POSSIBLE PROLIFERATION RISKS
OF FUTURE TOKAMAK FUSION REACTORS

Matthias Englert*a, Fabio Balloni*b, Wolfgang Liebertb

a) Center for International Security and Cooperation (CISAC), Stanford University, United States.
b) Interdisciplinary Research Group in Science, Technology and Security (IANUS), Darmstadt University of Technology, Germany.

Abstract. Although fissile material is usually not considered when thinking of fusion reactors (except in fusion-fission hybrid concepts), they have a potential to breed nuclear weapon relevant material (Pu, Tritium) which should not be neglected. We developed a MCNPX model of the 2006 published concept A of the European Power Plant Conceptual Study to analyze the potential for Pu production in a fusion reactor. Production potentials are calculated for varying uranium content replacing the Pb-17Li alloy in different blankets of the reactor. The results show that significant amounts of fissile material can be produced even with limited amounts of source material. The production in different zones will be limited by additional heating due to fission and due to a reduced tritium breeding rate. Burnup calculations indicate that the produced plutonium is weapon usable with over 90% Pu-239 even for extremely high burnups. As the technology is and will be in development for the next decades, there is sufficient time to implement and test applicable safeguard measures or develop proliferation resistant designs.

1 Introduction

It is true that in a pure fusion reactor no materials used under normal operating conditions are subject to the provisions of the non-proliferation treaty and its related safeguards system. The lack of continuous use of fertile or fissile material in a pure fusion reactor is indeed more resistant to proliferation than in fission reactors or hybrid fusion-fission reactor concepts. However the strong neutron fluxes provided in a fusion reactor could also be used covertly or in a break-out scenario to produce fissile material for weapon purposes.1

There are some historic studies mentioning or investigating the proliferation risks of fusion power plants [3; 4; 5; 6]. Recently there is renewed interest in the topic. In [11] calculations were published for plutonium production in different blanket materials for an idealized reactor geometry. A project to investigate the impact on the current nonproliferation regime was also conducted by the European Fusion Development Agency (EFDA), although results are not published [10]. In [7] detailed plutonium and U-233 production calculations were made for the dual coolant lead-lithium blanket design proposed by the United States for the ITER fusion experiment. The authors provide a thorough analysis of proliferation risks of a research facility and assess covert or clandestine production and break-out scenarios. One conclusion is that a

1 It has to be acknowledged that large amounts of tritium will be used by the fusion reaction and have to be continuously reproduced in the breeding blankets of the reactor. Tritium is used in advanced weapon designs to boost the fission reaction with additional neutrons and enhance the efficiency of a weapon. This reduces the mass of fissile material needed to achieve a certain weapon yield. Tritium boosting is considered as one of the important steps in weapon design to minimize the size of a warhead that it is usable on e.g. a rocket. Typically only several grams of tritium are sufficient for boosting. In a large power plant several kilograms will be in the inventory and the annual production rate well beyond 100 kg. More on the proliferation impact of tritium can be found in [1; 2]. Tritium is currently not under international control.
clandestine scenario would be very unlikely certainly for a full gigawatt power plant, but also for smaller clandestine machines.

There is renewed interest [13; 14] in the old idea [12] of hybrid fusion-fission systems, for which the design idea of the whole systems is the production of fissile material for a satellite fleet of fission reactors. The proliferation implications of such systems where discussed earlier e.g. in [15] and the need to investigate these implications and to provide a comparison to pure fission energy production for different kinds of pure fusion and fusion-fission hybrids is expressed e.g. in [8].

Analyzing the proliferation risks associated with tokamak fusion power plants one important preliminary clarification has to be made. There is still disagreement within the energy community, if at the end of this century fusion-technology will contribute significantly to the global energy production. Without knowing the answer to this question, we consider it still necessary to pursue as early as possible the conceptual development of proliferation resistance measures for fusion-technology, to implement this criterion in technological design choices and to develop adequate procedures for control [9]. This will be even more necessary if a future world without nuclear weapons is envisioned and any production capability for fissile material will be important.

2 The Power Plant Conceptional Study

In January 2006 the European Fusion Development Agency (EFDA) has published its Power Plant Conceptual Study (PPCS) which describes four promising fusion reactor designs PPCS A-D to be realized in the future [16]. While reactor concept A relies mostly on materials and technologies already available for fission reactors, concept B, C, and D need increasingly more development efforts and time, but will be much more efficient. Accordingly, the reactor concept PPCS A could be the first fusion reactor working as a commercial power plant at the mid of the century. The entire concept will also be based on the knowledge and results that are hoped to be gained during the lifetime of the International Thermonuclear Experimental Reactor (ITER) currently under construction in Cadarache (France).

3 Reactor Model

We developed an MCNP [19] model (fig. 1) of the reactor geometry [20], which is the basis of the reactor description below. Detailed information on the dimensions of the blanket modules was derived from the MCNP model in [17] and from [16] Annex 4. Additional geometric information was available from [18; 21; 22]. The thermal power of PPCS-A is 5.5 GW. Including the superconducting coils the total height of the torus is 18 m. The height of the plasma chamber from the divertor zone to the top is 10.7 m with a maximal width of 6.7 m. Typically an inner zone (inboard) and outer zone (outboard) is distinguished. The torus is divided in 20˚-sectors, with a port every two sectors to exchange the blanket modules with a remote handling machine (about every two years). The modules have to be small enough to be still transportable, and large enough to allow for a short maintenance period so that the overall plant capacity factor does not drop below 75-85%. In our MCNP model we used only one 20˚ section of the torus with 3 inboard and 3 outboard modules (figure 1).
geometry [20], which is the basis of the reactor description below. Detailed information on the dimensions of the blanket modules was derived from the MCNP model in [17] and from [16] Annex 4. Additional geometric information was available from [18; 21; 22]. The thermal power of PPCS-A is 5.5 GW. Including the superconducting coils the total height of the torus is 18 m. The height of the plasma chamber from the divertor zone to the top is 10.7 m with a maximal width of 6.7 m. Typically an inner zone (inboard) and outer zone (outboard) is distinguished. The torus is divided in 20°-sectors, with a port every two sectors to exchange the blanket modules with a remote handling machine (about every two years). The modules have to be small enough to be still transportable, and large enough to allow for a short maintenance period so that the overall plant capacity factor does not drop below 75-85%. In our MCNP model we used only one 20° section of the torus with 3 inboard and 3 outboard modules (figure 1).
**Figure 1:** MCNP model of PPCS-A fusion power plant (20° section). Right: 3d representation. Left: x-z cut through the model at y=0 cm. Below: x-y cut (z=-82.5 cm). In the MCNP model the origin is at (-459.82,0,85) cm.
The breeding material is lithium (enriched to 90% Li-6) in a liquid lead-lithium alloy (Pb-17Li). The structural material is the low activation martensitic steel EUROFER [23]. The blankets are cooled by light water to temperatures below 670K. The inboard modules have four blankets each, the outer modules five. A real module and each real blanket would have a steel structure with cooling pipes. In our MCNP model the assumption was made that each part of a module and each blanket is filled with a homogeneous mixture of the material (H$_2$O, Pb-17Li, EUROFER) without any internal blanket structure following a detailed description in [17]. The shielding and the divertor complete the entire reactor structure.

The source strength for a 20$^\circ$ sector and therefore the normalization constant for all MCNP results is a neutron rate of $R_n = 1.08 \cdot 10^{20}$ neutrons/s according to to the energy of 4.4 GW from the 14.1 MeV fusion neutrons in the reactor.

### 4 Plutonium Production

To assess the possible plutonium production in the MCNP model different concentrations of natural uranium (10, 5, 1, 0.5, 0.1, 0.05, 0.01, 0.001 vol%) were added to the homogeneous mixture in the breeding blankets of the reactor.$^2$

**Limitations of Adding Uranium**

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 effect the overall tritium breeding ratio of the reactor.

Fig. 2 shows the impact of the addition of uranium to the power deposition in selected blankets. Even at low concentrations the blankets near the plasma experience an increase in power due to fission. At a volume fraction of 0.01 vol% the additional power deposited by fission is increasing for all blankets except the very remote blankets far from the plasma. Note also the small power depressing poisoning effect for low concentrations of natural uranium for all blankets except for those close to the plasma. For blanket 5 in Module VI even at a concentration of 10% the power just reaches the same level as without uranium in the Pb-17Li alloy. Blankets far away from the plasma are therefore attractive for production with higher uranium content in the breeding material. For the purpose of this analysis we consider a 10% increase in power still operable for the cooling equipment installed under nominal conditions. A 10% increase in power should be the minimum tolerance a cooling system should have without any short term consequences. If the complete Pb-17Li alloy in the reactor would contain uranium, a 10% power increase would be reached by adding 1 vol% of natural uranium to the alloy.$^3$

The second limitation is due to the poisoning effect of uranium addition on the tritium breeding ratio (TBR). Calculations showed that the overall TBR decreases by 0.02 for concentration up to 1% natural uranium in the alloy and increases then significantly for higher contents. Unless the TBR is not dropping below a critical threshold of 1.06 [17] this will not affect the operability of the reactor.

---

$^2$Such a strategy of course is an idealization and is not necessarily realistic (see below).

$^3$More details in [20].
Figure 2: Additional heating for selected blankets with uranium addition in comparison to a pure Pb-17Li alloy without uranium over the volume fraction of uranium added.

Simplifying Assumption

The following simplifying assumptions were made

- The Pu-239 production rate is considered to be only dependent on \( (n,\gamma) \) reactions in \(^{238}U\) without any burnup calculations.\(^4\)

- The production rates are strictly taken the production of an excited state in \(^{239}U\ast\). As \(^{239}U\) and the daughter product \(^{239}Np\) have a half life much lower than the production time, the \(^{239}U\) production rates are almost identical with the Pu-239 production.

- There is no consideration of any time necessary for cooling down the blankets after irradiation and for reprocessing which would be necessary to extract the produced plutonium.

- The production was calculated for a continuous operation and has to be considered as production per year available irradiation time. Usually maintenance and other interruptions will occur. To be economical fusion power plants have to reach a capacity factor of at least 75-85%.

- All blanket materials are homogeneous mixtures, no structure is implemented. In reality higher concentrations of uranium can only be added to the alloy at high temperatures (see below).

\(^4\)This corresponds to a continuous immediate extraction of the produced plutonium.
Figure 3: Plutonium production (Pu-239) in kilogram per year (100% capacity) for different volume fractions natural uranium in the blankets of the inboard (--) and outboard (—) modules I-VI of the MCNP model (20° section) of PPCS-A over the radial distance to the first wall (midpoint of blanket). Lines connect the production rates in the blankets of a specific module.

Production Rates

In fig. 3 the radial dependence of the Pu-239 production rate for different concentrations of natural uranium in the Pb-17Li alloy is shown. One point in the figure gives the production rate in one single blanket. As can be seen the production rate drops significantly with increasing distance to the plasma. Due to their larger volume the outboard modules have higher production rates. As the spectrum and the flux characteristics are only loosely coupled to the uranium content the assumption can be made that using uranium in one module is not influencing the flux in other modules. The production rates of fig. 3 can be used just for that module or also cumulatively. Without any further optimization the maximum production rate for a 20°-section would then 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). For a realistic maximal uranium concentration of 1 vol% in the blankets near the plasma the content of produced Pu-239 in the uranium can reach about 20 kg/tHM in the blankets facing the plasma after a year irradiation, which is much higher than in a reactor.

Breeding Strategies

Without restrictions on the deposition of additional fission power or on the availability of source material, the best location for production in terms of highest production rates is in the blankets close to the plasma. If source material is limited it will also be favorable to use the high fluxes
Figure 4: Plutonium production (Pu-239) per year year (100% capacity) for different volume fractions (0.001, 0.01, 0.05, 0.1, 0.5, 1, 5, 10 vol%) natural uranium in four selected blankets over the additional heating due to fission. A constant conversion factor of 10 kg/MW y is shown as solid line.

near the plasma to get high end concentrations of plutonium per source material (burnup will be treated below). Of course due to the high fluxes in the vicinity of the plasma there is also more additional heating deposited. A constant production rate can be achieved by either adding low concentrations in blankets near the plasma or higher concentrations further away from the plasma. However the ratio between produced plutonium to additional fission power is not constant over the distance from the first wall. As can be seen in fig. 4 almost the same production rate can be achieved by using e.g. 0.01% natural uranium in blanket 1 of module V near the plasma or by using 1% natural uranium in blanket 5 of the same module far away from the plasma. But the difference is that there will be significantly less additional heating released for the same production rate in the blankets farther away from the plasma.

Burnup

We conducted burnup calculations for four blankets of module II with 0.01% natural uranium using the Mathematica based burnup code MC²MATH [20; 24]. The calculations show that the simplifying assumption of neglecting burnup during Pu-production is justified for short burnup times. Calculating the total plutonium production from the macroscopic (n,γ) cross section of U-238 differs from the total plutonium content (all isotopes) including all burnup reactions and fission product buildup by about 17% after one year and by 43% after 1800 days. For the production rates in fig. 3 this means a correction factor of up to 40% percent depending on burnup. The isotopic composition of the plutonium is excellent for weapons purposes with a Pu-239 content of well over 90% even for long burnups. Contamination with Pu-238 is also present for high burnups, but with contents of about 1% this has no immediate effect on the weapon usability of the bred plutonium.
5 Realistic Scenarios

The assumption of a homogeneous mixture of all materials in the MCNP model implies that the natural uranium has to be diluted in the Pb-17Li alloy. This is only possible to a certain extent. The phase diagram of the Pb-U system [25] shows that uranium starts to dissolve in Pb at temperatures higher than 600 K. In [26] the results of several experiments are summarized and the authors give an empirical temperature dependent formula for the solubility

\[ \log[L_U] = 3.921 - \frac{5121}{T} \]

of uranium in lead. As the maximal working temperature in the PPCS-A concept should not exceed 475 °C due to increased corrosion at higher temperatures, this temperature would yield a maximal solubility of about 0.001 at% in the Pb/17Li alloy. For an order of magnitude higher solubility one would need temperatures up to 800°C. In standard operation the solubility would be also different due to temperature gradients and there is the risk that uranium would crystallize at cool spots. To overcome these difficulties uranium might be added in the form of small particles. In all cases it will be technically challenging to extract low concentrations of uranium from big amounts of lead. Anyway production rates at such low concentrations will be not very attractive.

In the presented analysis we did not calculate any structures implemented in the breeding blankets. Generally one could implement breeding structures like rods or use the wall structures clad them with corrosion resistant materials or ultimately use moderated breeding structures connected to the light water cooling system. This is leading finally to the design challenges of fusion-fission hybrid systems.

6 Control Measures

The fact that there should be absolutely no fissile material present in a fusion reactor offers a clear-cut detection criterion to any covert use of a declared facility. It should be also mentioned that because of that absence fusion reactors are not falling under any international non-proliferation treaty requirements unless more than what the IAEA defines as an effective kilogram is customarily used in the facility. Fusion reactors also do not fall under the definition of the IAEA term of ‘reactor’.\(^5\)

Control mechanisms could be implemented straight forward in the blanket exchange procedure of modules either by weighing the elements, optical inspection, active interrogation or gamma measurements. Detectors could be placed in the tokamak hall or blanket storage pools and other areas of the facility to detect typical fission products.

Especially for an break-out scenario although it would be important to inhibit the principal capability for an illegitimate use by intrinsic proliferation resistance measures and safeguards by design as far as such measures might be applicable.

---

\(^5\) This is a common problem for strong neutron sources other than reactors. Cf. [27] this conference.
7 Conclusions

The PPCS-A concept for a tokamak fusion power plant was modeled in MCNP to conduct calculations of it’s plutonium production potentials. The model used a homogeneous mixture of materials in the blanket zones without detailed structures. In adding different volume fractions of natural uranium to the Pb-17Li alloy we calculated Pu-239 production rates. For blankets near the plasma production rates between 10-20 kg Pu-239 can be achieved in a 20° sector. Even with low concentrations of 0.1 vol% production rates of 1-2 kg per year are possible in a single blanket near the plasma (blanket 1). For lower concentrations it is necessary to use several blankets or modules for a significant production. Concentrations below 0.001 vol% are too low with a total production of 2.8 kg in the complete reactor to be considered significant.

The results of a burnup calculation show that neglecting burnup and taking the \((n,\gamma)\) reactions in U-238 as the plutonium production yields 20-40% higher production rates depending on the burnup for a concentration of 0.01% natural uranium in the alloy. The results for the isotopic composition shows that the plutonium is weapon usable with over 90% Pu-239 even for high burnups. The tritium breeding ratio of the plant is not affected except for medium concentrations between 0.1-1%. Due to additional heating from fission, the maximum addition of uranium will be limited by the additional cooling requirements. Of course the solubility of uranium in the Pb-17Li alloy is limited to low concentrations far below 0.01% for the operating temperatures in the reactor. Nevertheless, the modeling of homogeneous mixtures with addition of uranium shows some principal features of possible breeding strategies and give an estimate of the production capability at different locations. For more realistic production estimates it will be necessary to investigate breeding structures in greater detail.

The absence of fissile material and fission products in a fusion reactor provides a clear-cut detection criterion to detect any covert activity in a declared facility. There is a need to develop adequate safeguard procedures. Safeguards should become effective as soon as one effective kilogram of source material will be customarily used in a facility. However, even very low masses of fertile material are sufficient to produce significant amounts of weapons usable fissile material (even depleted uranium could be used) and could be exempt by a state from IAEA safeguards. Additionally fusion power plants do not fall under the IAEA definition of a reactor or a facility. So it might be not necessarily so that safeguard procedures will be implemented in a fusion power plant as they are implemented for fission reactors. Even if control mechanisms are applied, a fusion power plant would give a host state a significant break out capability, which is important especially when thinking of a future nuclear weapon free world. As far as it is applicable the design of a reactor should also integrate intrinsic proliferation resistance criteria therefore. It should also be mentioned that a reprocessing capability would be indispensable for a proliferator to get access to possibly produced plutonium.

---

6 If a state has signed the additional protocol however, there will be certain inspection possibilities.
7 E.g. in the case of the PPCS reactor designs the concept A has to be considered more proliferation resistant than the concept B with a pebble bed breeding blanket, in which it will be much easier to mix solid uranium pebbles than in the liquid concepts.
References


