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 material can be divided into three main categories: 1) clandestine production of fissile 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 risk from fusion. For each case, we find that the proliferation risk from fusion systems can be much lower than the equivalent risk from fission systems, if commercial fusion systems are 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 fissile 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 for weapons purposes without concealing the effort, *i.e.*, after exiting from nonproliferation agreements. In this paper we address each of these categories of risk from fusion. We do not address the legal aspects of bringing fusion energy systems under IAEA safeguards, 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 power system. 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. Weapon-Usable Material Production via Fusion in a Lead-Lithium Blanket Module

The IAEA has defined "significant quantities" of plutonium and highly enriched uranium to be *"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. These significant quantities are: 8 kg of plutonium, 8 kg of

^{233}U, and 25 kg of ^{235}U contained in highly enriched uranium [1]. Our 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 power system.

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

To estimate the hypothetical weapon-usable material production potential of a DT fusion power system using a lead-lithium breeder/coolant, or the use of such a blanket to produce weapon-usable 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 fusion power system 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 fusion power system, we note that the global TBR will have to be above unity, while the test module operates at TBR ≈ 0.74. In practice, a local breeding ratio of 1.05–1.07 will provide a necessary margin for uncertainty as well as losses, decay, and inventory stockpiling. The increase in the TBR will come from greater breeding depth 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 first wall. The back reflector has been added to simulate a more realistic power system environment. Design and data adapted from [3], Table 3.1-1, p. 3-2.

[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.

Simulation 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 fusion power plant. An injection system is provided to introduce 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 be possible to shut down the power plant 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. 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 two fundamental constraints that may limit the loading of fertile material: loss of tritium production and increased heat load in the blanket. Table II and Figure 1 summarize the main results of the MCNP simulations of the scaled test blanket module.

	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 ^{238}U or ^{232}Th per incident neutron. Maximum fissile material (FM) production specifies the production rates of ^{239}U and ^{233}Th providing upper limits for annual ^{239}Pu and ^{233}U production in the fusion system 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 ^{238}U). 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 be reduced by the necessary margin to re-establish the heat load of 2180 MW. With this assumption and with the effective transmutation rate (^{238}U captures per incident neutron) determined in the simulations, an upper limit for the fissile material production in the blanket can be specified.

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

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

shown in Figure 1, the effect of neutron absorption 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.

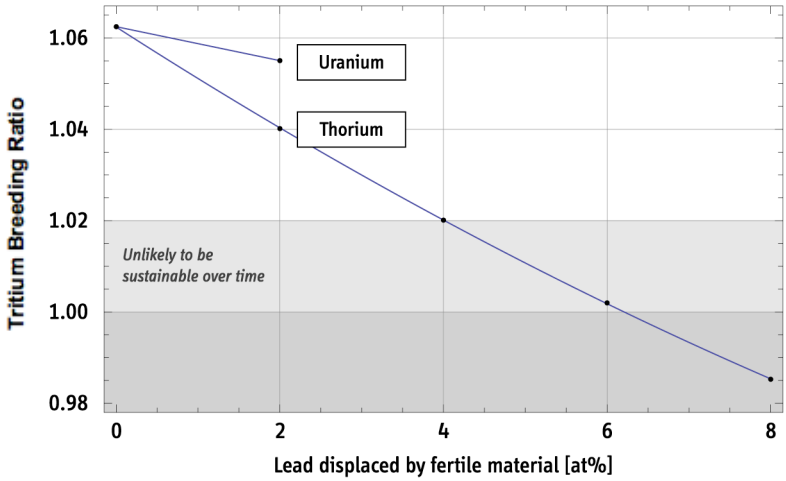

FIGURE 1. Local tritium breeding ratio of scaled blanket module. The concentration of fertile material may be constrained in some scenarios by decrease of TBR.

3. Clandestine Production of Weapon-Usable Material

There is no credible risk that a true power-producing fusion power system 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 weapon-usable material could such a fusion device support? and 3) Could such a device could be operated clandestinely?

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] 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 the neutrons are captured in the blanket. Current fusion experiments have produced 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 up to 1000 MVA 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. Current fusion research facilities, which could produce, in principle, 28.5g of Pu per year pose no significant proliferation risk.

[4] Columns 1 and 2 in Table II of [4] represent much more fission than fusion power, and 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 (used here), in which 22.4 MeV is released in the blanket per fusion neutron.

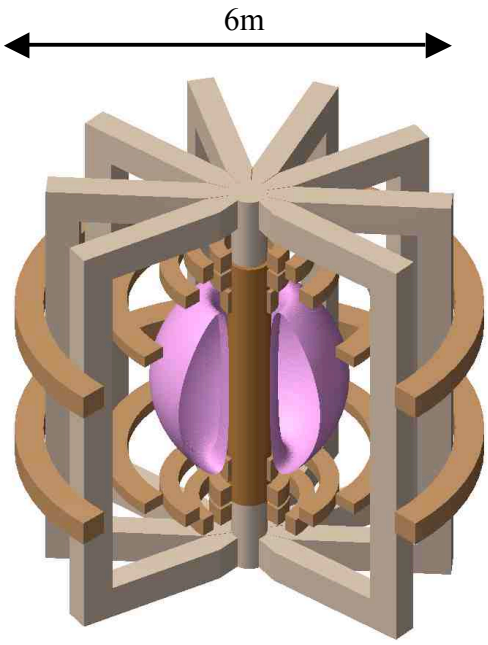

FIGURE 2. Compact Fusion Research Facility for DD Operation

New experimental facilities are being considered, however, to study the management of the high heat fluxes from long-pulse, high-power density 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. It would require a similar site to the TFTR, but with higher steady input power and cooling. Its cost would be in the range of hundreds of millions of dollars. (If superconducting magnets were employed, the site power could be reduced by ~ 1/3, but then a large and visible cryoplant would be required. The device itself would also be larger and more expensive.) If this facility 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. Its blanket would intercept approximately 50% of the 14.1 MeV fusion neutrons. Ignoring the fact that a thicker blanket/shield would actually be required for DT operation and using the factor of 2.85 kg/MW-year discussed above, 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 commercial 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 at least 200 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, in addition to the environmental signatures of fertile and fissile materials. Overall, it is not credible that such a facility could be constructed and operated clandestinely.

4. Covert Weapon-Usable Material Production in a Declared Fusion Power Plant

The capability of detecting the presence of nuclear materials will be necessary at a declared fusion power system to ensure that no undeclared weapon-usable 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 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

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

(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 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. 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 ^{208}Tl decay) is strong. Table IV summarizes the main results showing the effectiveness of the measurements. In both cases detection appears to be 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 TBMs 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 covert extraction of 8 kg of fissile material dissolved in 1500 tonnes of PbLi, 5.3ppm, does not appear to be a practical strategy [12]. The use of TRISO-like particles would facilitate the extraction of the fissile material. Nonetheless the injection and extraction systems should be detectable in regular Design Information Verifications.

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, looking for either gammas or neutrons in coincidence, or by using the 14.1 MeV active neutron interrogation techniques that have been developed for detection of nuclear

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

[7] Methodology adapted from [11].

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 produce one significant quantity per year.

Sensitive environmental sampling techniques would provide strong additional confidence in detecting covert use of a fusion power plant to produce weapon-usable material, since no fertile or fissile materials at all 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 weapon-usable material as quickly as possible. A variant of this for fission systems is "abrupt diversion" where diversion is begun without announcement in the hope of gaining time before detection. For fusion systems real-time monitoring, for example of gamma-ray lines emitted by the blanket coolant, would be desirable to minimize the impact of abrupt action. 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 weapon-usable material has already been produced at the time of such a breakout*.[8] 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 weapon-usable material after breakout.

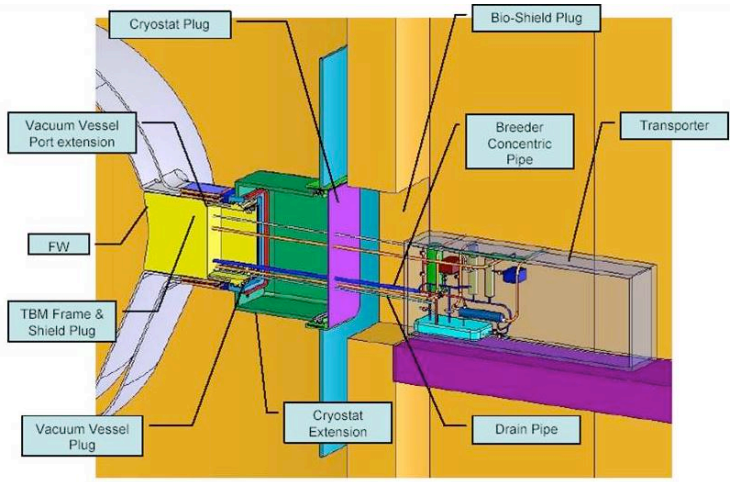

FIGURE 3. Test blanket module installed on ITER.

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 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. The material could instead be introduced in the form of hundreds of 0.5mm diameter TRISO

[8] 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 position. 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 destroyed the buildings but left the plutonium intact, however, would also leave the plutonium available for military use when action was halted. The plutonium from the Yongbyon site was ultimately used to construct nuclear explosives.

particles per cc of lead-lithium. It is difficult to imagine that either could be accomplished in much less than one month, although engineering analyses of this should be undertaken[9].

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 weapon-usable material, 5.3 ppm, in about 1500 tonnes of Pb-Li, representing an immense reprocessing challenge, unless the fertile material were concentrated in particles. Extraction of 8 kg of ^{233}U or Pu from 30 tonnes of TRISO-like particles would still be a significant challenge. 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 power system 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 [13]. ITER uses three midplane ports for test blanket modules, with a total area of 8 m^2. A commercial power plant 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 weapon-usable material in 8 days. Perhaps this area for test blanket modules should be limited in commercial fusion systems in order to extend the required period of time.

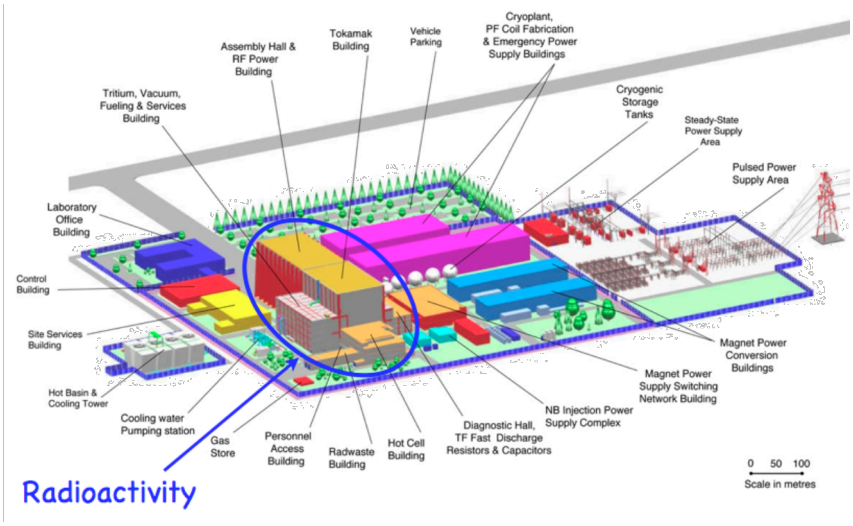

FIGURE 4. Layout of ITER site.

In sum, it appears that a time scale of at least 1–2 months would be required to produce one significant quantity of weapon-usable material in a fusion power plant after breakout. 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 fissile 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 weapon-usable material. Fusion power plants require many supporting facilities that are

[9] The powerful pumps required to circulate the coolant may be (or could be made to be) incompatible with "gritty" fluids, and the filters that will normally be present to maintain purity of the coolant may also present an important impediment. Alternatively it may be desirable to include difficult-to-remove filters to prevent the circulation of fertile particles in the coolant, in order to increase the time required to introduce such particles.

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 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 confinement system itself, and could be disabled without significant risk of nuclear contamination. The fact that this can accomplished before a significant quantity of weapon-usable material is produced represents a qualitative difference from the fission breakout scenario.

6. Conclusion

The possibility of producing fissile materials for weapons purposes is a proliferation concern associated with several technologies and facilities used in the nuclear fission fuel cycle today. An undeclared centrifuge enrichment plant, for example, is extremely difficult to detect: a plant sized to produce four significant quantities of highly enriched uranium per year draws less than 1 MW and occupies an area of perhaps 50x50 m^2. 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 spent nuclear fuel from 40 light-water reactors, this corresponds to an uncertainty of about 80 kg/yr of plutonium. The availability of weapon-usable material, at reactor sites and especially at reprocessing plants under national control, makes the breakout scenario for fission a credible risk. For fission there is an additional long-term risk of covert diversion or breakout 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 total nuclear energy output associated with 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 weapon-usable material does not appear to be qualitatively different from fission systems with reprocessing, since substantial processing of nuclear fuels would be required in all cases, although hybrids may allow different processing options. 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 power plants would present low proliferation risk compared to fission. We have shown that there is not a credible technique for clandestine production of significant quantities of weapon-usable material 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 if adequate safeguards are implemented. The breakout scenario for fusion is qualitatively

different from that for fission, because no weapon-usable material is available at the time of breakout.

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 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 restart a fusion power plant. The proliferation risks of different fission-fusion hybrid schemes should also be carefully analyzed. Finally, and most importantly, we recommend that it would be appropriate now to pursue the conceptual development of safeguards approaches for fusion power plants.

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