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Abstract
Nuclear proliferation risks from magnetic fusion energy associated with access to fissile materials can be divided into three main categories: 1) clandestine production of fissile material in an undeclared facility, 2) covert production and diversion of such material in a declared and safeguarded facility, and 3) use of a declared facility in a breakout scenario, in which a state openly produces fissile material in violation of international agreements. The degree of risk in each of these categories is assessed, taking into account both state and non-state actors, and it is found that safeguards are required for fusion energy to be highly attractive from a non-proliferation standpoint. Specific safeguard requirements and R&D needs are outlined for each category of risk, and the technical capability of the ITER experiment, under construction, to contribute to this R&D is noted. A preliminary analysis indicates a potential legal pathway for fusion power systems to be brought under the Treaty for the Non-Proliferation of Nuclear Weapons. "Vertical" proliferation risks associated with tritium and with the knowledge that can be gained from inertial fusion energy R&D are outlined.

1. Introduction

Considerable progress has been made in fusion energy R&D, which has led to the beginning of the construction of the ITER international fusion energy experiment in southern France, as an collaboration of China, Europe, India, Japan, Russia, South Korea and the United States. ITER is to produce hundreds of MW of thermal fusion power for pulse lengths of 300 – 3000 seconds, with a peak duty factor of 25%, with 4% yearly average. This represents a large step forward for fusion R&D, but much remains to be done in preparation for a practical demonstration fusion power plant. Here we argue that one element of this preparation should be the development of appropriate safeguards for fusion energy systems.

We have previously analyzed[1] the safeguards risks of fusion energy systems with respect to clandestine production of fissile material in undeclared facilities, covert production and diversion of fissile material from declared facilities, and breakout from international safeguards. In sections 2 - 4 we summarize that work, taking into account both state and non-state actors, and focus on the implied needs for additional safeguards studies. In section 5 we consider the technical possibilities for the use of ITER to develop safeguards technologies for fusion power systems.

Fusion systems appear attractive from a non-proliferation perspective, but only if safeguards are implemented. Section 6 comments on the legal issues involved in bringing fusion power plants under the Treaty on the Non-Proliferation of Nuclear Weapons. In section 7 we discuss the "vertical" proliferation risks associated with tritium and with the knowledge that may be gained from inertial fusion energy R&D. These are not pertinent to the acquisition of first-generation nuclear weapons, but may play a role in more advanced weaponry. Section 8 comprises our conclusions and recommendations.

2. Clandestine production of fissile material in an undeclared facility

One can ask if there is a fusion equivalent to the relatively small fission reactors, typically fueled with natural uranium and moderated with heavy water or graphite, that have been used by some nations to breed fissile material for weapons. The 14.1 MeV neutrons produced from DT fusion can be used to transmute ^{238}U or ^{232}Th to ^{239}Pu or ^{233}U, and indeed some have proposed using fusion systems to produce fuel for fission reactors. While we do not consider such systems as fusion power systems, and do not treat them otherwise in this article, some small-scale prototypes have been considered. These provide a useful basis to consider the possibility for clandestine production of fissile material.

Most recently studies have been undertaken[2] by Kuteev et al., with the goal to determine the minimum size fusion device that can be used to prototype the production of fuel for fission reactors. With optimistic extrapolations for both plasma physics and fusion technology, they find that a relatively compact device, drawing approximately 40 MW continuously from the grid, could produce 1.8 MW of continuous fusion power. With an optimistic duty factor of 85%, and assuming that 80% of all neutrons are captured in a uranium-bearing blanket, it could in principle produce 3.5 kg of ^{239}Pu or ^{233}U per year, somewhat less than one-half of an IAEA-defined "significant quantity" (SQ) in either case.

If such a device were able to be operated clandestinely for a period of years, it would constitute a proliferation risk, but the requirements for ~40 MW of continuous power input and cooling, and so a large electric supply line, large power conversion buildings to provide the DC power required to power the magnet coils, and a very large well shielded reactor building would make such an installation quite visible. The remote handling capabilities needed for such a high-duty-factor DT facility would also be very visible, and trace levels of tritium lost from the facility would be detectable for a distance of tens of kilometers, in addition to the environmental signatures of fertile and fissile materials. In our judgment, it is overall not credible that such a facility could be constructed and operated clandestinely.

There appears to be no credible role for non-state actors in producing fissile materials using clandestine fusion systems.

We conclude that modifications to existing safeguard protocols are not needed to detect clandestine fusion facilities. However, it is also clear that application of the Additional Protocol would facilitate more rapid access to suspect facilities, and so could be a significant benefit.

3. Covert production and diversion of fissile material in a declared and safeguarded facility

The fuel in a fusion reactor is surrounded by a "blanket" designed to absorb 14.1 MeV neutrons and produce both high-grade heat for power generation and tritium to maintain the DT reaction. These blankets are likely to need to be replaced every 3 – 4 years due to neutron damage. Thus if fertile material were covertly inserted into these blankets they could be used to breed weapons materials.

We have analyzed[1] in some detail the case of blankets cooled with lead-lithium eutectic, which also functions as the tritium-breeding material. This case is particularly insidious, because the fertile material, ^{238}U or ^{232}Th, could in principle be introduced covertly into the flow of coolant in the form of TRISO-like particles, which could later be extracted mechanically from the flowing coolant. Dissolution of U or Th in lead-lithium and its later chemical extraction appears much more difficult.

We found that to produce 8 kg of ^{239}Pu or ^{233}U per year would require about one 1mm diameter TRISO particle per cm^3 of coolant. A total of about 2.6t of fertile material would need to be to be covertly diverted from a safeguarded nuclear fuel cycle or produced in an undeclared facility.

We analyzed the possibility of passively detecting the presence of these particles, and found it to be surprisingly easy. If a one-liter volume of coolant is presented to a gamma detector, it appears that the presence of the necessary concentration of ^{238}U can be detected in minutes, while the small quantity of ^{232}U produced after six months could be detected in seconds. Of course extraction of one liter of coolant for chemical analysis would easily reveal the 1000 TRISO particles, and general environmental sampling could be quite effective as well, since the only uranium that might be present at a fusion reactor could be the small, well contained quantity in beds used to hold tritium, and no thorium should be present at all. The handling of tons of U or Th would likely leave considerable evidence.

R&D is needed, however, to confirm these conclusions. What is the likely background radiation environment that could confound the measurements described, both during operation and during down periods? How difficult will it be to assure that all coolant loops can be sampled? How strong would be the environmental signature of handling 2.6t of TRISO particles laced with fertile material? How easily would the equipment to inject and recover the TRISO particles be detected?

In the case of blankets which are cooled with high pressure helium gas or water, for which the tritium breeding medium is in the form of lithium bearing pebbles, with beryllium for neutron multiplication, the risk is that ^{238}U or ^{232}Th could be inserted into the blankets in small quantities, and when the blankets were later extracted the fissile material would be recovered. To avoid this would require inspection of the blanket modules just before they are installed in the fusion device. This might be accomplished by passive means, looking for either γ's or neutrons in coincidence, or using the 14.1 MeV active neutron interrogation techniques that have been developed for detection of weapons materials in shipping containers. On removal from the fusion system these blanket modules would contain fissile material and fission products that should be passively and actively detectable. As with the previous scenario, sensitive environmental sampling would likely pick up the signature of ^{238}U or ^{232}Th.

Again, however, R&D is needed for the various blanket designs to determine how best to assure the absence of fertile material. These are massive structures that will exhibit considerable self-shielding, so specific studies will be needed. While on the way into the fusion system the background radiation levels will be low, post-irradiation examination will necessarily be difficult both from a practical point of view due to high radiation levels, and due to background signal. One can also ask how well the environmental signatures of fertile materials, and – post irradiation – fissile materials, transuranics, and/or fission products can be detected.

There appears to be no credible role for non-state actors in producing fissile material covertly in a declared fusion energy system. Such an actor could not credibly insert and extract material from blanket modules without detection. Since there is no fissile material in either the fuel or the waste from a fusion reactor, there is also no possibility of theft from transport or storage.

In general it seems clear, however, that a Red Team approach is needed to assure that all credible avenues for a state host to present fertile materials to the fusion system have been eliminated.

4. Breakout scenario

In the final scenario we will consider, a state expels safeguards inspectors, removes monitored seals, and begins using a fusion power plant openly to produce fissile material. A key distinction between this scenario and that of a fission power plant is that, in the case of fission, fissile material has already been produced and is in storage in the form of Pu contained in spent fuel. As was seen in North Korea, little can be done short of invasion to prevent a determined sovereign nation from processing its own Pu for use in nuclear weapons. Massive bombing of the spent fuel in Yongbyon would have resulted in widespread contamination, an unacceptable consequence. More limited bombing would have required frequent repetition to prevent access to the fuel buried in the rubble – also an unacceptable consequence.

By contrast, in the case of fusion, no fissile material is present at the time of breakout, and the challenge is to prevent operation of the fusion power plant without risk of contamination. A fusion power plant comprises many large and separated non-nuclear subsystems such as power conversion and conditioning equipment, cryogenic cooling systems, and heat-rejection systems. If any of these are disabled the plant is not able to operate and produce fissile material, but the risk of contamination is minimal.

A state engaging in breakout using a fusion power plant would be motivated to act quickly, due to the above considerations. A complete rebuild of the blanket system would be a massive undertaking, and probably not practical due to the different services required for steady operation of such a fissile-material breeding system. If the system used flowing lead-lithium, however, TRISO particles could in principle be introduced into the flow to produce fissile material at a much more rapid rate than in the clandestine scenario above. To produce fissile material at a rapid but potentially practical rate would require that TRISO particles containing ~500t of fertile material had been produced clandestinely in advance, evading safeguards. (Note for comparison that the yearly heavy metal loading of a 1 GWe light water reactor is about 20t of enriched uranium, which requires processing of about 200t of natural uranium.) We estimated that with the introduction of 500t of TRISO particles approximately 20 kg of ^{239}Pu or ^{233}U, 2.5 SQ, could be produced per week. We judged that a period of at least 1 month would be required to introduce this material into the system, and noted that there are outstanding questions as to how such "gritty" fluid would flow in a complex fusion blanket, in which the magnetic fields act differently on the conducting lead-lithium fluid compared with the insulating TRISO particles.

There is an alternative breakout scenario which involves the misuse of test blanket modules. ITER is equipped with 3 ports containing a total of 6 modules for testing approaches to fusion blankets. If one of these modules in ITER were fully optimized for the production of fissile material, it would produce about 130g of fissile material per year, due to ITER's low yearly duty cycle and relatively low fusion power production compared with a fusion power plant. However it would be credible for test blanket modules to be included in early fusion power systems, and at 80% duty cycle (20x higher than ITER) and 5x higher power production than ITER, six modules together, of the same size as ITER's, would produce about 1.9 kg/week of fissile material. Perhaps the test blanket modules could be a modest factor larger in a power plant, as we speculated, but equally likely the need to assure tritium self-sufficiency could limit their size and number. Even though these test modules are designed for replacement without a major rebuild of the device, we judged that at least 1-2 months would be required to replace existing pure-fusion modules with fissile material breeding modules and restart the device. Again, the fertile material would need to be prepared in advance, and placed in the breeding modules, in violation of safeguards.

There are a number of avenues for productive R&D in this area. How will TRISO particles flow in lead-lithium in the presence of strong magnetic fields? Would the necessary pumps and means to purge the fluid of contaminants be compatible with such particles? Are there design options that would make such misuse less feasible? How different are the services required for a fissile breeding blanket from those required for a flexible test blanket program? How long would it take to replace a conventional test blanket module with one optimized for fissile material production?

Prima facie, as for the other scenarios, there does not appear to be a role for non-state actors in the breakout scenario, except in the secondary sense – for all cases – that a state could make nuclear materials or weapons acquired through these means available to non-state actors.

5. Technical perspective on use of ITER to develop safeguards

The ITER fusion energy experiment, under construction now in Cadarache, France, is not itself a fusion power plant, but does include many of the relevant technologies. In particular test blanket modules will be provided by Members of ITER for exposure to the plasma. As noted above, in our judgment these Test Blanket Modules could not produce significant quantities of fissile material under any foreseen circumstances. Furthermore, the ITER Agreement requires full compliance with all applicable Export Controls of the Members. The ITER test blanket modules appear, however, to provide a potentially valuable technical context for developing fusion safeguards. From the analysis above, this could include:

- Measurements of background radiation spectra near lead-lithium pipes during and after fusion operation of ITER.
- Determination of optimal locations for measuring potential fertile material content in the flow, and tests of such measurements. (Test measurements of fertile material content would not be done on ITER itself, but on mockup flow loops based on ITER designs.)
- Development of optimal methods to assure that blanket modules do not contain fertile materials or (after irradiation) fissile materials. These tests would start, for example, with Monte-Carlo neutron studies, but could benefit from experimental validation, particular in the case of post-irradiation studies.
- Examination of the feasibility of transporting significant quantities of ~1mm TRISO particles in realistic flow geometries, including pumps, means to purge the fluid of contaminants, and magnetic fields. Examination of techniques to make this more difficult. (Again such tests would not be done on ITER itself, but on mockup flow loops based on ITER designs.)
- Practical experience with the length of time required to replace a test blanket module and restart a fusion device.

6. Comments on legal issues associated with bringing fusion power plants under the NPT

The Treaty on the Non-Proliferation of Nuclear Weapons (NPT) was developed with the three goals of stopping the spread of nuclear weapons, providing aid for the development of nuclear energy, and nuclear disarmament. Article III, paragraph 1 of the NPT reads, in full:

> Each non-nuclear-weapon State Party to the Treaty undertakes to accept safeguards, as set forth in an agreement to be negotiated and concluded with the International Atomic Energy Agency in accordance with the Statute of the International Atomic Energy Agency and the Agency's safeguards system, for the exclusive purpose of verification of the fulfillment of its obligations assumed under this Treaty with a view to preventing diversion of nuclear energy from peaceful uses to nuclear weapons or other nuclear explosive devices. Procedures for the safeguards required by this article shall be followed with respect to source or special fissionable material whether it is being produced, processed or used in any principal nuclear facility or is outside any such facility. The safeguards required by this article shall be applied to all source or special fissionable material in all peaceful nuclear activities within the territory of such State, under its jurisdiction, or carried out under its control anywhere.

In light particularly of its first sentence, this paragraph appears to us to require inclusion of fusion reactors, even if their declared design information does not include the use of any "source or special fissionable material" (fertile or fissile materials), because nominally peaceful fusion energy systems can be misused to produce such materials, as discussed above. The later sentences of Art. III clarify that safeguards should apply to source or special fissionable material under the control of the State, wherever they are located; they do not that specify that safeguards must *only* be applied to source or special fissionable material[3]. Thus we estimate that the NPT itself would not require amendment to allow the inclusion of fusion power plants. We are not qualified to judge, however, whether a statement by the IAEA Board of Governors or an NPT Review Conference might be necessary to insure their inclusion.

Furthermore, Paragraph 106 of IAEA INFCIRC/153, "The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons" defines the *facilities*[4] to be safeguarded as "(a) A reactor, a critical facility, an isotope separation plant or a separate storage installation; or (b) Any location where greater than one *effective kilogram* is customarily used." A fusion power plant is certainly a nuclear reactor, so, in our opinion, could naturally be included. However amendment might be required, for example, to Paragraph 79, which states, inter alia, "The Agreement should provide that in the case of *facilities* and *material balance areas* outside *facilities* with a content or *annual throughput*, whichever is greater, of *nuclear material* not exceeding five *effective kilograms*, routine inspections shall not exceed one per year." Any necessary amendment could be helpfully informed by the R&D we recommend in this article.

It is interesting to note that 20t of either thorium or depleted uranium (^{235}U content less than 0.5%) corresponds to one *effective kilogram,* as defined in INFCIRC/153. Paragraph 37 indicates that quantities of *nuclear material* in excess of one *effective kilogram* cannot be exempted from safeguards. The 500t required for one of the breakout scenario described above greatly exceeds this amount.

Paragraph 39 of INFCIRC/153 states:

> The Agreement should provide that the Agency and the State shall make Subsidiary Arrangements which shall specify in detail, to the extent necessary to permit the Agency to fulfill its responsibilities under the Agreement in an effective and efficient manner, how the procedures laid down in the Agreement are to be applied. Provision should be made for the possibility of an extension or change of the Subsidiary Arrangements by agreement between the Agency and the State without amendment of the Agreement.

This appears to provide the necessary flexibility to include fusion power plants.

7. "Vertical" proliferation risks of tritium and of inertial fusion energy R&D

The NPT focuses on verification of fertile and fissile nuclear materials as the primary means to assess compliance with the articles of the treaty associated with the non-proliferation of weapons to Non-Nuclear Weapons States (NNWSs). However there are societal risks associated with "vertical" proliferation, which we define here to include increasing sophistication of the nuclear arsenals not just of the five Nuclear Weapons States (NWSs) of the NPT, but particularly of other states that possess more primitive nuclear arsenals. The availability of more powerful and more deliverable weapons can fuel regional arms races and lead to increased risk of more destructive regional and potentially global nuclear war.

The first generation of nuclear weapons comprised gun-type and implosion devices that relied exclusively on nuclear fission to provide explosive energy. A next generation of devices, however, included a small amount of deuterium-tritium (DT) gas to "boost" the fission yield, allowing either significantly more yield for a given amount of fissile material, or a significant reduction in fissile material for a given yield. This improved the deliverability of nuclear weapons.

It should be noted, however, that DT boost is not required for missile-based nuclear arms. The first missile-launched nuclear weapons in the U.S. and French arsenals are reported not to have included DT boost. Pierre Billaud, a pioneer of the French nuclear weapons program has written[5], "... for the missiles deployed on the Plateau d'Albion, we had proposed a boosted charge... . But the ministry representatives preferred the non-boosted solution." The Intermediate Range Ballistic Missiles in place during the 1970's (and later versions with upgraded warheads) were capable of reaching the Soviet Union. We also note that unconventional delivery of nuclear weapons is a considerable risk today.

The U.S. has published[6], in reference to the tritium reservoirs of its nuclear weapons, that "the amount of tritium in a reservoir is typically less than 20g." If we consider the neutron economy of a fission reactor used to produce Pu and T, we can see that a single neutron not required to sustain the fission chain reaction can be used to produce either a single Pu or a single T nucleus, from ^{238}U or ^{6}Li, respectively. Thus the production of 20g of T replaces the production of approximately 1.6 kg of Pu, or 20% of an SQ. Thus any nation that is producing Pu for weapons use can, with relatively minor perturbation, produce adequate T to "boost" these weapons, even taking into account the ~5% loss of T per year through radioactive decay.

It is highly desirable that fusion power systems not contribute to the availability of tritium for "vertical" proliferation. Clandestine T production with fusion is not credible: the small fusion system described in Section 2 might be able to produce at most a few grams per year of excess T, but more likely would be a net tritium consumer due to its configuration with very strong external power input, which takes up space needed for tritium-breeding blanket modules.

Covert diversion of tritium from an operating fusion power plant is, however, not incredible. Significant advances in accurate measurement, surveillance and containment will be required to minimize this risk. The strong efforts on ITER in these areas should be useful to inform future directions. It is worth noting that the NPT would require substantial change to incorporate T controls within its framework, so an alternative legal framework may be more appropriate.

Tritium breakout is an inherent risk for fusion systems because a significant inventory of T is accumulated over time for the startup of future systems. However it should be recognized that a state must have access to fissile material to take advantage of tritium, however plentiful, because boosting is not possible without a nuclear fission reaction to drive DT fusion. A nation with fission and fusion reactors could in principle break out with its fissile material and get to boosted weapons more quickly than one with only fission reactors, since the latter would not have a tritium inventory at hand, although 100s of grams of tritium could be bred in a few months using a 1 GWe light-water reactor. A nation with only fusion reactors, on the other hand, would not have a military use for T.

The most powerful and deliverable modern nuclear weapons employ two distinct stages, in which a boosted fission "primary" produces x-rays that compress and ignite a physically distinct "secondary" that employs ^{6}LiD as fusion fuel. The scientific basis of Inertial Confinement Fusion, ICF, (but not Magnetic Confinement Fusion) overlaps with that of advanced nuclear weapons, so R&D, and ultimate deployment, of fusion energy systems based on this technology could present a risk of dissemination of sensitive information for vertical proliferation. A careful DOE review in 1995[7] concluded that the proliferation risks associated with the U.S. National Ignition Facility (NIF) were acceptable because 1) "in general, without access to data from nuclear tests, ICF or unclassified NIF data would be of very limited utility to proliferators" and 2) classified NIF data could be maintained secret. Since 1995 we have found that proliferating states do perform nuclear tests, and indeed this should have been expected of vertical proliferators. Furthermore, states with access to their own NIF-type facilities as part of their own ICF R&D programs, or with access to world-wide ICF R&D data, could in principle gain access to the equivalent of classified NIF data. As a result the 1995 NIF review does not represent an adequate basis for assurance that the risks associated with worldwide ICF R&D can be controlled. These risks need to be examined directly and as transparently as practicable, and then weighed against the means to minimize the dissemination of sensitive information[8]. While this does not represent the safeguarding of material, information in this case plays a parallel role.

8. Conclusions and recommendations

We conclude that fusion has attractive nonproliferation features if appropriate safeguards are applied. We do not foresee any clandestine way to produce fissile material using fusion. Covert misuse of a fusion system for fissile material production should be easily and quickly detectable, but R&D is needed to develop the appropriate procedures. The breakout scenario for fusion is different from that for fission, because no fissile material should be available at the moment of breakout. The international community can prevent a breakout fusion power plant from operating and producing fissile material without risk of radioactive contamination. R&D is needed in this area to understand better, and potentially extend, the time scale for breakout. There is no evident risk of independent action by non-state entities.

It appears to the present authors that the Treaty on the Non-Proliferation of Nuclear Weapons should be applicable to fusion power plants without amendment. It is possible that the IAEA Board of Governers, or an NPT Review Conference, would need to make a statement to this effect, and small modifications would be required to subsidiary documents.

There are technical opportunities to advance the necessary safeguards technology for fusion using the ITER facility currently under construction in southern France. These include, inter alia, measurements of background radiation spectra in the vicinity of lead-lithium coolant loops, trials of means to verify that no fertile material is included in blanket modules, and assessments of the turn-around time for replacement of test blanket modules with fissile breeding modules. We recommend that these opportunities be further assessed and pursued as appropriate.

Tritium from fusion systems could contribute to “vertical” proliferation by states that have newly acquired nuclear weapons, and we recommend that means be pursued to minimize this risk. However tritium is available to such states by other routes. The sensitivity of information that can be acquired through Inertial Confinement Fusion R&D that could contribute to “vertical” proliferation, and possible means to limit the dissemination of sensitive information, need further assessment, and we recommend that this be undertaken.

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[4] Terms in italics have specially defined meanings within INFCIRC/153

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