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Plutonium Disposition in the BN-800 Fast Reactor: An Assessment of Plutonium Isotopics and Breeding

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According to the Plutonium Management and Disposition Agreement, which was signed in 2000 and amended in 2010, Russia and the United States agree to dispose of 34 tons of excess weapon plutonium each. Russia plans to use the plutonium as fuel in its sodium-cooled fast reactors BN-600 and BN-800. This article analyzes BN-800 core models with and without breeding blankets for the plutonium isotopic vector in spent fuel, plutonium production in breeding blankets, breeding ratios for different plutonium concentrations in fuel, and possible annual material throughput. It finds that any spent fuel in the core contains less than 90 wt% plutonium-239, but using breeding blankets the reactor can be configured to be a net producer of plutonium, even with a breeding ratio below one, and that plutonium produced in blankets will be weapon-grade.

INTRODUCTION

In 1998, U.S. president Bill Clinton and Russian president Boris Yeltsin released a joint statement offering to withdraw 50 metric tons (MT) of plutonium each from their respective military stockpiles.[1] It was agreed that this plutonium should be rendered unusable for nuclear weapons either by irradiation in existing commercial reactors or by immobilization.[2]

In 2000, Russia and the United States agreed on the "Plutonium Management and Disposition Agreement" (PMDA). The agreement defined the task in detail, including the obligation for both sides to dispose of 34 MT each of their respective stockpiles. According to the original disposition agreement the United States planned to immobilize about a fourth and irradiate the rest as

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mixed plutonium-uranium oxide (MOX) fuel in light-water reactors. Russia chose a pure reactor based elimination using VVER-type light-water reactors and the BN-600 fast reactor.[3]

In 2010, the two countries negotiated an amendment to the original PMDA,[4] because of technical problems, construction delays, legal disputes, and for financial reasons.[5] Both sides agreed to postpone the start of their disposition efforts to 2018, and reduced the required disposition rate to 1.3 MT per year. The amendment allows Russia to dispose of weapons plutonium in the BN-800 fast reactor as well as the BN-600. This replaces the option to use the VVER and enables Russia to integrate plutonium disposition in its long term nuclear energy strategy by establishing a closed nuclear fuel cycle with fast breeder reactors.[6]

The amendment further includes special provisions to prevent new production of plutonium in both fast reactors while they are used to dispose of weapon-grade plutonium: the BN-800 has to be operated with a breeding ratio below one; no reprocessing of fuel (manufactured with disposition plutonium and irradiated in the reactor) nor of the radial blanket of the BN-800 is allowed until all the excess plutonium is disposed.[7] However, two exceptions exist under the condition that they do not result in accumulation of new separated weapon-grade plutonium by itself or in combination with other materials. Russia is allowed to reprocess spent uranium fuel assemblies used in the BN-600 and to reprocess 30 percent of those BN-800 fuel assemblies that contained plutonium other than disposition plutonium prior to irradiation. This is supposed to be for research purposes aiming at closing the nuclear fuel cycle.[8]

For plutonium disposition efforts, the BN-800 will be used in burn mode. But with different core configurations, it could be used as a breeder reactor, to produce more plutonium than it consumes. Calculating the quantities and specific isotopics of plutonium disposed and/or produced in this reactor will make it possible to clarify to what extent plutonium disposition in the BN-800 will help to irreversibly reduce plutonium stockpiles. Many results from calculating the BN-800 will be applicable for the BN-600 as well.

After a short description of the BN-800 construction history and current status, the following section summarizes information about the design and fuel composition as used for the neutronic model of the BN-800. The software "MCMATH," which is used for burnup calculations, is presented in the section "Calculation System," including the definition of breeding ratios used in the calculations.

The "Results" section addresses four issues, the change of the plutonium isotopic vector in the core for PMDA specified minimum burnup levels,[9] the plutonium production in the breeding blankets, the breeding ratio of the reactor, and finally possible plutonium throughput of excess weapon-grade plutonium in the BN-800 as well as the net plutonium reduction. In the conclusion, the article discusses these results in light of the plutonium disposition framework between the United States and Russia and final conclusions will be drawn regarding the plutonium production potential of the BN-800 beyond this agreement.

HISTORY OF THE BN-800

Efforts in Russia to establish a closed nuclear fuel cycle using sodium-cooled fast breeder reactors date back to the 1950s and 1960s culminating in the construction of the BN-600 at Beloyarsk Nuclear Power Plant, operated since 1980. Its successor, the BN-800 reactor, is based on a similar design, construction of which started in 1984 at Beloyarsk Nuclear Power Plant and at the South-Ural Nuclear Power Plant. However, after the Chernobyl accident in 1986, construction stalled due to lack of funding[10] and because fast breeder reactors were not economically competitive with Russia's light water and graphite moderated thermal reactors at the time.

In 1997 the construction license of the BN-800 was renewed. Within the "Program of Development of Nuclear Power in the Russian Federation for 2000–2005 Period and up to 2010" authorized by the Russian Government,[11] construction restarted in 2002 with several improvements compared to the 1980s design.[12]

In 2010 Russia's new federal program "Nuclear Power Technologies of a New Generation for Period of 2010–2015 and With Outlook to 2020" the BN-800 is considered as a first of a kind plant intended to be a key element in the strategy to develop and demonstrate a closed nuclear fuel cycle.[13] A 2007 article reported a total cost of 60 billion ruble, approximately $2.4 billion at the time.[14]

First criticality was achieved in June 2014.[15] The initial fuel loading mainly consists of uranium oxide fuel, only a quarter of the core is filled with MOX. The form of the MOX fuel is partly pellets and partly vibrocompacted, coming from different origins. In the future, most of the MOX fuel is planned to be produced at the Mining and Chemical Combine (MCC) Zheleznogorsk. It is expected that the reactor will switch to complete MOX cores in 2015 or 2016.[16]

Table 1: BN-800 general core geometry (International Atomic Energy Agency, "Fast Reactor Database 2006 Update," IAEA-TECDOC-1531, Vienna, Austria, 2007).

Parameter	Value
Number of fuel elements	211+156+198
Number of blanket elements	90
Number of control elements	30
Height of fissile column	880 mm
Height of lower axial blanket	350 mm
Lattice pitch	100 mm
Can thickness	2.75 mm

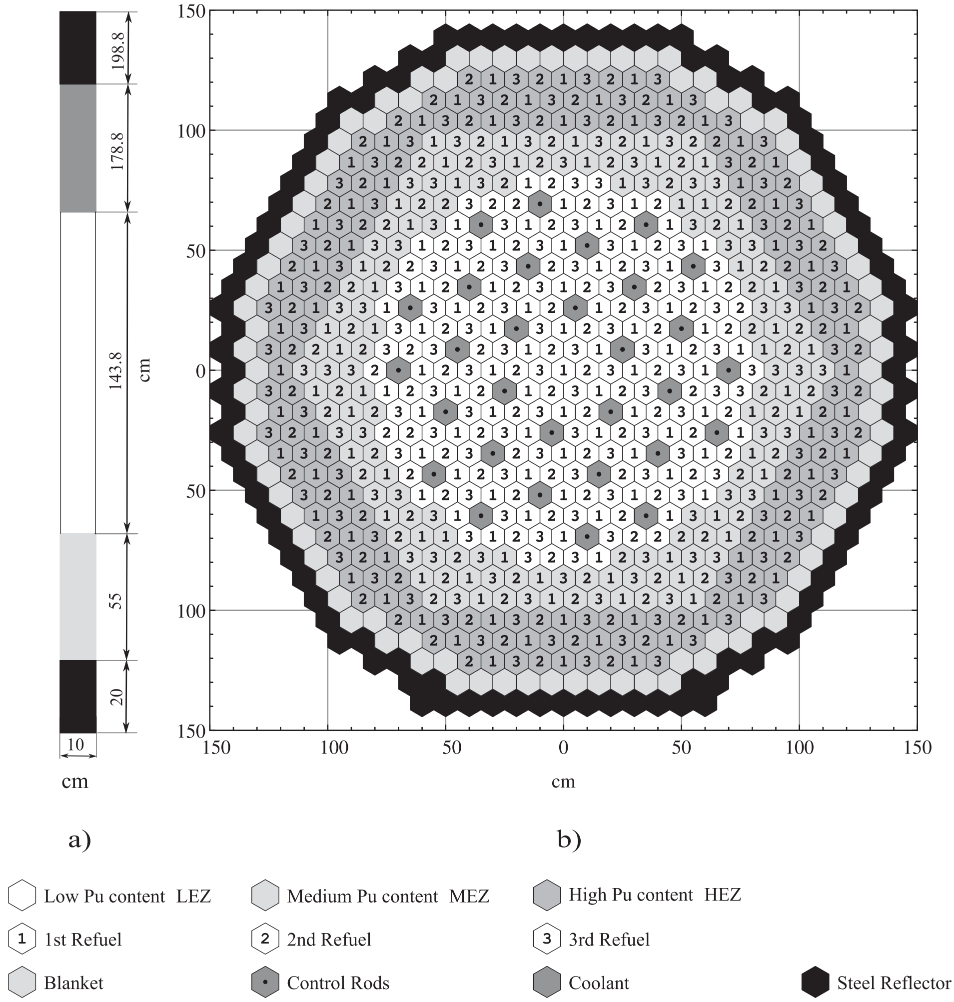

Figure 1: General core geometry layout structure. a) shows the vertical section of one fuel element and b) a horizontal cross section of the total core. There is no blanket placed above the active zone, only below. The numbers refer to the refueling of the elements in batches. One batch consists of all fuel elements replaced at the same time.

CORE CHARACTERISTICS

The BN-800 is a sodium-cooled fast breeder reactor. The geometric core model used in this article is mainly based on the core description in the Fast Reactor database of the International Atomic Energy Agency (IAEA).[17] The reactor has a gross electricity production of 864 MWe and a thermal power of 2100 MWt.[18] The core consists of 565 hexagonal fuel elements that are loaded with mixed oxide fuel, separated into three zones with different plutonium contents to achieve a more homogeneous flux distribution in the core. Recently, there have

Table 2: Geometry information for fuel and blanket elements in the core (International Atomic Energy Agency, "Fast Reactor Database 2006 Update," IAEA-TECDOC-1531, Vienna, Austria, 2007).

Element Design	Fuel	Blanket
Number of pins per element	127	37
Outer pin diameter	6.6 mm	14 mm
Cladding thickness	0.4 mm	0.4 mm

been discussions about whether to have only one or two zones,[19] but this has not been considered in the following model. Fuel element and core dimensions are listed in Table 1, a sketch of the core and an individual fuel element are shown in Figure 1.

There are 30 elements containing control and safety rods in the core. Radial breeding can take place by inserting 90 breeding blanket elements around the core. The design does not include an upper axial blanket, but does have a lower axial blanket.

Fuel element characteristics are listed in Table 2. For the depletion calculation, each fuel element is treated as a homogeneous material mixture calculated from the original geometry and materials.

The three zones with different plutonium contents can be seen in Figure 1b. Elements containing regulating or safety rods are both shown as control elements. For the calculations, it has been assumed that no control elements have been inserted in the core.[20]

The initial reactor design proposes reactor-grade plutonium as fuel. No isotopic vector is given in the IAEA database, hence a generic vector for spent light water reactor fuel with a burnup of about 30 megawatt days per kilogram heavy metal (MWd/kg HM)[21] has been assumed.[22] The isotopic vector is shown in Table 3. The table also shows a typical isotopic

Table 3: Isotope vector for weapon-grade and reactor-grade plutonium.

	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Reactor-grade plutonium	1.80	59.00	23.00	12.20	4.00
Weapon-grade plutonium	0.01	93.80	5.80	0.13	0.02

Note: Reactor-grade plutonium data as in NEA Nuclear Science Committee, Physics of Plutonium Recycling, Plutonium Recycling in Pressurized-water Reactors, a Report, Volume II (Paris, France: Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, 1995), weapon-grade plutonium data as in National Research Council Panel on Reactor-Related Options for the Disposition of Excess Weapons Plutonium, Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options (Washington, DC: The National Academies Press, 1995), http://www.nap.edu/openbook.php?record_id=4754.

Table 4: Materials and their densities as used in the core model.

	Material	Density (g/cm^3)
Fuel	MOX	8.60
Cladding and structure	ChS-68 steel	7.75
Blanket	Uranium dioxide	9.70
Coolant	Sodium	0.84

Note: The given density for the fuel is the "smeared density of fuel with fuel assumed to occupy whole space inside the cladding tube," similarly for the blanket, from International Atomic Energy Agency, *Fast Reactor Database 2006 Update*, IAEA-TECDOC-1531 (Vienna, Austria, 2007), 57, 59. A density for austenitic steel for an average cladding temperature has been assumed, see International Atomic Energy Agency, *Thermophysical Properties of Materials For Nuclear Engineering: A Tutorial and Collection of Data*, (Vienna, Austria, 2008). To calculate the Sodium density, an average coolant temperature of 450° *C* has been assumed. The density was calculated using an empirical formula (Jacques Rouault et al., "Sodium Fast Reactor Design: Fuels, Neutronics, Thermal-Hydraulics, Structural Mechanics and Safety," in Handbook of Nuclear Engineering, ed. D. G. Cacuci (New York: Springer, 2010), 2354).

vector for weapon-grade plutonium. It is assumed that Russian weapon-grade plutonium has a higher plutonium-239 content, but the exact initial plutonium composition that will be used to fuel the BN-800 is not published. Even if Russia would have stockpiles of plutonium with higher plutonium-239 fractions, the country would be allowed to blend this plutonium with other material according to the PMDA.

According to the IAEA Fast Reactor Database, the inner zone consists of 211 fuel elements with a plutonium content of 19.3 percent (low enrichment zone, LEZ).[23] It is surrounded by 156 fuel elements with 21.9 percent plutonium content (medium enrichment zone, MEZ) and another 198 elements with a content of 24.5 percent (high enrichment zone, HEZ).

To keep reactor characteristics similar to a reactor-grade model, in this article the plutonium content was reduced in a way that the average fission cross section of the new weapon-grade plutonium fuel is nearly equal to a reactor fueled with the generic reactor-grade plutonium fuel. An average content of weapon-grade plutonium of 20.2 percent has been calculated, giving values of 17.8 percent, 20.2 percent, and 22.7 percent for the different zones.[24]

The blanket element geometry described in Table 2 only applies to the radial blanket whereas for the axial blanket, the same geometry as the fuel elements is assumed. If the blankets are not used, they are replaced by sodium.[25] Cladding and reflector material is ChS-68 steel.[26] The materials are summarized and their densities given in Table 4. The temperature is set to 1200 K for the fuel elements and breeding elements and to 600 K for the rest of the core.

A reactor power of 2100 MWt and a cycle length of 420 full power days (FPD) for every fuel element has been modeled. Every 140 FPDs a third of the core is replaced with fresh fuel elements. Hence three different core batches were modeled. Figure 1 shows the different batches by assigning numbers 1, 2,

Table 5: Minimum burnup values as agreed on in the Plutonium Management and Disposition Agreement.

	HM atoms fissioned	
Unit	% HM	MWd/kg HM
Fuel Element, comissioning period	3.9	36.4
Fuel Element, main operation	4.5	42.1
Batch, comissioning period	5.0	46.7
Batch, main operation	6.0	56.1

and 3 according to the period after which every element is replaced by a fresh fuel element.

Axial blankets, if present, are replaced together with fuel elements. Radial blankets are assumed to have an irradiation time of 840 days.

Irradiation simulations begin with a full core of fresh fuel. More than three full reactor cycles (1400 days in total) were simulated to let the reactor reach an equilibrium operation mode. Results for fuel element depletion were taken from the period when all core areas had been refueled at least twice. If radial blankets were present, the first batch was irradiated only for 420 days. Results for blanket compositions were calculated starting at this time.

The average final burnup proposed in the literature is 66 MWd/kg HM. According to the PMDA, different minimal burnup values should be reached before withdrawal of elements from the core. During a two-to-three year commissioning period, lower values are allowed. During normal (main) operation, it is expected that higher burnup values can be achieved. The agreed values are shown in Table 5.

CALCULATION SYSTEM

Burnup Calculations: MCMATH

The burnup calculations for this article are done using MCMATH, which couples Mathematica with Monte Carlo N-Particle eXtended (MCNPX) Code.[27] MCMATH was developed since 1998 at the Technische Universität Darmstadt's IANUS group for depletion calculations related to light water reactors, fast reactors, and fusion reactors.[28] While several other depletion codes exist, the use of MCMATH has benefits regarding the specific task considered in this article[29] because not only averaged conversion ratios but also time dependent conversion ratios for specific materials or cells can be extracted from this data set.

Extensive validations of MCMATH have been carried out, using other computer codes with different methods and nuclear cross-section data. For thermal reactors, results were compared to a OECD/NEA benchmark.[30] It consisted of nine participating groups, among them the U.S. Oak Ridge National Laboratory and the French Commissariat à l'ènergie atomique. For the main plutonium isotopes, the results of these different systems and MCMATH generally showed differences of only 3–5 percent and comparison with other benchmarks showed similar results.[31]

MCMATH was also validated against different sodium-cooled fast reactor models.[32] Benchmark participants had to calculate different properties of these models, among them the change in isotopic composition, based on burnup calculations. Regarding absolute plutonium-239 contents and plutonium-239 fractions, MCMATH results for one model were always inside of a standard deviation of the mean of all benchmark participants, and for a second reactor model MCMATH matched the mean. The end-of-life content for all plutonium isotopes combined was close to the mean of results produced with other codes in the benchmark.

Conversion Ratio

An important quantity for the BN-800 plutonium disposition capabilities is its breeding ratio (or conversion ratio, CR). If CR > 1, the reactor is called a breeder, because it produces more fissile material than it consumes. The conversion ratio is also referred to as breeding ratio (BR), often both terms are used synonymously.

One definition for CR uses the ratio of masses of fissile materials in the reactor. The numerator is the net balance ($M_{t2}^{tot} - M_{t1}^{tot}$) plus the amount that has been destroyed $M_{destruction}^{tot}$ in the same period by the neutron-absorption processes fission, radiative capture and (n, xn) processes. The denominator is just the amount that has been destroyed.

$$\mathrm{CR} = \frac{M_{t2}^{tot} - M_{t1}^{tot} + M_{destruction}^{tot}}{M_{destruction}^{tot}} = \frac{M_{t2}^{tot} - M_{t1}^{tot}}{M_{destruction}^{tot}} + 1 \tag{1}$$

It is important to note that even if the conversion ratio can be calculated using masses, mass production rates of reactors and conversion ratios are different quantities.[33]

The quantity $M_{destruction}^{tot}$ of a reactor over burnup is difficult to derive. Instead of using mass ratios, a more general definition of conversion ratios can be given as a ratio of the average production and destruction rates of fissile isotopes:[34]

$$\mathrm{CR} = \frac{\overline{R_{\text{production}}}}{\overline{R_{\text{destruction}}}} \tag{2}$$

The results are equivalent to the first equation. Numerator or denominator of Equation (1) divided by the length of the period $(t_2 - t_1)$ are the respective average production or destruction rates. MCMATH gives time and space dependent rates, from which the average rates are derived as follows

$$\overline{R_{\text{production}}} = \frac{\int_{V_r} \int_{t_1}^{t_2} d\vec{r} dt R_{\text{production}}(\vec{r}, t)}{V_r(t_2 - t_1)} \tag{3}$$

Similarly for $\overline{R_{\text{destruction}}}$. For the time-and space-dependent destruction rate of fissile isotopes, MCMATH uses the following equation

$$\begin{aligned} R_{\text{destruction}}(\vec{r}, t) = & \sum_{i \in AFi} \left(\int_0^\infty dE(\sigma_f^i(\vec{r}, E, t) \right) \\ & + \sum_{i \in AFi} \left(\int_0^\infty dE \sigma_a^i(\vec{r}, E, t) \phi(\vec{r}, E, t) N^i(\vec{r}, t) \right) \\ & + \sum_{i \in DFi} \lambda^i N^i(\vec{r}, t) \end{aligned} \tag{4}$$

where AFi are the fissile nuclides that can be fissioned or undergo other neutron reactions (all fissile materials), DFi are the fissile nuclides that decay. For fissile material production the different possible ways of producing fissile isotopes have to be added.

In addition to the more general average conversion ratios, one can calculate time dependent conversion ratios, conversion ratios for specific isotopes, or specific reactor regions.

RESULTS

The following results are obtained from burnup calculations using MOX with weapon-grade plutonium as defined above in Table 3. Unless otherwise noted, results show data obtained for an equilibrium cycle, where the core contains one third of fresh fuel elements at the start of the cycle. Each fuel element is treated as a homogeneous material mixture calculated from the original geometry and materials.

Fuel Elements

Figure 2 shows the development of the plutonium-239 fraction in the simulated model. The solid line shows the fraction of plutonium-239 averaged over all three zones of one refueling batch. Starting with the initial weapon-grade plutonium composition, the plutonium-239 fraction drops to 84.6 percent after 420 full power days. Additional calculations show that breeding blankets

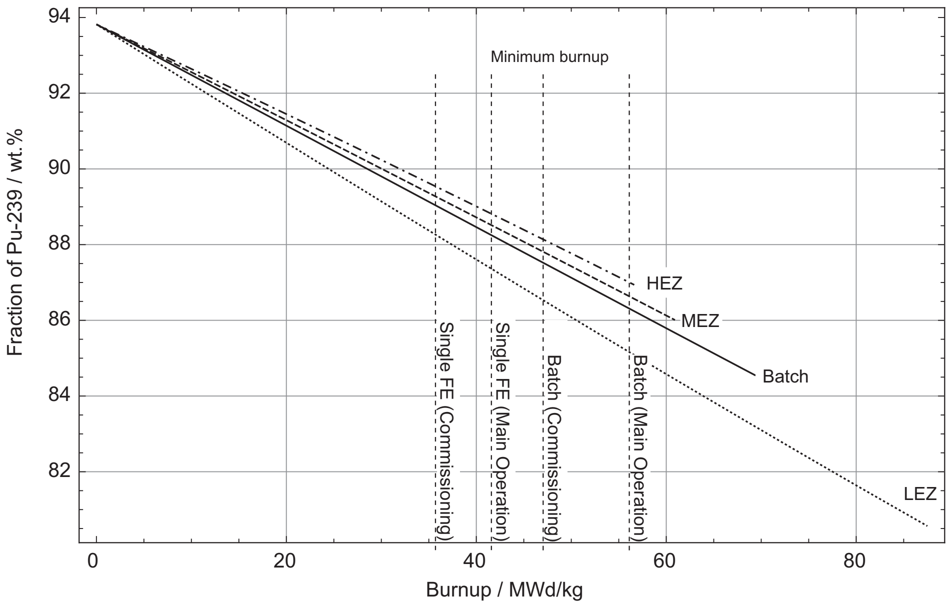

Figure 2: Plutonium-239 fraction in fuel over burnup. Averaged for one refueling batch (solid), and averaged for fuel elements from three zones with different plutonium content respectively, LEZ (17.8 percent plutonium in MOX, dotted line), MEZ (20.2 percent, - -) and HEZ (22.7 percent, -.-). Vertical lines for minimum batch average at x = 46.7 MWd/kg HM and x = 56.1 MWd/kg HM and for minimum fuel element average at x = 36.4 MWd/kg HM and x = 42.1 MWd/kg HM during commissioning and during main operation respectively.

have only a minor impact on the plutonium-239 fraction in core fuel elements. The fraction remains slightly higher (e.g., 86.6 wt% instead of 86.5 wt% at a burnup of 56.1 MWd/kg HM). During commissioning of the reactor, a minimum average burnup of 46.7 MWd/kg HM is required by the PMDA before discharging the batch. This corresponds to an average 87.6 wt% plutonium-239 (Table 6). For the main operation, the PMDA specifies a burnup level of 56.1 MWd/kg HM before discharge of a batch of disposition fuel elements resulting in a plutonium-239 fraction of 86.3 wt% according to our model.

Although the PMDA only specifies a minimum batch-average discharge burnup, single fuel elements are exposed to different flux levels and burnup conditions depending on their position in the reactor core. The elements in the zone with the lowest plutonium content (LEZ) reach very high burnup beyond 80 MWd/kg HM at end of life (EOL, 420 full power days). Accordingly LEZ has the lowest plutonium-239 fraction at EOL, but still above 80 percent which no longer meets the usual definition of weapon-grade material. However, the plutonium-240 fraction remains much lower than in spent fuel from light water reactors. Overall, the plutonium-239 fraction is still closer to typical weapon grade than reactor-grade plutonium compositions, typically 60 percent plutonium-239. Zones with high and medium plutonium content (HEZ

Table 6: Plutonium isotopic composition calculated for a batch of fuel elements and for the zone with highest initial plutonium content (HEZ) in the core periphery at the minimum burnup required by the PMDA and at end of life (EOL). The last column gives the total plutonium mass balance in percent.

Unit	Burnup MWd/kg HM	^{238}Pu wt%	^{239}Pu wt%	^{240}Pu wt%	^{241}Pu wt%	^{242}Pu wt%	240/239	Pu Bal. %
Batch (Commissioning)	46.7	0.04	87.6	11.5	0.63	0.05	0.13	−6.4
Batch (Main operation)	56.1	0.05	86.3	12.6	0.76	0.06	0.15	−7.5
Batch (EOL, 420 FPD)	69.4	0.06	84.6	14.2	0.96	0.08	0.17	−9.
HEZ (Commissioning)	36.4	0.03	89.5	9.8	0.44	0.04	0.11	−6.5
HEZ (Main operation)	42.1	0.03	88.8	10.5	0.5	0.04	0.12	−7.5
HEZ (EOL, 420 FPD)	56.6	0.04	87.	12.1	0.67	0.05	0.14	−9.8

and MEZ) have a burnup of only 56.6 and 60.9 MWd/kg HM resulting in comparably higher plutonium-239 fractions of 87 percent and 86 percent (Figure 2 and Table 6).

According to the PMDA agreement, fuel elements should not be removed before a burnup of 36.4 MWd/kg HM is reached during the commissioning stage or 42.1 MWd/kg HM during main operation. Comparing fuel elements from the fuel zones at these thresholds, fuel elements with the highest initial plutonium content (HEZ) have the highest plutonium-239 fraction as they are exposed to the lowest flux in the outer core regions, hence less plutonium is burned. Therefore upon discharge in HEZ the plutonium-239 fraction is still 89.5 wt% and 88.8 wt% respectively. MEZ fuel elements have a slightly lower plutonium-239 fraction and LEZ only 1–2 percent less. Comparing the batch average to the different zones it is clear that the main contribution to the isotopic shift results from the comparably high burnup of LEZ fuel elements in the core. The PMDA requirement of a fraction of plutonium-240 and plutonium-239 greater than 0.1 is met, independent of the original plutonium fraction. In the model, a discharged batch would have a 240 to 239 ratio of 0.17. According to a report by the U.S. Department of Energy, a chief engineer of the BN-800 has estimated the same ratio for discharged batches.[35]

Besides rendering the excess plutonium inaccessible and reducing the attractiveness of the isotopic composition, plutonium disposition in a reactor could also reduce the overall amount of plutonium. At the end of a reactor cycle, the elements in HEZ contain nearly 10 percent less plutonium compared to fresh fuel (last column of Table 6).

For an initial isotopic composition of plutonium containing more than 98 percent plutonium-239, simple estimates suggest that the curve for the plutonium-239 does not change its gradient. One can safely conclude therefore that a very good estimate of the plutonium-239 content can be derived by adding or removing simple offsets to the results presented in this section.

Breeding Blankets

The blanket elements in the radial blanket zone (see Figure 1) can be loaded into and removed from the reactor independent of the fuel reloading strategy in the reactor core during shutdown. The buildup of actinides and fission products in the blanket elements is analyzed over an irradiation period of a maximum of 840 full power days (Figure 3 and Table 7). Initially no plutonium exists in the blanket. After 204 days about 1 wt% of all heavy metal in the blanket is super grade weapon plutonium with an isotopic vector of 98.1 wt% plutonium-239. After 420 days, the typical EOL for core fuel elements, the plutonium content doubles. If left in the reactor for 840 days, it reaches nearly 4 wt% of all heavy metal. Even after such a long irradiation period the produced plutonium is 93.6 wt% plutonium-239.

Compared to the fuel elements in the core, the fraction of fission products in the breeding blanket elements remains much lower. After 840 FPD, only 1.1 wt% fission products are contained in the heavy metal (Figure 3). Fuel elements in the core contain 7 wt% fission products after discharge (420 FPD). The activity due to cesium-137 in the blanket after 840 FPD would be 1.26×10^{12} Bq/kg HM, compared to more than 8×10^{12} Bq/kg HM in spent

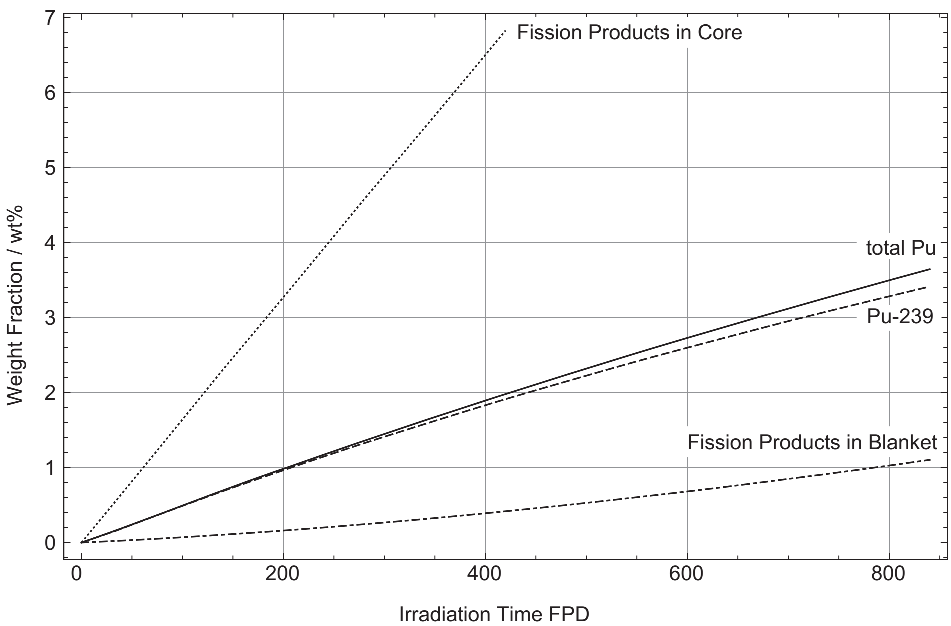

Figure 3: Plutonium and fission product content in the radial breeding blankets over time as fractions of the total heavy metal inventory. The solid and dashed line show the plutonium-239 and the total plutonium content respectively. The accumulation of fission products in the breeding blanket is given as well (-·-). For comparison the dotted line shows the fission product content in the fuel of the reactor core without blankets (··).

Table 7: Plutonium isotopic composition for the blankets. The last two columns give the fraction of plutonium and of fission products per ton heavy metal. The last row shows a mixture of core, axial blanket (after 420 days) and half of the radial blanket (after 820 days).

Unit	^{238}Pu wt%	^{239}Pu wt%	^{240}Pu wt%	^{241}Pu wt%	^{242}Pu wt%	Pu/HM wt%	FP/HM wt%
Radial blanket							
204 days	0.01	98.1	1.81	0.04	<0.01	1.00	0.16
420 days	0.02	96.5	3.36	0.12	<0.01	1.98	0.41
840 days	0.05	93.6	6.03	0.3	0.01	3.65	1.1
Axial blanket, 420 days							
separated	0.01	97.5	2.49	0.04	<0.01	1.57	0.23
Both blankets							
mixed with fuel	0.05	86.3	12.6	0.78	0.07	11.6	4.79

core fuel. The lower fission product fraction in the blanket elements results in a lower radiological barrier, and hence enables easier reprocessing of the breeding blankets.

The radial blanket zone of the BN-800 as proposed in the IAEA Fast Reactor database is relatively small (one row); other reactor designs have much larger breeding zones. After 840 days of irradiation, the 90 breeding elements combined hold a total of 240 kg plutonium, enough material for 30 nuclear warheads (assuming the IAEA significant quantity criterion of 8 kg of plutonium for a weapon).

The specifications of the BN-800 in the IAEA Fast Reactor database include an axial blanket below the active core, none above. To estimate plutonium production in the axial blanket the region below the active part of the fuel rods is filled with uranium. It is assumed that the axial blanket is integrated into the fuel elements and will be replaced whenever the related fuel rods are replaced, hence they are irradiated for 420 FPD. After irradiation the axial blanket would then contain on average 1.57 percent plutonium in heavy metal, and only 0.23 percent fission products (see Table 7). The isotopic vector of the plutonium is weapon-grade with 97.5 wt% plutonium-239 in the mixture.

The PMDA does not specify any minimum irradiation time for blankets. However if fuel elements would be withdrawn upon meeting their minimum burnup requirements but before the full irradiation time of 420 FPD (as allowed under the agreement), axial blankets would be withdrawn as well. In this case, they would contain less plutonium, but with a plutonium-239 fraction higher than 97.5 wt%.

Under the PMDA Russia is not allowed to reprocess radial blankets until the end of the agreement. Axial blankets are not explicitly mentioned in the agreement. However, during future discussions Russia could seek to mix the irradiated blankets with irradiated spent fuel before reprocessing. The last row of Table 7 shows the isotopic composition of such a mixture. The composition is calculated based on reactor core and axial blankets after an irradiation time of 420 FPD, mixed with half of the radial blanket irradiated for 840 FPD. A double irradiation time of the radial blanket has been assumed, hence every time one full reactor would be discharged only half of the blanket would be removed from the reactor. The result would be plutonium with 86.3 wt% plutonium-239 and 12.6 wt% plutonium-240, not weapons-grade any more. However, compared to reprocessed light water reactor plutonium it could still be considered an attractive weapon material. While the assumption on irradiation periods and discharge times are theoretical and could differ in reality, the data given in the table gives a good indication of possible plutonium fractions in case of core-blanket-mixing.

Breeding Ratio of the Reactor

The breeding ratio is calculated based on the ratio of production and destruction of four major fissile isotopes (plutonium-239, plutonium-241, uranium-235, uranium-233) according to Equation 4. Using the reactor model presented earlier with breeding blankets inserted into the periphery, the breeding ratio for several refueling cycles was calculated. In such a configuration the reactor will be a burner with a breeding ratio of only 0.81. Without blankets, the breeding ratio drops to 0.57. The time dependent breeding ratio varies around the average value as shown in Figure 4. At the beginning of life, the breeding ratio starts close to zero as only plutonium-240 can be turned into a fissile material immediately, while the production path via uranium-238 is limited by the required two subsequent decay processes with half-lifes in the order of days. Due to this, the production rate of plutonium-239, and subsequently the breeding ratio, increases quickly in the beginning. After every 140 days a third of the core will be replaced and a larger dip can be seen. The smaller irregularities are a result of the numerical method and the use of continuous functions to interpolate the change in material compositions during depletion calculation. The requirement of the PMDA to keep the breeding ratio below one would be met by reactor configurations with and without blankets.

The effect of different plutonium contents (plutonium fraction of 15 percent, 18 percent to 25 percent and 27 percent) in MOX fuel on the breeding ratio for a reactor model with blankets and a reactor model without blankets has been analyzed.[36] The results are summarized in Figure 5. As expected, the reactor with breeding elements has a higher breeding ratio. The breeding ratio increases with decreasing plutonium content for two reasons. Less plutonium in MOX results in a higher uranium-238 content, increasing the amount of fertile material in the reactor. With a lower plutonium content, less fissile material is in the core. To achieve a pre-defined constant thermal power output,

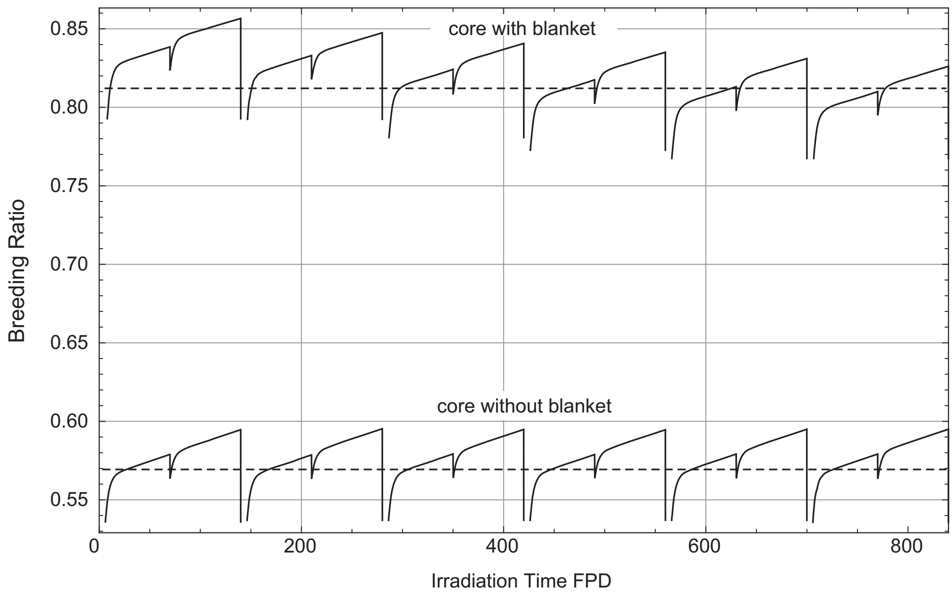

Figure 4: Average and time dependent conversion ratios for BN-800 with and without breeding blankets during equilibrium cycle. Two subsequent fuel element cycles are shown to account for a full blanket irradiation. Graphs are cut off below selected values to increase clarity.

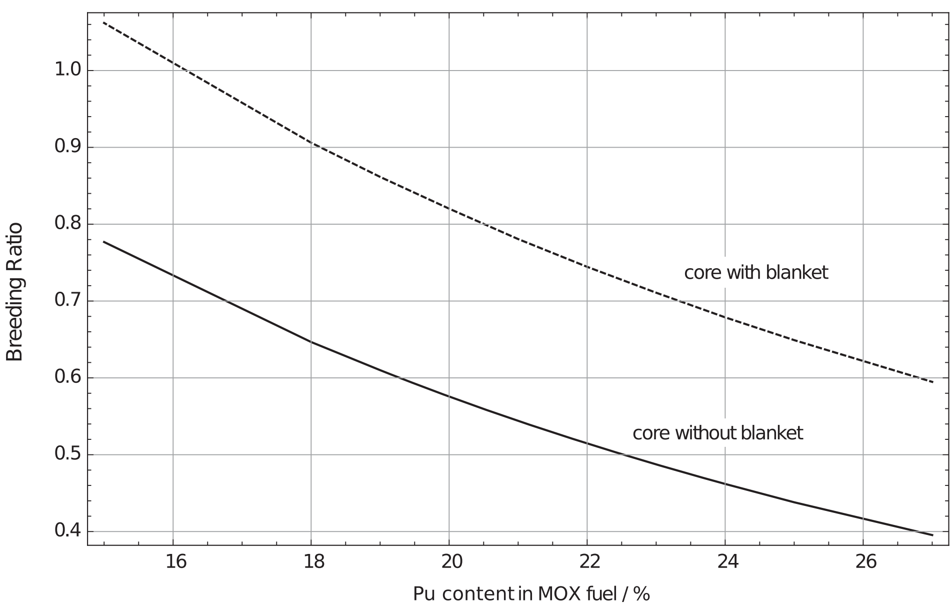

Figure 5: Conversion ratio over different plutonium fractions in the fresh fuel.

Table 8: Material throughput in the reactor for core and blanket per year. There is a small net production of plutonium in general, but considering only fissile plutonium isotopes (plutonium-239 and plutonium-241), there is a destruction of more than 100 kg per year. For the calculation, a capacity factor of 80 percent has been assumed.

Unit	Pu tot kg/a	Pu fiss kg/a	^{238}Pu kg/a	^{239}Pu kg/a	^{240}Pu kg/a	^{241}Pu kg/a	^{242}Pu kg/a
Start-up core	2,572	2,421	0.26	2,418	150	3.4	0.52
Reload	1,794	1,689	0.18	1,686	104	2.3	0.36
Discharge core	1,641	1,418	0.88	1,404	221	13.8	1.18
Core balance	−153	−271	0.70	−282	116	11.4	0.82
Discharge							
Radial blanket	84	78.4	0.04	78.1	5	0.25	< 0.01
Axial blanket	78	76.1	< 0.01	76.1	2	0.03	< 0.01
Annual total balance	9	−116	0.76	−128	124	11.7	0.83

a higher flux has to be achieved in the core. Thus between the 15 percent and 27 percent plutonium fraction, the flux in the reactor core varies by a factor of up to 1.4. Higher neutron flux together with the higher fraction of uranium-238 results in a higher production rate of plutonium-239. The destruction rate should not be affected by the higher fraction, hence the increase in breeding ratio with lower plutonium content.

The assumption of a plutonium fraction of 20.4 percent for the model results in excess reactivity and suggests that it is possible to reduce the overall plutonium fraction in the core. Such measures would increase the breeding ratio to over 0.9 (with breeding blankets). However higher breeding ratios are unlikely unless the reactor configuration would be changed. No geometry modifications of the BN-800 have been studied.

Annual Fuel Loading and Discharge

The PMDA requires Russia to process 1.3 MT of disposition plutonium per year (reduced from the earlier agreed 2 MT per year target). Using the results from the discussion above, it would in theory seem possible to use 1.79 MT of plutonium per year in the BN-800 alone, if it were only fueled with disposition plutonium (Table 8). On average 2.09 fuel batches are loaded into the core per year considering a cycle length of 420 FPD and a reactor load factor of 0.8.[37] Radial blanket elements are irradiated for 840 FPD, the annual production figures are about 35 percent of the total blanket inventory.

At start-up, the core, not yet in equilibrium state, contains 2.57 MT of plutonium. This is slightly less than specified in the IAEA Fast Reactor database, due to the higher plutonium-239 content in the weapon-grade plutonium.

While 1.79 MT of plutonium could be used as fuel every year, the spent fuel assemblies still contain 1.64 MT of plutonium when they are removed from the core. The axial and radial blankets would each account for a production of about 80 kg of plutonium per year. This results in a total annual net production of 9 kg of all plutonium isotopes. While the positive balance makes the reactor a net plutonium production reactor, the number is too small compared to uncertainties of depletion calculations and depends sensitively on reactor parameters. But clearly, using the BN-800 with a full set of blankets would at no time lead to a significant reduction of plutonium stockpiles. Having a positive plutonium balance and a breeding ratio below 1 is not a contradiction; as mentioned before, the breeding ratio only accounts for production of fissile isotopes. For the fissile plutonium isotopes there is a large reduction per year taking place, more than 100 kg of fissile isotopes get fissioned or converted to plutonium isotopes with even mass numbers.

CONCLUSION

Neutron transport and depletion calculations to assess the weapon plutonium disposition capabilities of the Russian BN-800 fast breeder reactor show that only very limited amounts (up to 10 percent) of the initial plutonium will be consumed in the core fuel elements during the irradiation cycle. Much of the plutonium consumed by fission events will be replaced by breeding reactions in-situ from the uranium in the MOX fuel elements.

The weapon-grade plutonium isotopic composition will be changed to non-weapon grade plutonium with a plutonium-240 to plutonium-239 ratio of more than 0.1 for all fuel elements and batches, if the minimum burnup requirements are met and assuming that the initial plutonium composition contains roughly 94 percent plutonium-239. Breeding blankets will produce significant amounts (approximately 162 kg per year) of super-grade weapon plutonium with concentrations of more than 2 wt% in the heavy metal after one typical core reload pattern of 420 full power days. Additionally, the radiation barrier from fission products produced in the blankets will be much lower than in the fuel. Even with breeding blankets, the reactor model shows a breeding ratio below 1. Calculations showed that several other reactor configurations (e.g., lower plutonium content in MOX) could be used while keeping the breeding ratio below the required level of 1. In the model, while the breeding ratio was only 0.81, the reactor produces a small net amount of plutonium due to the shift from fissile plutonium isotopes to isotopes with even atomic numbers.

The reactor, if operated with breeding blankets, will inevitably produce new weapon-grade plutonium contained in the irradiated blanket elements. Separation of blanket material is currently not planned. However, as reactors have several-decade-long lifetimes, and since the BN-800 is a key element in Russia's strategy to establish a closed nuclear fuel cycle, weapon grade plutonium reprocessing and handling might occur in the future raising questions about proliferation issues.

According to the model presented, the BN-800 has a total capacity to be loaded with 1.79 MT of plutonium in MOX fuel per year. This is significantly more than what is agreed upon in the PMDA (1.3 MT per year). Although Russia will use the reactor for its research program on a closed nuclear fuel cycle, some of this capacity could be used to increase the rate of plutonium disposition or even reduce plutonium stockpiles from other countries, given that the necessary MOX fuel fabrication capacities are installed.

For the purpose of disposing of stockpiles of weapon-grade plutonium with MOX fuel, irreversibility should be the main priority. This would imply not using blankets at all in the reactor to avoid the production of new weapon-grade plutonium, but using the reactor as a pure burner. It would still breed plutonium in the core, but this would remain in spent fuel. Further research should be carried out to assess the feasibility of running the Russian fast reactors without any breeding blankets. While not part of the current PMDA, other disposition options like immobilization could be technically better suited for irreversible reduction of stockpile weapon plutonium. Other reactor based options, like inert matrix fuels, could achieve much higher plutonium reductions, however these fuels are currently not actively being developed.

Quicker start of U.S. measures to dispose of plutonium might reduce Russian ambitions in plutonium breeding. However further delays might open up new rounds of negotiations, which might include discussions regarding possible permission to reprocess spent fuel. Finally, it should be mentioned that in addition to the disposition of military plutonium, more tasks await consideration regarding civilian stockpiles, for example in Japan and the United Kingdom. Findings in this article might be applied to these and other more general discussions of plutonium disposition, for example in fast reactors that have no blankets on design basis.

NOTES AND REFERENCES

1. Today global separated plutonium stockpiles total to about 500 MT, 230 MT of which is reserved for military purposes, see International Panel on Fissile Materials, “Global Fissile Material Report 2013,” Princeton, New Jersey, 2014.

2. Presidents of the United States and Russia, “Joint Statement on Principles for Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes,” September 2, 1998, https://www.fas.org/news/russia/1998/98090216_tpo.html.

3. Governments of the United States and Russia, “Plutonium Management and Disposition Agreement,” 2000, http://www.state.gov/documents/organization/18557.pdf. The United States declared a total 52.7 MT of plutonium, including 38.2 MT of weapon-grade plutonium, as excess to national security needs in 1995; (United States General Accounting Office, *Plutonium Needs, Costs, and Management Programs*, (Washington, DC: Department of Energy, 1997), 1. The latest Global Fissile Material Report, however,

lists 53.7 MT as excess military material, including material already disposed of; International Panel on Fissile Materials, "Fissile Material Report 2013," 18.

4. Governments of the United States and Russia "Protocol to the Plutonium Management and Disposisition Agreement," 2010, http://dtirp.dtra.mil/pdfs/pmda_protocol_text.pdf.

5. International Panel on Fissile Materials, "Global Fissile Material Report 2007," Princeton, New Jersey, 2007, 33; Elena Sokova, "Plutonium Disposition," NTI Analysis, 2010, http://www.nti.org/analysis/articles/plutonium-disposition-14/; Anatoli Diakov, "Disposition of Excess Russian Weapon HEU and Plutonium," UNIDIR Resources, United Nations Institute for Disarmament Research, 2012, http://www.unidir.org/files/publications/pdfs/disposition-of-excess-russian-weapon-heu-and-plutonium-387.pdf.

6. This issue has been described, for example, in a statement of the United States Department of State, "2000 Plutonium Management and Disposition Agreement—Fact Sheet," April 13, 2010, http://www.state.gov/r/pa/prs/ps/2010/04/140097.htm.

7. Governments of the United States and Russia, "Disposition Agreement," 2.

8. In the context of the treaty and its amendment, "weapon-grade plutonium" means plutonium with an isotopic ratio of plutonium-240 to plutonium-239 of no more than 0.10, Governments of the United States and Russia, "Disposition Agreement," 2.

9. Governments of the United States and Russia, "Protocol," 16.

10. Thomas B. Cochran et al., eds., *Fast Breeder Reactor Programs: History and Status* (Princeton: International Panel on Fissile Material, 2010), 65.

11. International Atomic Energy Agency, *Status of Fast Reactor Research and Technology Development*, IAEA-TECDOC-1691 (Vienna, Austria, 2012), 200.

12. International Atomic Energy Agency, *Fast Reactor Database 2006 Update*, IAEATECDOC-1531 (Vienna, Austria, 2007), 13.

13. International Atomic Energy Agency, *Fast Reactor Research*, 200.

14. NR2 New Russia LP News Agency, 2007, http://www.nr2.ru/economy/147920.html. An archived version of the website can be seen at https://web.archive.org/web/20131202235019/http://www.nr2.ru/economy/147920.html.

15. Nuclear.ru, "BN-800 will be brought to criticality today, Rosatom's executive," June 26, 2014, http://en.nuclear.ru/news/92486/.

16. International Panel on Fissile Materials, "BN-800 Fast Reactor to reach criticality in April 2014," 2013, http://fissilematerials.org/blog/2013/12/bn-800_fast_reactor_to_re.html.

17. International Atomic Energy Agency, *Fast Reactor Database*.

18. All data according to International Atomic Energy Agency, *Power Reactor Information System*, 2014, http://www.iaea.org/pris. A different gross electricity production of 870 MWe is mentioned in International Atomic Energy Agency, *Fast Reactor Database*, however only the thermal power level is important for depletion calculations.

19. e.g., Yu. S. Khomyakov et al., "*Core Design and Fuel Cycle of Advanced Fast Reactor with Sodium Coolant*," *Fast Reactors and Related Fuel Cycles Challenges and Opportunities* [FR09] (Vienna: International Atomic Energy Agency, 2012).

20. This is a reasonable assumption for depletion calculations. During calculations, total neutron flux levels were normalized according to the overall reactor power.

21. Megawatt days per kilogram heavy metal (MWd/kg HM) is the common unit to describe energy produced by a specific amount of reactor fuel.

22. During the design phase of the BN-800 this has been a typical burnup of light water reactors; today commercial reactors can reach higher burnup levels. The reactor-grade plutonium composition was taken from NEA Nuclear Science Committee, *Physics of Plutonium Recycling, Plutonium Recycling in Pressurized-water Reactors, a Report, volume II* (Paris, France: Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, 1995).

23. In IAEA-TECDOC-1531, the plutonium content is not given explicitly but rather an enrichment defined as the mass of fissile atoms divided by the mass of fissile and fertile isotopes. The published values of 19.5 percent, 22.1 percent, and 24.7 percent respectively include uranium-235 in the total fissile mass. Exact enrichment of uranium-235 in not given in the document, it has been assumed to be depleted uranium with an enrichment of approximately 0.3 percent uranium-235 to derive the plutonium content. This is consistent with the specified inventory of uranium-235 and uranium-238.

24. The adjustment regarding fission cross-sections will lead to different absorption cross-sections compared to reactor-grade plutonium. No detailed reactor control strategy has been considered in this article, which also would have to take into account the actual number of MOX and possibly HEU elements. The plutonium content might also be adjusted. However, results achieved with the mentioned levels of plutonium content can also give good indications for similar plutonium contents.

25. Replacing the blanket elements with reflector elements has only a small influence on reactivity and depletion of average fuel elements.

26. Different sources list different materials, ChS-68 is chosen as listed in International Atomic Energy Agency, "Structural Materials for Liquid Metal Cooled Fast Reactor Fuel Assemblies—Operational Behaviour," *IAEA Nuclear Energy Series*, NF-T-4.3 (2012): 13. The material composition was assumed according to Porollo et al., "Swelling and Microstructure of Austenitic Stainless Steel ChS-68 CW after high dose irradiation," *Journal of Nuclear Materials* 393 (2009): 61–66.

27. Mathematica has been used in version 8.0.1, MCNPX in version 2.7a; Denise B. Pelowitz, *MCNPX Users' Manual Version 2.7.0*, vol. LA-CP-11-00438 (Los Alamos National Laboratory, 2011). Neutron cross sections for MCNPX are used from the Joint Evaluated Fission and Fusion File of OECD/NEA in version 3.1.2. OECD/NEA, "JEFF 3.1.2—Neutron Data," Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, http://www.oecd-nea.org/dbforms/data/eva/evatapes/jeff_31/JEFF312/ and A. Santamarina et al., "The JEFF-3.1.1 Nuclear Data Library," Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, 2009.

28. Alexander Glaser, "Abbrandrechnungen für ein System zur Eliminierung vonWaffenplutonium" (Diploma thesis, Technische Universität Darmstadt, 1998); Christoph Pistner, "Entwicklung und Validierung eines Programmsystems für Zellabbrandrechnungen plutoniumhaltiger Brennstoffe" (Diploma thesis, Technische Universität Darmstadt, 1998); Christoph Pistner, "Neutronenphysikalische Untersuchungen zu uranfreien Brennstoffen"(PhD diss., Technische Universität Darmstadt, 2006); Moritz Kütt, "Proliferationsproblematik beim Umgang mit Plutoniumbrennstoffen: Abbrandrechnungen zur Rolle von 238Pu" (Bachelor Thesis, Technische Universität Darmstadt, 2007); Matthias Englert, "Neutronenphysikalische Simulationsrechnungen zur Proliferationsresistenz nuklearer Technologien" (PhD diss., Technische Universität Darmstadt, 2009); Moritz Kütt, "Neutronic Calculations: Proliferation risks of Fast Reactors" (Master thesis, Technische Universität Darmstadt, 2011).

29. Mathematica is used to control the overall iterative process. Burnup is divided into steps of specified time length. For each step an MCNPX input deck is created by Mathematica. MCNPX is used to calculate single group cross neutron sections (effective

cross-sections) for given material compositions in multiple burnup regions (cells). Mathematica reads the output files and uses the cross sections and nuclear decay properties to solve the burnup equations. New material compositions are calculated and MCNPX input decks for the next step are created.

30. OECD/NEA, *Burn-up Credit Criticality Benchmark. Phase IV-B: Results and Analysis of MOX Fuel Depletion Calculations* (Paris, France: Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, 2003).

31. Pistner, "Programmsystem für Zellabbrandrechnungen"; Pistner, "Untersuchungen zu uranfreien Brennstoffen."

32. NEA Nuclear Science Committee, *Physics of Plutonium Recycling, Fast Plutonium-Burner Reactors: Beginning, a Report*, *volume IV* (Paris, France: Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, 1995); NEA Nuclear Science Committee, *Physics of Plutonium Recycling, Plutonium Recycling in Fast Reactors, a Report, Volume V*, Physics of Plutonium Recycling (Paris, France: Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, 1995).

33. This can be illustrated by a simple example. Consider two reactors with conversion ratios of 1.1 and 1.2. Both operate for 100 days with a power of 10 MW, they produce a total energy of 1000 MWd. As a rough estimate, it is possible to assume that the fission of 1 g fissile material is necessary for the production of 1 MWd. When both start with an inventory of 100 kg, final inventories will be 100.1 kg and 100.2 kg respectively (destruction by absorption or decay are not taken into account).

34. Karl Wirtz, *Lectures on Fast Reactors* (Karlsruhe [Germany]: Kernforschungszentrum, 1978).

35. United States Department of Energy, "Report of the Plutonium DispositionWorking Group: Analysis of Surplus Weapon-Grade Plutonium Disposition Options," 2014, B-43.

36. With the very low and very high plutonium fraction, criticality of the reactor would probably not be sufficient or too high, respectively. Nevertheless calculations for conversion ratios were carried out to estimate the general tendency.

37. The load factor is an optimistic estimate. Axial blankets would be replaced with the same frequency as the fuel elements.