STRONG NEUTRON SOURCES
IS THERE AN EXPLOITABLE GAP?

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Abstract. All neutron sources are capable in principal to produce weapon relevant material. A comparison of the potential to produce fissile material with reactors, spallation neutron sources and fusion plants will be presented. Possible advantages and disadvantages of the respective technologies with their completely different underlying physical processes will be discussed. One focus will be on the possible capability of fusion plants and spallation sources to produce significant quantities with less source material than what defines "one effective kilogram". Furthermore the question will be raised if the corresponding technologies are adequately covered by current IAEA terms like "facility" and "reactor". A preliminary tentative redefinition of the term of "reactor" will be proposed to encourage critique and discussion.

1 Introduction

Historically the production of plutonium for weapon purposes took place in dedicated fission reactors by irradiation of U-238 in the fuel and subsequent reprocessing of the produced plutonium. Of course, if U-238 is irradiated with neutrons plutonium will always be produced. However, the production rate, the end concentration of plutonium isotopes in the heavy metal and the isotopic composition of the plutonium will vary depending the time of irradiation as well as on the spectrum and the neutron flux. There are several processes which will be able to reach fluxes as high or higher as in a reactor ($> 10^{13} n/cm^2 s$) like fusion or spallation.[1] In this article we will compare certain advantages and disadvantages of those processes to breed plutonium for proliferation purposes.

2 Pu Production in Fission Reactors

In the early fissile material production programs of the official nuclear weapon states graphite moderated reactors were commonly used. Heavy-water moderated reactors were used in the programs of Israel, India and Pakistan.[2] Typically the irradiation time is short to inhibit buildup of heat producing plutonium isotopes (Pu-238) or isotopes with high neutron rates (Pu-240, Pu-242, Pu-238) which would increase technical sophistication for a weapon design.[3]

[1] There exist other particle nucleus reactions like Li(d,xn), which might be used e.g. in IFMIF.

[2] The nuclear programs of the United States (e.g. Hanford), Russia (Tomsk-7) and China (Jiuquan) used light water cooled systems, France (G-series) and the U.K. (Calder Hall) used gas-cooling. The DPRK used graphite moderation (Yongbyon).

[3] Typically more than 93% Pu-239 is used in plutonium for weapon purposes.

Reactor	P [MWth]	B [GWd/t]	init. U [t]	Years in React	Conc. FE [kg/tHM]	Conv [g/MWd]	Pu Rate [kg/y]
PWR commercial	3000	30	100	3.4	8.5	0.285	250
PWR weapons	3000	1	100	0.15	≈0.5	0.5	330
France G1	≈40	0.2	100	1.7	0.19	0.95	11
Calder Hall	180	0.4	112	0.83	0.36	0.925	50
Hanford-N	4000	1.21	379	0.39	0.85	0.5	580
Yong-byon	≈ 25	0.3	48	1.97	0.28	≈0.9	7
Spallation	**I [mA]**	**P [MW]**	**Target [t]**	**Years in SNS**	**Conc. T. [kg/tHM]**	**Conv [g/MWd]**	**Pu Rate [kg/y]**
Conservative	0.1	0.1	19	1	0.015	9.9	0.288
Moderate	1	1	19	1	0.15	9.9	2.88
Progressive	10	10	19	1	1.5	9.9	28.8
Conservativ	0.1	0.05	19	1	0.0042	5.5	0.08
Moderate	1	0.5	19	1	0.042	5.5	0.8
Progressive	10	5	19	1	0.42	5.5	8
Conservativ	0.1	0.05	2.2	1	0.024	11.9	0.052
Moderate	1	0.5	2.2	1	0.24	11.9	0.52
Progressiv	10	5	2.2	1	2.4	11.9	5.2
Fusion reactor	**P [MW]**	**Conc. [vol%]**	**Mass [t]**	**Years in Blanket**	**Conc. Bl. [kg/tHM]**	**Conv [g/MWd]**	**Pu Rate [kg/y]**
Module II Blanket 1	15.8	0.1	0.022	1	39.1	0.14	0.68
Module II Blanket 2	5.4	0.1	0.022	1	15.5	0.17	0.28
Module II Blanket 3	2.0	0.1	0.023	1	5.9	0.19	0.11
Moduel II Blanket 4	0.9	0.1	0.023	1	2.8	0.19	0.05
Module II Blanket 1	18.2	1	0.22	1	21.2	0.7	4.05
Module II Blanket 2	6.13	1	0.22	1	9.4	0.94	1.72
Module II Blanket 3	2.23	1	0.23	1	3.7	1.04	0.68
Module II Blanket 4	0.97	1	0.23	1	1.8	1.10	0.32

Table 1: Comparison of different specifications for the production of plutonium with reactors, spallation neutron sources and fusion reactors.
All reactor production rates calculated according to [1], data for North Korean reactor Yong-byon see [2]. Note that the calculations for SNS and fusion do not include burnup, whereas the production rates for reactors are calculated taking burnup into account. Including burnup would decrease production rates for fusion and spallation by roughly 20% after one year. This reduction however is insignificant compared to other factors like a more sophisticated target geometry in the case of SNS, which could increase the production rate by a factor of 2, or the use of several or all blankets in the module II or in several modules or in more than one 20˚-segment in the case of fusion. All production rates are calculated for 80% capacity factor (60% for possible military use of an LWR).
P: power; B: Burnup in reactor; init. U: initial uranium loading of reactor; Mass: Mass in blanket; Years in Reactor/in SNS/ in Blanket: duration of irradiation of fuel element in reactor/in spallation target in SNS/ in fusion reactor blanket; Conc: concentration of produced plutonium in FE: fuel element, in T: target, in Bl: blanket; Conv: conversion factor defined as ratio of production rate to thermal power for reactors (burnup considered) [1], to beam power for SNS, to thermal power in fusion blanket; Pu Rate: production rate of Pu; I: beam current; Target: uranium content in target; Conc.: volume fraction natural uranium in Pb-17LI alloy.

Due to the short irradiation times the concentration of plutonium in the irradiated heavy metal will be low and therefore large amounts of source material is necessary to produce a significant quantity of plutonium. Total production rates for some reactors are given in table 1. The production rates were calculated with a typical conversion factor for how much plutonium will be produced in a reactor per MWd [1, Annex A] and using the nominal thermal power of the reactors. For the low powers of early reactors like the french G-1 production rates of 11 kg Pu-239 per year can be calculated for an initial uranium loading of roughly 100 tons [1, chapter 3]. For an advanced production reactor like Hanford-N with 4 GW thermal power the production rate is significantly higher of course. A commercial light water reactor will usually have much higher burnups and the plutonium concentration will be much higher. But high burnups will also increase the content of neutron producing plutonium isotopes, which will demand a higher technical sophistication for a practical weapon design. The content of Pu-239 will be well below 70%.

Of course a light water reactor could also be operated in a way that the fuel elements will be exchanged more frequently. As constant refueling is not possible in that reactor type, the total capacity per year would drop as a consequence to an estimated maximum of 60% or lower.[4] But even for a burnup of only 1 GWd/tHM and a conservative estimate of the plutonium concentration of 0.5 kg/tHM [1, Figure 5.3, 5.4] the production rate per year is higher than for the commercial operation. However, the source material consumption in such an operation mode would be significantly higher on the downside.

These calculation give only a rough estimate and the real production might be higher or lower, but for the purpose of this article we are not interested in the complexity of nuclear archeology [3; 4] and the estimates will be sufficient for comparison with other neutron producing technologies.

3 Spallation Neutron Source (SNS)

A first analysis of the proliferation potential of SNS and accelerator driven systems (ADS) can be found in [6] and [7].[5] Such analysis seemed to be necessary as in the last decades SNS performance increased significantly (see [8], Fig. 13 p. 520). In particular, there is a renewed interest in SNS for research facilities and for industrial application e.g. accelerator transmutation of waste and ADS. 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. Beam currents up to 100 mA for linear accelerators have been proven successfully [9]. For the

[4]For the proliferation concerns associated with light water reactors cf. [5].

[5][6] also mentions several programs set up since the 1950s which were dedicated to investigate electronuclear fissile material production.

purpose of this assessment beam currents of 100 μA can be considered as conservative assumption, 1 mA as moderate and 10 mA as progressive.

By using MCNPX [10] simulations of protons hitting a uranium spallation target we calculated the production rates for different target sizes (masses). As space is limited we do not repeat the specific assumptions of these calculations which were published in [11; 12; 13]. 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 reactors (see tab. 1). For powers above 1 MW however the production rates are comparable to a small fission reactor.

In the MCNPX simulations carried out for the production figures presented in tab. 1 the protons hit the ground surface of a target cylinder and it is depending on the actual geometry of the target how much neutrons will leak out of the geometry. Reducing the target dimensions from length 90 cm radius 60 cm (90x60 cm) with 19 t natural uranium to 60x25 cm with 2.2 t reduces the production rate from 0.8 to 0.52 kg/year for an 1 MW target, but increases the concentration of produced plutonium in the heavy metal significantly. For high power targets the concentration could be increased further. Note also that by reducing neutron losses and optimizing the target geometry and design, one could easily achieve higher production by a factor 2 or more. 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.

4 Fusion Power Plant

We calculated production rates in different blankets of a fusion power plant using the conceptual design of a tokamak fusion power plant published by the European Fusion Development Agency (EFDA) in 2006 [14]. Detailed calculations and discussion of results are published in [13; 15]. In tab. 1 we reproduce some of the results. The MCNP model of the reactor used only a 20° segment of the full torus. Each such segment has six modules which are arranged poloidal facing the plasma chamber. The three inner modules contain four blankets the outer modules five blankets each. Blanket one is the innermost blanket with the highest neutron flux near the plasma. Blankets 2,3,4 and 5 are increasingly further away from the plasma and experience significantly less neutron flux. Under normal operation these blankets are used for tritium production and filled with a liquid Pb-17Li alloy. To calculate possible production rates we added different volume fractions of natural uranium to the alloy and conducted MCNP simulations.

As for the case of spallation these calculations are only rough estimates under several simplifying assumption which are described in [13; 15] in greater detail. For the purpose of this comparison however the focus is on the achievable production rates, which can only reach the rates in a fission reactor for high concentrations of uranium (1 vol%) near the plasma (blanket 1) for a single blanket. But using more than one blanket in one or several modules or even in more than one 20°-segment would have a cumulative effect and much higher production rates could be achievable. The achievable concentrations can be much higher than in a fission reactor without compromising the purity of the isotopic composition which will contain more than 90% Pu-239 even for extremely high burnups due to the hard spectrum in the blankets. Even with masses much lower than 1 t natural (or even depleted) uranium production rates in the kilogram range are possible.

5 Proliferation Concerns

The main advantage of a SNS and a fusion plant compared to the production of plutonium in a fission reactor is the relatively low initial mass of natural or even depleted uranium and the possibility to achieve high end concentrations in the material without reducing the Pu-239 content in the isotopic composition. Due to the hard flux even for high burnups the weapon usability is high with much higher Pu-239 fractions than in fission reactors. The low mass is also advantageous for the reprocessing of the uranium to extract the plutonium. Additionally in an SNS or a fusion reactor there is no need to keep up criticality like in the early production reactors.[6]. The total irradiation time is therefore only limited by the radiation and thermal stress of the target material.

The comparison of SNS and fusion plants with reactors so far did not discuss the probability that these technologies might be used in the future for plutonium production at all. E.g. in terms of economic competitiveness large megawatt SNS facilities are more expensive than a reactor, but medium energy SNS with high currents using small cyclotrons might become more available in the nearer future reducing the cost argument. With respect to fusion the development of a operating fusion power plant will be decades or longer away, although depending on the success of fusion research more intense neutron sources might be build for research purposes. It is difficult to predict the impact and the availability of these technologies and the timeline of their implementation or if they ever will play a role in a proliferation scenario. 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. However, in a world with a rigorous control on the typical fissile material production paths or even increasing restriction in access to fission technology, these technologies might be more interesting for an actor, especially if an actor wants to keep a latent fissile material production capability open. Possession of an intense neutron sources by a country will be a concern especially in a future nuclear weapon free world as such a country could develop or maintain an option to use this facility covertly or after a break-out.

Although one can safely conclude there is no immediate threat today, it will be easy and straight forward to implement and test safeguard strategies and to enhance the proliferation resistance of the design to be prepared for the coming decades.

[6] In some more advanced production reactors driver fuel was used with depleted uranium targets for production purposes

6 Is There an Exploitable Gap?

Nearly every member state to the NPT has a comprehensive safeguards agreement (INFCIRC, 153 [16]) with the IAEA. The document states that all materials which contain uranium or thorium have to be reported to the IAEA if these materials are exported from or imported in a non-nuclear weapon state unless the material is imported for specifically non-nuclear purposes. For such material it is sufficient to state the composition and quantity, and the destination in case of an export. Safeguards will be applied without exception to any nuclear material "of a composition and purity suitable for fuel fabrication or for being isotopically enriched"[16] if the material leaves the plant or process stage or if it is imported into the state. Nuclear material can, at the request of the State, be exempt from safeguards. This includes ten tons in total of natural uranium, ten tons depleted uranium (>0.5% enrichment) or 20 tons (<0.5% enrichment) according to the standard definition of one effective kilogram. However, such an amount might be enough for a significant production according to the discussion above.[7] In the above definitions it is also unclear what exactly is termed to be a "non-nuclear purpose" or "non-nuclear activity". Construction and operation of an SNS in the U.S. e.g. is not a nuclear activity since the term "atomic energy" in the Atomic Energy Act statutory definition limits the definition to energy released in fission and fusion.[8]

So far we have described the safeguard system controlling the material flows. The IAEA should also receive reports about the "facilities" in a country. "Facility" means: "a) A reactor, a critical facility, a conversion plant, a fabrication plant, a reprocessing plant, an isotope separation plant or a separate storage installation; or b) Any location where nuclear material in amounts greater than one effective kilogram is customarily used." [16][9] Neither spallation nor fusion facilities fall under these categories because the definition of a reactor is specified in the IAEA glossary according to the definition in the older facility specific safeguards (INFCIRC 66)[10] and is based on the terms fission and chain reaction.[11] The definition of reactor in the additional safeguards protocol (INFCIRC 540), which is not ratified so far by all members of

[7] The "Consolidated Trigger List" of the Zangger Committees (INFCIRC 209, Rev. 2) requires the report of an export of source material within 12 months. Exempt from report are less than 0.5 t natural uranium and 1 t depleted uranium or thorium. Members to the Zangger Committees are Argentina, Australia, Austria, Belgium, Bulgaria, Canada, China, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Kazakhstan, Republic of Korea, Luxembourg, The Netherlands, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Slovenia, South Africa, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom and United States of America. (http://www.zanggercommittee.org).

[8] Thanks to David Moses, Oak Ridge National Laboratory, for this and several other arguments in this section.

[9] Effective kilogram: for plutonium 1 kg. For uranium with enrichment >1% weight of the material is multiplied with the square of the enrichment (e.g. 25 kg 20% LEU is 1 effective kilogram). For uranium enriched to 0.5-1% it is 10 t, for depleted uranium (<05%) and thorium it is 20 t.

[10] Facility specific safeguards according to INFCIRC/66 were replaced by the comprehensive safeguards INFCIRC/153 and exist for only few facilities in countries outside the NPT regime.

[11] "Reactor' means any device in which a controlled, self-sustaining fission chain-reaction can be maintained." (INFCIRC 66) "Reactor' means any device in which a controlled, self-sustaining fission chain-reaction can be maintained. Nuclear reactor means an apparatus, other than an atomic weapon, designed or used to sustain nuclear fission in a self-supporting chain reaction" (IAEA glossary)[17].

the NPT, is also based on these terms.[12] One could argue that an SNS or fusion plant would fall under the definition of facility if more than 1 kg Pu is “customarily used". But in this case there would have to be some attention of the IAEA on such high intensity neutron facilities to detect a missing declaration of the use of uranium in such a facility.

The old facility specific safeguards (INFCIRC 66) and the additional protocol also specify an annual production rate of 100 g Pu per year as a threshold for safeguards in reactors.[13] INFCIRC 66 additionally specified a thermal power of 3 MW as an additional threshold for reactors.

Based on these findings it might be favorable to use a different definition of what defines a reactor by including all neutron producing processes.[14] A tentative new definition might be the following:

Reactor means any device in which a controlled, self-sustaining fission chain-reaction can be maintained. This includes also any subcritical assemblies with external driven neutron source, or any facility providing intense neutron fluxes, which can be operated in such a manner that they

a) produce plutonium with a rate of production exceeding 100 grams of plutonium per year; or

b) is determined by the Agency to have a maximum calculated power for continuous operation greater than 3 thermal megawatts.

Such a definition would generally include strong neutron sources like SNS or fusion into safeguards. This are facilities which will not contain by design any fissile material, but could be used for fissile material production. Of course there have to be certain control mechanisms implemented to guarantee that such facilities are not used for any illegitimate activities.

[12] "‘Nuclear reactors capable of operation so as to maintain a controlled self-sustaining fission chain reaction, excluding zero energy reactors, the latter being defined as reactors with a designed maximum rate of production of plutonium not exceeding 100 grams per year."’ The explanatory note says: “A ‘nuclear reactor’ basically includes the items within or attached directly to the reactor vessel, the equipment which controls the level of power in the core, and the components which normally contain or come in direct contact with or control the primary coolant of the reactor core. It is not intended to exclude reactors which could reasonably be capable of modification to produce significantly more than 100 grams of plutonium per year. Reactors designed for sustained operation at significant power levels, regardless of their capacity for plutonium production, are not considered as ‘zero energy reactors.’"

[13] Not based on production rates but on masses are the definition of the “Consolidated Trigger List” of the Zangger Committees (INFCIRC 209, Rev. 2) with only 50 g Pu exempt from declaration. In the Convention on the Physical Protection of Nuclear Materials (INFCIRC 255 Rev.3) three categories (I-III) are applied based on masses requiring different protection measures: For unirradiated plutonium: category I: > 2 kg, category II: >500g, category III > 15g. For uranium with >20% enrichment I: >5 kg, II: > 1 kg, III: >15g. For uranium with 10-20% enrichment I: –, II: > 10 kg, III: 1 bis 10 kg. For uranium with <10% enrichment I: –, II: –, III: >10 kg. For uranium-233 I: > 2 kg, II: >500 g, III: >15 g.

[14] Thanks to David Moses, Oak Ridge National Laboratory, for discussion and a first proposal for the case of subcritical assemblies.

7 Conclusions

The relative advantages and disadvantages of plutonium production in a fission reactor compared to other strong neutron sources like spallation neutron sources and fusion reactors were discussed. In SNS and fusion facilities high concentrations of plutonium can be bred thus dramatically reducing the amount of source material necessary for production. Even with amounts well below 10 t natural uranium, which can be exempt from safeguards, significant production is possible. The isotopic composition of the produced plutonium is weapon usable with Pu-239 contents of more than 90%.

Today, there is no immediate proliferation concern with regard to SNS and fusion, as both technologies are currently not widely used or in the case of fusion, development will take several decades. This allows for enough time to research and implement preventive mechanisms to enhance the proliferation resistance by developing safeguard procedures and by finding, if applicable, proliferation resistant designs. As currently SNS and fusion reactors are not directly covered by IAEA terms and because of the low requirements of source material in such facilities, we gave a tentative redefinition of the term “reactor”, which would allow to include SNS and fusion plants into the IAEA safeguards system.

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