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RESEARCH NOTE

BN-800: Spent Fuel Dose Rates and the Plutonium Management and Disposition Agreement

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ABSTRACT
In 2000, Russia and the United States signed the Plutonium Management and Disposition Agreement to dispose of 34 tons of declared excess weapon plutonium each. A 2010 amendment allows Russia to dispose of its weapon-grade plutonium as MOX fuel in its BN-600 and BN-800 fast reactors with the condition that 30 years after irradiation the spent fuel must still emit at least one sievert per hour. Using depletion simulations for the BN-800 reactor, this note presents dose rates for fuel and blanket materials after different irradiation and cooling times. After the full irradiation time of 420 days, the fuel fulfills the disposition criteria. This is not true for shorter irradiation times, however. Furthermore, the dose rate from blanket elements, which breed weapon grade plutonium, declines even more quickly after irradiation. For some blanket element positions, the spent fuel standard is not fulfilled after 960 days of irradiation. To provide confidence in the agreement, Russia, the United States and the International Atomic Energy Agency should agree on monitoring of reactor power and irradiation times for plutonium disposition in such fast reactors.

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In their Plutonium Management and Disposition Agreement (PMDA), Russia and the United States agreed to dispose 34 metric tons of excess weapon plutonium each. The amount is a significant fraction of both countries' military plutonium stockpiles. The disposition of that material is an important step towards nuclear disarmament. The original agreement was concluded in 2000.[1] At that time, both countries planned to dispose most of the plutonium in mixed oxide (MOX) fuel, mainly for light water reactors.

In 2010, the agreement was amended.[2] According to the amendment, Russia has U.S. permission to use its excess weapons plutonium in fuel for its two fast-neutron reactors, BN-600 and BN-800. The BN-800 is Russia's newest fast reactor in Beloyarsk, currently the largest fast reactor in the world. The reactor reached first criticality in June 2014 and was connected to the electricity grid in December 2015. At

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full power, it can produce 789 MW of electricity. During its initial cycle, the reactor core will also contain highly enriched uranium fuel due to limitations in Russia's capabilities to produce MOX fuel.

A newly constructed MOX fuel fabrication facility was formally commissioned in September 2015 at Russia's Mining and Chemical Combine (MCC) Complex in Zheleznogorsk. It is expected to reach its full capacity of 400 fuel assemblies per year in 2017. With such a capacity, the plant would be able to supply fuel for multiple BN-800 reactors. As the plant only reached operational status after the BN-800 reached first criticality, the first BN-800 MOX fuel elements were produced at a research facility, NIIAR in Dimitrovgrad. The first MOX fuel from the Zheleznogorsk plant should be ready for the reactor's first refueling. The plant will be able to process plutonium of any isotopic composition.

In April 2016, Russia criticized the United States for halting the construction of the U.S. MOX fuel fabrication plant.[3] Later that year, Sergei Kiriyenko, the head of RosAtom, announced that Russia would fulfill its obligation under the agreement.[4]

The PMDA specifies specific requirements for the reactor's spent fuel in the Annex on Technical Specifications, Section II:

> Disposition plutonium shall be considered disposed if the spent plutonium fuel resulting from irradiation in the BN-600 and BN-800 reactors meets the four criteria below:
>
> […] 4. The radiation level from each spent plutonium fuel assembly is such that it will become no less than 1 Sv/h, 1 meter from the accessible surface at the centerline of the assembly 30 years after irradiation has been completed.[5]

Depletion calculations for the BN-800 allowed for a detailed analysis of the isotopic composition of the irradiated plutonium.[6] Based on these results, radiation dose rates were calculated to check if the BN-800 spent fuel would be in compliance with the requirements defined in the PMDA when the required minimum Pu-240/Pu-239 ratio of 0.1 was achieved. Dose rate estimates were carried out for three different zones of the core which have different plutonium fractions in the MOX fuel (LEZ, MEZ, HEZ) and for irradiated breeding blankets. Fuel was irradiated for 420 days. According to the PMDA, the reactor should be run with a breeding ratio below one, but can have breeding blankets. Radial breeding blankets where assumed to have been irradiated for 960 days (slightly more than two fuel irradiation periods), axial blankets are irradiated for the same time as the fuel (420 days). The different reactor zones are shown in Figure 1, which displays half of the full reactor core. For all calculations, the material composition was taken from previous depletion calculations, applying different cooling periods before calculating dose rate.[7]

A simple hexagonal fuel element geometry was assumed, based on the reported width of a single fuel element and the length of the active core (88 cm) in the BN-800. For calculating radiation doses, the fuel elements were treated as a smeared mixture of fuel and cladding, without sodium and surrounded by air. It has been shown that for complete fuel elements, the homogeneous and heterogeneous dose rates at the axial midpoint are nearly identical.[8]

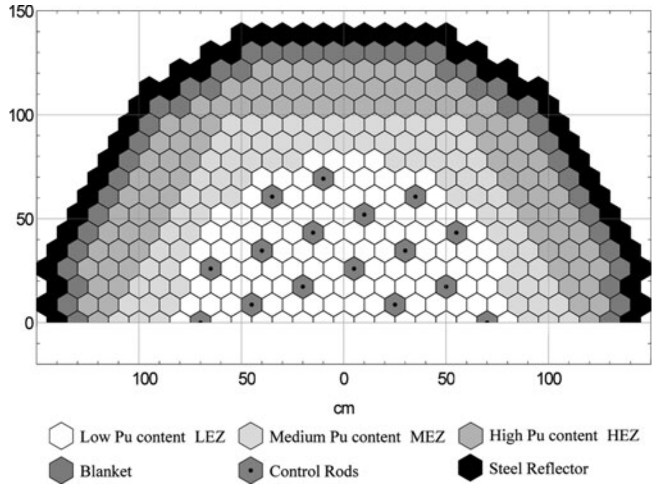

Figure 1. BN-800 Core Layout, showing zones with different plutonium content as well as other reactor zones.

Calculations were carried out using MCNPX 2.7, transporting only gamma rays. Source gammas have been produced using the "PAR = SP" parameter of the MCNP source card that uses internal data to produce photons with energies of all radioactive isotopes in a given material (in this case the spent fuel). To estimate the gamma spectrum a ring detector for photons was been placed one meter from the surface of the element at the vertical center of the element at a distance. The detector count was divided into 25 energy bins. Dose rates where then calculated using fluence-to-dose conversion factors.[9]

All BN-800 spent fuel was found in compliance with the minimum PMDA dose rate requirement. Dose rates for the zones LEZ, MEZ, and HEZ were calculated as 2.15, 1.58, and 1.55 Sv/h, respectively after a cooling time of 30 years. After being irradiated for 960 days and a subsequent cooling time of 30 years, however, the radial breeding blankets were found to emit a radiation dose of only 0.13 Sv/h. In the BN-800 core, there exist additional axial blankets below each fuel element, but none above. This material could be used to separate plutonium after it has been chopped off from the fuel rods. Dose rates for axial blankets have been calculated for HEZ, the zone with the highest plutonium content. This zone receives the lowest neutron flux during irradiation, and is therefore the zone with the lowest dose rate. After 30 years of cooling, axial blankets emit only 0.03 Sv/h, and already after two years less than 1 Sv/h (0.79 Sv/h).

Shorter burnup of reactor fuel would, of course, result in lower dose rates as less fission products would be produced. Figure 2 shows the dose rates for different irradiation times. Periods were selected similar to the typical refueling intervals of the BN-800. At these times, the reactor is shutdown in normal operation to replace fuel elements in one third of the core with fresh fuel. Even when no earlier withdrawal is intended, it might sometimes be necessary to remove elements at these stages because of safety concerns (e.g., mechanical failure or leakage). The figure shows that no fuel fulfills the requirements set by the PMDA when withdrawn

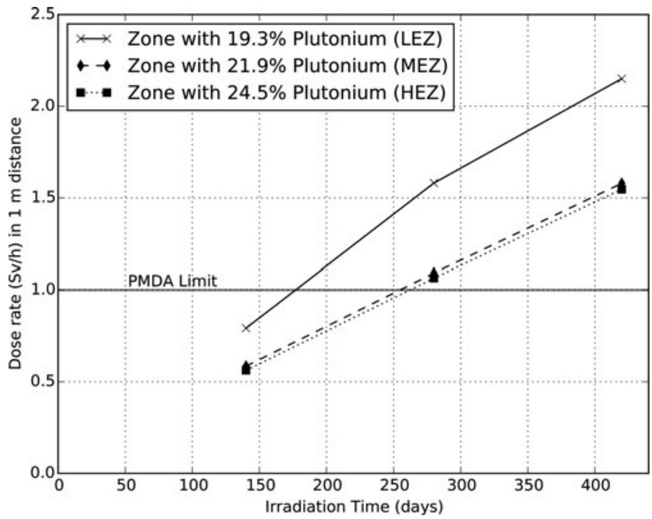

Figure 2. Calculated dose rates of BN-800 spent fuel for different irradiation times, all values calculated based on 30 years cooling period.

after one third of the full irradiation period. Fuel from the zone with higher plutonium enrichment (MEZ and HEZ) barely reaches the limit after two thirds of the time.

To illustrate the effect of cooling on the radiation dose, calculations were also done for different cooling times, as shown in Figure 3. The results show that, in the first years after fuel has been removed from the reactor, dose rates are very high. As already noted, for fuel that has been irradiated a full period of 420 days, the dose rate never gets below the PMDA limit within 30 years. This does not hold true for fuel that has only been irradiated for one third of the burnup: for these fuel assemblies, it would only take 10 years for enough fission products to decay to result in a dose rate

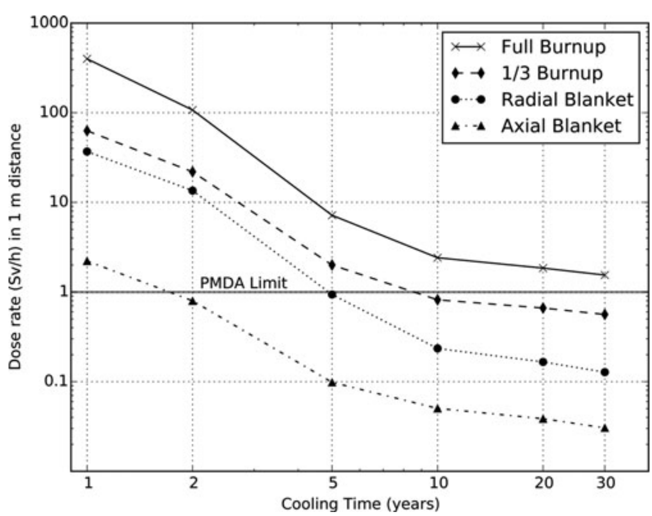

Figure 3. Dose rates for different cooling times, both data sets are based on fuel from zone HEZ in the reactor.

below the limit of 1 Sv/h. For radial breeding blankets, the blanket assemblies already emit less than the required dose rate five years after discharge from the reactor and after two years only slightly more than 1 Sv/h. Axial blankets that are separated from the active core drop below the 1 Sv/h level even earlier, after only two years of cooling time. No calculations have been carried out for cooling periods longer than 30 years. Clearly, dose rates would continue to decrease.

While a special annex on monitoring and inspections is part of the agreement, it leaves many details open for further negotiations ("procedures to be agreed by the Parties").[10] While it is agreed that these procedures should include a way to confirm the dose rate ("confirm the fulfillment of the criteria specified in the Annex on Technical Specifications") it is not clear how this will be done.

Dose rates from spent fuel can be measured easily, but what remedy for a low result is unclear. Most likely, it would be impossible to reuse the fuel for additional irradiation without reprocessing it and fabricating new fuel elements. It therefore would be helpful to monitor the irradiation times of the fuel and radial blanket. Nearly continuous monitoring of the reactor power output could provide the basis for a good estimate for plutonium isotopic change and the concentration of fission products.

Unfortunately, the status of the additional agreement on monitoring and inspection is still open. In 2010, Russia and the United States submitted a joint letter to the IAEA asking the agency to "undertake an important verification role under the amended Agreement."[11] The letter also included the goal to achieve legally binding agreements in this regard until 2011. In 2012, Anatoli Diakov wrote that a trilateral dialogue was still ongoing, "Not much is known about this consultation but Russian experts involved in this process do not expect serious difficulties."[12] The issue of verification is further complicated by the fact the United States might change its disposition plan from the MOX option to direct disposal. If the PMDA would need to be renegotiated due to such a change, the negotiations could also include discussions on the international verification. Independent of negotiated and formally binding verification measures, it would be advisable for both countries to achieve unilateral transparency during all steps of the plutonium disposition. Such measures would increase trust among the two parties, but could act as examples for other countries and future disarmament measures.

In conclusion, the PMDA is a very useful agreement and disarmament measure. As recent developments have shown, progress is slow, and sometimes more difficult to achieve then initially thought. The dose rate calculations presented here show that short burnup times or breeding blankets could reduce the difficult for early retrieval of the contained plutonium. Breeding blankets are a special concern in this context, since they contain new produced plutonium and their radiation barrier declines quickly. A level of less than 1 Sv/h is reached, at least for certain positions, already two years after removal from a reactor. Overall, comprehensive monitoring and inspection mechanisms should be applied while the disposition takes place. The best way would probably be careful observation of reactor power and irradiation times.

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