Strong Neutron Sources - How to cope with weapon material production capabilities of fusion and spallation neutron sources?

Matthias Englert, Giorgio Franceschini, Wolfgang Liebert

Introduction

Historically the production of plutonium for weapon purposes took place in dedicated fission reactors by irradiation of U-238 in the fuel or the reactor blanket and subsequent separation of the produced plutonium. Only within a nuclear fission reactor it was possible to provide the neutron fluxes necessary for a significant production of plutonium. However, in future other strong neutron sources – such as fusion power plants or spallation neutron sources (SNS) – could also potentially be used to produce fissile material for weapon purposes. In this article we investigate the potential and relevance for weapon material production in such facilities and sketch what should be done to strengthen these technologies against a non-peaceful use. The focus of this article will be mainly on fusion, but some conclusions also apply to SNS. What we propose in this article is a thought experiment in preventive arms control, or – more ambitiously – in anticipatory governance of future nuclear technologies.

Proliferation Potential of Fusion Reactors – quantitative and qualitative assessments

Tritium Diversion

The easiest way to use a fusion plant for nuclear weapon purposes would be the diversion of tritium, a material constantly produced and consumed during reactor operation and stored in large quantities at the plant[1]. Only a few grams of tritium are enough to boost the yield of a nuclear weapon, thereby enhancing the efficiency (yield-to-weight ratio) of the weapon and allowing for its minimization. In a large gigawatt fusion power plant several kilograms of tritium will be in the inventory at any time, the daily consumption will amount to several hundred grams and the annual production rate will exceed 100 kg. It will be impossible to use material accountancy to detect the diversion of some few grams in such an environment[2].

Huge Plutonium Production Potential

Besides tritium diversion another possibility to use a fusion plant for military purposes is to use the tritium breeding blankets, replace a significant part of the lithium containing alloy with uranium, and breed plutonium instead.

Note that the use of fertile or fissile nuclear material is not proposed in the reactor

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[1] Current fusion reactors use deuterium and tritium as reactor fuel. Tritium is produced during reactor operation through neutron irradiation of lithium-6 targets in the reactor blanket; deuterium is supplied externally.

[2] For a detailed discussion of the proliferation dimension of tritium see (Kalinowski and Colschen 1995 and Kalinowski 2004).

concepts by the European Fusion Development Agreement (EFDA) and it is stated that "none of the materials required are subject to the provisions of non-proliferation treaties" (Maisonnier et al. 2005, p5), and consequently the "default materials" (deuterium and lithium/tritium) would not fall under the radar of nuclear safeguarding authorities.

Modern fusion concepts usually do not foresee the production or use of fissile materials in the reactor, but throughout the history of fusion research the idea of a fusion-fission hybrid reactor raised interest time and again (Bethe 1979, Manheimer 1999, Gerstner 2009).
The original design idea of fission-fusion hybrids is the production of fissile material in a fusion reactor to provide fuel for a satellite fleet of fission reactors. Coupling fusion and fission is not unproblematic though, and the proliferation implications of such systems where recognized already in the 1980s (Holdren 1980). Today, although mainstream fusion research gears towards a pure fusion reactor (no fissile material byproducts), there is some renewed interest in such systems (Freidberg and Kadak 2009, Feder 2009).

For the purpose of this paper we used the first detailed conceptual design for a future tokamak fusion power plant of the European Fusion Development Agreement (EFDA) (Maisonnier et al. 2005). EFDA published four power plant conceptual studies (PPCS) in 2005, the reactor prototypes A, B, C and D. We developed a detailed MCNP model of the reactor geometry of the PPCS-A prototype (Englert 2009, Englert et al. 2010). PPCS-A is the concept in need of less R&D requirements compared to the concepts B,C, and D. This reactor concept is a tokamak based commercial fusion reactor design with a total thermal power of 5.5 GW. The torus is divided in 20˚-sectors, with a port every two sectors to allow for easy module exchange by remote handling machines (the goal will be a module lifetime of five years). The modules have to be small enough to be transportable, and large enough to allow for an overall short maintenance period so that the plant capacity factor does not drop below 75-85%. We modeled only a 20˚ section of the torus with 3 inboard and 3 outboard modules (fig. 1 at the end of the paper). The inboard modules have four blankets, the outer modules five blankets totaling 27 blankets in a 20˚ section. Thus the whole torus of the reactor would have 108 modules and 486 blankets neglecting the space for ports.[3]
The breeding material is lithium (enriched to 90% Li-6) in a liquid lead-lithium alloy (Pb-17Li) contained in the blankets , which are cooled by light water to temperatures below 670K. The shielding and the divertor complete the entire reactor structure.

Homogeneous Model
In our first MCNP models the assumption was made that each blanket is filled with a homogeneous mixture of the materials (H2O, Pb-17Li, EUROFER Steel) without any internal blanket structure following a detailed description in (Chen et al. 2003) using a simplified model. A real blanket of course would have a steel structure with cooling pipes. We replaced a certain volume fraction of the Pb-17Li alloy by adding uranium to

[3] Naturally in such a model the inboard blankets have much less volume than the outboard blankets. Such a model is good for neutronic calculations. In the original PPCS-A design some inboard and all outboard modules are subdivided so that in total there are 189 modules in the reactor taking ports into account.

the homogeneous mixture and calculated possible annual plutonium productions. The results of these calculations are discussed in detail in (Englert 2009, Englert et al. 2010) and summarized here in table 1.

		Uranium in Alloy			
		10%	1%	0.1%	0.01%
20° sector	One Blanket close to Plasma	25-65	4-10	1-2	0.1-0.2
	One Blanket far from Plasma	1-3	0.3-0.6	<0.1	<0.10
	All Blankets close to Plasma	260	36	8.6	1.3
	All Blankets far from Plasma	15	2.7	0.4	0.3
	All Blankets	414	71	12.5	1.5
Complete Reactor		7450	1280	225	27

Table 1. Plutonium production in kilogram per year in blankets with different volume fractions of the lead-lithium alloy replaced by uranium. (No burnup considered, 100 % capacity assumed). The range in production reflects the fact that outboard blankets have a much larger volume than an inboard blanket.

One blanket close to the plasma chamber with neutron fluxes as high as 10^{15} n/cm^{2}s will produce 4-10 kg Pu per year with 1 vol% of the lead lithium alloy replaced by uranium (roughly 3.5 kgPu/m^3 after one year). In the blankets far from the plasma the flux and therefore the Pu production drops significantly by roughly one order of magnitude although the blanket volume is the same.
Without any further optimization the maximum production rate for all blankets in a 20°-section would be 71 kg for a uranium concentration of 1 vol% natural uranium. Even for a concentration of only 0.01 vol% uranium in the alloy, production rates in the kilogram range are achievable (1.5 kg). A volume faction of 0.001 vol% is the lower limit for which production even in all modules of a 20° sector becomes insignificant (155 g Pu-239).

Two factors will limit the possibility of adding uranium to the alloy. The additional fission in U-238 will increase the heating and secondly will reduce the tritium production rate and affect the overall tritium breeding ratio (TBR) of the reactor.

Fig. 2 shows the impact of additional uranium on the power deposition in selected blankets exemplified for module V. At a volume fraction of 1 vol% significant additional power is deposited in all blankets even in remote ones far from the plasma chamber. Assuming that a blanket cooling system is designed to remove a specific nominal heat production a conservative assumption would be that any cooling system should be capable to remove 10% additional heat. In a proliferation scenario such a use would reflect a partial conversion of the plant for a use not intended for in the design specifications. 10% additional heat would give roughly a limit of 1 vol% additional uranium in a blanket.

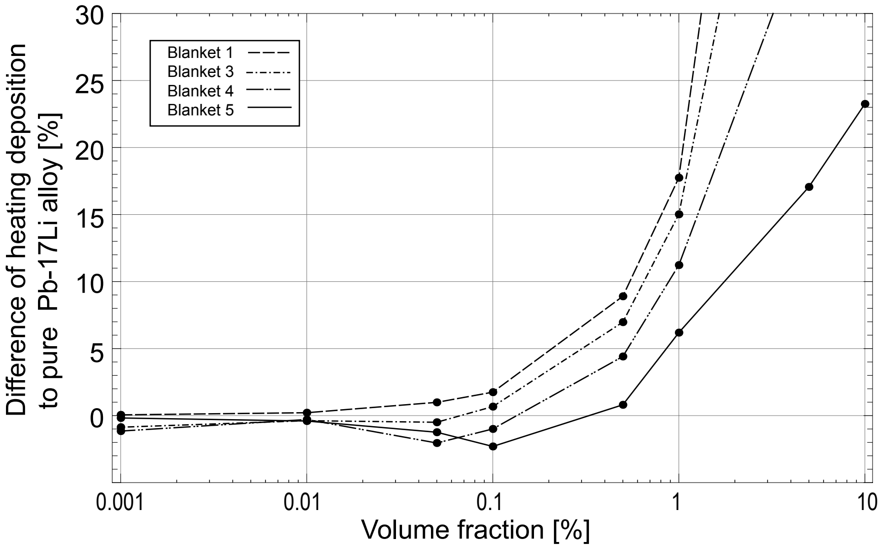

Fig. 2 Additional heating for selected blankets of module V with uranium addition in comparison to a pure Pb-17Li alloy without uranium over the volume fraction of uranium added. Blanket 1 is close to the plasma blanket 5 far from the plasma.

The total additional heat would be several MW for blankets close to the plasma and only several kW for blankets far from the plasma, so that additional heat in blankets far from the plasma is less critical and cooling might be accomplished without redesigning and reconstructing the blanket with e.g. additional tubes, pumps etc. The use of depleted uranium could also somewhat reduce the effect of heating.
Calculations also showed that the overall TBR decreases by only 0.02 in the maximum (1 vol% uranium) due to replaced volumes of Pb-17Li and a neutron poisoning effect of U-238. Replacing higher volumes increases the TBR again as additional fission neutrons become available. Unless the TBR is not dropping below a critical threshold of 1.06 (Chen et. al 2003) this will not affect the operability of the reactor.

More Realistic Breeding (Inhomogeneous Model)
Higher concentrations (>0.001 vol%) of uranium can only be dissolved in the alloy at temperatures higher than 670 K (for details cf. Englert et al. 2010). However, the use of very small solid state particles (TRISO) in the liquid lead lithium alloy could be envisioned. In such a case results in table 1 can be considered accurate within the uncertainties of the model.[4] Other EFDA reactor concepts like PPCS-B also consider pebble beds in the breeding blankets.

Another possibility for breeding is the introduction of breeding structures, such as fuel rods or uranium plates instead of homogeneous dissolutions. The first approach to implement breeding structures in the simulations was the replacement of the uranium

[4] Uncertainties here stem mainly from the assumption of a homogeneous mixture with water, which considerably softens the neutron spectrum. Others are the negligence of burnup and uncertainties of the geometry and the neutron source.

contained in the blankets of the module II (inboard, straight module) by fuel rods. In the homogeneous model the mass of the uranium contained in one blanket is 25 kg natural uranium given a blanket volume of 1.3 m^3, a uranium fraction of 0.1 vol% and a density of 19.05 g/cm^3.

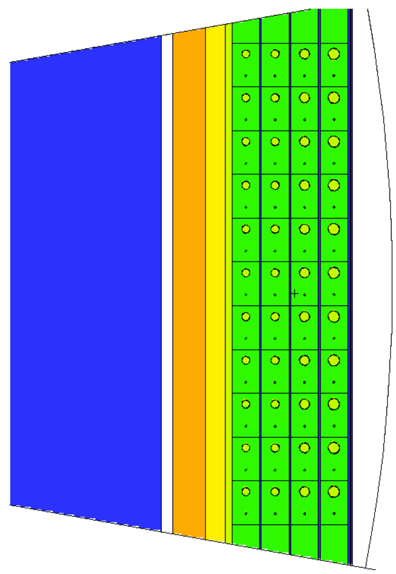

Fig. 2 Inboard module II. Blanket structure in a horizontal cut in the xy-plane (compare fig. 1 lower left cut). Blanket 1,2, 3 and 4 contain the breeding structures, in this case 11 fuel rods and cooling pipes. The radius of the water cooling pipes decreases as the water content is decreasing with distance to the plasma (simplifying assumption).

We chose a typical light water fuel rod geometry as a breeding structure in the blankets, which is filled with uraniumoxide UO_2. The fuel rod radius is 0.424 cm with a cladding of 0.5 mm. Thus the total amount of 25 kg or uranium is now contained in the fuel rods in the form of uraniumdioxide with a density of 10.97 g/cm^3 (9.67 gU/cm^3). There are 11 such fuel rods with a length of 419.6 cm filling the blanket 2 with a 20 cm distance (fig. 3). In between 2 rods is a water cooling pipe with an inner radius of 2.2 cm and a cladding of 1 mm containing water with a density of 0.7245 g/cm^3 (blanket 2). The rest of the blanket still contains a homogeneous mixture of steel and Pb-17Li alloy, but of course now without water and uranium. A simplifying assumption was made that only the radius of the water cooling pipes changes from blanket to blanket, but not the number of pipes.[5] The radius corresponds to the volume percentage of water in the homogeneous mixture according to (Chen et al. 2003).

In the homogeneous calculations described above a content of 25 kg of pure uranium in the homogeneous mixture yields e.g. a total production of 350 g Pu-239 per year in blanket 2 with a 0.1 vol% addition of uranium. The same amount of uranium in the form

[5] The design radius and the number of cooling pipes as well as other dimensions and the exact geometry of the nominal blanket design structure is not known to the author. The choice of radius and numbers of pipes is arbitrary for this analysis.

of uranium oxide in 11 fuel rods yields only 90 g Pu-239 per year, which is significantly less.

Two effects cause this results. Due to geometric separation of the materials, the thermalization of the neutron energy spectrum due to the water is now effective only in certain spatial regions in the blanket zone thereby reducing the efficiency in the resonance region of the (n,γ) cross section of U-238. Changes to the flux intensity due to self-shielding effects[6] are less important.

The calculations (Table 2) show that the loss in production is less pronounced further away from the plasma, as the neutron spectrum becomes softer. Whereas in the plasma facing blanket the drop ratio is almost 6, i.e. the homogeneous calculations give 6 times higher Pu production rates than with the fuel rods structures, the further away from the plasma the lower is the ratio falling below 3 in blanket 4 (Englert 2011). Nevertheless, if breeding structures are going to be used to produce plutonium without any moderator like water near the uranium, the production numbers from the parametric study with homogeneous material mixtures in Tab. 1 have to be corrected with a factor of roughly 3-6.

	Rods Pu [g]	Homogeneous Pu [g]	Ratio
Blanket 1	144	856	5.9
Blanket 2	77	346	4.5
Blanket 3	40	133	3.3
Blanket 4	22	62	2.8

Tab. 2 Plutonium production with fuel rods implemented in all blankets (inhomogeneous model). Absolute production numbers as well as drop ratio compared to homogeneous mixture are given. (Module II, 25 kg uranium in one blanket)

When assessing the maximum production potential of a fusion reactor, a conservative assumption is that it should not be problematic to load the breeding blankets with 1 vol% uranium. For such a scenario the homogeneous model yields a maximal annual production of 1.28 tons of Pu for the whole reactor. However, such a scenario seems to be not realistic except the reactor is designed as a fusion fission hybrid reactor, in which case production could reach several tons by further increasing the uranium load. The more "realistic" inhomogeneous scenario yields several hundred kg of Pu per year. Changes to the blanket design would be necessary in any case.

Weapon Grade Isotopic Vector

One effect of the very hard neutron spectrum in the blanket is that the plutonium isotopic composition even after long irradiation times has a high content of Pu239. For blankets far from the plasma the isotopic composition is almost pure Pu239 (>99%) even after 5

[6] Usually self-shielding refers to the absorption of emitted neutrons by the emitting material itself. Here self shielding refers to the shielding of parts of the geometry so that e.g. the interior of the fuel rod does not see much neutrons, because of absorption at the periphery of the rod

years of irradiation. Hence, even after several years the plutonium bred in the reactor blankets would still be weapon-grade (fig. 3).

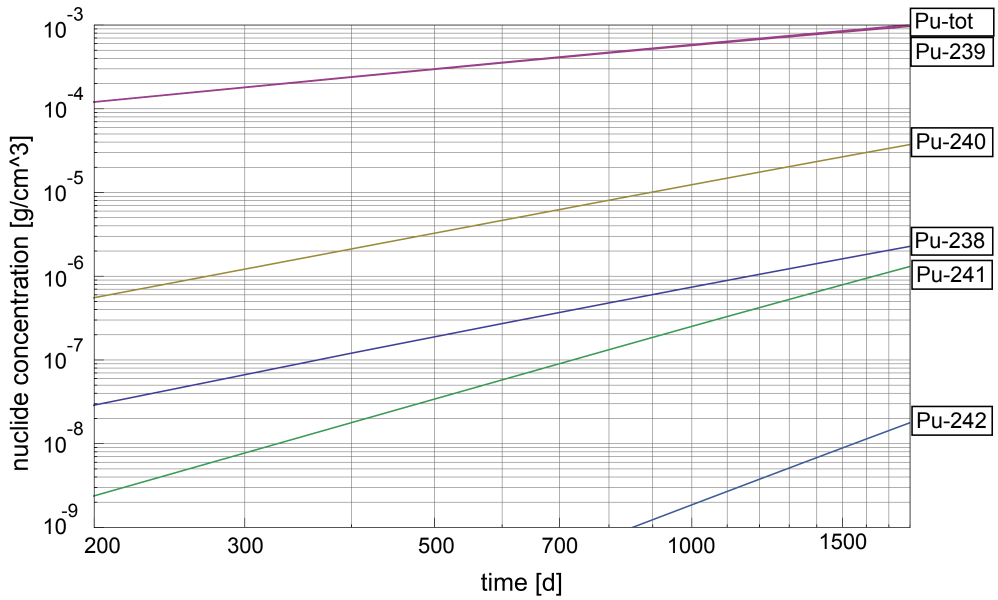

Fig. 3 Burnup calculation with MCMATH (VESTA verified) for module II Blanket 2, 0.1 vol%. uranium. Such isotopic composition of the plutonium is excellent for weapons purposes. Other blankets also have a Pu-239 content of well over 90% even for very long burnups.

Low Source Material Requirements

In comparison to plutonium production in a fission reactor uranium is not needed for neutron production, it can be primarily used as blanket material for plutonium production. There is no need for large amounts of uranium therefore. Typically in a fission reactor several ten tons of uranium would be needed to produce enough neutrons for a significant production. In a fusion reactor much less material is needed. In addition the end concentration of plutonium per ton heavy metal can be much higher than in a fission reactor especially when comparing similar isotopic compositions of plutonium. Due to the largely thermal spectrum in a fission reactor short irradiation times are necessary to produce weapon quality plutonium. The irradiated heavy metal contains only low concentrations of plutonium and large amounts of source material are necessary to produce a significant quantity of plutonium. Typical end concentrations for low burnup, weapon quality plutonium are 1 kg/tHM in a gas graphite production reactor. In a civil power plant with reactor grade plutonium production concentrations of about 10 kg/tHM are reached after 30 GWd/tHM burnup. In a fusion plant concentrations can reach up to 20 kg/tHM[7] for burnups comparable to those in commercial reactors but with weapon quality isotopic compositions. As an example it is possible to produce 4 kg weapon quality Pu per year with roughly 200 kg of natural or even depleted uranium in one blanket (Tab. 3) (for details confer Englert and Liebert 2010a).

[7] For some locations even 50 kg/tHM.

Proliferation Potential of Spallation neutron Sources

As mentioned we address only briefly the proliferation potential of SNS which is discussed in much more detail in (Englert 2006, Englert 2009, Englert et al. 2010).

In the last decades SNS performance increased. In particular, there is a renewed interest in SNS for research facilities and for industrial application e.g. accelerator transmutation of waste and ADS, and there were several advanced projects for potential accelerator production of tritium (APT) for weapons purposes. Additionally, dynamics of accelerator development led to more sophisticated, smaller accelerators and there is a growing commercial market for accelerator technology and components. This raises questions about proliferation risks, which might be associated with accelerator driven systems and SNS in particular. The power of an SNS directly depends on the proton beam current and energy. The technological developments of the last decades raised available currents from several 100 µA to several mA today and beam currents up to 100 mA for linear accelerators have been proven successfully.

By using MCNPX simulations of protons hitting a uranium spallation target we calculated the production rates for different target sizes (masses). The production rates scale linearly with the beam current as well as with the beam energy for energies above 300 MeV. For low powers the production rates will not be comparable to production by fission or fusion reactors. For powers above 1 MW however the production rates are comparable to a small fission reactor (Englert et al. 2010). Like in a fusion blanket the spectrum of a spallation neutron source is extremely hard and burnup calculations show that even after one year of irradiation the Pu-239 content will be 99% in the total mass of produced plutonium. Like in a fusion reactor source material requirements are very low and concentrations of fissile material in the heavy metal will be higher than in a typical fission reactor. Thus there is an attractive potential.

A military dimension of nuclear fusion: how likely is it?

Whether nuclear fusion will play any role in future non-proliferation challenges will depend first and foremost on its technological feasibility and its commercial viability. Although the prospects of nuclear fusion are still not clear today, we nevertheless decided to venture into the “impossible” question of nuclear fusion and nuclear proliferation with some help from the academic literature and the community of experts.

Forecasting nuclear proliferation has become a trendy discipline within the Political Sciences recently (Potter and Mukhatzhanova 2010) and receives increased attention by scholars of nuclear policy. When reviewing the forecasting literature nevertheless we do not get a coherent picture on future proliferation trends, since most findings are contested (Sagan 2011). Thus, any statement about future military use of fusion reactors in this paper, although “grounded in theory”, will remain somewhat speculative. Furthermore, most studies focus almost exclusively on horizontal proliferation (the nuclear weapon program of a non-nuclear weapon state) and hardly tackle the ambitions of nuclear weapon possessors for quantitative and qualitative improvement of their arsenals (vertical proliferation). But in the context of a sophisticated technology such as fusion the focus cannot exclude nuclear weapon states such as China, France, India, the U.K. or the U.S., which will most probably be the early adopters of large fusion power reactors.

A Delphi study among experts we conducted in 2011 on this issue led to rather sober

results on the potential of nuclear fusion, both in the civilian and even more in the military realm. Many experts we interviewed question the viability of the commercial fusion option and suggest that fusion reactors might have prohibitive costs and might remain high-maintenance devices even in the second half of the 21^{st} century. Still, a number of experts do not exclude that fusion reactors might overcome these challenges on the long run and could provide a substantial share of base load electricity in the late 21^{st} century (these experts, often from the fusion research community itself, highlight the importance of continuity of research funding to meet their ambitious goal of commercial fusion energy by 2050).

Fusion energy could account for a substantial share in the energy demand – according to some experts – if the following conditions are met (for a detailed discussion see Goldston 2011): first, future energy policies are directed towards a substantive reduction of carbon emissions; secondly, these carbon-constrained economies cannot be sustained without a substantial nuclear share, since renewable energies and carbon capture and sequestration (CCS) strategies are not sufficient to meet the necessary climate goals; thirdly, in the nuclear segment incumbent technologies such as light-water reactors (LWR) and emerging technologies such as fast breeder reactors (FBR) cannot meet the growing demand for nuclear energy because of scarcity of uranium resources (LWR) and because of technical challenges and proliferation-concerns (FBR). Under these circumstances of a lasting nuclear renaissance fusion reactors could gradually increase their share within the nuclear segment, and on the long run, also over the overall energy mix.[8]

Besides energy policy, a second dynamics, which might impinge on the future of nuclear fusion and nuclear proliferation, is the gradual power transition we will witness in the 21st century. Although, current GDP figures see the “West” still leading world economy (World Bank 2010), by the middle of the 21^{st} century emerging markets will probably shift the balance of economic power in a dramatic way: many projections see China (Goldman Sachs 2009) or India (Citigroup 2011) as the leading economies in 2050, and predict a relative (economic) decline of the US, the EU and Japan at the same time. This shift in the global economy will have a number of repercussions in global politics, according to most analysts.
One major impact regards the military capabilities of the rising powers, which today are still a fraction of those of the incumbent powers, both in the conventional as well as in the nuclear realm. According to an important school of thought in International Relations theory, this gap in military capabilities will be closed with the rise of new powers, such as China and India. Especially in the nuclear field, one can expect that “Chindia” will strive

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[8] Rob Goldston discusses a typical carbon-constrained energy scenario for the 21^{st} century, which is based on these assumptions: in the model discussed in (Goldston 2011) the electricity demand will triple by 2050 and increase a factor of six by the end of the century with respect to 2010; assuming a 30% share for nuclear energy (together with a 30% share of renewable energies and a 40% of CCS combustion technologies), this would imply that the current reactor fleet would have to increase by a factor of ten by the end of the century; hence, about 4,000 typical 1 GWe reactors would be online by 2100. Current estimates on uranium resources suggest that a once through nuclear fuel cycle could probably not sustain this nuclear renaissance and would have to be “supported” and, ultimately, supplanted by FBR and/or fusion reactors.

for (at least) strategic parity with the U.S. and Russia, whose nuclear arsenals and fissile material stockpiles are roughly a hundred times larger than those of Beijing and Delhi today (for exact figures see IPFM 2010). Thus, unless Washington and Moscow draw down their nuclear stockpile by two orders of magnitude in the next decades, both China and India are expected to increase their nuclear arsenal and – at least India – also their fissile material stock. Since both countries are ITER members and will be early adopters of commercial fusion, they could – in principle – also recur to their fusion reactors to breed weapon-grade material – i.e. plutonium and tritium – after 2050.[9]

A military dimension of commercial fusion reactors: too early to think of?

If a certain technology carries a risk to be used in a proliferation scenario is a complex question. Most political analysts see the “demand side” as the critical variable of nuclear proliferation: they emphasize the “motivational” aspect – security, interests, status and norms – in nuclear decision-making, and thus direct their attention away from the technology. On the other hand “supply side” theoreticians highlight the risky dual-use character inherent to all nuclear technologies, including fusion and SNS. Although still a minority within the nuclear forecasting community, “supply side” theoreticians lay their analytical focus in the potential of a technology to be used in a military context rather than in the “unpredictable” motivational aspects of the technology holders. They direct their attention typically towards the suitability of a given nuclear technology to produce weapon relevant material. This *potential* is mostly given by technical features (quantity, quality, time, complexity and detectability of weapon material production) of the technology itself.

The implicit assumption of this “dual-use” school of thought is that there will always be a certain demand for nuclear weapons. To avoid that this demand leads to a gradual proliferation of nuclear weapons, it is important to “harden” civilian nuclear technologies against their rededication for non-peaceful purposes. A common approach to reduce these risks is to devise both intrinsic and extrinsic measures, which should hamper the conversion of a civilian nuclear program into a military endeavor. These measures are designed to bolster the so called “proliferation resistance” (PR) of nuclear technologies. Still, when thinking about proliferation resistance of emerging technologies (such as fusion and SNS) timing is of essence: many intrinsic PR features can only be implemented at a very early stage of the R&D process, as they affect directly the design of the technology. But also extrinsic PR features such as safeguards are usually much more effective and efficient, when they are incorporated into the original design right from the beginning (“safeguards by design”) instead of being implemented after the launch of the technology. What sounds as a commonplace statement is nevertheless highly topical for a number of emerging nuclear technologies such as fusion and SNS, as both communities do not seem to be fully aware of the dormant proliferation potential residing in their technologies. This is partly due to the fact that the “commercialization” and wide spread use of these technologies still seem to be far away from today’s

[9] Note that the current Indian weapon-grade plutonium production amounts to 30 kg / year; and our conservative estimate suggest that a fusion reactor could breed about 10 times this amount of plutonium.

perspective.
The fusion community has to concentrate on many challenges ahead before reaching the stage of market launch. We argue that it would be economically and politically wise to think of proliferation resistance already today, as this endeavor would require a negligible fraction of the current fusion research budget, and safeguards by design could be implemented in a way that is cost-effective by minimizing the intrusiveness of inspections in future fusion reactors. It would make sense to explore some of these features prospectively with the current ITER reactor, before refining them with the successor models (the DEMO reactors and the commercial fusion reactor prototypes).

Conclusions

These reflections show a possible military dimensions of future commercial fusion reactors: first, they provide an easy source of tritium for weapons, an element that does not fall under safeguards and for which diversion from a plant could probably not be detected even if some tritium accountancy is implemented. Secondly, large fusion reactors – even if not designed for fissile material breeding – could easily produce several hundred kg Pu per year with high weapon quality and very low source material requirements.

Fusion power plants will have a remarkable potential to produce fissile materials during operation. Pure fusion reactors, like the PPCS-A concept we analyzed in this paper, show a remarkable potential for mass production of plutonium (several hundred kg per year), although such an operation is not foreseen in the design specifications. A fusion reactor with similar power but optimized for fissile material production (e.g. in a fusion-fission hybrid design) could easily produce several tons of weapon-grade plutonium per year. Although technically challenging, this potential exceeds anything we know from the world of fission reactors. If used for military purposes the main advantages over fission reactors would be a relatively small requirement of source material (natural or depleted uranium)[10] with high concentrations and an isotopic composition of Pu in the product, which would be well-suited for weapons purposes. Due to the hard neutron flux in a fusion reactor Pu-239 fractions and hence the weapon usability are typically higher than in fission reactors of comparable power.[11] The low mass requirements for uranium are also advantageous for separation campaigns to extract plutonium from the uranium breeding targets..

If fusion-only reactors will prevail over fission-fusion hybrids in the commercialization phase of fusion technology, the safeguard challenge will be more of a legal than of a technical nature. In pure fusion reactors there should be no nuclear material present at any time by design. The presence of undeclared nuclear material would indicate a military use of the plant. This fact offers a clear-cut detection criterion for a covert use of

[10] Since fusion reactors and SNS – unlike fission reactors – do not require critical masses of uranium, these uranium insertions can be arbitrarily small.
[11] The Pu-239 content in the isotopic composition calculated for blankets in the PPCS-A concept will be well above 90% even for high burnups.

a declared facility[12] (Cook et al. 2001). Such a scenario could be easily deterred, if suitable control mechanisms were implemented using state of the art safeguards technology e.g. during the blanket exchange procedure, by weighing the elements, by optical inspection, active interrogation or gamma measurements of the blankets. Additionally, detectors could be placed in the tokamak hall or blanket storage pools and other areas of the facility to detect typical fission products. The major obstacle of safeguarding fusion reactors lies for the time being in a mixture of bureaucratic inertia and a certain legal intransparency and unclarity with respect to this issue.
Why is the legal framework developed for nuclear fission systems currently inappropriate for strong neutron sources like fusion and SNS?
First, a fusion reactor or SNS would not fall under the term "facility", as it is neither a reactor[13] nor a critical facility nor a location where nuclear material in quantities more than an *effective kilogram* is customarily used. In a pure fusion reactors and most SNS *no nuclear material at all* should be present at the site at any time by design.
Secondly, its operation might involve a *potential* production of more than one effective kilogram of plutonium. So one could argue that a fusion plant (or a SNS) would fall under the IAEA definition of a "facility" and thus should be considered for inspection. However, the wording of the INFCIRC/153 restricts the inspection mandate only to those sites ("facilities"), where more than 1kg of Pu is "customarily used" (meaning de facto production here).
Additionally an effective kilogram of uranium corresponding to ten tons in total of natural uranium or 20 tons of depleted uranium (<0.5% enrichment) can be exempt from safeguards at the request of a State. As noted above, amounts far less than one effective kilogram of uranium are sufficient for a significant plutonium production in a fusion reactor and an SNS.
The current IAEA INFCIRC/153 agreements are intransparent and unclear with regard to inspections in high intensity neutron facilities such as SNS or fusion reactors and offers insufficient protection in this cases. Because no nuclear material is used in the nominal operation of pure fusion reactors and because tritium does not fall under the definition of „nuclear material", strictly speaking these facilities are not directly falling under any international non-proliferation treaty requirements.
As we have seen, these shortcomings are of legal nature and could be addressed by amending and updating the glossary and some of the definitions in INFCIRC/153 in order to integrate fusion reactors and SNS. A preliminary attempt in this direction was already proposed by some of the authors as a starting point for further discussion (Englert et al. 2010 gap).[14]

The examples of fusion reactors and SNS discussed above point to a broader challenge for the nuclear safeguards practice of the 21st century: How to treat facilities in the

[12] As said, we assume that the covert diversion of small amounts of tritium could not be detected, therefore the safeguards reflections presented here are focused on the covert production of fissile material within the fusion reactor.
[13] Fusion reactors and SNS do not fall under the IAEA definition "reactor", as all definitions mention a selfsustaining fission chain reation.
[14] Thanks again to David Moses, Oak Ridge National Laboratory, for earlier discussion and an earlier first proposal for the case of subcritical assemblies.

safeguards system, which have the capability, but are not directly designed for fissile material (or tritium) production and do not contain fissile material under normal circumstances? The standard protocol INFCIRC/153 (comprehensive safeguards agreement) with its focus on existing nuclear material and its loophole on production potentials of facilities ("virtual" fissile material) will need some amendment on the long run.[15,16] This holds especially, if we will witness some multilateral FMCT in the future. Here the focus also shifts away from fissile materials to facilities and their production potential.

Our final considerations touch upon the question whether the discussion of regulating strong neutron sources is of any relevance today. After all, commercial fusion might materialize (and proliferate) only by the mid of the century, although post ITER next generation experimental or demonstration reactors, which could be also constructed under national control, would also clearly have a significant proliferation potential. In terms of economic competitiveness both fusion and large megawatt SNS facilities are more expensive than a reactor, today. But medium energy SNS with high currents using small cyclotrons might become more available in the nearer future reducing the cost argument there. With respect to fusion the cost argument is even more complex, as the economics of nuclear fusion power is not predictable nowadays.. From today's perspective it is fair to conjecture that as long as fissile material production is more economical and technical easier to achieve by current reactor technologies it is definitely not very likely that other neutron sources will be considered for military use, if a state has access to both technologies. However, in a world with rigorous controls on "traditional" fissile material production paths or even increasing restriction in access to fission technology or in changing energy scenarios, strong neutron sources as described here might be more interesting for a state to produce weapons materials. This is in particular the case if a state wants to keep a latent fissile material production capability for weapon purposes. The control over intense neutron sources will be a special concern in a future nuclear weapon free world as it would give a country the option to use this facility covertly or after a break-out.

Although these technologies do not represent any immediate threat today, it would be prudent to implement and test safeguard strategies already today and to enhance the proliferation resistance of these emerging technologies.

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15 It might turn out that some of the issues could be addressed under the broader mandate of the Additional Protocol.

16 Ironically, the older protocol INFCIRC/66, which was supplanted by INFCIRC/153, focused on facilities rather than on fissile materials. An amendment therefore would combine both approaches, ideally.

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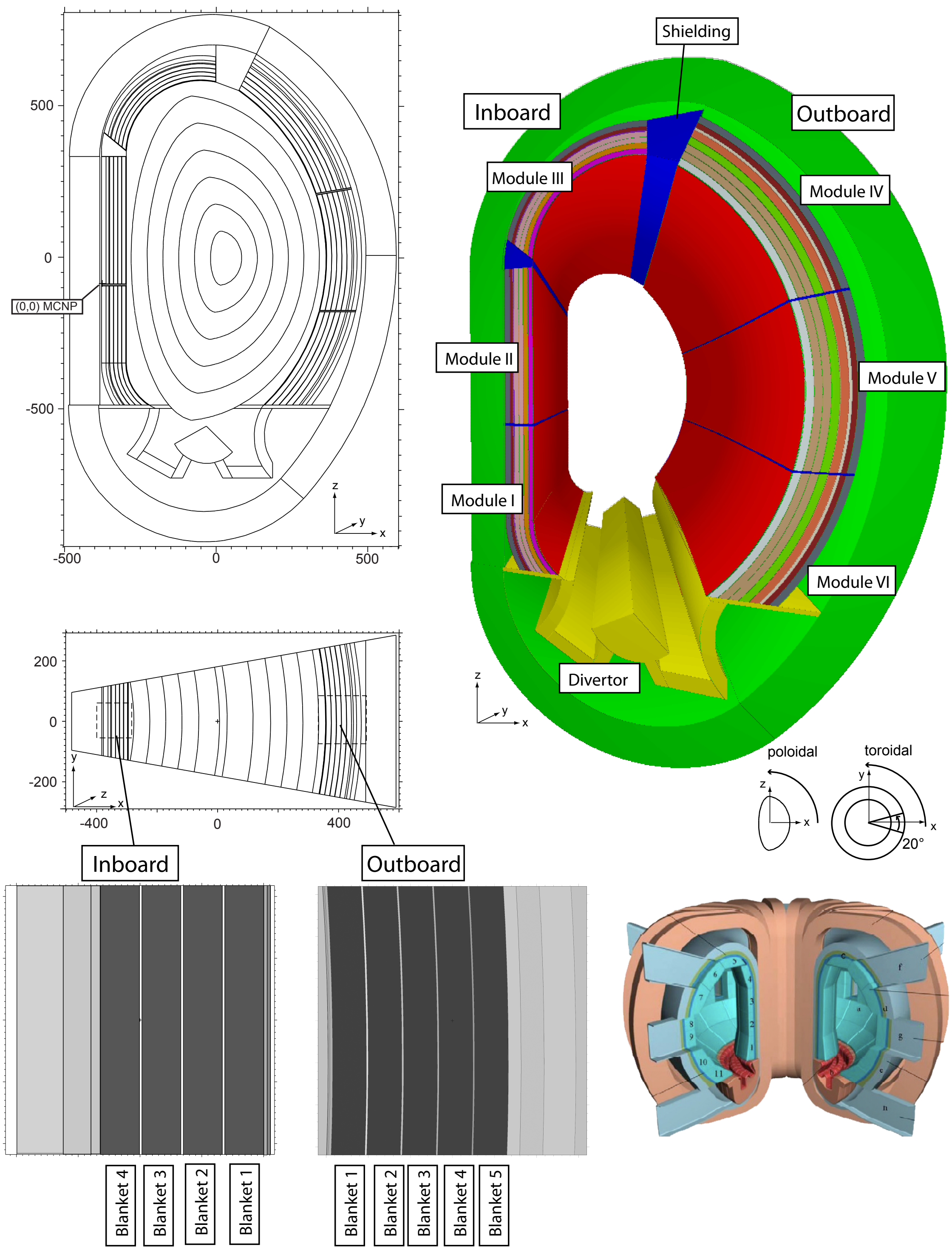

Fig. 1. MCNP model of PPCS-A fusion power plant (20° section). Right Top: 3d representation. Right Bottom: Sketch of concept PPCS-C (Maisonnier et al. 2005).