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Proliferation issues related to fast SMRs

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ABSTRACT

This paper contributes to the literature on proliferation risks of small modular reactors. After a general discussion of SMR developments, in the main section of this paper we present an analysis of a generic sodium-cooled fast reactor designed to sustain an unusual lifetime of 30 years, similar to concepts such as the Toshiba 4S. For this reactor, material composition over lifetime is calculated and its material attractiveness compared to (spent) fuel from other reactor types. Depletion calculations show that a significant amount of plutonium is produced over time with an isotopic composition highly attractive for military purposes.

1. Background

In recent years, small modular reactors (SMRs)[1] have gained attention as possible alternatives to large scale commercial nuclear power plants (Ingersoll, 2012; IAEA, 2012, p. 9ff). SMRs usually are reactor designs with a power level of less than 300 MWth and a unit size small enough for transportation with rail, trucks, or barges. The small size might allow for line assembling in central manufacturing facilities (WNA, 2012; IAEA, 2007, p. 9, p. 26, p. 43). The possibility of mass fabrication and the anticipated lower initial costs per unit are supposed to compensate for the economy of scale advantage of large nuclear power plants. At the same time asserted enhanced security and safety features of SMRs are stressed as arguments to deploy SMRs globally (O'Meara, 2013).

Several countries discuss SMRs as a viable option to increase the nuclear share in total electricity generation (Sun, 2011; Kelly, 2013, p. 6ff; WNN, 2012; WNA, 2012; IAEA, 2012, p. 1). To support its member states, the International Atomic Energy Agency (IAEA) developed a program on "Near-term & small and medium sized reactor technology development" (Amano, 2013; IAEA, 2013). SMRs are envisioned to be deployed in remote areas or countries that are new to nuclear power, thus compensating for a declining nuclear reactor market in traditional nuclear energy producing countries such as the United States and Europe (Kessides and Kuznetsov, 2012; Schneider and Frogatt, 2013, p. 11). However, economic feasibility seems to be a major problem in several cases and vendors often demand governmental subsidies (Lyman, 2013, p. 5; Makhijani, 2013, p. 6f). If SMRs became economically attractive, the number of deployed SMRs might grow to several hundreds or even thousands, raising questions about safety and proliferation risks (Reis, 2012; WNA, 2012; Energy Policy Institute, 2010, p. 22).

Some publications have already addressed potential proliferation risks of SMRs, but quantitative assessment of plutonium production capabilities of long-lived SMR cores is rare (Glaser et al., 2013; Makhijani, 2013; Koreshi and Hussain, 2014). This paper analyzes a generic small, sodium-cooled reactor based on the Toshiba 4S design.

Like alternative concept such as the Small, Sealed, Transportable, Autonomous Reactor (SSTAR), IAEA (2007, pp. 591–624), a fast reactor design which uses lead as a coolant instead, the sodium-cooled fast reactor as well as the lead-cooled fast reactor rank among advanced generation IV fast reactor designs (GIF, 2014). But the Toshiba 4S design is the only small fast reactor design the IAEA currently considers to be deployable near-term (IAEA, 2013). A demonstration plant was planned for Galena, Alaska, and the pre-application process with the U.S.

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[1] SMR - Small, Modular Reactor, IAEA – International Atomic Energy Agency, U.S. NRC – United States Nuclear Regulatory Commission, HEU – Highly Enriched Uranium, BOL – Beginning of Life, EOL – End of Life, FOM – Figure of Merit, UOX – Uranium Oxide.

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Nuclear Regulatory Commission (NRC) was initiated. However, because of the high installation and operating costs, the project seems to be stalled (Holdmann, 2011, pp. 13–16).

In 2013 the Daily Yomiuri announced that Toshiba is developing a small nuclear reactor for use in oil sands mining (Shimbun, 2013). The article states further that Toshiba is still waiting for the results of the design approval procedures with the U.S. NRC before undergoing safety checks in Canada.[2]

Like all long-lived cores, the 4S is specifically designed for areas that are not connected to a central electricity grid or infrastructure in general (Tsuboi et al., 2012). Specifications are the long core lifetime of thirty years and the absence of refueling or shuffling of fuel elements during operation. To achieve a core lifetime of several decades, the core is fueled with uranium with maximum enrichment close to 20% ^{235}U (U.S. DoE, 2014). Uranium with 20% or less enrichment is considered as low enriched uranium by the IAEA. Enrichment above 20% is highly enriched uranium and requires stronger safeguards (IAEA, 2001, p. 32).

At the beginning-of-life (BOL), the fuel is transported to the reactor site and loaded into the core. At the end-of-life (EOL), there will be in-vessel cooling before the spent fuel is removed from the core and transported back to a central (re) processing facility (Tsuboi et al., 2012). To remove the spent fuel from the core, a fuel handling machine is necessary. To impede unauthorized withdrawal of fissile material, this machine would not be permanently installed at the reactor site. Whether these commonly used machines and facilities will be owned and operated by states, international organisations like the IAEA, or private companies is not clear in most scenarios. Especially countries deploying several SMRs will probably argue for their own processing facility. The in-core cooling of the spent fuel makes spent fuel pools at the reactor site unnecessary. It is not clear how the energy demand is supposed to be met during cooling times when the reactor does not produce energy. Compared to maintenance periods of large commercial LWRs, the in-core cooling period of the SMR is considerably longer (IAEA, 2012).

After initial fueling, the core is sealed to impede unauthorized access. Comparing the proliferation resistance with LWR, a fast SMR could be considered a "nuclear battery" as it does not have to be opened for many years so that no diversion could occur during refueling. In comparison with LWR, this specific feature renders such a reactor more proliferation resistant. To ensure the integrity of the seals during operation, regular safeguards inspections are required. A high number of deployed SMRs will bring current safeguard practices under more stress and raise costs. Remote sensing and video monitoring are under development, but it is not yet clear if these measures can provide the same level of security as on-site inspections. The nuclear industry also argues for less stringent licensing and siting requirements, not only with regard to safety aspects such as the size of the emergency evacuation zones but also in regard to security requirements. Some vendors argue, without going into further detail, that a 70–80% reduction in security staff is possible (Ramana et al., 2013; Lyman, 2013; Azad, 2012, p. 5). Placing SMRs in countries with lacking experience in regulation and operation of nuclear power plants might also further simplify access to nuclear material for a possible proliferator.

Many aspects impact the proliferation resistance of a fast SMR. The availability of fuel that is already enriched to nearly 20% can reduce time and costs to produce weapon usable highly enriched uranium.[3] It is therefore a possible proliferation pathway, especially for countries with existing, but limited enrichment capabilities. Also, for the acquisition of plutonium the fast SMR can be an interesting option. The quality of plutonium produced in fast reactors is better suitable for building nuclear weapons, since fast reactors in general produce more than double the amount of excess neutrons per fission than thermal reactors, which can subsequently used to produce (breed) more plutonium (Taube, 1974).[4]

Front and back end facilities in a closed fuel cycle envisioned for future SMR generations are equally important to assess. In this paper however we restrict our analysis to core isotopics of a generic sodium cooled reactor similar to the Toshiba 4S and to the fissile material production itself.

2. Reactor design and simulation strategy

A core model of a fast SMR has been developed to assess the plutonium production capabilities and the isotopic composition of plutonium produced in the core. Important parameters are summarized in Table 1. The model is based on publicly available design information of the Toshiba 4S. The reactor has an electric output of 10 MW and an expected lifetime of 30 years without refueling or reshuffling of fuel elements (IAEA, 2007, pp. 395–419; Yacout, 2008; Tsuboi et al., 2012).

Fig. 1a shows the vertical section of the core model. The full core consists of 19 elements. The central element contains the hafnium absorber and space for the emergency shut-down rod. The fuel is a uranium–zirconium alloy (10 wt% Zn) with an enrichment of 17 wt% or 19.9 wt% ^{235}U. The six outermost elements contain the higher enrichment to flatten the neutron flux distribution in the core. Each element comprises 169 fuel rods that are densely packed, a typical characteristic for sodium coolant. The core has a total heavy metal inventory of 9.24 tons. Two thirds of the uranium is enriched to 17% and one third to 19.9%.

Fig. 1b depicts the vertical section of the reactor model. Only the lower part of fuel rods is filled with fuel, the upper half is a gas plenum to contain resulting fission gases.The fuel rods are surrounded by either a reflecting steel region (gray) or by tanks filled with helium (dotted).

During operation, the annular reflector moves progressively upwards and covers new regions of the core, Fig. 2, (IAEA, 2009). Thus the neutron flux varies greatly over the length of one fuel pin. Criticality is reached by covering a part of the core large enough to reflect sufficient neutrons back into the core to sustain a chain reaction. The reflector movement can be seen as continuously adding fresh fuel to the reactor. After 15 years, the reflector finally surrounds the complete active region. To extend the lifetime for another 15 years, the reflector returns to the lower position of 150 cm and the hafnium absorber is withdrawn to compensate the loss in reactivity. Then the reflector starts another upward movement and the fuel is burned for the second half of the fuel cycle.

Criticality and flux calculations were carried out with this model of the reactor core to validate the geometry. Fig. 3 shows the neutron flux in arbitrary units as a function of the reflector position for the first and the second half of the reactor operation

[2] Though the name 4S is not mentioned in the original source, the characteristics of the reactor model are the same as for the 4S. Further, the article mentions that Toshiba has started licensing procedures with the NRC for construction in the US and has been introducing the described reactor model to arctic communities as a small-scale power station.

[3] To produce 25 kg of uranium with 90% enrichment in ^{235}U from light water reactor fuel (3.5% enrichment, tails with 0.3% enrichment) needs about 1782 Seperative Work Units (SWUs). If uranium of 20% enrichment is provided, this value drops to 462 SWUs. Depending on the burn-up and the conversion ratio in the core, the uranium at EOL might still have a significant enrichment of ^{235}U (WISE Uranium Project, 2009).

[4] Taube gives the effective excess neutrons per fission in a simplified table (Taube, 1974, p. 117). For U-235 thermal reactors have 0.5 excess neutrons, fast systems have 1.2. For Pu-239 thermal reactors have 0.9 while fast systems have 1.8 excess neutrons per fission.

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