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Proliferation Resistance of Future Fusion Reactors

Technical and Political Contributions For a Just 21st Century Nuclear Order

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Introduction and Context

Fusion power could provide a substantial contribution to the global energy supply in the second half of the 21st century. Still, before commercial fusion reactors will become available, research reactors must demonstrate the technical and economic feasibility of future fusion power reactors. The ITER and DEMO reactors, which will be constructed and operated in an ambitious international cooperation project, shall be these precursors of the commercial fusion reactors (see Fig. 1).

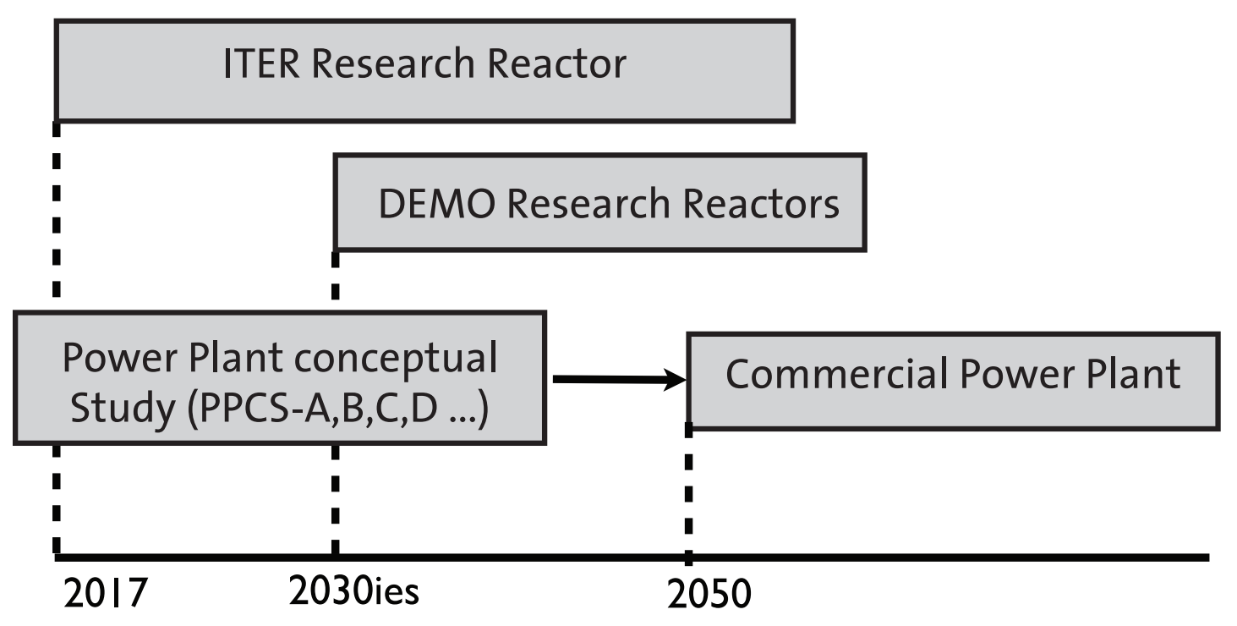


Fig. 1 Current rough timeline envisioned for the devlopment of a commercial fusion power plant.

ITER, DEMO and the commercial power plant concepts of our study will use deuterium (^2H) and tritium (^3H) as fuel. The fusion of deuterium and tritium will occur in a magnetically confined plasma – a so called "tokamak" – and yield helium and a high-energy neutron (see Fig. 2).

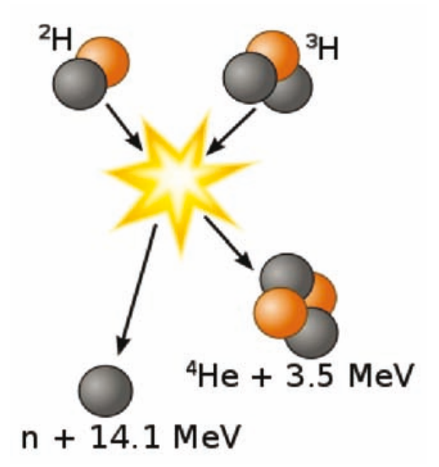


Fig. 2 The D-T Fusion Process. Deuterium and Tritium fuse to Helium. A neutron is produced

This "fusion neutron" will penetrate the walls of the fusion reactor torus where it will be captured by lithium atoms to produce tritium. The lithium is contained in huge blankets in the reactor chamber walls. A self-sufficient reactor will breed at least as much tritium in this blankets as it consumes in the fusion reaction. In our investigations we assume that some lithium is replaced by uranium in the blankets: if bombarded with fusion neutrons, this mixture will yield tritium (from Li) and the fissile material plutonium (from U). Producing fissile material in a fusion reactor could open up a new "plutonium route" for a number of countries interested in the nuclear weapon option. Note that the use of fertile or fissile nuclear material is not foreseen in most reactor concepts. The European Fusion Development Agreement (EFDA) states for their reactor designs that "none of the materials required are subject to the provisions of non-proliferation treaties" [1], and consequently the "default materials" (deuterium and lithium/tritium) would not fall under the radar of nuclear safeguarding authorities.

Neutronic Simulation of Fusion Plant

Historically the production of plutonium for weapon purposes took place in dedicated fission reactors by irradiation of ^{238}U 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 – could also potentially be used to produce fissile material for weapon purposes. For our simulations we used the first detailed conceptual designs of commercial fusion reactors, which were published by EFDA in 2005 [1,2]. EFDA published four power plant conceptual studies (PPCS) in 2005, the reactor prototypes A, B, C and D (Fig. 3 shows plant concept C).

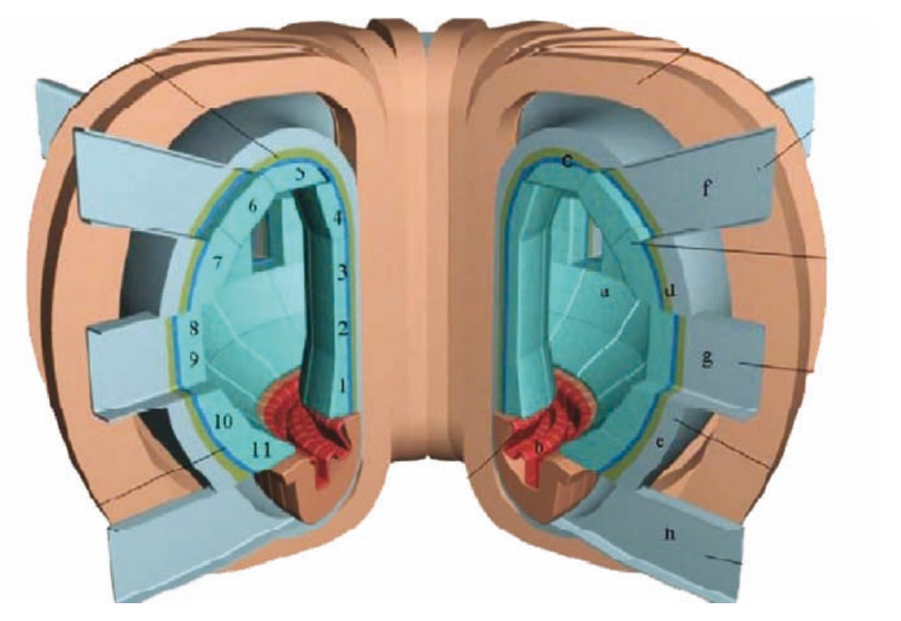


Fig. 3 Cross Section of the PPCS-D model with Shielding Supraconducting coils (magenta) and blankets (cyan), divertor (red). [1]

We developed a detailed MCNP model of the reactor geometry of the PPCS-A prototype [3,4]. 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. We modeled only a 20˚ section of the torus with 3 inboard and 3 outboard modules containing blankets to produce tritium by irradiating the lithium in the blankets (Fig. 4).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.

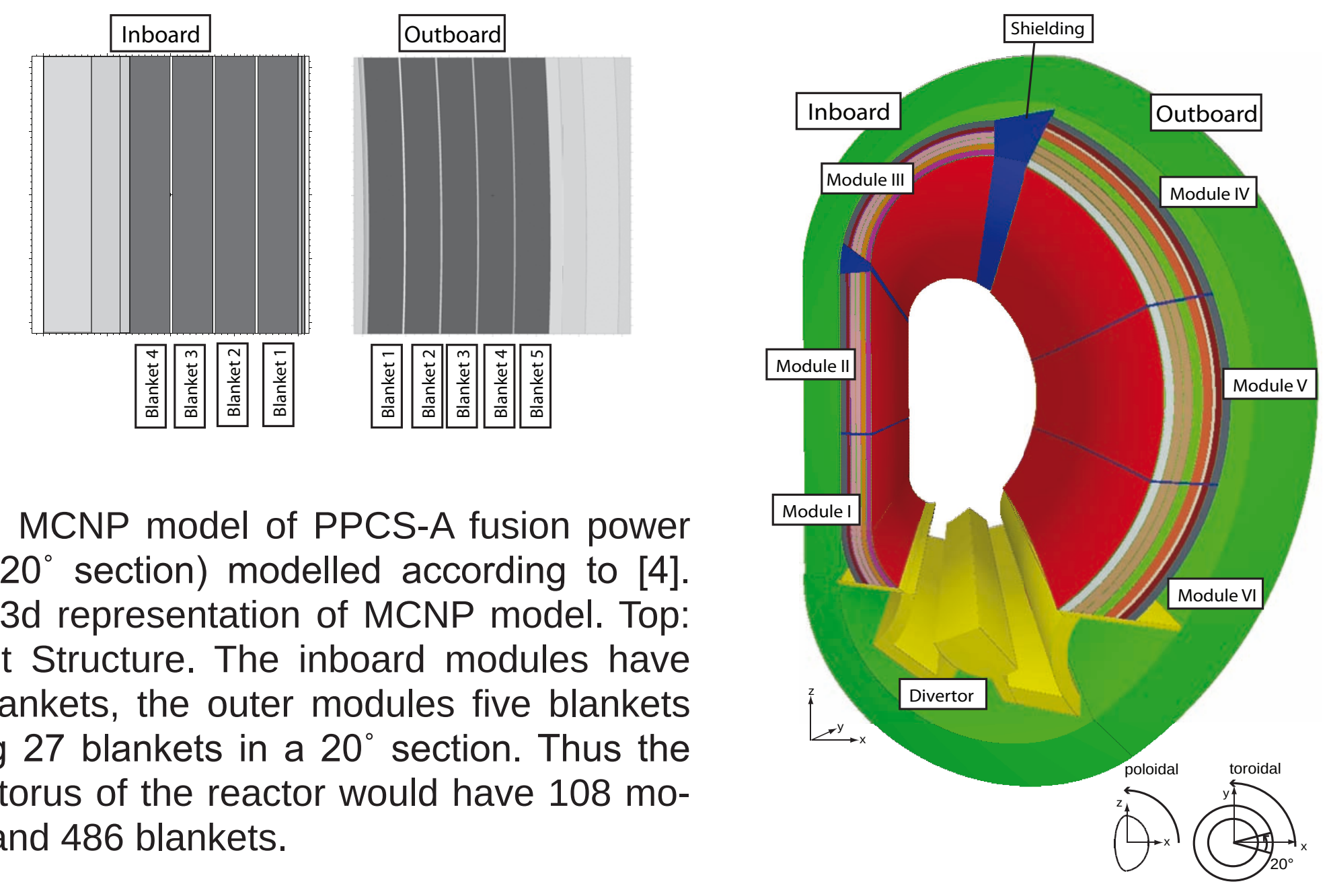


Fig. 4 MCNP model of PPCS-A fusion power plant (20˚ section) modelled according to [4]. Right: 3d representation of MCNP model. Top: Blanket Structure. The inboard modules have four blankets, the outer modules five blankets totaling 27 blankets in a 20˚ section. Thus the whole torus of the reactor would have 108 modules and 486 blankets.

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. 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. It will be impossible to use material accountancy to detect the diversion of some few grams in a commercial fusion reactor.

Huge Plutonium Production Potential

We calculated possible annual plutonium production rates (Tab 1) [3,4,5] by modelling a homogeneous material mixture in the blankets and replacing a certain volume fraction of the Pb-17Li alloy by uranium. 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. One blanket close to the plasma chamber will produce 4-10 kg Pu per year with 1 vol% of the lead lithium alloy replaced by uranium, enough for one weapon. Even for lower concentrations production rates in the kilogram range are achievable by using more than one blanket.

		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	0.43	0.31
	All Blankets	414	71	12.5	1.5
Complete Reactor		7450	1280	225	27

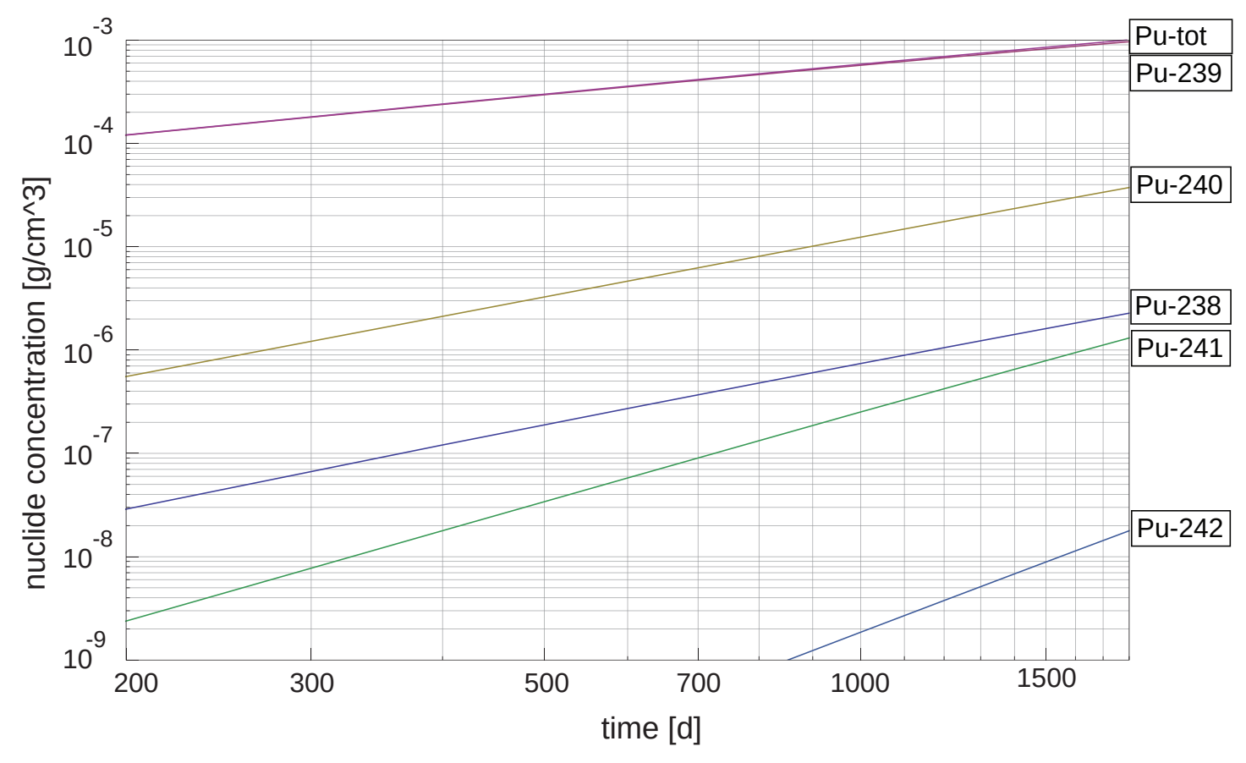
Tab. 1 Plutonium production in kilogram per year in blankets with different volume fractions of the lead-lithium alloy replaced by uranium. (No burnup considered, 100 % capacity assumed). The range in production reflects the fact that outboard blankets have a much larger volume than an inboard blanket.

The homogeneous model yields a maximal annual production of 1.28 tons of Pu using all blankets with 1 vol% uranium. However, such a scenario is 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. Calculations with breeding structures such as fuel rods yield a significant drop in production numbers up to a factor 2-6 depending on the geometry and position in the reactor [5]. Using uranium in the blankets would make changes to the blanket design necessary in any case.

Weapon Grade Plutonium

One effect of the characteristic neutron energy spectrum in a fusion blanket is that the plutonium isotopic composition even after long irradiation times has a high content of ^{239}Pu. For blankets far from the plasma the isotopic composition is almost pure ^{239}Pu (>99%) even after 5 years of irradiation (Fig. 5). Hence, even after several years the plutonium bred in the reactor blankets would still be weapon-grade.

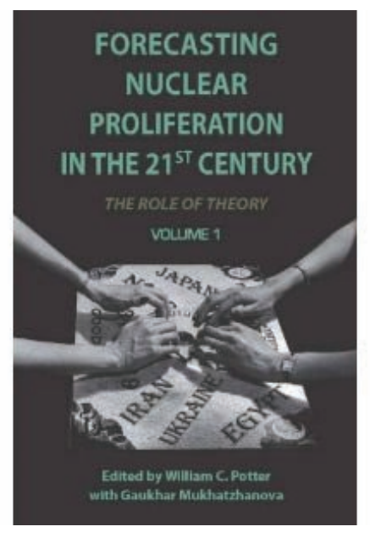
Fig. 5 Burnup calculation with MCMATH for module II Blanket 2, 0.1 vol%. uranium. Other blankets also have a ^{239}Pu content of well over 90% even for very long burnups. [5]



Low Source Material Requirements

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 [6]. 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. 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, whereas in a fission reactor more than ten tons of uranium would be needed.

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 [7] and the community of experts. Unfortunately 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.

Fusion Share in Energy Mix

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. Still, a number of experts do not exclude that fusion reactors could provide a substantial share of base load electricity in the late 21st century if the following conditions are met (for a detailed discussion see [8]). 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.

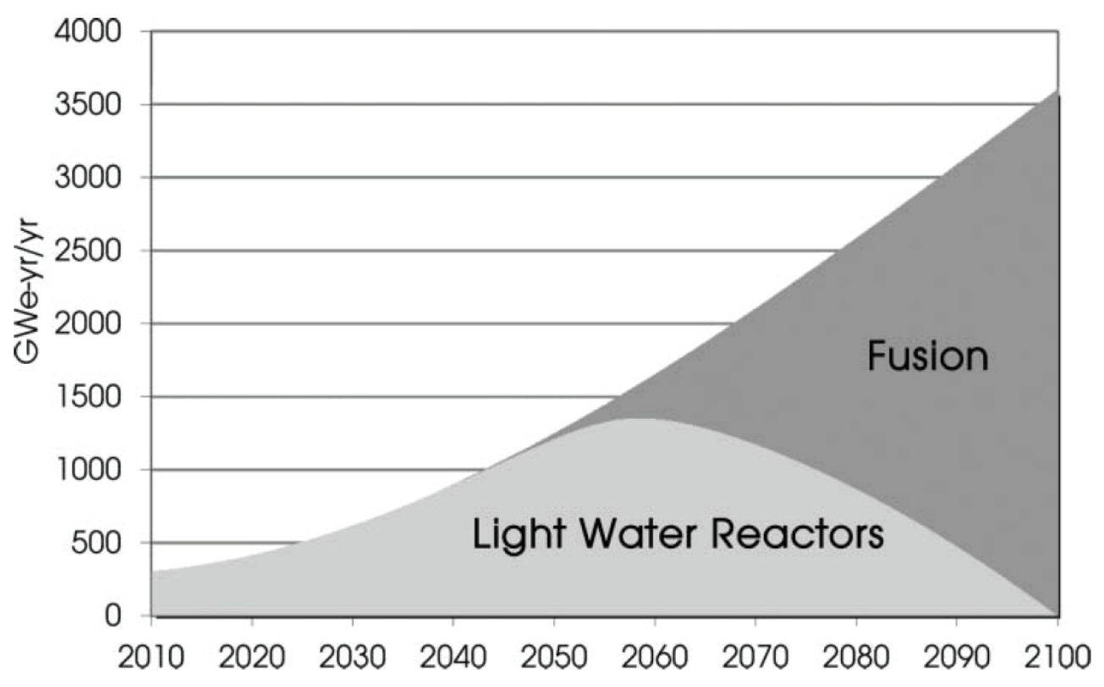


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Fig. 6 Possible scenario for the use of fusion energy in until 2100 (from [8]).

Power Transition

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, by the middle of the 21st century emerging markets will probably shift the balance of economic power in a dramatic way: many projections see China (Fig. 7) or India 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.

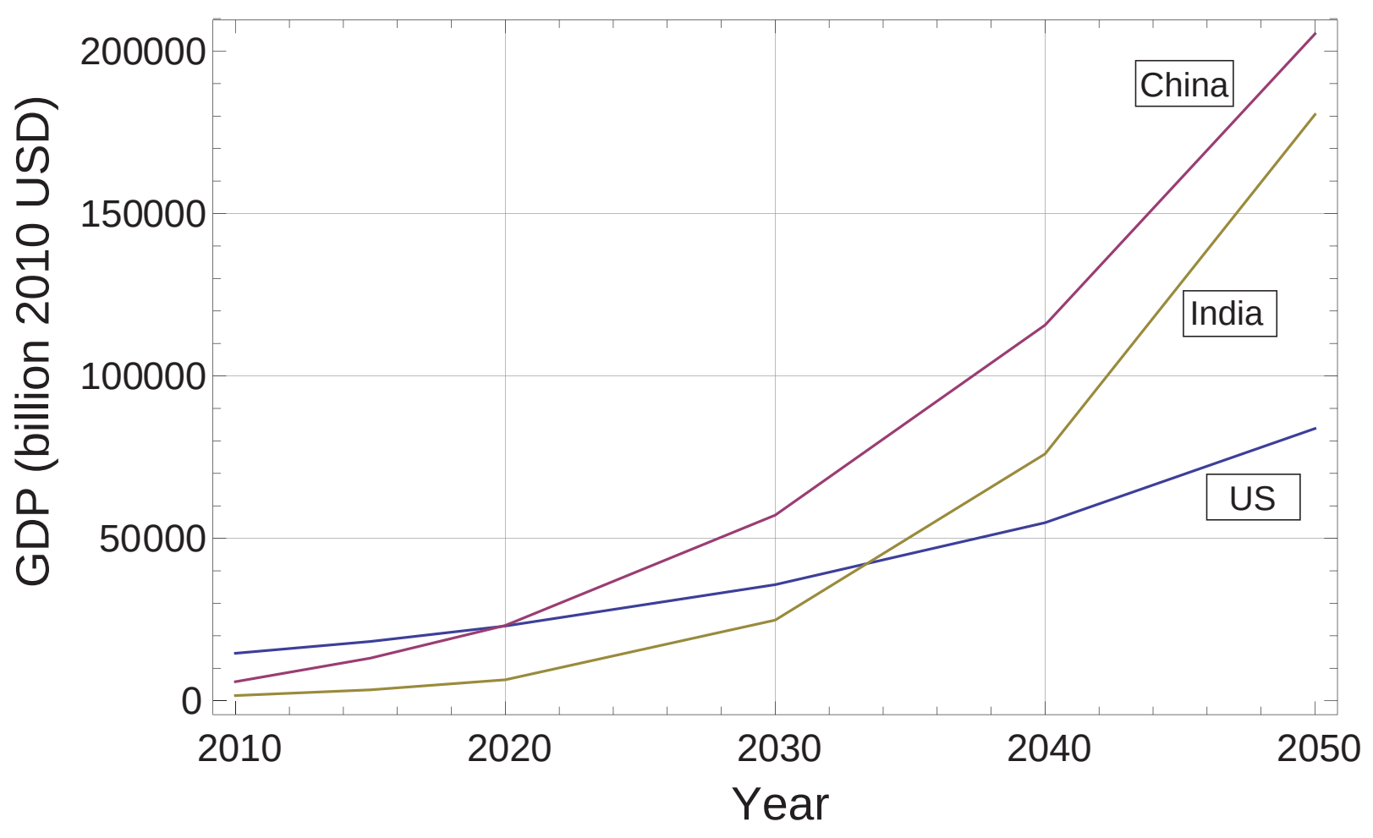

Fig. 7 Expected power transition from US to China and India represented in GDP forecast figures (Data from [9]).

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. Especially in the nuclear field, one can expect that "Chindia" will strive 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 (Fig. 8). 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.

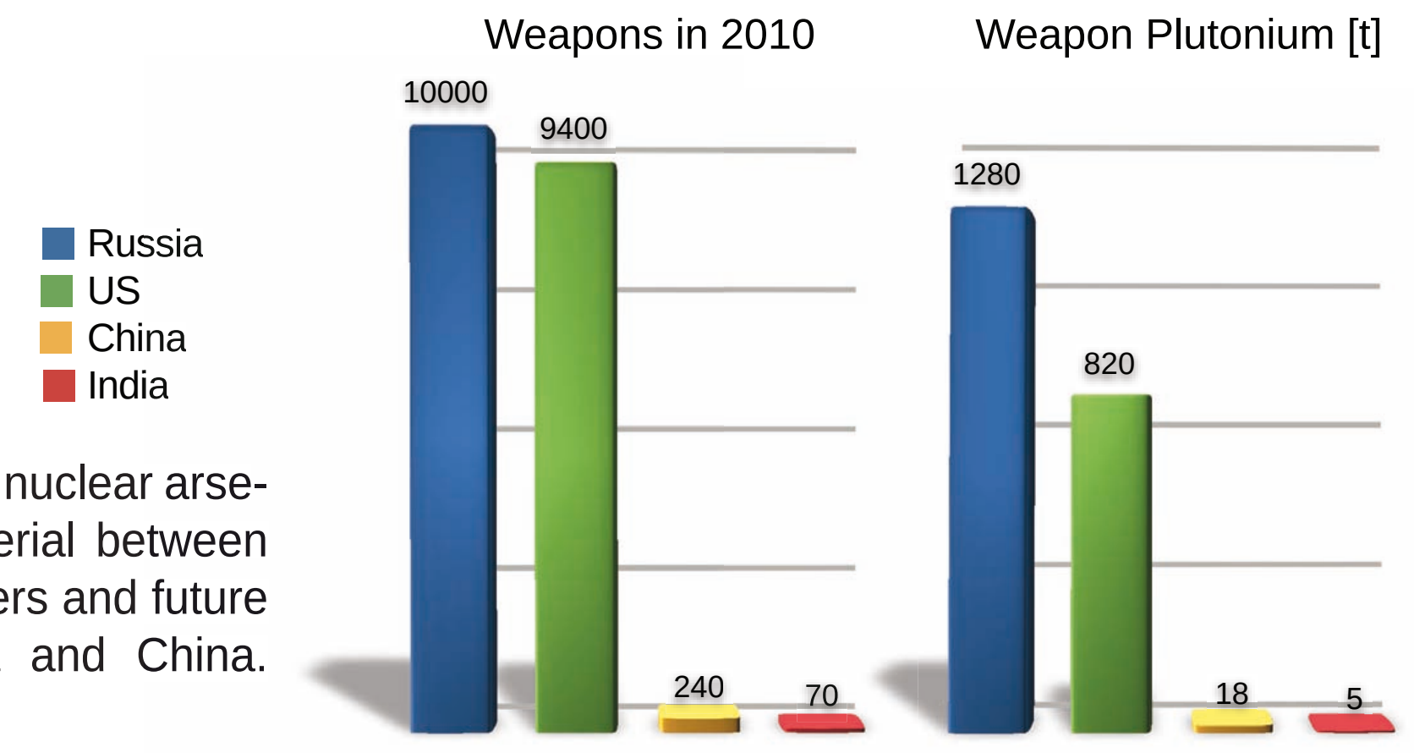

Fig. 8 Differences in nuclear arsenals and fissile material between today's nuclear powers and future major powers India and China. (Data from [10])

Conclusions and Outlook

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.

Our research on fusion reactors also points to a broader challenge for the nuclear safeguards practice of the 21st century: How to treat facilities in the 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 minimum requirement to limit the military potential of a fusion reactor is to put it under safeguards. This requires some legal amendment to the current safeguard regulations and the committment of the fusion research community to integrate safeguards issue into the current fusion R&D process.

This process should start now.

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