The Nonproliferation Review

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/rnpr20

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Published online: 02 Dec 2013.

To cite this article: Giorgio Franceschini, Matthias Englert & Wolfgang Liebert (2013) Nuclear Fusion Power for Weapons Purposes, The Nonproliferation Review, 20:3, 525-544, DOI: 10.1080/10736700.2013.852876

To link to this article: http://dx.doi.org/10.1080/10736700.2013.852876

NUCLEAR FUSION POWER FOR WEAPONS PURPOSES
An Exercise in Nuclear Proliferation Forecasting

Giorgio Franceschini, Matthias Englert, and **Wolfgang Liebert**

Fusion reactors have the potential to be used for military purposes. This article provides quantitative estimates about weapon-relevant materials produced in future commercial fusion reactors and discusses how suitable such materials are for use in nuclear weapons. Whether states will consider such use in the future will depend on specific regulatory, political, economic, and technical boundary conditions. Based on expert interviews and the political science literature, we identify three of these conditions that could determine whether fusion power will have a military dimension in the second half of this century: first, the technological trajectory of global energy policies; second, the management of a peaceful power transition between rising and declining powers; and third, the overall acceptance of the nuclear normative order. Finally, the article discusses a few regulatory options that could be implemented by the time fusion reactors reach technological maturity and become commercially available; such research on fusion reactor safeguards should start as early as possible and accompany the current research on experimental fusion reactors.

KEYWORDS: Nuclear fusion; nuclear proliferation; safeguards; tritium; plutonium

Whether nuclear fusion will become a concrete energy option in the twenty-first century is still a matter of debate. While skepticism on the feasibility of fusion power persists, the scientific community involved in the development of this new energy source is confident that the first commercial reactors will go online a few decades from now.[1] If fusion energy becomes a concrete global energy option around the middle of this century, a number of regulatory issues will have to be addressed, mainly with respect to the safety and environmental impact of this emerging technology.[2]

An aspect often overlooked in the technology assessment and the theoretical debate on nuclear proliferation is the possible military dimension of fusion power, especially in its more promising version for commercial applications, the magnetically confined reactor.[3] Moreover, little attention has been given to the political conditions enabling (or constraining) such an option. As a consequence, there is practically no ongoing debate concerning the technological and regulatory options to prevent nuclear fusion from being used in a non-peaceful context.

Routledge
Taylor & Francis Group

Nonproliferation Review, 2013
Vol. 20, No. 3, 525–544, http://dx.doi.org/10.1080/10736700.2013.852876

In this article, we address both issues by quantifying the proliferation potential of commercial fusion with numerical simulations and by assessing fusion-based proliferation scenarios through expert polls and the political science literature.

Since the success of the "grand fusion bet" to provide safe, reliable, and affordable electricity at some point in the future cannot be taken for granted, the ideas put forward in this article are inevitably speculative. Still, nuclear fusion research enjoys significant financial support worldwide, and if it can overcome a number of its major obstacles in the following decades, fusion could well become a widely available technology in the second half of this century. In light of this, it is reasonable to suggest some initial ideas on how to prevent its military use at this early stage. Prospective technology assessments show that anticipatory interventions in designing and regulating new technologies are generally more efficient when conducted at an early stage of the research and development (R&D) process of an emerging technology.[4] With the International Thermonuclear Experimental Reactor (ITER) under construction in France and some ambitious plans to build laser-driven fusion plants in the United States within the next decade, the time has come for a comprehensive discussion (regarding both theory and practice) of the military dimension of fusion reactors.[5]

Nuclear Fusion: Past, Present, and Future

First initiated in the 1950s shortly after the development of thermonuclear weapons (which combine nuclear fission and fusion), civilian research on nuclear fusion has witnessed both periods of strong political support as well as prolonged phases of skepticism and neglect.[6] Today, new hopes for a breakthrough lie primarily with the ITER project, a multibillion euro joint venture funded by the European Union, the United States, Japan, Russia, China, South Korea, and India. The ITER project foresees the construction of a larger-scale 500 megawatt experimental reactor by 2017, which is viewed as a first step toward the long-term goal of commercial fusion power. It will be followed by a series of demonstration reactors (DEMO) in the 2030s and beyond. If ITER and DEMO prove that fusion power generation is both technologically and economically viable, the first commercial fusion power plants could go online by the middle of the twenty-first century.

The final, approved design of these reactors does not exist, but a number of conceptual studies have already been undertaken that outline some technical parameters and basic features of future power reactors based on ITER and DEMO technologies. The European Fusion Development Agreement (EFDA) published a rather detailed "Power Plant Conceptual Study" (PPCS) in 2006.[7] On the basis of key figures provided by this and other studies, we calculated the amounts of material relevant to nuclear weapons (tritium and fissile material) that a commercial fusion power reactor might yield during its operation.[8]

Nuclear Fusion in a Military Context: The Numbers

A typical first generation fusion power plant is represented by the PPCS-A model, which is described in some detail in Appendix A. The key figures for this type of plant are remarkable with respect to weapon-usable material.

First, several kilograms (kg) of tritium are in the inventory of the plant at any given time. Also, daily production and consumption of this special hydrogen isotope amounts to several hundred grams, whereby the production rate will always exceed the consumption rate by a few grams per day. Boosted nuclear weapons rely on only a few grams of tritium. As it currently stands, it is infeasible to detect diversions of this scale in such an environment.[9] Some simulations carried out for ITER claim that, as of today, even the loss of 100 grams of tritium could not be detected with an acceptable (90 percent) probability (see Appendix B).

Second, the plants under study, although not designed for fissile material production, could be reconfigured (i.e. loaded with uranium) in an appropriate manner and yield substantial amounts of plutonium (Pu). Depending on the uranium loading, the annual plutonium production could vary from a few kilograms to several hundred kilograms or even several tons (see Appendix C).

Third, calculations to analyze the isotopic composition of the plutonium produced in the reactor reveal its suitability for weapon purposes: the plutonium consists of well over 90 percent of Pu-239 with very limited contamination by higher plutonium isotopes and Pu-238. This result does not change significantly for higher irradiation times (i.e., several years) and thus indicates that plutonium produced in a fusion reactor like PPCS-A is well-suited for weapon purposes, regardless of the irradiation time.[10]

Fourth, the amount of natural or even depleted uranium necessary for the production of a significant quantity of 8 kg of plutonium can be as low as several hundred kilograms. This is a unique characteristic compared to fission reactors, where more than roughly 10 metric tons of natural or enriched uranium are required to operate the reactor and to achieve criticality.[11] Additionally, the final concentration of the produced plutonium in the uranium source material can be much higher than in a fission reactor. This circumstance reduces the amount of required source material (i.e., uranium), the amount of heavy metal to be reprocessed to extract the plutonium, and the size of a reprocessing facility.[12] Since the radiation levels of the irradiated uranium discharged from a fusion reactor are typically lower than the corresponding levels of fission reactor fuel, requirements for radiation protection are also reduced. Therefore, clandestine operation of a reprocessing facility would be easier than a plant handling fission reactor spent fuel. A simple, small-scale reprocessing facility would be sufficient to produce several significant quantities of plutonium per year from irradiated uranium discharged from the fusion plant.

Nuclear Fusion in a Military Context: The Experts

According to the EFDA, the first commercial fusion reactors are not expected to go online before 2050, and the eventual dissemination of fusion power plants around the globe will occur only in the second half of the twenty-first century.[13] At the same time, several energy analysts doubt that commercial fusion power will *ever* play a role in any future energy mix because of its almost prohibitive technological complexity.[14]

Against this backdrop, any assessment on the military dimension of fusion power will be mostly speculative. We tried to address this almost impossible question in expert discussions and in an opinion poll conducted in 2010 and 2011 utilizing the Delphi method.[15] The results of the workshops and the poll ("Delphi study") were rather sobering with respect to our research focus: most scholars we interviewed acknowledged the potential of fusion reactors for fissile material production and tritium withdrawal, while simultaneously doubting that nuclear fusion will play a significant role in future proliferation challenges. Still, for some interviewees, it seemed natural that a nuclear weapon state might consider withdrawing small quantities of fusion reactor tritium for its military program instead of building (or maintaining) dedicated tritium facilities for this purpose. Furthermore, since the *potential* of fusion reactors to breed several hundred kilograms of high-grade weapon-usable plutonium per year with very low source material requirements was remarkable, some experts were sympathetic to the idea considering appropriate risk mitigation measures regarding fusion power.

As a rule, the Delphi experts stressed the difficulty of predicting nuclear trajectories along timescales that characterize the slow emergence of commercial nuclear fusion. As a matter of fact, widely available fusion power might only become a "geopolitical" reality in the second half of this century, or at a time when the economic, technological, demographic, normative, and military boundary conditions no longer resemble today's distribution of hard and soft power.

Nuclear Fusion in a Military Context: The Theory

Nevertheless, there is a rich and promising body of political science literature that links some of these "boundary conditions" to the complex process of nuclear decision making.[16] Some of the most recent literature on this issue even ventures so far as to attempt to *forecast* future nuclear weapon trends based on some of these theoretical and historical insights.[17] Hence, when asking under what circumstances nuclear fusion might be used in a military context, it is certainly useful to study this growing body of nuclear scholarship.

Unfortunately, there are three limitations to applying these theoretical insights to an emerging technology such as fusion: first, the predictive range of most proliferation forecasts is typically limited to a decade, and not several decades as commercial fusion power would require. Second, most studies focus almost exclusively on the phenomenon of *horizontal proliferation* (the nuclear weapon ambitions of a non-nuclear weapon state) and hardly address phenomena of *vertical proliferation*, i.e. quantitative and qualitative improvement of existing arsenals. And third, reviewing the rich forecasting literature does not give a consistent picture, since most findings are contested. Any statement about future use of fusion reactors in a military context—even if firmly grounded in some theory—will therefore remain controversial.

The fundamental division within the different theoretical approaches lies in the debatable role of nuclear technology in the proliferation puzzle.

Supply Side

One school of thought argues that the very availability of nuclear technology represents a proliferation risk. In its most basic version, this so-called "supply side" school does not distinguish between specific nuclear technologies, and hence cautions against the spread of *all* nuclear technologies (and thus, implicitly also against nuclear fusion). Such a skeptical view of nuclear technology has been put forward both by policy scholars such as Texas A&M University's Matthew Fuhrmann as well as some anti-nuclear grassroots movements.[18] According to this logic, the dissemination of fusion power in the second half of the century would inevitably encourage the temptation to explore the military dimension of this emerging technology. With respect to nuclear fusion, it seems obvious to speculate that the temptation would stem from the remarkable production capacity of fissile material—both in terms of quantity and quality—and the simultaneous availability of boosting material (tritium), that the operation of fusion reactors would entail. Still, Fuhrmann's argument does not rely on any specific characteristics of nuclear technology, such as its suitability within a weapon program, but rather cautions against *any* civilian nuclear endeavor. In this light, the spread of commercial fusion might fuel nuclear weapon proliferation, simply because fusion is a nuclear technology.[19]

Other scholars within the supply-side camp argue along similar lines, but distinguish between "ordinary" and "sensitive" nuclear technology. According to Georgetown University's Matthew Kroenig, only the availability of *sensitive* nuclear technology increases the risk of proliferation due to its intrinsic dual-use characteristics.[20] Kroenig defines uranium enrichment, spent fuel reprocessing, nuclear weapon designs, and weapon-grade fissile material as sensitive items, but not the availability of research and power reactors. In this sense, fusion reactors would not qualify as "sensitive" nuclear technology, since a proliferator would still need a reprocessing plant to extract the plutonium eventually produced in the reactor, and tritium, the fusion reactor fuel, is not considered "sensitive" by the author. Thus, following Kroenig's logic, the diffusion of fusion reactors would not pose a genuine proliferation threat as long as "truly sensitive" reprocessing technologies do not spread simultaneously.

Demand Side

A variety of scholars do not accept the basic tenets of the "supply side" theories since they suppress the most substantial element in nuclear decision making, namely the human factor (and not the factor of technology). Instead of focusing on the intrinsic properties of a technology, "demand side"-oriented scholars emphasize "motivational" (and thus political) aspects when explaining nuclear history and forecasting nuclear futures. What matters to them are the security perceptions, the interests, the status claims, and the normative premises of the players involved in the decision-making process. According to most of these scholars, the mere availability of nuclear technology (be it fission or fusion) does not allow anything to be inferred about the demand for nuclear weapons within a state. Rather, within the "demand side" camp, the focus shifts on security aspects (the realist school of international relations, or IR), nuclear preferences of influential societal groups (the liberal school of IR), or ideational factors like norms and identities (the constructivist school of IR). These variables are considered to be key factors for the emergence—and sometimes the disappearance—of nuclear weapon ambitions, according to "demand side" theorists. The implications for nuclear fusion are threefold: first, realists would consider nuclear fusion reactors as militarily relevant if their use in a non-peaceful context proved to be effective, especially in counterbalancing (perceived) security gaps and emerging threats in the future. Secondly, liberals tie the military use of fusion reactors to the emergence of appropriate domestic lobby groups advocating exactly such a non-peaceful use of the technology. Finally, constructivists would refer to the trends in the normative discourse on nuclear energy (and especially on nuclear fusion) when assessing the likelihood of fusion power being used in a military context.

Between Supply and Demand: A Third Way to the Bomb

University of Texas-Austin's Itty Abraham offers some middle ground between the "supply-side" and the "demand-side" approach. Abraham argues that government leaders might not have strong opinions on nuclear power or nuclear weapons when embarking on a (civilian) nuclear program, but may be unconsciously paving the way for a weapons option.[21] They simply provide the physical and organizational foundation for a "strategic enclave" (i.e. a "pro-bomb" interest group within the state), which then waits for an opportune moment to push through its interests. Moreover, several analyses of former nuclear programs emphasize that the international and domestic balance of power—as well as the international normative context—can change over time, and to the same extent that they can temper the appetite for the bomb at some point in time, they could also fuel the demand for nuclear weapons at another. These historical insights caution against the spread of fusion technology as a widely available power source. Indeed, following Abraham's logic, the dissemination of nuclear technology (fission *and* fusion) represents a ticking proliferation risk, regardless of the geopolitical (i.e. security), domestic, or normative context accompanying the diffusion of this technology.

Critical Proliferation Triggers

When considering the military dimension of fusion power in the future, these preliminary reflections suggest that it is necessary to speculate about the boundary conditions that will accompany the emergence of this new energy source. The chances of non-peaceful uses of fusion will therefore depend on future trends in energy policy (according to supply-side theoreticians), security policy (according to realists), domestic politics (according to liberals), international dynamics of nuclear norms (according to constructivists), or an appropriate combination of supply and demand factors (Itty Abraham). Table 1 gives an overview over these theoretical approaches.

TABLE 1
Framework conditions favoring the non-peaceful use of fusion, according to different theoretical approaches.

Theoretical classification	**Proliferation trigger**	**Critical long-term trends (2050 and later)**	**Factors favoring non-peaceful uses of fusion**
Supply-side	Availability of nuclear technology (Fuhrmann)	Nuclear renaissance	Large availability of fusion technology
	Availability of *sensitive* nuclear technology (Kroenig)	Spread of *sensitive* nuclear technology	Availability of fusion and reprocessing
Demand-side	Security (Realism)	Power transition/ readjustment of alliances	Military use of fusion efficient for counterbalancing of threats
	Domestic politics (Liberalism)	Changes in the domestic balance of power	Domestic lobby favors use of fusion for non-peaceful purposes
	Normative order (Constructivism)	Future of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT)	Norm erosion of peaceful nuclear fusion
Middle ground	Supply and demand factor(s) (Abraham)	All of the above	Availability of fusion and demand for its non-peaceful use

Combining Numbers, Experts, and Theories

Numbers, experts, and theories do not give a coherent picture of the risks associated with the non-peaceful use of commercial fusion reactors. Numerical simulations show that these reactors have a remarkable proliferation potential with respect to the quantity and quality of weapon-usable material they could provide. Thus, if their operation and maintenance were to become economically and technically manageable, their use in a non-peaceful context should not be discarded, as fusion reactors display a number of "advantages" over fission reactors of similar size and power with respect to their fissile material production capabilities (see Appendix C).

At the same time, the expert discussions, as a rule, dampened the worries of such a scenario and based their skepticism on two arguments. First, nuclear fusion is a demanding technology and will probably remain confined to a restricted user circle of advanced industrialized states for quite some time (most likely the members of the ITER consortium); these early adopters of nuclear fusion are either established nuclear weapon states, or non-nuclear states with—supposedly—a limited appetite for the bomb. But the main reason to dismiss nuclear fusion reactors as a meaningful military option—according to most experts—is that current technologies to produce weapon-grade fissile material (uranium enrichment and reprocessing of spent fuel from fission reactors) are technologically less demanding and already in use in several advanced nuclear energy-producing states. Thus, the military use of fusion reactors for fissile material production, according to most experts, represents a low-probability scenario restricted to a small number of states. Rather, these materials would be produced through established technologies, and the contribution of fusion to a weapon program would be limited to the possible provision of tritium.

This finding was consistent with a theoretical risk assessment based on status quo assumptions. But, at the same time, the various theories did not preclude non-peaceful uses of fusion energy for the future, under the assumption that some decisive framework conditions might change over the next few decades, for instance: the energy mix, and especially the nuclear fusion share within this mix (supply-side); the (worsening) great-power relationships as a consequence of international power shifts (realism); the domestic balance of power in some states (liberalism; or Abraham's middle ground); and the normative fabric regulating nuclear matters (constructivism).

Supply-side theories suggest that the chances of using nuclear fusion in a military context grow with the availability of the technology itself. From the present-day perspective it seems natural that a state with both fission and fusion infrastructure might resort to more established fission technologies for a potential military endeavor. Alas, states with no fission but only fusion power might base their weapon ambitions on the latter, according to a crude supply-side reading of nuclear proliferation.[22] It stands to reason that fusion technologies are probably more difficult to handle in a military program, but our simulations show that they are inherently as dual-use capable as fission reactors. As a consequence, supply-side theorists rightly point out that any state in possession of such a reactor effectively has a latent proliferation potential and, if it operates a reprocessing plant, a remarkable break-out capability—both from the NPT or from a world without nuclear weapons.

The realist school of IR suggests another focus for assessing the military dimension of nuclear fusion: the possible shifts in power in the international system that are anticipated for the twenty-first century. With its narrow focus on military capabilities, a realist reading of international politics might suggest that, behind the background of a global power transition process, China and India, the two emerging giants in Asia, will try to establish a new balance of power with the former superpowers of the Cold War. Especially in the nuclear field, one can expect that "Chindia" will strive for some sort of strategic parity with the United States and Russia, the nuclear arsenals and fissile material stockpiles of which are roughly a hundred times larger than those of Beijing and Delhi today.[23] Thus, as viewed from a realist perspective, unless Washington and Moscow draw down their nuclear stockpiles drastically within the next few decades, both China and India are expected to increase their nuclear arsenal and their associated material stocks. Since both countries are ITER members and will be among the first users of commercial fusion, they could—in principle—also resort to their fusion reactors to breed part of the necessary weapon-usable material—plutonium and tritium—within this hypothetical catch-up process.[24] This scenario is certainly more grounded in neo-realist theory than on observable facts today, as neither Beijing nor New Delhi seem to follow the strategic trajectory predicted by the neo-realist school, and since both states already have an established nuclear infrastructure at their disposal for (moderate) weapon-grade fissile material production.[25] Still, whereas some realists attempt to explain the current "under-balancing" of the emerging powers, other studies highlight that the actual power transition (i.e., China—and eventually India—overtaking the United States as the primary economic driver) will only occur by the middle of the century.[26] Thus, the rebalancing dynamic accompanying this transition might still lie ahead of us, and within this geopolitical readjustment process the realist logic would certainly not exclude the possibility that new hegemonic powers might turn to bulk production of nuclear weapons at some point in the future. And, if fusion is the most efficient technology to turn a given mass of uranium into weapon plutonium—as our simulations suggest—it could certainly be an interesting military technology within a program aimed at mass production of weapon plutonium, especially for a country with limited uranium resources such as India.

The realist school of thought cautions not only against the rising powers and their growing military ambitions, but also against the effects of declining powers on their security alliances. If Washington's ability to provide credible security guarantees is questioned among its partners, realism would not exclude the possibility that some US allies might consider developing their own nuclear deterrent. This primarily holds for Japan, Taiwan, and South Korea, which face dramatic geopolitical changes in their region with the rise of China.[27] But it also applies to US allies in Europe to a lesser extent. Several US allies could have fusion reactors at their disposal in a few decades, and some could operate them in conjunction with large processing plants (e.g., Japan and maybe South Korea); additionally, in the second half of the twenty-first century, fusion might be the only commercial nuclear technology used in some other US allied states such as Germany, Italy, and possibly Japan. As mentioned above, a fleet of commercial fusion reactors would give these states direct access to substantial amounts of tritium and the production capability of remarkable amounts of weapon-grade fissile material. Hence, a realist reading of international relations would recognize that some of these states—especially under the impression of a weakening US nuclear umbrella—might resort to some self-help strategies and consider the military potential that lies dormant within their civilian fusion program.

Constructivists argue that nuclear weapon ambitions correlate with the global normative discourse accompanying these weapons. Within this discourse, the NPT is certainly the central element, since it is believed to have been instrumental in persuading a number of advanced nuclear states to either abandon their weapon program or to stick to a strictly peaceful nuclear program.[28] The treaty is now more than forty years old, and it is not certain whether it can survive another forty years and thereby regulate nuclear-related matters beyond 2050; in recent years, several experts have warned against a growing number of challenges that emanate both from outside and inside the NPT, threatening the treaty's future.[29] In the case of the treaty collapsing, constructivist scholars would not exclude a possible return to a nuclear world of anarchic self-help, which characterized the pre-NPT nuclear age; in such a world, most nuclear programs would have a military dimension, and the dividing line between peaceful and non-peaceful nuclear technology, and between nuclear weapon states and non-nuclear weapon states would increasingly lose its meaning. Thus, if nuclear fusion is launched in an era of nuclear anarchy, its military application—at least as a tritium source—seems logical for many states.

If the NPT nevertheless persists as the major bulwark against nuclear proliferation, constructivists would suggest focusing primarily on states already possessing nuclear weapons as candidates for fusion-based military ambitions (in an *ideal* sense, constructivists see non-nuclear armed members of a robust NPT as disinterested in nuclear weapon acquisition, since they internalized the norm of nuclear abstention). In an NPT-world, constructivists would therefore focus mainly on scenarios of *vertical proliferation*—the increase of nuclear weapons by existing nuclear weapon states.

Abraham's middle ground approach decouples the decision to pursue nuclear weapons from the launch of a civilian nuclear fusion program. It is therefore plausible that a state might develop a *sudden* nuclear weapon ambition after many years of peaceful nuclear fusion uses, and that it might try to base such an endeavor on its existing nuclear fusion infrastructure rather than building dedicated fission-based facilities from scratch.

In sum, our analysis suggests that possible proliferation candidates basing their endeavor on commercial nuclear fusion extend beyond the current list of "states of concern." This conclusion is also summarized in Table 2, which describes what nuclear proliferation might look like according to the previously explained theories and experts.

TABLE 2
Most likely proliferation candidates using fusion (for physical or virtual arsenals), according to experts and according to different theoretical approaches.

According to	More precisely	Most likely proliferation candidates using fusion
Experts	From Delphi poll and three expert workshops	Advanced industrial states, typically ITER members
Supply-side theories	Fuhrmann version	Fusion-only states
	Kroenig version	Fusion-only states with reprocessing capabilities
Demand-side theories	Security (Realism)	Emerging powers; Insecure US allies ("waning nuclear umbrella")
	Domestic politics (Liberalism)	Any nuclear fusion state with appropriate nuclear weapon lobby
	Normative order (Constructivism)	Nuclear weapon possessors (NPT world) None (nuclear weapon-free world) Many (nuclear anarchy)
Middle ground theories	Supply and demand factor(s) (Abraham)	Any nuclear fusion state facing changes in the domestic balance of power, in its security, or normative environment.

Conclusions

Nuclear fusion is likely to enter the arena along with two major global trends: a probable power transition in the international system and a possible nuclear renaissance in the context of a carbon-restricted global energy turnaround. These trends will unfold amidst the uncertainty of the NPT's future, which provided the foundation of the nuclear order over the last few decades.

Since the breakthrough of nuclear fusion might only occur within the second half of this century, it is legitimate to address regulatory issues concerning the military-technological dimension. Several arguments speak in favor of engaging in some anticipatory governance of this emerging technology.

In one instance, short of inhibiting the diffusion of a promising technology (as supply-side theories suggest), anticipatory insights into the potential of commercial fusion gives designers the opportunity to strengthen the proliferation resistance of future reactors. Since fusion reactors are still in the research and development (R&D) phase and since commercial reactors have not been specified in complete detail, there is still plenty of maneuvering room to optimize the design in a way that would maximize its intrinsic proliferation resistance. Our simulations have shown that several factors make breeding fissile material in a tokamak (see Appendix A) fusion reactor more difficult: the cooling requirements of the machine, the tritium production in the blankets, and the solubility of the fertile material in the blanket solution.[30] Commercial reactor developers can therefore incorporate these findings and further insights of the nonproliferation community at this early stage in the design process. At the same time, considerations from the supply-side school would suggest avoiding fission-fusion hybrid designs. Several states, including the United States, have actually renewed their interest in these designs.[31] But fission-fusion hybrids would *optimize* the fissile material production capacity of a fusion reactor, and—although an interesting concept from the point of view of energy economics—would be highly problematic from a nonproliferation perspective.

Secondly, realist logic suggests that, in order to avoid new nuclear arms races, it is advisable that declining and rising states establish a new balance of power at the lowest nuclear threshold possible. Thus, Russian and US arsenals and fissile material stocks should be reduced drastically in the next few decades, and both rising and declining nuclear weapon states should accompany this process by capping their arsenals and fissile material stocks in such a way as to achieve a gradual and steady reduction in nuclear weapons and their associated material stocks. Since nuclear weapon dismantlement and fissile material elimination proceeds at a rather slow pace, such a reduction process should start immediately and should not be postponed until a power shift actually transpires and nuclear fusion becomes a widely available commercial power source. If, on the other hand, the projected power transition took place in the context of large nuclear disparities and deployed commercial fusion devices were able to provide large amounts of plutonium and tritium in almost no time, the realist logic would imply that the exclusively peaceful use of this new power source cannot be guaranteed.

Lastly, to restrict fusion power to exclusively peaceful uses, constructivist considerations call for the preservation of normative barriers against nuclear weapons, which, in practical terms, translates to the preservation and deepening of the NPT and its associated safeguards culture. In this context, there can be no doubt that commercial fusion reactors should be subjected to International Atomic Energy Agency (IAEA) safeguards.[32] Before regular safeguards can be applied, two preliminary steps must be carried out. Firstly, safeguards agreements and IAEA glossaries must be amended in order to include fusion technology within the IAEA regulatory frameworks.[33] Secondly, fusion reactor safeguards must be designed and specified in order to allow their implementation in a number of fusion power designs. Whereas the former task is not urgent, the issue of safeguards design should be taken up as soon as possible. The experience accumulated over more than half a century by the IAEA and the European Atomic Energy Community suggests that timing is critical when designing safeguards for nuclear technologies: the most effective, minimally intrusive safeguards are usually achieved when they are conceived and designed concomitantly with the R&D process of the technology itself. Hence, because fusion power will remain in a progressive R&D process over the next few decades, it would be advisable to accompany this process with a parallel program aimed at incorporating safeguards into the design of the machine. Moreover, the costs of such a "safeguards by design" process would be negligible compared with ordinary fusion research budgets. As the ITER reactor is slated to test a number of blanket configurations during its operation, accompanying safeguards research could already conceivably begin in forthcoming years. The experimental reactor would be a formidable test site for exploring first ideas and concepts on how to safeguard future fusion reactors and on how to improve tritium accountancy.

In summary, the advent of fusion by the middle of the century calls for three preventive actions in the fields of multilateral arms control, technology design, and safeguards development. If the incentives for weapon-usable material production are kept low, and fusion reactors are designed and safeguarded in a way that makes such production unattractive or at least reliably detectable, then the dissemination of this emerging technology in the second half of the century might keep possible proliferation risks at bay. If, on the other hand, fusion power enters the arena in the midst of an "unmanaged" power transition and if the technology can easily be upgraded to produce large quantities of fissile material, its exclusively peaceful use cannot be guaranteed.

Our call for preventive action involves states (arms control), international organizations such as the IAEA (safeguards), as well as epistemic communities (shaping of the technology and design of safeguards). At a later stage, when the commercial aspects of nuclear fusion will be more pronounced, the multistakeholder governance can also include private sector business players. As the nuclear industry timidly discovers the principles of corporate social and environmental responsibilities (mainly, for the time being, in the arena of nuclear safety), it can play a leading role in the process of ensuring that commercial nuclear fusion and nuclear weapon development will remain two completely separate spheres of activity.

ACKNOWLEDGMENTS

The authors thank Franz Fujara, Chris Lee-Gaston, Amanda Quinlan, Klaus Dieter Wolf, and two anonymous reviewers for their constructive feedback and useful comments on earlier drafts of this article.

NOTES

1. A recent study commissioned by the European Union predicts market penetration around the year 2050 and does not exclude that fusion could account for up to 30 percent of electricity worldwide by the end of the century. Lawrence Livermore National Laboratory's Laser Inertial Fusion Energy project schedules the first commercial fusion plants in the 2030s. For the former, see Francesco Romanelli et al., "Fusion Electricity: A roadmap to the realisation of fusion energy," European Fusion Development Agreement, November 2012, <www.efda.org/wpcms/wp-content/uploads/2013/01/JG12.356-web.pdf?5c1bd2>; for the latter, see Lawrence Livermore National Laboratory, "Laser Inertial Fusion Energy," <life.llnl.gov>. For a skeptical view, see Charles Seife, *Sun in a Bottle: The Strange History of Fusion and the Science of Wishful Thinking* (New York, NY: Viking Adult, 2008).
2. John P. Holdren et al., "Report of the Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy," UCRL-53766 (Lawrence Livermore National Laboratory, September 1989); Jürgen Raeder, "Report on the European Safety and Environmental Assessment of Fusion Power (SEAFP)," *Fusion Engineering and Design* 29 (1995), pp. 121–40; I. Cook et al., "Safety and Environmental Impact of Fusion," EFDA–S–RE-1 (European Fusion Development Agreement, April 2001).
3. Nuclear fusion requires either "magnetic confinement" (MCF) or "inertial confinement" (ICF) of the hot plasma fuel. MCF is widely seen as the dominant paradigm in attempts to produce electricity from nuclear fusion, whereas research on ICF is mainly carried out by national laboratories with a focus on nuclear weapon optimization and maintenance. See William J. Nuttall, *Nuclear Renaissance: Technologies and Policies for the Future of Nuclear Power* (New York, NY: Taylor & Francis Group, 2005), pp. 241–301. Historically, most studies on the possible military dimension of fusion reactors focused on ICF devices. Studies on military applications of MCF have come out only recently. See, for example, André Gsponer and Jean-Pierre Hurni, "ITER: The International Thermonuclear Experimental Reactor and the Nuclear Weapons Proliferation Implications of Thermonuclear Fusion Energy Systems," Independent Scientific Research Institute, ISRI-04-01.17 (February 2, 2008); F. Faghihi, H. Havasi, and M. Amin-Mozafari, "Plutonium-239 Production Rate Study Using a Typical Fusion Reactor," *Annals of Nuclear Energy* 35 (May, 2008), pp. 759–66; Fabian Sievert and Daniel Johnson, "Creating Suns on Earth: ITER, LIFE, and the Policy and Nonproliferation Implications of Nuclear Fusion Energy," *Nonproliferation Review* 17 (July, 2010), pp. 323–46; A. Glaser and R. J. Goldston, "Proliferation Risks of Magnetic Fusion Energy: Clandestine Production, Covert Production and Breakout," *Nuclear Fusion* 52 (April 2012), pp. 1–9.
4. Wolfgang Liebert and Jan C. Schmidt, "Towards a Prospective Technology Assessment: Challenges and Requirements for Technology Assessment in the Age of Technoscience," *Poiesis & Praxis* 7 (June 2010), pp. 99–116.
5. Whereas ITER is built on the principle of MCF, laser-driven fusion plants are based on ICF. Although the ICF community has recently announced first-of-its-kind fusion plants for the late 2020s and commercial fusion power plants in the 2030s, most experts still assign magnetic confinement fusion a higher probability to succeed in commercial applications (Nuttall, *Nuclear Renaissance*, p. 289). Our analysis is therefore restricted to MCF designs, but most of our findings are applicable to ICF devices as well.
6. Dale Meade, "50 years of fusion research," *Nuclear Fusion* 50 (2010), pp. 1–14.
7. D. Massonier et al., "A Conceptual Study of Commercial Fusion Power Plants: Final Report of the European Fusion Power Plant Conceptual Study (PPCS)," EFDA-RP-RE-5.0, (European Fusion Development Agreement, April 13, 2005).

8. Y. Chen et al., "The EU Power Plant Conceptual Study—Neutronic Design Analyses for Near Term and Advanced Reactor Models," Forschungszentrum Karlsruhe GmbH, 2003, <http://bibliothek.fzk.de/zb/berichte/FZKA6763.pdf>.
9. Jörg Reckers, "Tritiumbilanzierung im Fusionsreaktor ITER: Anwendung statistischer Testtheorie auf Inspektionsstrategien bei Messunsicherheit" [Tritium Accountancy for the ITER Fusion Reactor: Application of Statistical Test Theory on Inspection Strategies with due Consideration of Measurement Uncertainty], Diploma Thesis, University of Hamburg, 2007.
10. By contrast, in a fission reactor, the longer the uranium is irradiated, the more plutonium isotopes are produced, which degrade the nuclear weapon performance. For details on the simulations, see Appendix C, note 1.
11. A comparison of plutonium production in fission and fusion reactors is given in Matthias Englert and Wolfgang Liebert, "Strong Neutron Sources, Is There an Exploitable Gap?," paper delivered at the 51st Institute for Nuclear Materials Management Annual Meeting, Baltimore, Maryland, July 11–15, 2010.
12. In a fission reactor, the concentration of plutonium in the heavy metal mixture is typically several per mil for weapon grade plutonium (low burnup), and up to 1 percent for "civilian" reactor grade plutonium (higher burnups).
13. Romanelli, "A Roadmap to the Realisation of Fusion Energy," p. 5.
14. Indeed, the technical and economic hurdles for the use of fusion as an energy source remain high and could even prove prohibitive for the commercialization of this technology: major technical challenges lie in the confinement of the ultra-hot plasma inside the fusion reactor chamber, which must be assured for a sufficient amount of time for commercial reactor operations; in the material requirements for structural parts and reactor components, which have to withstand various forms of stresses (from radiological damage to high-energy neutron activation) unknown in fission reactors; and in nuclear waste handling needs, which still depend on materials not yet available. See also Michael Moyer, "Fusion's False Dawn," *Scientific American* 302 (March 2010), pp. 50–57; Sievert and Johnson, "Creating Suns on Earth," pp. 331–35.
15. We polled 140 international experts on both nuclear fusion and nuclear proliferation with an email questionnaire in 2010 and received 22 answers and comments. Details of this Delphi study can be found at a dedicated website of the Interdisciplinary Research Group in Science, Technology and Security of the Darmstadt University of Technology, <www.ianus-tu-darmstadt.de/fusion>. Additionally, we held a number of small workshops with senior experts on the military dimension of nuclear fusion at Darmstadt University of Technology in 2011.
16. Scott D. Sagan, "The Causes of Nuclear Weapons Proliferation," *Annual Review of Political Science* 14 (June 2011), pp. 225–44.
17. William C. Potter with Gaukhar Mukhatzhanova, eds., *Forecasting Nuclear Proliferation in the 21st Century, Volume 1: The Role of Theory* (Stanford, CA: Stanford University Press); William C. Potter with Gaukhar Mukhatzhanova, eds., *Forecasting Nuclear Proliferation in the 21st Century, Volume 2: A Comparative Perspective* (Stanford, CA: Stanford University Press).
18. Matthew Fuhrmann, "Spreading Temptation: Proliferation and Peaceful Nuclear Cooperation Agreements," *International Security* 34 (Summer 2009), pp. 7–41.
19. For a critical appraisal of Fuhrmann's hypothesis, see Christoph Bluth et al., "Correspondence: Civilian Nuclear Cooperation and the Proliferation of Nuclear Weapons," *International Security* 35 (Summer 2010), pp. 184–200.
20. Matthew Kroenig, "Importing the Bomb: Sensitive Nuclear Assistance and Nuclear Proliferation," *Journal of Conflict Resolution* 53 (April 2009), pp. 161–80.
21. Itty Abraham, "The Ambivalence of Nuclear Histories," *Osiris* 21 (2006), pp. 49–65.
22. The chances that selected states might operate *only* fusion reactors are not so remote: Italy abandoned its nuclear program in the 1980s, and Germany and Switzerland are currently phasing out (fission) nuclear power. As all three countries are heavily involved in the ITER research project, it is not excluded that they might re-enter the nuclear energy club once commercial fusion reactors become available on the market.
23. For exact figures, see International Panel on Fissile Materials, "Global Fissile Material Report 2011: Nuclear Weapons and Fissile Material Stockpile and Productions," (IPFM, 2011), and Hans M. Kristensen and Robert S. Norris, "Global nuclear weapons inventories, 1945–2013," *Bulletin of the Atomic Scientists*

69 (September/October 2013), pp. 75–81, <http://bos.sagepub.com/content/69/5/75.full.pdf+html>. Strategic parity does not necessarily mean numerical parity in weapons and material stocks, and leading realists emphasize the potential to achieve nuclear parity with small arsenals possessing secure second-strike capabilities. At the same time, strategic analysts are observing growing US efforts to achieve nuclear primacy vis-à-vis Washington's nuclear competitors, see Keir A. Lieber and Daryl G. Press, "The Rise of U.S. Nuclear Primacy," *Foreign Affairs* (March/April 2006), pp. 42–54. While this primacy could be maintained "for a decade or more" vis-à-vis China, realists would warn that Beijing will have no other choice than to improve its nuclear capabilities both qualitatively and quantitatively in the future (ibid); and that China's strong economic growth will give Beijing's strategic planners the means to reduce these vulnerabilities soon.

24. Note that current Indian weapon-grade plutonium production amounts does not exceed 20–25 kg per year; see "Dhruva Research Reactor," Nuclear Threat Initiative, September 1, 2003, <www.nti.org/facilities/837/>; our conservative estimate suggests that a fusion reactor could breed more than ten times this amount of plutonium.
25. On China's current policy of nuclear restraint, see Lora Saalman, "Placing a Renminbi Sign on Strategic Stability and Nuclear Reductions," in Elbridge A. Colby and Michael S. Gerson, eds., *Strategic Stability: Contending Interpretations* (Strategic Studies Institute and U.S. Army War College Press, 2013), pp. 343–81.
26. On the issue of underbalancing, see Keir A. Lieber and Gerard Alexander, "Waiting for Balancing: Why the World is Not Pushing Back," *International Security* 30 (Summer 2005), pp. 109–39. On the projected timelines for the global power transition, see the economic growth forecasts published by Goldman Sachs, HSBC, Price Waterhouse Cooper, and CitiGroup. While the United States is still the leading economy today, all major forecasts agree that it will lose its economic primacy to China or to India (or both) by 2050. For an overview over these forecasts, see Witold Kwasnicki, "China, India and the Future of the Global Economy," MPRA Paper 3255, July 25, 2011, <http://mpra.ub.uni-muenchen.de/32558/1/MPRA_paper_32558.pdf>.
27. For the strategic triangle of Washington-Tokyo-Beijing, see Michael D. Swaine et al., *China's Military and the US-Japan Alliance in 2030: A Strategic Net Assessment* (Washington, DC: Carnegie Endowment of International Peace, 2013).
28. Harald Müller and Andreas Schmidt, "The Little-Known Story of Deproliferation: Why States Give Up Nuclear Weapons Activities," in Potter and Mukhatzhanova, *Forecasting Nuclear Proliferation in the 21st Century, Volume 1: The Role of Theory*, pp. 124–58.
29. William C. Potter, "The NPT & the Sources of Nuclear Restraint," *Daedalus* 139 (Winter 2010), pp. 68–81.
30. See Appendix C, note 3.
31. Ed Gerstner, "Nuclear Energy: The hybrid returns," *Nature* 460 (July 2, 2009), pp. 25–28.
32. It is advisable to safeguard also larger experimental reactors. In two decades, several national DEMO reactors might go online in various ITER countries. These reactors will offer relevant plutonium production and tritium diversion potentials.
33. Formally, safeguards are not foreseen for fusion reactors, at this stage. The main reason is legalistic, i.e. a fusion reactor—according to the IAEA guidelines—would not fall under the term "facility" and is therefore not subject to IAEA safeguards, since it is neither a "reactor" (defined by a nuclear chain reaction), nor a "critical facility," nor a location where nuclear material in quantities more than an *effective kilogram* is customarily used. See International Atomic Energy Agency, "The Structure and Contents of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," INFCIRC/153 (Corrected), June 1972.

Appendix A—A Magnetic Confinement Fusion Power Reactor: The PPCS-A Model

Like its predecessors, ITER and DEMO, the commercial PPCS-A reactor design is based on the tokamak principle, i.e., it magnetically confines very hot plasma of the hydrogen isotopes deuterium (D) and tritium (T) into a toroidal reactor chamber (see Figure 1).[1] If the plasma temperature is high enough, the deuterium and tritium nuclei can fuse yielding helium (He) and a high-energy neutron (n), according to the formula:

$$\mathrm{D} + \mathrm{T} \rightarrow \mathrm{He} - 4 + \mathrm{n} + 17.6\ \mathrm{MeV}$$

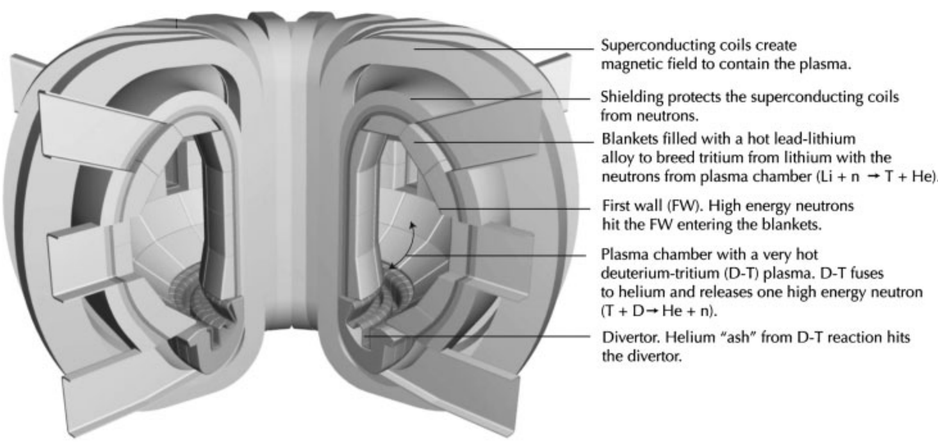
where the last term indicates the kinetic energy that the reaction products (He and n) will carry away. The bulk of the energy—about 80 percent—is transferred to the high-energy, fast "fusion neutrons," which will irradiate the surrounding of the reactor chamber.

The structure surrounding the plasma chamber consists of a complex pattern of "blankets" of different size, width, and shape. These blankets will be subjected to the strong neutron flux resulting from the D-T fusion reaction. The high-energy neutrons will escape the (toroidal) plasma chamber, penetrate the surrounding blankets, and deposit their energy there. The heat that results from this neutron bombardment will be removed from the blankets by a water cooling system; it will then be transferred to an external turbine hall, where the actual electricity generation will take place. The other reaction product, the "helium ash," will drop to the bottom of the reactor, depositing about a tenth of the total thermal energy on the "divertor" and posing substantial material development and design challenges.

Beside the cooling system for heat removal, the blanket modules contain a hot liquid lead-lithium alloy. The purpose of the lithium (Li) in the blanket is to breed tritium

FIGURE 1

Typical representation of the toroidal construction of the reactor chamber of a fusion power plant.



Source: Adapted and reproduced with permission from D. Massonier et al., "A Conceptual Study of Commercial Fusion Power Plants: Final Report of the European Fusion Power Plant Conceptual Study (PPCS)," EFDA-RP-RE-5.0, (European Fusion Development Agreement, April 13, 2005), p. 3, <www.ipp.mpg.de/ippcms/de/presse/archiv/PPCS_summary.pdf>.

(T) during reactor operation by using the fusion neutrons ejected from the plasma chamber into the blankets:

$$\mathrm{Li}-6 + \mathrm{n} \rightarrow \mathrm{T} + \mathrm{He}-4$$

The fusion reactor will thus produce that part of its fuel—tritium—which is not found in sufficient abundance on Earth as part of its own reactor process.

As the blanket modules wear out over time due to continuous neutron irradiation, they will have to be replaced regularly (about every two to five years) by remote handling or robotic systems. This exchange of modules is technologically demanding, and will require the fusion reactor to be shut down. It is important to note that, during this maintenance procedure, an operator has direct access to the blankets (189 in case of PPCS-A). This is a key nonproliferation concern, should the blankets be used to breed fissile materials.

The thermal power of the PPCS-A amounts to 5.5 gigawatts, which corresponds to the thermal output of the largest fission reactors in use today. The total height of the reactor is 18 meters. These key figures show that PPCS-A describes an unusually large machine, which will be highly visible and difficult to hide. However, much smaller machines could be constructed in principle.

NOTE

1. The EFDA study discusses four promising commercial power plant concepts termed "Power Plant Conceptual Study" (PPCS) A, B, C, and D, respectively. While the reactor concept A relies partly on "established" materials and technologies used in the commercial fission reactor industry today and is therefore closer to possible realization, concepts B, C, and D are technologically more demanding and will require considerably more R&D effort. Assuming that the first commercial fusion power reactors will be built on the basis of the "simpler" PPCS-A model, the only design considered here and the basis for all numerical simulations presented in this article is concept A.

Appendix B—Military Option 1: Tritium Withdrawal

The easiest way to use a fusion plant for nuclear weapon purposes would be via the diversion of tritium, which is constantly produced (in the blankets) and consumed (in the plasma) during normal reactor operation. Tritium is not an indispensable material for a first generation or crude nuclear weapon, but it can serve several purposes within a nuclear device and therefore most modern weapons use this hydrogen isotope.[1] The main rationale for tritium within a nuclear fission weapon is to increase its yield with an intelligent coupling of nuclear fission (involving plutonium or uranium) and nuclear fusion (involving deuterium and tritium).

Since only a few grams of D and T are enough to significantly "boost" the yield of a nuclear weapon, tritium addition allows for a dramatic increase in the yield-to-weight ratio and thereby an improvement in the efficiency of a nuclear weapon. In a large gigawatt fusion power plant along the lines of the PPCS-A model, several kilograms of tritium will be in the inventory at any time, daily consumption will amount to several hundred grams, and the annual production rate will exceed 100 kg.

It has to be noted that tritium is not presently considered a weapon-relevant, special nuclear material by the IAEA; current arrangements between the IAEA and its member states do not require tritium accountancy. Tritium diversion for weapons purposes could probably escape international scrutiny in large fusion devices such as ITER, DEMO, or commercial fusion reactors. This loophole calls for a major study on how to improve tritium accountancy for the time when fusion reactors will be widely available. A starting point for such a study could be represented by the experiences in tritium measurement and accountancy currently implemented in the Joint European Torus (JET) experiment or the Tritium Laboratory in Karlsruhe, Germany.

NOTE

1. For an overview, see Martin Kalinowski, *International Control of Tritium for Nuclear Nonproliferation and 740 Disarmament* (Boca Raton: CRC Press, 2004).

Appendix C—Military Option 2: Fissile Material Production

Any neutron-producing technology has the potential to produce fissile material. Thus, fusion neutrons could, in theory, be used for fissile material production. As the blanket modules within a fusion reactor have to be exchanged on a regular basis, it is possible to replace a fraction of the lead-lithium alloy in the blanket with fertile nuclear material (e.g. natural uranium or thorium). The fertile material will be irradiated with the fusion neutrons

TABLE 3
Annual production rate of plutonium at various concentrations of uranium in the blanket under the assumption of a 100 percent capacity factor (no reactor shutdowns).

	10 percent U	1 percent U	0.1 percent U	0.01 percent U
One blanket close (~ 2 cm) to plasma	25-65 kg	4-10 kg	1-2 kg	100-200 g
One blanket far (~ 42 cm) from plasma	1-3 kg	300-600 g	<100 g	<10 g
Complete reactor (360 degrees)	7,450 kg	1,280 kg	225 kg	27 kg

Note: Numbers are based on a simulation of 27 (4 × 3 inboard, 5 × 3 outboard) blankets in a 20 degree section of the PPCS-A concept with a thermal power of 5.5 GW. The production span reflects minimum and maximum production depending on the actual volume of one blanket. For further technical details of the geometry and the simulation, see "Proliferationsresistente Gestaltung von Fusionsreaktoren" [Designing Proliferation Resistant Fusion Reactors], Darmstadt University of Technology, <www.ianus.tu-darmstadt.de/fusion>.

to produce fissile materials (plutonium or uranium-233) until the reactor is shut down again for the next maintenance cycle. This operation is not foreseen under the "nominal" operation and maintenance regime of the PPCS-A fusion power reactor, but it is a scenario of which the nonproliferation community should be aware.

After removal of the irradiated blanket from the reactor during a routine blanket exchange, the fissile material could then be chemically separated. With the help of dedicated computer software, we computed the theoretical annual production rate of plutonium within a commercial fusion reactor of the geometrical dimensions and thermal output of the PPCS-A model for various volume fractions of uranium replacing the lead-lithium alloy within the blankets.[1] The technical details of the simulations are published elsewhere.[2] Only some aggregate results of these simulations are displayed in Table 3, which quantitatively illustrates three general facts: first, the greater the amount of fertile material there is in a blanket, the larger the quantity of fissile material that can be bred. Second, blankets close to the plasma are exposed to a stronger neutron flux and will thus produce more plutonium than blankets farther away from the plasma. Third, the larger the number of blankets filled with fertile material, the larger the quantity of fissile material that can be produced within a reactor.

The figures of Table 3 furthermore suggest different proliferation scenarios which might involve fusion reactors: for a proliferator interested in the clandestine production of about one critical mass per year, it would be enough to "manipulate" one single blanket close to the plasma and replace one percent of the volume content with natural uranium. A state interested in "mass production" of fissile material, on the other hand, might insert fertile material in many or *all* blankets and—if this were done with the same concentration of one percent—could obtain more than a metric ton of weapon-grade plutonium per year. However, such an operation would certainly not remain undetected if appropriate safeguards were applied to the fusion reactor.

If a state decided to breed fissile material within a PPCS-A type fusion reactor as described above, it would still have to be aware of some limitations for this endeavor due to additional heat caused by fission and the reduction of tritium breeding if neutrons are diverted for fissile material production.[3]

NOTES

1. All neutronic simulations reported in this article were carried out by using the Monte Carlo N-Particle Transport Code (MCNP), D. Pelowitz, MCNPX User's Manual Version 2.7.0, LA-CP-11-00438 (2011). Burnup calculations were carried out using MCMATH developed at the IANUS Institute of Darmstadt University of Technology and VESTA, W. Haeck, VESTA User's Manual, IRSN Report, DSU/SEC/T/2008-331 –745 Index A (2009).
2. For technical details on the neutronic simulations, please refer to documents and papers available at the Interdisciplinary Research Group in Science, Technology and Security website, <www.ianus.tudarmstadt.de/fusion>, especially Matthias Englert, Giorgio Franceschini, and Wolfgang Liebert, "Strong Neutron Sources—How to cope with weapon material production capabilities of fusion and spallation 750 neutron sources," Paper delivered at the European Safeguards Research and Development Association/Institute for Nuclear Materials Management Annual Meeting, Aix-en-Provence, France, October 16–20, 2011.

3. First, a fraction of the uranium will fission when exposed to the high-energy neutrons coming from the plasma. A fusion reactor such as PPCS-A with a nominal thermal power of 5.5 gigawatts can certainly handle a limited amount of surplus heat, so we assumed that 10 percent of the "excess heat" in some blankets of the reactor would not compromise the safe operation of the reactor. Under these rather conservative assumptions, our simulations suggest that a proliferator could not load all the blankets with 10 percent uranium, as this would overheat the machine. Still, an overall 1 percent uranium load factor would allow safe operation of the reactor. Second, the introduction of uranium into a blanket automatically reduces the amount of lead-lithium within the module. Because lithium is necessary to breed tritium—one of the reactor fuels—an excessive amount of uranium in the blankets would deplete the lithium and hence the (tritium) fuel supply of the machine. Nevertheless, since tritium is as volatile as hydrogen and decays radioactively, a fusion reactor is always designed to produce more tritium than it consumes. Therefore, by replacing only 1 percent of the lead-lithium alloy with fertile material, the steady tritium supply to the plasma reaction chamber would still be guaranteed. Measuring overall tritium production might be also an interesting safeguard measure, since a deviation from the expected tritium production might allow detecting a diversion of neutrons from tritium production.

Appendix D—Covert Operation and Safeguards

The chances of operating a fusion reactor in a clandestine or covert manner and escaping detection are generally seen as rather low.[1] A covert program would imply that fusion reactor safeguards are circumvented, and weapon-grade material is withdrawn from the reactor and diverted to a nuclear weapon program. Although fusion reactor safeguards have not been specified yet, such an operation might be feasible for tritium withdrawal, if no accountancy regime is developed to detect small diversions of tritium.[2] A covert fissile material production program, on the other hand, would hardly be conceivable if appropriate safeguards were implemented around the reactor blankets. In such a case, a proliferator would try to manipulate the lead-lithium blankets, introduce small quantities of fertile material, and hope to escape the monitoring equipment installed at the reactor. If such an operation could be carried out covertly, it could yield something between one to ten critical masses of plutonium, depending on the number of affected blankets and their proximity to the plasma (see Table 3).

While the circumvention of safeguards is already a very challenging endeavor, the chances of a clandestine operation of such a facility are even more remote. Doing so would imply that a fusion reactor, typically a bulky facility with a number of support units, would be constructed in complete secrecy, and be operated and maintained without leaving any tangible physical signature. Such a scenario is highly unlikely, unless the entire fusion power plant were constructed underground, an effort that would be difficult to hide completely.

NOTES

1. Glaser and Goldston, "Proliferation risks of magnetic fusion energy," pp. 1–9.
2. Reckers, "Tritiumbilanzierung im Fusionsreaktor ITER."