Proliferation Risks of Fusion Energy: Clandestine Production, Covert Production, and Breakout

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ABSTRACT

Nuclear proliferation risks from fusion associated with access to weapon-usable materials can be divided into three main categories: 1) clandestine production of weapon-usable material in an undeclared facility, 2) covert production of such material in a declared and safeguarded facility, and 3) use of a declared facility in a breakout scenario, in which a state begins production of fissile material without concealing the effort. In this paper we address each of these categories of risks from fusion. For each case, we find that the proliferation risk from fusion systems is much lower than the equivalent risk from fission systems, if the fusion system is designed to accommodate appropriate safeguards.

1. Introduction

In this paper we examine the proliferation risks that would be associated with the implementation of future fusion power systems, based on the deuterium-tritium (DT) fusion process. The DT fusion reaction produces a 14.1 MeV neutron, which can in principle be used to transmute fertile material to weapon-usable material. There are three basic scenarios for nuclear proliferation based on this process: 1) clandestine production of weapon-usable material in an undeclared facility, 2) covert production of such material in a declared and safeguarded facility, and 3) use of a declared facility in a breakout scenario, in which a state begins production of fissile materials for weapons purposes without concealing the effort, *i.e.*, after exiting from nonproliferation agreements. In this paper we address each of these categories of risks from fusion. We do not address the legal and diplomentic issues of including fusion systems in international Safeguards regimens, which are typically based on declared inventories of fissile material, but we assume that this can be accomplished.

In Section 2 we provide computational estimates of the maximum rate of production of ^{239}Pu or ^{233}U from natural uranium or thorium mixed into a Pb-Li coolant for a fusion reactor. In Section 3 we consider the risk of clandestine production, estimating the power consumption and land use, and therefore detectability, of a fusion system capable of producing material for a few weapons per year. In Section 4 we discuss the covert use of a fusion system for production of weapon-usable material, estimating the required amount of fertile material and its detectability. In Section 5 we consider the possibility of breakout, and estimate the time required to produce a significant quantity of weapon-usable material. In Section 6, we conclude by contrasting the proliferation risks of fission and fusion systems, and make recommendations for further work.

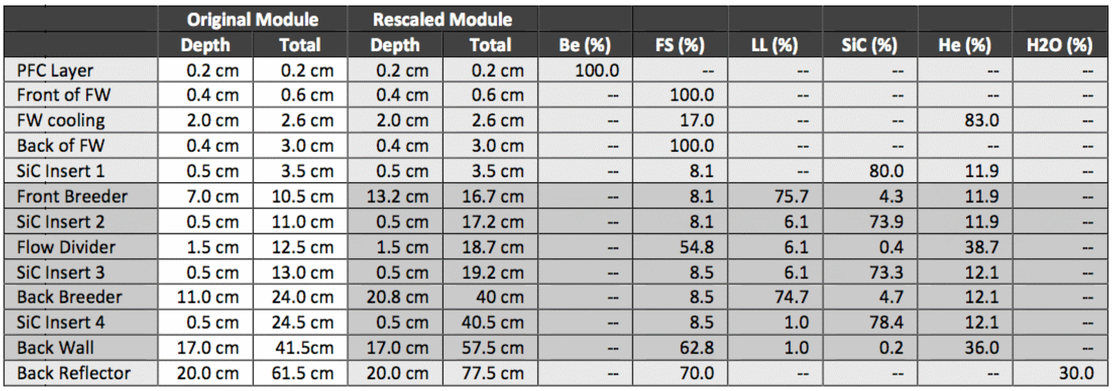
2. Weapons Material Production via Fusion in a Lead-Lithium Blanket Module

The IAEA has defined so-called "significant quantities" for plutonium and highly enriched uranium, which define *"the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded,"* taking into account losses due to conversion and manufacturing processes. The significant quantities are: 8 kg of plutonium, 8 kg of ^{233}U, and 25 kg of ^{235}U contained in highly enriched uranium [1]. This analysis focuses on the production of plutonium and ^{233}U through irradiation of natural uranium or thorium introduced into the blanket material of a DT fusion reactor.

Model of a Lead-Lithium Tritium Breeding Blanket[1]

To estimate the hypothetical covert weapons material production potential of a DT fusion reactor using a lead-lithium breeder/coolant, or the use of such a blanket to produce weapons material after breakout, we model a test-blanket module (TBM) based on the attractive dual-coolant liquid lead-lithium blanket (DCLL) proposed by the United States for testing in the international ITER fusion experiment currently under construction in Cadarache, France.[2] Although it is a test blanket, it will perform similarly to a power-reactor blanket. The specifications of the U.S. DCLL design are detailed in the U.S. DCLL Design Description Document submitted to the ITER Test Blanket Working Group [3]. We use this design information to simulate a TBM using the Monte Carlo N-Particle code MCNP.

Tritium breeding blankets are characterized by their local tritium breeding ratio (TBR), which is the number of tritium atoms produced in the blanket per incident 14.1 MeV neutron. To calculate the plutonium produced in a power reactor, we note that the overall TBR for a power reactor will have to be above unity, while the original test module operates at TBR ≈ 0.74. In practice, a breeding ratio of 1.05–1.07 will provide a necessary margin for uncertainty as well as possible losses, decay, and inventory stockpiling. The increase in the TBR will come from larger breeding channels in the final TBM. We performed an iterative process using MCNP and determined that a TBR of 1.06 corresponds to an additional 16 cm of depth divided between the front and back breeding zones in conformity with the existing depth ratios.



	Original Module		Rescaled Module							
	Depth	**Total**	**Depth**	**Total**	**Be (%)**	**FS (%)**	**LL (%)**	**SiC (%)**	**He (%)**	**H2O (%)**
PFC Layer	0.2 cm	0.2 cm	0.2 cm	0.2 cm	100.0	--	--	--	--	--
Front of FW	0.4 cm	0.6 cm	0.4 cm	0.6 cm	--	100.0	--	--	--	--
FW cooling	2.0 cm	2.6 cm	2.0 cm	2.6 cm	--	17.0	--	--	83.0	--
Back of FW	0.4 cm	3.0 cm	0.4 cm	3.0 cm	--	100.0	--	--	--	--
SiC Insert 1	0.5 cm	3.5 cm	0.5 cm	3.5 cm	--	8.1	--	80.0	11.9	--
Front Breeder	7.0 cm	10.5 cm	13.2 cm	16.7 cm	--	8.1	75.7	4.3	11.9	--
SiC Insert 2	0.5 cm	11.0 cm	0.5 cm	17.2 cm	--	8.1	6.1	73.9	11.9	--
Flow Divider	1.5 cm	12.5 cm	1.5 cm	18.7 cm	--	54.8	6.1	0.4	38.7	--
SiC Insert 3	0.5 cm	13.0 cm	0.5 cm	19.2 cm	--	8.5	6.1	73.3	12.1	--
Back Breeder	11.0 cm	24.0 cm	20.8 cm	40 cm	--	8.5	74.7	4.7	12.1	--
SiC Insert 4	0.5 cm	24.5 cm	0.5 cm	40.5 cm	--	8.5	1.0	78.4	12.1	--
Back Wall	17.0 cm	41.5cm	17.0 cm	57.5 cm	--	62.8	1.0	0.2	36.0	--
Back Reflector	20.0 cm	61.5 cm	20.0 cm	77.5 cm	--	70.0	--	--	--	30.0

TABLE I. BLANKET DESIGN AND VOLUME PERCENT COMPOSITIONS USED IN MCNP CALCULATIONS. Some lithium-lead (LL) is present in zones behind and between the breeding zones in the model from LL flow pipes. PFC denotes the plasma-facing component; FW denotes the front wall. The back reflector has been added to simulate a more realistic reactor environment. Design and data adapted from [3], Table 3.1-1, p. 3-2.

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[1] The MCNP model used in these simulations and initial results on the implications for proliferation risks of fusion were first presented in [2].

[2] ITER is planning also to study He and water-cooled ceramic breeders, He cooled lead-lithium, and mixed helium and lead-lithium cooled ceramic breeders.

Simulations and Results

Using the MCNP model of the U.S. DCLL TBM as an approximation of a general, commercial lead-lithium cooled tritium-breeding module, we consider the following scenario. A quantity of uranium or thorium is brought to the site of a power fusion reactor. An injection system is provided to dissolve these elements in the coolant. As the fissile material is bred, a dedicated extraction system performs separation of the nuclear material from the lithium-lead. In a breakout scenario, it would also be possible to shut down the reactor prior to insertion of the fertile material, then to restart and operate the plant, and finally to extract the material during another shut-down period of the reactor. In this case, it would also be possible to replace the blanket modules with alternate systems bearing fertile material in solid form, such as analyzed in [4].

There are three fundamental constraints that potentially limit the loading of fertile material: loss of tritium production, increased heat load in the blanket, and solubility in the lithium-lead eutectic. We focus first on tritium production and heat load. Table II and Figure 1 summarize the main results of the MCNP simulations.

	TBR	Thermal Power in Blanket	Transmutation Rate	Maximum FM Production	Significant Quantites
$Pb_{83}Li_{17}$	1.062 (reference)	2180 MW (15.4 MeV/n)	---	---	
2% Uranium	1.055 (-0.7%)	2480 MW (17.5 MeV/n)	0.035 at/n	345 kg/yr (at 2180 MW)	43/yr
4% Thorium	1.020 (-4.0%)	2300 MW (16.2 MeV/n)	0.078 at/n	797 kg/yr (at 2180 MW)	99/yr
6% Thorium	1.002 (-5.7%)	2360 MW (16.7 MeV/n)	0.113 at/n	1125 kg/yr (at 2180 MW)	140/yr
8% Thorium	0.985 (-7.3%)	2420 MW (17.1 MeV/n)	0.149 at/n	1418 kg/yr (at 2180 MW)	177/yr

TABLE II. MAIN RESULTS OF THE MONTE CARLO SIMULATIONS. The plasma of the reference plant produces 2500 MW of fusion energy, equivalent to $8.85\ 10^{20}$ neutrons per second (14.1 MeV neutrons, 80% of energy release in plasma, about 2000 MW thermal). The transmutation rates correspond to neutron captures in uranium-238 or thorium-232 per incident neutron. Maximum fissile material (FM) production specifies the production rates of uranium-239 and thorium-233 providing upper limits for annual plutonium-239 and uranium-233 production in the reactor for the same reference power level.

Uranium: Loss of tritium production in uranium is weak due to the production of extra neutrons from fast-fission events in uranium (mostly in uranium-238). For the same reason, however, additional heat deposition in the blanket is also significant. As listed in Table II, for a 2-percent loading of uranium,[3] the total energy deposition in the blanket already increases by about 14% from 2180 MW to 2480 MW when the rate of incident 14.1-MeV neutrons is fixed at its reference value. We assume that the power level of the plasma would have to be reduced by the necessary margin to re-establish the heat load of 2180 MW. With this assumption and with the effective transmutation rate (uranium-238 captures per incident neutron) determined in the simulations, an upper limit for the fissile material production in the blanket can be specified.

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[3] We define the loading as percent of lead atoms substituted. The lithium concentration remains constant, i.e., the lead-to-lithium ratio is no longer exactly 83:17.

Thorium. Compared to uranium, additional heat production in the blanket is much lower when thorium is used as the fertile material. The maximum concentration of 8% thorium considered here results in an 11% increase, *i.e.,* still less than for the 2% uranium case. As shown in Figure 1, the effect of neutron absorptions in thorium on the tritium-breeding ratio, however, is much more pronounced. Besides thorium-solubility constraints, the degradation of this ratio (rather than the heat load) would determine the long-term sustainability of certain fissile-material production scenarios, and it is unlikely that more than 4–6% of the lead could be substituted with thorium without consuming more tritium than is produced in the plant.

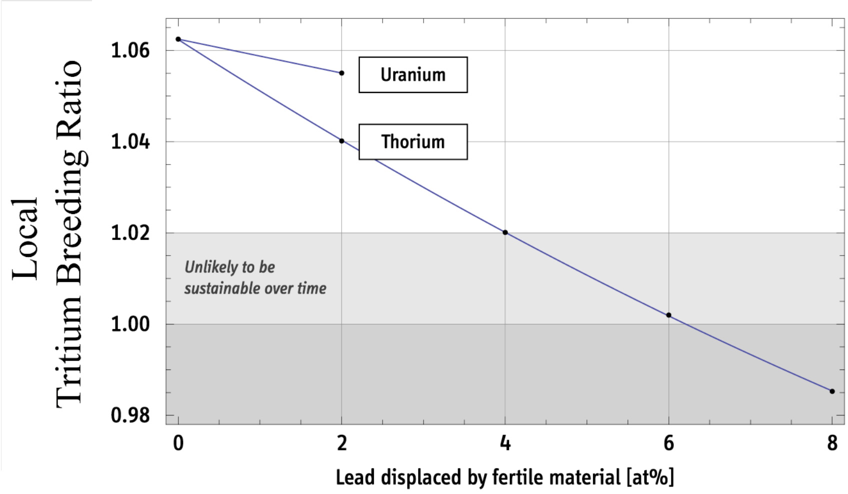
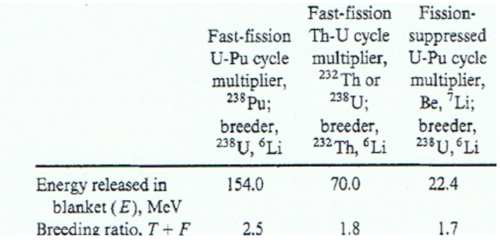


FIGURE 1. Factors constraining the fertile-material loading in the blanket. Besides potential limits imposed by the solubility of uranium or thorium in the blanket coolant (liquid lead-lithium eutectic), the concentration of the fertile material may be constrained by decrease in TBR or by additional heat load in the blanket, which would have to be counterbalanced by corresponding power reduction in the fusion plasma.

3. Clandestine Production of Weapons Material

There is no credible risk that a true power-producing fusion reactor could be operated in a clandestine fashion. However, since the current world-wide fusion research program operates devices that produce 14.1 MeV neutrons, one can ask the questions 1) Is there a fusion equivalent to the small fission research reactors that produce plutonium? 2) What rate of production of weapons material could such a fusion device support? and 3) Could such a device could be operated clandestinely?



	Fast-fission U-Pu cycle multiplier, ^{238}Pu; breeder, ^{238}U, ^{6}Li	Fast-fission Th-U cycle multiplier, ^{232}Th or ^{238}U; breeder, ^{232}Th, ^{6}Li	Fission-suppressed U-Pu cycle multiplier, Be, ^{7}Li; breeder, ^{238}U, ^{6}Li
Energy released in blanket (E), MeV	154.0	70.0	22.4
Breeding ratio, $T + F$	2.5	1.8	1.7

TABLE III. HYBRID PARAMETERS, from [4].

Studies have been made of fission-fusion hybrid systems designed to breed fuel for fission reactors. It has been estimated that each 14.1 MeV fusion neutron could be used to produce up to 0.64 plutonium or ^{233}U atoms [4], corresponding to Column 3 of Table III, assuming a TBR of 1.06.[4] This corresponds to 2.85 kg plutonium per MW-year of DT fusion power production, assuming that all of

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[4] Columns 1 and 2 represent much more fission than fusion power, so are not considered here. Column 1, with about 10x more fission than fusion power, would provide 2.25 times more weapons material per fusion neutron than Column 3.

the neutrons are captured in the blanket. Current fusion experiments have produced up to about 10 MW of DT power, but at very low duty factor ~10^{-3}. They are also very visible. For example, the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory used 600 MW of pulsed magnet power. Operation required large energy storage and power conversion equipment. The site covers about 10 hectares, and the buildings cover 7000 m^2, not including the power substation, control room or cooling tower. The facility is easily discernable in publicly available satellite imagery.

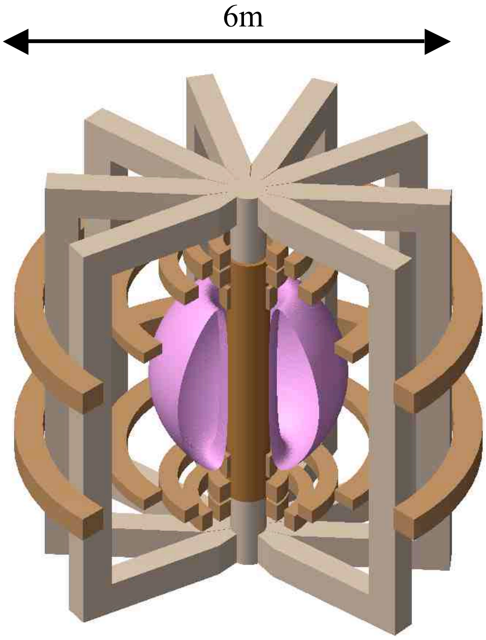

FIGURE 2. Compact Fusion Research Facility for DD Operation

New experimental facilities are being considered, however, to study the management of the high heat fluxes from long-pulse fusion systems, although only for hydrogen or deuterium operation. A pre-conceptual design for a compact facility [5] with this scientific goal has been developed for about 3% duty factor operation in deuterium, not DT (Figure 2). It would use copper magnets and 50 MW of plasma heating power, so would draw 300 MW from the grid, and would require a similar site to the TFTR, but with higher steady input power and cooling capability. If this device were operated in DT, it would produce about 25 MW of fusion power. It includes a 50 cm shield (not shown) for the lower energy and much less abundant neutrons from DD fusion. If we imagine that it were used for DT operation, geometrically it could capture approximately 50% of the fusion neutrons. Ignoring the fact that a thicker blanket/shield would actually be required for DT operation, and using the factor of 0.64, it would produce 1.1 kg of plutonium per year. If a duty factor in the range of 85% could be achieved, as is desired for a fusion power device, this facility would produce 30 kg of plutonium (about four significant quantities) per year. If such a device were able to be operated clandestinely, it would be a credible proliferation risk, but the requirement for several hundred megawatts of continuous power input and cooling, and so a large electric supply line, large power conversion buildings, and a significant cooling facility as well as a large, very well shielded hall would make such an installation quite visible. The large remote handling capabilities for such a high-duty-factor DT facility, much greater than would be required for 3% duty factor deuterium operation, would also be very visible. Based on experience with TFTR, trace levels of tritium lost from the facility would be detectable for a distance of tens of kilometers. Overall, it does not appear credible that such a facility could be constructed and operated clandestinely.

4. Covert Weapons Material Production in a Declared Fusion Reactor

The capability of detecting the presence of nuclear materials will be necessary at a declared fusion reactor to ensure that no undeclared fissile material production is taking place. Ideally, measurements would be made minimally invasive while still ensuring appropriate detection probability.[5] In the case of lead-lithium coolant the most promising approach could be the

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[5] Alternatively, samples could be drawn from the system for a chemical analysis of the material, or active interrogation techniques could be applied.

detection of characteristic gamma emissions from either the fertile or the fissile material present in the lithium-lead matrix. To estimate the feasibility of this method, we consider a covert production scenario, in which a very small concentration (0.05%) of fertile material is added to the coolant. The literature differs on whether this is below the solubility limit for thorium in Pb-Li at a high inlet temperature of 500C [6,7], but is likely not for uranium, in which case the uranium might form a fine precipitate [8,9]. As an alternative to dissolution, the fertile material might be introduced in a form similar to TRISO particles [10]. This concentration would be sufficient to produce about one significant quantity (8 kg) of plutonium or ^{233}U per year.[6] We envision different detection strategies for the uranium and the thorium scenarios: in the case of uranium, one could seek direct detection of the ^{238}U based on its 1.001 MeV gamma line; in contrast, in the case of thorium, one could seek detection of ^{232}U, which is produced via (n,2n) reactions in the ^{233}U bred in the thorium matrix. We have used MCNP to generate spectrum-averaged neutron cross-sections and neutron flux profiles in the blanket module to calculate the ^{233}U and ^{232}U concentrations during irradiation. As expected, the concentration of ^{232}U remains extremely low, but the gamma line of one of its daughter products (2.614 MeV from thallium-208 decay) is highly penetrating. Table IV summarizes the main results showing the effectiveness of the measurements. In both cases detection is straightforward, although further work should be undertaken to evaluate background signal levels expected at a commercial fusion plant. Scalable results should be obtainable from the TBM's on ITER.

	Uranium-238/Plutonium-239	Thorium-232/Uranium-233
Mass of fertile material in 1000 cc	35 g of U-238	35 g of Th-232
Mass of material for measurement	35 g of U-238	0.006 mg of U-232 (about 10% of final concentration)
Gamma emission rate	2835 per second (1.001 MeV)	1.6 million per second (2.614 MeV)
Fraction of gammas escaping (self-shielding in sphere)	0.151 (for 1.001 MeV gammas in lead)	0.238 (for 2.614 MeV gammas in lead)
Detector signal	3.4 counts per second	30200 counts per second
Time to detection	(seconds)	(immediate)

TABLE IV. DETECTING COVERT PRODUCTION OF FISSILE MATERIAL.[7] We assume that a volume of 1000 cubic centimeters (containing about 7 kg of lead) is available for the measurement. To estimate detection rates, we place a detector with an active area of 100 cm^2 at 10 cm distance (about 8% detectable fraction) and assume a detector efficiency of 10%. For the thorium case, we calculate an effective capture cross section for ^{232}Th of about 0.40 barn and an (n,2n) cross section for ^{233}U of 0.01 barn. Approximate uranium isotopics after one year of irradiation are about 0.002% ^{232}U, 99.6% ^{233}U, and 0.4% ^{234}U.

The covert injection of about 750 kg of fertile material into the coolant would be difficult, and the challenge of covertly extracting 8 kg of fissile material dissolved in 1500 tonnes of PbLi, 5.3ppm, would be immense[8]. However, the use of TRISO-like particles would facilitate the

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[6] This estimate is based on scaled values listed in Table 2.

[7] Methodology adapted from [11].

[8] In preliminary discussions with experts in the area of reprocessing, extraction of 8 kg of weapons material from 1500 tonnes of Pb-Li was not considered a credible operation. It is likely that the device would need to be operated for a much longer period of time to establish a more significant concentration of fissile material in the fertile matrix or to accommodate an inefficient extraction process.

extraction of the fissile material. Nonetheless the injection and extraction systems should be visible to inspectors.

In the case of solid breeder blanket modules, it would be necessary for incoming components to be inspected for the presence of fertile material. This might be accomplished by passive means or by using the 14.1 MeV neutron interrogation techniques that have been developed for detection of weapons materials in shipping containers. Assuming the same transmutation rates as calculated in Table 2, 750 kg of fertile material would need to be brought on site to achieve one significant quantity per year.

Sensitive environmental sampling techniques would provide strong additional security against covert use of a fusion system to produce weapons materials, since no fertile or fissile material need be present at a fusion system.

5. Breakout Scenario

The final case that we will consider is the "breakout scenario" in which a nation operating a fusion power plant subject to IAEA safeguards expels the inspectors and begins the production of weapons material as quickly as possible. A variant of this for fission systems is "abrupt diversion" where the activity is begun with the hopes of gaining time before detection. Real-time monitoring is needed to minimize the impact of this variant, but this is now routinely performed where it is considered appropriate. The breakout scenario is currently a real concern in the case of fission, as illustrated by the recent experience with the Democratic People's Republic of Korea (DPRK). A critical aspect of the breakout scenario with fission is that *significant weapons material has already been produced at the time of such a breakout.*[9] The case of a fusion power plant, however, is significantly different. As discussed in Section IV, *no plutonium or ^{233}U would be available at the time of breakout* if the facility were previously operated as declared and safeguarded. To put this distinction in perspective, we estimate the minimum period that would be required to produce one significant quantity of weapons material after breakout.

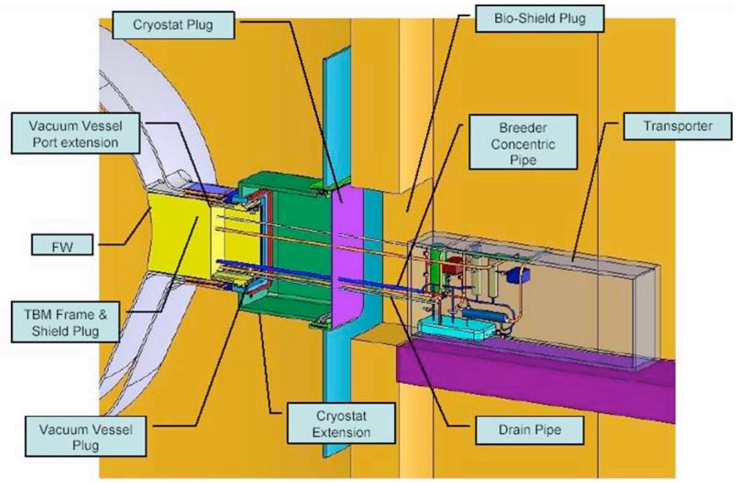

FIGURE 3. Test blanket module installed on ITER.

First, it would be necessary to introduce ^{238}U or ^{232}Th into the blanket system. In the case of dissolution in a Pb-Li coolant, Palenzona et al. [6] suggests that up to about 2% of the lead in the coolant may be able to be replaced

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[9] Discussions with officials from the Clinton Administration and the nonproliferation community indicate that the announcement of the DPRK in 1993 of its intent to withdraw from the NPT put the United States and the international community in a very difficult situation. Plutonium was already available in cooling ponds and in the reactor itself. Destruction of those facilities could have lead to widespread radiological contamination. A more carefully targeted approach that left the plutonium intact, however, would also leave it available for military use when action was halted. The plutonium from the Yongbyon site was ultimately used to construct nuclear explosives.

with dissolved thorium. This corresponds to 30 tonnes of material, which would need to be introduced into a highly radioactive coolant loop, maintained at high temperature. Alternatively this could be introduced in the form of TRISO-like particles. It is difficult to imagine that this could be accomplished in much less than one month, although engineering analyses of this should be undertaken. It may be necessary to include filters or other systems to prevent the circulation of fertile particles into the coolant, in order to increase the time required to introduce and irradiate such particles. Alternatively the filters that will normally be present to maintain purity of the coolant may present an important impediment to injecting over 40 0.5mm diameter TRISO particles per cc of lead-lithium.

The analyses of Section II indicate that about 400 kg of ^{233}U could be produced, for a 2% thorium loading, in one year once the device was operating. Thus in about one week of operation, approximately one significant quantity of ^{233}U could be produced. It should be recognized that this would correspond to a very small concentration of weapons material, 5 ppm, in about 1500 tonnes of Pb-Li, again representing an immense reprocessing challenge, unless the fertile material were concentrated in particles. Neither the loss of tritium breeding nor excess heating would be a limitation in this scenario.

Alternatively, one can consider replacement of the breeding blankets with optimized systems as discussed in Section 3. If the reactor were equipped with test blanket access ports, as ITER will be (Figure 3), then use of these ports would likely constitute the quickest approach. ITER targets being able to replace test blanket modules in a period of one month. The additional time for restart of the facility would be at least one additional month [12]. ITER uses three midplane ports for test blanket modules, with a total area of 8 m^2. A commercial reactor might allocate similar space for testing new blanket designs; a practical upper limit for this might be 24 m^2. This would constitute an equivalent fusion power of about 100 MW, which would provide one significant quantity of weapons material in 8 days, following the logic presented in Section 3. Perhaps this area for test blanket modules should be limited in commercial fusion systems in order to extend the required period of time.

In sum, it appears that a time scale of at least 1–2 months would be required to produce one significant quantity of weapons material in a fusion reactor, after inspectors were expelled. This period is dominated by the time required to reconfigure and restart the facility. More analysis is required to refine this estimate, but it gives a sense of the time scale over which the international community would be able to react without concern that significant quantities of weapons material had already been produced. As with the fission breakout scenario, there are political and diplomatic options at this point, but unlike the fission case there is also the option to disable the plant and prevent the production of weapons material. Fusion power plants require many supporting facilities that are completely non-nuclear in nature, but if deactivated would immediately prevent the power plant from operating. These include the massive power input and power conditioning equipment that

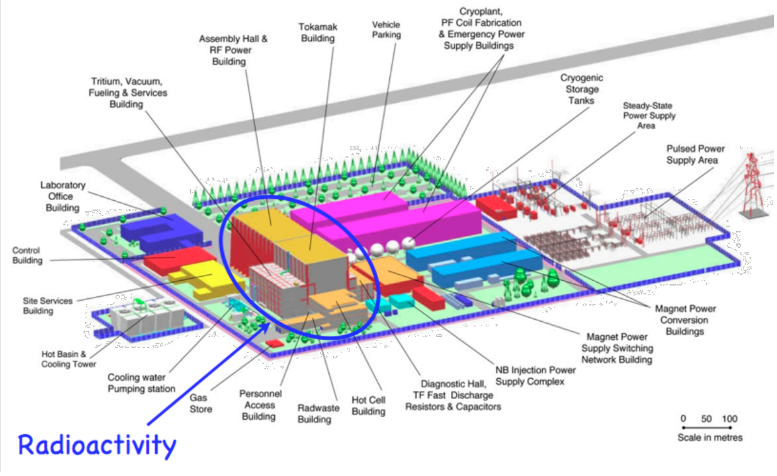

FIGURE 4. Layout of ITER site.

provides electricity to the magnets, a very large cryoplant that provides liquid nitrogen and liquid helium to these magnets, and the secondary cooling system that removes heat from the system. Such facilities can be seen in the layout of the ITER site, shown in Figure 4. These are distant from the fusion reactor itself, and could be disabled without significant risk of nuclear contamination. Experts who had been directly involved with the DPRK breakout scenario considered this difference to be very important.

6. Conclusion

The possibility of producing fissile materials for weapons purposes is a proliferation concern associated with many technologies and facilities used in the nuclear fission fuel cycle today. A clandestine centrifuge enrichment plant drawing less than 1 MW and occupying an area of 1000 m^2 can produce approximately four significant quantities of highly enriched uranium per year. Similarly a 40 MW(th) research reactor can produce about 10 kg/yr of plutonium annually. Covert diversion of plutonium from a declared reprocessing facility is another concern, since the measurement uncertainties in even the most modern facilities cannot be reduced to much less than 1%. In the case of a commercial-size reprocessing plant, accepting spend nuclear fuel from 40 light-water reactors, this corresponds to an uncertainty of about 80 kg/yr of plutonium. The availability of fissile materials, especially at a reprocessing plant under national control, makes the breakout scenario for fission a credible risk. For fission there is an additional category of long-term risk associated with Pu in stored nuclear waste.

Some researchers have considered “hybridizing” fusion and fission. In principle the neutrons from fusion can be used for three purposes related to fission power: 1) multiplying the 20-MeV energy output from each fusion reaction by inducing fission reactions (200 MeV each) in a sub-critical fission blanket surrounding the fusion system; 2) breeding fuel for fission systems by transmuting ^{238}U or thorium to plutonium or ^{233}U; and/or 3) using the energetic neutrons from fusion to “burn” plutonium and other transuranics or even long-lived fission products recovered from the reprocessed spent fuel of fission power plants. Combinations of these have also been examined. Relative to fission without reprocessing, some proposed approaches would reduce the need for uranium enrichment, and so would reduce the risk associated with clandestine centrifuge systems derived from national efforts. The risk of diversion of weapons material does not appear to be qualitatively different from fission systems with reprocessing, since significant handling of nuclear fuels would be required in all cases. The risk of breakout would be similar to fission with reprocessing. Some forms of fission-fusion hybrid would reduce the long-term risk associated with Pu in stored waste. Overall, however, hybrid systems appear to inherit the main risks of fission with reprocessing, although more analysis should be done for specific proposals.

Ultimately, if designed to accommodate appropriate safeguards, fusion reactors would present low proliferation risk compared to fission. We have shown that there is not a credible technique for clandestine production of weapons materials using fusion research facilities. Detection of the covert use of a declared fusion power plant to produce even very small amounts of plutonium or ^{233}U appears to be straightforward. The breakout scenario for fusion is qualitatively different from that for fission, because no weapons material is available at the time of breakout. We estimate that the world community would have 1–2 months to respond and prevent the production of weapons materials.

We recommend future research to make these analyses more comprehensive: better measurements of the solubility of uranium and thorium in fusion blanket coolants, more detailed assessment of the time required to add significant quantities of these materials to fusion blanket coolants, assessment of techniques to prevent the flow of particles of fertile material, assessment of techniques to extract plutonium or uranium from blanket coolant at very low concentrations, assessment of the background radiation near the coolant loops, more detailed analysis of the use of passive or active means to assay incoming materials at a fusion power plant, and more detailed engineering assessment of the time to replace test blanket modules and then to restart a fusion power plant. The proliferation risks of different fission-fusion hybrid schemes should also be carefully analyzed.

We recommend that it would be appropriate now to pursue the conceptual development of nonproliferation protocols and safeguards for fusion power plants.

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