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# Analyzing the Nuclear Weapons Proliferation Risk Posed by a Mature Fusion Technology and Economy

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**Abstract:** Nuclear fusion is widely promoted as the ultimate environmentally friendly solution to the world's energy demands. However, the medium/long-term nuclear weapons proliferation risks from a hypothetical fusion economy are rarely considered. Using risk assessment tools, this paper undertakes a trial scoping of proliferation hazards arising from fusion energy technologies, focused on the implications of a global 'Mature Fusion Economy' (MFE). In the medium term, an MFE could (1) facilitate construction of large, efficient, and reliable nuclear arsenals by producing tritium and the fissile materials Plutonium-239 and Uranium-233; and (2) erode the barriers constraining nuclear weapons acquisition by facilitating the spread of nuclear knowledge, technologies, and materials. Given the potential scale of a global MFE, management via monitoring of proliferation and diplomacy could become unworkable. Therefore, policy development must include independent and comprehensive expert and informed community assessment of such fusion-enhanced risks, transparent oversight by the nuclear disarmament community, and systematic analysis of the issues raised in this paper and their implications for fusion into the very long-term future.

**Keywords:** nuclear fusion; nuclear proliferation; risk assessment; mature fusion economy

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## 1. Introduction

For 60 years, electricity generation by nuclear fusion has been promoted as the ultimate environmentally friendly solution for the energy demand of future generations. The fusion research community contends that its environmental risks and impacts are trivial or manageable. Until recently, this 'clean green' image has rarely been critiqued and the early analysis of John Holdren [1–5] still provides one of the best cautions available in the open literature. Since then, fusion and competing energy technologies have evolved substantially and literature on fusion power generation principles and nuclear weapons has become more accessible. The need for non-carbon-based energy has also become even more urgent, along with the question of which pathway is preferable, renewables, nuclear, or a mixture, and in the latter instance, in what proportions.

Fusion literature predominantly presents an optimistic view of fusion power's feasibility and environmental desirability [1,6–9]. To illustrate:

> *The Vision . . . is clear . . . Fusion power plants will be located around the world providing clean energy . . . without significantly endangering the public . . . [Fusion] will not be held hostage to . . . natural resources (locations) located in difficult places. Fusion will provide the energy foundation necessary for mankind to prosper and grow.* [10]

and

> *Assuming no...surprises . . . Fusion could . . . play an important role in the...second part of the (21st) century. The central issue is . . . to make it work reliably and economically on the scale of a power station . . . To meet this challenge . . . we must . . . follow the aggressive programme . . . the 'Fast Track to Fusion'.* [11]

This optimistic narrative is often reproduced by science journalists and supported by the general energy and environmental science community, e.g., [12–14], while criticism focuses on fusion's commercial viability [15–17].

Nevertheless, sporadically, concerns over nuclear weapons proliferation also appear. Lawrence Lidsky [18], founding editor of the *Journal of Fusion Energy*, suggested fusion technology was too dangerous to make universally accessible because of proliferation risks. Though supportive of 'pure' fusion, Holdren [4] questioned the fusion–fission hybrid (FFH) concept [8]. Meanwhile, inertial fusion technology—e.g., using lasers to compress and heat nuclear fuel—has been claimed to be a cover for nuclear weapons development [19]. Glaser and Goldston [20] showed how, either covertly, or overtly, a single rogue nation might produce fissile material from a single Deuterium–Tritium (D–T) fusion reactor. Franceschini et al. [21] published quantitative estimates of the nuclear weapons-relevant materials, Plutonium-239 (Pu-239) and tritium, that could be produced in future commercial fusion reactors. They used a Delphi method to examine whether "fusion power will have a military dimension in the second half of this century" and found that this is indeed the expert view. Schmidt et al. [22] recognized that there is a huge gap in the risk and environmental assessment conceptualization and implementation process, especially given what it is claimed fusion will do. Very recently, Carayannis et al. [23] argued that, as with fission, fusion power, if feasible, can be weaponized.

Our paper focuses on the long-term issue of the risks of nuclear weapons proliferation arising from a mature fusion economy (MFE). We use a risk assessment framework, as discussed in Section 2, to illustrate the potential of modern management techniques to systematically identify and evaluate environmental impacts.

We recognize that an MFE may never eventuate. The transition to a global energy system based mainly on wind and solar photovoltaic (PV) power, supplemented by hydroelectricity, is well under way in several countries and the levelized costs of electricity from these variable renewable energy technologies are already less than from new fossil-fueled power stations [24,25], even after storage has been added to firm energy supply [26], and these costs are still declining. Furthermore, the levelized costs of electricity from wind and solar PV are much lower than from new nuclear fission power stations [25,26]. Due to the immense difficulties of achieving controlled fusion in a reactor and the resulting complexity of such a system, electricity from a possible future commercial nuclear fusion reactor is likely to be at least as expensive as from fission. Therefore, it is unlikely that nuclear fusion could ever compete economically with a future renewable energy system. The rapid growth and low cost of renewable energy has weakened past arguments that fusion is needed solve some of the world's most pressing problems, such as energy poverty and lack of access to natural resources. Low-cost renewable energy is already playing increasing roles in rural communities in low-income countries, and in mining and minerals processing by large corporations.

Nevertheless, billions of US dollars equivalent continue to be spent on research and development of nuclear fusion, of which the most expensive project is the International Thermonuclear Experimental Reactor (ITER) under construction in France (see https://www.iter.org, accessed on 15 January 2023). The ITER is funded jointly by seven members—China, the European Union, India, Japan, Korea, Russia, and the United States, comprising 35 nations in total—at an estimated total cost of 18–22 billion euros [27]. The huge continuing financial commitment to fusion suggests that if research and development are successful, poor economics may not be sufficient to halt the future creation of an MFE. After all, poor economics did not stop the expansion of nuclear fission power although, in recent years, its growth has plateaued ([28], Figure 6). Regulation based on comprehensive risk assessment is likely to be more effective before fusion technology becomes established than afterwards.

## 2. Materials and Methods

Systematic comprehensive assessment of the case for and against commercial fusion power poses challenges. Discussions of nuclear weapons proliferation, energy supply, and environmental impacts generate divergent views and emotions with the result that even impartial assessments can become, or be perceived as, biased and unbalanced. Analysis of commercial fusion energy's prospects is necessarily speculative, as even electricity generation from Tokamak/ITER magnetic containment technology still appears decades away. Finally, a complete analysis would have to consider timeframes ranging from the short-term to potentially thousands of years in the future, given fusion's final solution claims and aspirations (something shared with renewable energy technologies).

Fortunately, in risk assessment (RA) [29], there is an established analysis system developed with such challenges in mind. RA obliges users to systematically integrate and prioritize information and place it in context. RA is routinely applied to environmental, social, health and financial problems e.g. [30–32], and the nuclear power industry [33,34]. It can be adapted to both short-term and rare catastrophic long-term risks [29].

The International Standards Organization, ISO 31000, *Risk Management—Guidelines* [35], provides principles, a framework and a process for managing risk (https://www.iso.org/iso-31000-risk-management.html, accessed on 15 January 2023). Its techniques and documentation requirements identify the following 10 distinct risk management tool categories which provide a checklist for what has and has not been undertaken:

- B.1 Techniques for eliciting views from stakeholders and experts
- B.2 Techniques for identifying risks
- B.3 Techniques for determining sources, causes, and drivers of risk
- B.4 Techniques for analyzing controls
- B.5 Techniques for understanding consequences and likelihood
- B.6 Techniques for analyzing dependencies and interactions
- B.7 Techniques that provide a measure of risk
- B.8 Techniques for evaluating the significance of risk
- B.9 Techniques for selecting between options
- B.10 Techniques for recording and reporting

Within this set of 10 tool categories, 42 qualitative and quantitative widely used RA tools are recognized [35], reflecting varying problems, their complexity, information availability, assessment resources (time, expertise, cost, data) and potential for quantification. An illustrative high-profile RA tool example is the hazard analysis of critical control points, developed for NASA and subsequently applied to food safety [36]. In fact, even this list is not comprehensive. One striking ISO omission is the long-established medical discipline of epidemiology, which is clearly relevant to nuclear health impacts. Additionally, there can be very different sub-types of assessment within many tools. For example, ISO31010 Tool B.7.1 toxicological risk assessment covers [35] such diverse tasks as ecological risk assessment and teratogenic chemical impacts.

The RA literature on fusion energy production is already substantial. However, its focus appears mainly to be operational concerns, such as occupational health and safety risks [4,37]. Such quantitative RA is only marginally feasible for analyzing proliferation risk, because available statistics [38–42] are still near-term and sparse. This begs the question of alternatives.

The approach we have applied to illustrate the potential of comprehensive RA combines the framework proposed by Garrick and Christie [29] for very rare but catastrophic risks, such as nuclear war, and selected qualitative RA tools identified by the ISO [35]. Consistent with RA practice, the framework involves the following steps:

1. Define the system.
2. Identify/characterize hazards, e.g., stored energy, toxic substances, and combinations.

3. Develop “what can go wrong” scenarios and estimate consequences and vulnerability.
4. Quantify the likelihoods of different scenarios and damage levels (severity).
5. Assemble the scenarios according to damage levels and prioritize.
6. Interpret the results to guide risk management.

Within this framework we trialed some qualitative RA tools judged appropriate to the data available [35] (Annexes A and B) by reviewing the literature from our perspective as scientists familiar with broad environmental assessment, nuclear technologies, and risk management. In line with best RA practice, we also recognize our limitations. A brief reading of the ISO toolkit shows the need for an enormous variety of expertise input and the use of specialist qualitative and quantitative techniques where issues are complex and have wide implications. That said, in light of failure to date to comprehensively deploy this toolkit, our initial scoping based on freely available auditable information appears a defensible initial exercise.

The literature appeared sufficient for Step (1): System Definition and Step (2): Hazards Characterization via a literature-based general risk view elicitation and identification, also known as a primary hazard analysis [35] (Tools B.1.1 and B.2.1). For preliminary scenario construction (Step 3) we extracted literature conclusions, examples, and analogies using IEC/ISO Tool B.2.5 ‘Scenario Analysis’ as a guide. Semi-quantitative risk estimation/characterization of scenario risks (Step 4) was judged unfeasible, even via the popular ‘Consequence/Probability Matrix’ (Tool B.10.3). (This latter familiar and popular tool has now been demoted to ‘Techniques for Recording and Reporting’. However, in our experience, it still provides a potential scheme for preliminary scoping—see [35] (Table A3).

Using the literature, it was possible to tabulate plausible risk scenarios with potentially severe consequences. For integration (Step 5), the most appropriate tool in principle appeared to be the qualitative ‘Cause and Consequence Analysis’ (Tool B.5.5), formerly known as ‘Cause and Effect Analysis’. Together these analyses allowed a provisional but nevertheless auditable assessment of potential fusion-linked proliferation issues suited to management and energy policy development (Step 6).

## 3. Results

### 3.1. Step 1: System Definition—Fusion Power Technologies

Though fusion publicity focuses on Tokamaks and the ITER project [14,43], fusion power is not a single technology. Over 100 distinct methods have been conceived for fusing light nuclei [44]. Currently, four major research themes are discernible: large magnetic containment (e.g., Tokamaks), fusion–fission hybrids (i.e., using high-energy fast neutrons from a fusion reactor to trigger fission in non-fissile fuels such as U-238 or Th-232) and inertial confinement fusion (i.e., using lasers to heat and compress the fuel) (Table 1).

**Table 1.** The most mature and promising fusion technologies.

| Technology Theme | Notable Technology Features | References |
|---|---|---|
| Large magnetic containment vessels (e.g., Tokamaks, Stellarators) | Full size Tokamaks should induce a Deuterium–Tritium (D–T) plasma sufficient to release 20 to 30 times the input energy over a plasma lifetime of tens of seconds. Energy is exported mainly as neutrons, which are absorbed by a ‘blanket’ of $^{6}$Li, neutron multipliers (Pb, $^{9}$Be) and heat exchangers breeding new T and extracting usable energy. Operating these processes concurrently with a reactor lifespan of 40 years is a major engineering challenge. Net energy production in principle was demonstrated by smaller Tokamaks (JET, J-60 and the TFTR) during the 1990s. Subsequent research e.g., in superconducting magnet technology refinement, and size, mean ITER should achieve net fusion energy production. | [11,45–47] |

**Table 1.** *Cont.*

| Technology Theme | Notable Technology Features | References |
|---|---|---|
| Fusion–fission hybrids (FFHs) | Most common approach proposes D–T-fueled Tokamak operating at reduced plasma density and optimized to transmute Uranium, Thorium, and/or Actinides, and $^6$Li. Useful energy is obtained from $^{233}$U, $^{239}$Pu and transuranic nuclei fission in conventional power reactors. Conceptually, one fusion reactor could support 25 fission reactors. Attractive features include: (i) magnetic containment less demanding; (ii) incineration of transuranic wastes using fusion neutrons; (iii) reduced neutron damage to reactor; (iv) finer control over transmutation than in fast fission reactors. Non-Tokamak based systems are also proposed. | [48–54] |
| Inertial fusion | Small fuel targets are compressed and ignited explosively by lasers or magnetic fields. Breakeven with D–T fuel is claimed to be close, however, a commercial reactor appears some way off. Working power stations would require manufacturing and injecting targets into the reactor, precise detonation, and waste clearance at >100,000 cycles per day. | [48,55,56] |
| Connected torus | Reportedly at 'Proof of Principle' phase. Though technologically less mature than Tokamaks and inertial fusion, it promises more effective containment and energy extraction and reduced reactor size. This could reduce costs and logistics for reactor development, construction, and modification. | [44,57] |
| Support technologies | Research addresses how to sustainably extract energy produced as fusion neutrons, X-rays, and ions. Themes include: (i) tritium breeding blankets for D–T reactors; (ii) structural materials resistant to neutron damage, e.g., SiC ceramics; (iii) tritium inventory management; (iv) robotics and monitoring systems for maintaining equipment in high radiation zones; and (v) modularization of reactor components for easier maintenance. Engineering challenges require a complementary international fusion material irradiation facility (IFMIF). | [11,58] |

### 3.2. Step 2: Hazards and Step 3: What Might Go Wrong (Scenarios)

Examination of the fusion literature (e.g., references in Table 1) suggests there are many proliferation hazards (Table 2). The concern of Lidsky [18] and Holdren [2] regarding the misuse of civilian power stations persists [20,49,51,59–64]. While the risks from breeding of fissile material are frequently discussed and widely accepted, FFHs appear still under serious consideration [49,65–67]. Tritium manufacture has diverse implications. Proliferation literature shows tritium is essential for modern nuclear weapons and that limiting its availability could be a proliferation control mechanism [68–70].

Tritium is used to boost the explosive power of a fission explosion, making fission bombs smaller and hence more suitable for use in missile warheads. Less than four grams is sufficient for boosting. Unfortunately, even a single DEMO scale Tokamak would manufacture hundreds of kilograms each year. Kovari et al. [71] state that although international control of tritium has been proposed, it is not regulated under International Atomic Energy Agency (IAEA) Safeguards and the risk of diversion would be a major concern.

Tritium and fissile material production arise because D–T fusion efficiently generates fast (14 MeV) neutrons, which can be slowed as desired and tailored to transmutation and neutron multiplication [72,73]. Another potential driver of proliferation is secondary commercial uses for neutrons to produce the fissile isotopes Pu-239 and U-233 [48,72,74,75]. The proliferation risk could appear as soon as fusion experiments succeed in producing a stream of neutrons. This could be long before electricity generation is achieved.

Beyond nuclear material generation, fusion research supports infrastructure and skills for working with nuclear materials and radiation, e.g., radiation resistant ceramics, containment cells, robotics for reactor maintenance, and breeding modules. Neutron generating fusion might be avoided by developing aneutronic ($^3$He and $^{11}$B based) fuels. However, achieving improved containment and lower Triple Product [18] would likely make fast neutron-producing D–D fusion viable, before boron became viable as a fuel.

**Table 2.** Hazards, risks, severity, and likelihood.

| Hazards and Hazardous Events | "What Could Go Wrong" Risk Scenarios | Information and Considerations Suggesting the Risk Scenario Is Plausible and Could Be Severe or Likely Should an MFE Eventuate | Supporting References |
|---|---|---|---|
| High neutron flux | Concurrent production of military fissile material | Concurrent breeding of fissile material and tritium appears easier than breeding of tritium alone. This is the basis for the symbiotic FFH concept. | [2,18,76] |
| Power generating FFHs | Diversion of fissile fuel ($^{233}$U, $^{239,241}$Pu) to military use | A 2100 MWe fusion reactor could breed between 34 and 177 "significant quantities" of fissile material p.a. Fuel generating FFHs could prove less expensive than pure fusion. | [4,50,59] |
| FFHs to transmute transuranic isotopes in waste | Generation of fissile Am and Cm isotopes making novel weapons possible | Waste transmutation produces fissile isotopes as an intermediate step when reducing actinides into short-lived isotopes. | [76–78] |
| Actinides from Thorium FFH Breeders | Breeding of fissile actinides additional to $^{233}$U, especially $^{239}$Pu | Due to decay product radioactivity, $^{233}$U is not an ideal weapons material. However, Th based FFHs could breed $^{234,235,236}$U, $^{237}$Np, $^{238}$Pu, and $^{239}$Pu. Diversion could be limited by adding spent fuel to Th. Alternatively $^{239}$Pu might be produced by adding $^{238}$U. | [60,77,79] |
| Tritium generation *ca* 0.5 kg·day$^{-1}$ per reactor potentially generates excess | Covert diversion of excess to weapons compromises control | Tritium makes small compact fission triggers (and) two- and three-stage thermonuclear weapons possible; "(Tritium) . . . increases the yield of nuclear weapons by a factor of five to ten. Warheads can . . . be built smaller and lighter, while retaining...yield. Most . . . modern nuclear weapons use T, either to boost the yield . . . or . . . combine it with deuterium in . . . thermonuclear weapons". | Quote adapted from [68]; [57,70,80] |
| | Overt military use/supply by civilian fusion power stations | Only 1.5 kg/yr of tritium is required to maintain US START stockpile. Diversion precedent already exists with fission. Tritium breeding is expensive and complex. Cost to breed 1 kg/yr for military purposes is one to six billion US dollars (1999 dollars) over 40 years. | [58,63,68,81,82] |
| | Emergency military reserve | ITER intends tritium inventory minimization (<1 kg) but practicality unclear. Some authors estimate inventories >10 kg. | [9,58] |
| | Supports enhanced radiation weapons | Details for enhanced radiation weapon design unavailable but reports indicate need for quantities of tritium in range of 20–30 g per device. | [63,83] |
| | Diversion of tritium produced for other commerce | To support new reactors and address inefficiencies, breeding blanket ratios exceed 1. A ratio of 1.1 could leave ca 10 kg/yr per power station for other uses. Value of tritium (currently $30 million·kg$^{-1}$) could promote manufacture. | [84] |
| | Reduced control of $^{6}$Li supply for weapons | $^{6}$Li required in abundance for D–T reactors is a controlled material because it is a component of two- and three-stage nuclear weapons. | [80] |
| Levels of containment sufficient for aneutronic fuels | Facilitation of D–T and D–D fusion | Aneutronic fuels (D-$^{3}$He, P-$^{11}$B, $^{3}$He-$^{3}$He) are harder to fuse than D–T. Research could facilitate D–D fusion and abundant neutrons for transmutation. | [85,86] |

**Table 2.** *Cont.*

| Hazards and Hazardous Events | "What Could Go Wrong" Risk Scenarios | Information and Considerations Suggesting the Risk Scenario Is Plausible and Could Be Severe or Likely Should an MFE Eventuate | Supporting References |
|---|---|---|---|
| Reactor components as modules and cassettes | Design style facilitates concurrent military/civilian fusion power station | Reactor components exposed to intense radiation need frequent access and replacement making modularization essential. A second level of modularity is arguably the use of 'pebble'-based blankets. | e.g., [84–90] |
| Exploitation of civilian research capacity | Use of expertise in weapons testing and design? | Most first attempts at nuclear devices by major nuclear powers were rapidly successful indicating given expertise, material, and high-quality machinery, developing weapons is straightforward. Already suggested as occurring with inertial fusion. | [19,63,80] |
| | Application of civilian technology for weapons production | Weapons manufacture needs precision tools and specialized radiation-resistant items. This could be supported by civilian skills. Technological capacity appears a predictor of whether a nation will develop weapons. | [2–4,42,80,91,92] |
| | Enhanced nuclear materials handling via robotics | Constraint on weapons manufacture and use is hazard posed by neutrons and gamma radiation. $^{235}$U and $^{239}$Pu are preferred over $^{232}$Th/$^{233}$U due to $^{232}$U decay leading to $^{212}$Bi and $^{208}$Tl gamma ray emission. | [59,79] |
| | Improved materials for all nuclear devices | The need for fusion power plant materials led to the IFMIF. Material needs are similar to fourth generation fission reactors. There is much overlap in the engineering research supporting fission and fusion reactors and FFHs. | [58,93] |
| Proliferation controls | Breakdown of arms control agreements spirit driven by economics and technology transfer | Examples: (i) production of tritium for weapons by US civilian reactors because it is not a special nuclear material. (ii) Planned transfer of French nuclear power technology following 'normalization' of India's nuclear weapons arsenal though they are non-signatory to the Non-Proliferation Treaty. | [68,81,82,94] |
| Less timely detection of illicit nuclear activities by regulators | Accelerated production of nuclear material and reduced available detection time | Detection of moderate tritium diversion seems difficult. Fissile isotopes more easily detected, but current international nuclear regulatory regime is underfunded and has limited access. Greatest reported vulnerability is diversion of civilian nuclear technology for military uses. | [63,94] |
| Mature Fusion Economy | Increased size of proliferation control task | Management of proliferation more difficult because of scale of MFE e.g., monitoring. | See discussion |
| | Probability of regulatory failure increases with time available | Conflicts over the past 77 years suggest nuclear war likelihood is rare but not negligible. *An MFE would embed fusion power risks in societal infrastructure potentially permanently.* | [95] |

**Notes:** Assessment and author conclusion in *italics*. FFH, fusion–fission hybrid; MFE, mature fusion economy; IFMIF, international fusion material irradiation facility.

### 3.3. Step 4: Likelihood and Severity

A range of scenarios were identifiable (Table 2, column 3) sufficient to evaluate (i) whether proliferation, in the eventuality of an MFE, was plausible, and (ii) why the 'consequences' could be very destructive.

#### 3.3.1. Likelihood

Efforts have been made to quantify the likelihood of a proliferation event and drivers relevant to fusion risks [38–42,92,96]. These analyses show that while nations capable of developing arsenals do not necessarily do so, there is still a high probability they will once capacity exists, and the decision is taken. Montgomery and Sagan [41] (Table 1) estimated that, of 25 nations that have considered acquisition, the numbers 'acquiring,' 'pursuing,' and 'exploring' nuclear arms were worryingly high (10, 6, and 9, respectively). They also indicate the acquisition period is 3–15 years, while Rauchhaus's [42] data suggests a global acquisition rate of 1.4 per decade. Conversely, of countries acquiring weapons, only South Africa has dismantled its stockpile. The main determinants of whether a nation will research and develop a nuclear arsenal appear to be technology and expertise availability, security and national prestige [92]. Overall, the statistics suggest that under-pressure nations will often acquire nuclear arms if they have the technical capacity, while the events of 1945 indicate repeated use if circumstances are deemed to warrant it.

Two other factors affecting likelihood are time and industry scale. Put simply, the larger an MFE and the more time elapses, the greater the likelihood of proliferation [40]. With respect to time, fusion's proponents discuss resource availability over millions of years [8,97]) indicating likelihood across hundreds of years and longer should be considered. With respect to scale, in 2007 and 2009 it was suggested by Dunn [94] that managing the spread of nuclear technology was problematic even in 2009 when operating capacity from fission was approximately 370 GWe. (It is approximately the same in 2021 [28] (Figure 6)).

An indication of the future scale of this challenge can be obtained from model MFEs and the trend in global energy demand. Several authors [75,98–102] estimate an industry in 2100 of 1000 to 3600 GWe based on DEMO-type power stations. Growth in global energy demand resulting from growing consumption per person and growing population could increase this substantially, resulting in an electricity/hydrogen based MFE with many thousands of DEMO-scale power stations.

#### 3.3.2. Severity

Re-examination of the nuclear winter scenario [103–105] with modern climate models indicates that catastrophic climate disruption could result from a regional war involving 'only' 100 intermediate-sized weapons [106–109]. Thus, the 'severity' of weapons control breakdown could be catastrophic for global human and environmental health, even for an 'intermediate'-scale war.

### *3.4. Step 5: Assembling the Risk Scenarios*

Some risks in Table 2 are a concern per se, e.g., FFH power stations as a source of fissile material. Another concern is the weakening of barriers to nuclear weapons acquisition (for examples, see [96]). To explore how fusion technology might impact on such barriers, we constructed a cause-and-effect analysis (Figure 1) based on how risk likelihood and severity (Table 2) could impact the proliferation process. Our assessment suggests that an MFE could compromise proliferation barriers and non-proliferation management, each in 12 ways. Further, even if all current international conflicts were resolved, an MFE could still potentiate risk in the distant future for reasons discussed in Hellman's [40] analysis: (i) because of increasing time available for hazardous events; (ii) the large number of reactors and misuse modes; and (iii) the number of nations likely to ultimately acquire fusion energy technology who could come into conflict.

Fusion's proponents frequently promote the potential in energy production and estimate radioactive waste management requirements for timespans of hundreds to thousands of years [101,110–112]. We suggest that such analyses must now include comprehensive assessment of proliferation risk, consistent with standard RA principles, task categories and tools [35,113]: e.g., involvement of all stakeholders and consideration of both near-term and the far future.

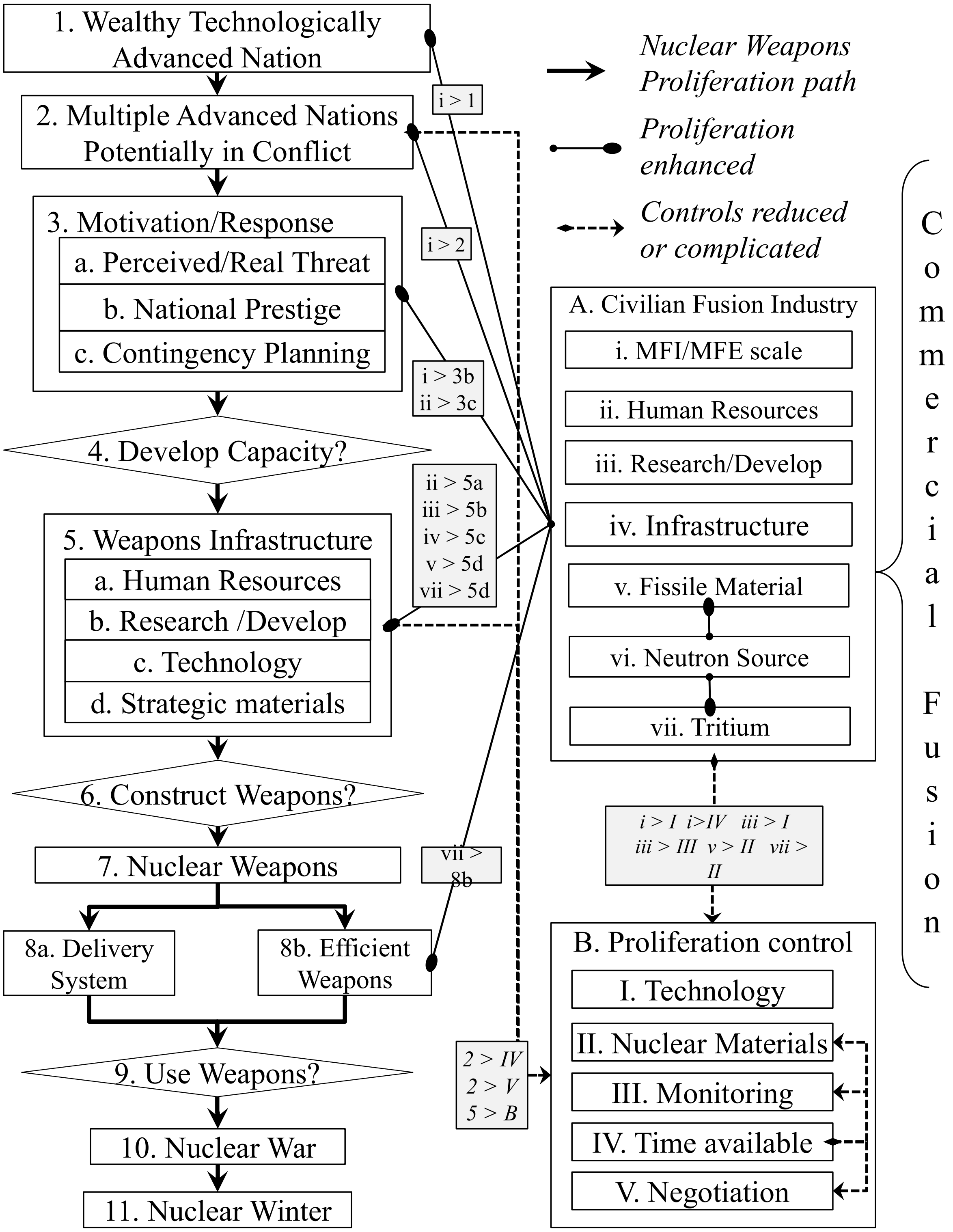

**Figure 1.** Proliferation risk pathway showing critical points where commercial fusion could increase the risk of a nuclear winter.

### 3.5. Uncertainties

A complete RA also identifies analysis uncertainties and limitations. Our analysis does not redress policy development gaps and is more of an initial exploratory scoping analysis which employs RA tools rather than a full RA per se. As noted initially, it is literature-based rather than the outcome of diverse team-based stakeholder inputs. Nevertheless, we suggest it is an essential first step in that it systematically outlines the potential links between an MFE and future weapons proliferation and how they may interact. Furthermore, it shows a clear way forward. This is the broad application of RA [35,113] to the development of fusion energy policy as well to operational concerns.

## 4. Discussion, Conclusion, and Step 6: Risk Management and Energy Policy

To date, proliferation focused risk assessment and management has involved the exploration primarily of engineering options for reducing the potential for fissile material production via fusion and hence the likelihood of proliferation [49,59,62,64,102,114]. However, it is unclear whether these technology-based controls would be effective beyond briefly delaying proliferation. Further, these options do not address economic and temporal scale and political uncertainties, especially:

(i). How will nation states and their relationships evolve in a crowded and resource-constrained future?
(ii). How will nations respond to disputes in coming centuries when each possesses an MFE?

It is puzzling and concerning that recent energy policy discussions and development on this long-term proliferation issue are so limited. Fusion power research has been funded over the decades by governments worldwide to the tune of billions of dollars. Yet the implications for energy policy beyond a promised unlimited energy supply seem inadequately critiqued using modern approaches that are designed to be balanced and comprehensive, such as RA. This is despite sufficient issues for consideration being identified quite early by Holdren [2–4] and Lidsky [18], followed up more recently by Franceschini et al. [21], Schmidt et al. [22], Caravannis et al. [23], and others. Subsequent to Holdren's and Lidsky's analyses, the United States has confirmed, by its decision to use a civilian reactor to supply tritium for weapons, that no solid dividing line exists between civilian and military nuclear power [68,81,82]. The significance of tritium in nuclear weapons construction has been publicly known for some time [68,69]. Yet, to judge by recent overviews [20,21,23,63,102], little progress has been achieved.

A possible reason why scholars have not extensively considered the proliferation potential of fusion power and policy implications may have been Holdren's [3] hypothesis, published in 1980, that "(in) 30 years . . . the international weapons proliferation problem will be well on its way to political solution, or every interested country will have gotten fission bombs by other routes". The past 42 years suggest this hypothesis is incorrect and technology availability is still an important moderator of proliferation likelihood.

We conclude that in the long term, an MFE could pose a great proliferation risk, and this possibility needs timely policy consideration. The risks of an MFE cannot be solely extrapolated from assessments of single-fusion reactor risks [20]. These implications contrast with the image of fusion power as a 'clean and green' solution to the energy/climate change crisis. As it is preliminary, our analysis should only be seen as a first step towards a comprehensive qualitative, quantitative, and systematically integrated risk assessment.

Though we were unable to assign specific probabilities to failure at each node (Figure 1), such a quantitative analysis should be possible when or if data could be assembled. Suitable risk assessment tools would likely include a greatly expanded cause and consequence analysis [35] (Tool B.5.5) and Bayes Nets and influence diagrams [35] (Tool B.5.3), [115], which offer a flexible approach to exploring scenario probabilities where likelihood is unclear.

We recommend, simultaneously with the expansion of a risk assessment, an international external review [23] of the safety, proliferation risks, and environmental and health impacts of different future reactor designs, both as individual reactors and as the basis of an MFE. Review committees should be broad in composition—with expertise in energy science and technology broadly, nuclear weapons proliferation and arms control, energy economics, international law, and ethics—and not be dominated by proponents of fusion. We also recommend that any future commercial fusion reactors and, in particular, tritium production, be subjected to IAEA Safeguards and that fusion reactor designs should be required to minimize tritium production [71]. We support the suggestion [21] that the experimental ITER reactor be used as a test site for exploring options on how to safeguard future fusion reactors and how to improve tritium accounting.

Finally, lest this assessment itself be seen as comprehensive rather than a first illustrative step toward a comprehensive assessment, we flag below for interested readers other matters we have yet to touch on. These, in effect, provide a further RA checklist.

ISO 31010 tools [35], which can be seen from the standards' summary as having potential, include those for control analysis, such as the bow-tie approach (Tool B.4.2); consequence and likelihood assessment tools, such as human reliability analysis (Tool B.5.8) and business impact analysis (Tool B.5.4); and tools for the analysis of dependencies and interactions, e.g., causal mapping (Tool B.6.1). Beyond ISO, there are further tools such as those developed for system risk analysis [116] and scoping global catastrophic risk [117]. Given the centrality of energy systems to future human society, the complex question of what constitutes 'acceptable risk' needs itself to be considered in a very broad context [118].

Separate from our scoping of the literature, we identified these further heads of consideration:

- Involvement of the wider community as part of communication and public consultation [119]
- Interested but marginalized disciplines, such as the ecological economics community ([120])
- The legal community, given the already vast literature on nuclear power and weapons regulation [119,121–125]
- The ethics of energy option selection [119]
- Commercialization and resource availability [116,126]
- Clandestine proliferation [127]
- Lateral proliferation [128]

Now is the time to ensure that military and future civil uses of fusion energy are kept separate. Of course, the same applies with greater urgency to fission energy. Negotiations are needed to bring nominally non-military uranium enrichment, reprocessing of spent fuel, and tritium production under international control.

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