across nations are a risk to the implementation of such security protocols and ultimately the secure advancement of this technology. As such, establishing harmonized standards, multilateral security arrangements, and a proactive role for the IAEA in developing fusion-specific guidelines is vital.

Fusion's emergence is a once-in-a-generation opportunity to transform the energy landscape while advancing international climate and development goals, but this transformation can only be realized responsibly if nuclear security is a central design requirement in the development phase of this technology. To facilitate this, security-by-design principles, comprehensive tritium accounting systems, strong cybersecurity frameworks, and legally binding international agreements must become integral components of the fusion ecosystem.

Overall, by addressing the specific nuclear security risks posed by tritium management as it relates to fusion energy; facility protection; legal and regulatory reform; knowledge management; and cybersecurity resilience, the global community can harness the full potential of this technology. If developed securely, then fusion could usher in a new era of energy abundance, climate resilience, and international cooperation. Without proactive security planning and legal innovation, however, it could also introduce new security vulnerabilities into an already complex and volatile world. Therefore, securing the future of fusion means securing the systems, materials, and institutions that will govern its rise.