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Dose Rate Estimates from Irradiated Light-Water-Reactor Fuel Assemblies in Air

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Discussion

It is generally considered that irradiated spent fuel is so radioactive (self-protecting) that it can only be moved and processed with specialized equipment and facilities. However, a small, possibly subnational, group acting in secret with no concern for the environment (other than the reduction of signatures) and willing to incur substantial but not lethal radiation doses, could obtain plutonium by stealing and processing irradiated spent fuel that has cooled for several years.

In this paper, we estimate the dose rate at various distances and directions from typical pressurized-water reactor (PWR) and boiling-water reactor (BWR) spent-fuel assemblies as a function of cooling time. Our results show that the dose rate is reduced rapidly for the first ten years after exposure in the reactor, and that it is reduced by a factor of ~ 10 (from the one year dose rate) after 15 years. Even for fuel that has cooled for 15 years, a lethal dose (LD50)* of 450 rem would be received at 1 m from the center of the fuel assembly after several minutes. However, moving from 1 to 5 m reduces the dose rate by over a factor of 10, and moving from 1 to 10 m reduces the dose rate by about a factor of 50. The dose rates 1 m from the top or bottom of the assembly are considerably less (about 10 and 22%, respectively) than 1 m from the center of the assembly, which is the direction of the maximum dose rate.

A person could stand 5 m from the center of an assembly that had cooled for 15 years for over an hour without receiving a lethal dose. Standing at the end of the assembly would further reduce the dose rate, allowing for significantly longer handling times. Although we have not done a time and motion study for the removal and processing

of spent fuel, our results appear to indicate that there may be cause for concern.

Specifically, spent fuel in the former Soviet Union, where more than 12,500 fuel assemblies from RBMK reactors have been cooling for at least 15 years, could be of concern. These RBMK assemblies are stored at civilian reactor sites. They only contain about one-fourth and two-fifths, respectively, the amount of uranium that is contained in the PWR assemblies (110 kg/469 kg) and BWR assemblies (185 kg/469 kg) that were used for the estimates in this paper. This could result in a dose rate reduction to 25% of the rate from a PWR assembly at the same burnup and cooling times. However, four times as many assemblies would have to be handled to obtain a given amount of plutonium. The RBMK fuel has been limited to 20,000 MWd/MT, which is about two-thirds of the exposure used for the estimates in this study. This would further reduce the dose rate to roughly two-thirds for fuel that has been cooled for several years. With less uranium per assembly and the reduced burnup, the dose rate from a RBMK fuel assembly would be considerably less (perhaps as little as 16%) of that estimated in this report for a PWR assembly. RBMK assemblies are almost 24 ft long. However, they can be disassembled into two bundles, each about 12 ft long, to facilitate handling and storage.

It should be clear that the estimates arrived at in this report indicate that protecting and monitoring spent fuel, to prevent diversion, is necessary.

*The designation LD50 means that if each person in a population received the specified dose, 50% would be expected to die.

Results

Estimates of dose rates (rem/hr) from an irradiated PWR fuel assembly are presented in Table 1 and are plotted in Fig. 1. The fuel assembly modeled is a Westinghouse array of 15×15 zirconium-clad uranium-dioxide fuel rods. The fuel enrichment is 3.11 wt% ^{235}U in uranium. The fuel assembly is 3.66 m (12 ft) high and 0.211 m (8.30 in.) square. The dose points are 1, 5, and 10 m from the center of the fuel assembly in the perpendicular direction, which is the direction of maximum dose (reflection from the four walls has not been taken into account).

Dose rates from the ends of the fuel (Fig. 2) were also estimated for a 30,000-MWd/MT burn-up and a 10-yr cooling time. The dose point is 1 m from the end of the fuel's head (top) or foot (bottom) piece. The dose-rate estimates at the top of the fuel are 300 rem/hr, and 630 rem/hr at the bottom of the fuel. The metal end pieces

(mostly 304 stainless steel) attenuate photons that originate in the fuel, but also contribute photons because they contain cobalt (Co-60) that becomes activated.

Estimates of dose rates that occur for an irradiated BWR fuel bundle are presented in Table 2 and are plotted in Fig. 3. The fuel bundle chosen for these estimates is a General Electric 8×8 bundle with zirconium-clad uranium-dioxide fuel rods. The fuel enrichment is 2.22 wt% ^{235}U in uranium for the 20,000-MWd/MT fuel, and 3.11 wt% ^{235}U in uranium for the 30,000 MWd/MT fuel. The estimates are for a 3.81-m (150-in.) high fuel bundle that is 0.138 m (5.44 in.) square. The dose points are 1, 5, and 10 m from the center of the fuel assembly in the perpendicular direction, in the same manner as shown for a PWR assembly in Fig. 1.

Method

References 1 through 3, respectively, provided us with essential information on fuel-assembly properties, fuel-assembly irradiation data, and shielding-code information for making dose-rate estimates.

Fuel-assembly properties of the Westinghouse 15×15 assembly (Ref. 1) include:

- A fuel rod pitch of 0.014 m (0.56 in.).
- A fuel rod outside diameter of 0.011 m (0.42 in.).

- A fuel pellet outside diameter of 0.009 m (0.37 in.).
- An active fuel length of 3.65 m (144 in.).
- A fuel density of 95% of theoretical density (theoretical density is 10.96 g/cm^3 for UO_2). (On the basis of this information, a homogeneous fuel density of 3.24 g/cm^3 was calculated for use in the self-shielding calculations.)

Table 1. Estimates of dose rates (rem/hr) from an irradiated PWR fuel assembly at 1-, 5-, and 10-m perpendicular to the fuel assembly at the center.

Burnup (MWd/MT)	Cooling time after irradiation (yr)							
	1	5	10	15	20	30	40	50
<i>1 m from fuel edge</i>								
30,000	19815	5304	2861	2123	1756	1302	1006	788
35,000	23685	6561	3433	2501	2057	1517	1169	915
<i>5 m from fuel edge</i>								
30,000	1581	423	228	169	140	104	80	63
35,000	1890	524	274	200	164	121	93	73
<i>10 m from fuel edge</i>								
30,000	411	110	59	44	36	27	21	16
35,000	492	136	71	52	43	31	24	19

Figure 1. Dose rate from a PWR fuel assembly.

Figure 2. Dose rates estimated at 1 m from the fuel assembly's head and foot pieces.

- An envelope of 0.214 m (8.43 in.) square and 4.06 m (160 in.) long.
- A weight of up to 667.7 kg (1472 pounds).
- An enrichment range between 1.85 and 3.8% ^{235}U in uranium.
- An average burnup of 36,000 MWd/MT and a maximum burnup of 50,000 MWd/MT.
- A value of 0.469 metric-ton initial heavy metal (MTIHM).

The photon spectra used in these calculations were taken from Ref. 2, which is a data base for the irradiation of the fuel assembly for various burnups, fuel enrichments, and cooling times after irradiation. In our data base, radioactivity information is developed for both the active fuel region and the assembly end pieces. The information in our data base was generated from the output of a large number of ORIGEN2 runs performed by Oak Ridge National Laboratory for

the Office of Civilian Radioactive Waste Management.

The number of photons/second per ton of initial heavy metal as a function of energy for the 18 groups were input directly into the MicroShield code. MicroShield is a point kernel code that is described in Ref. 3. Taylor build-up factors for air were selected because they produced the highest dose rates. The other build-up factors in the code (Berger and Geometric Progression) produced a result within about 20% of the value in Table 1 for a 30,000-MWd/MT burnup and 10-year cooling time.

Issues involving dose rates from neutrons and neutron-induced gammas, effects of fuel pin self-shielding, and some experimental data for fuel-assembly dose rates are discussed in the following sections.

Table 2. Estimates of dose rates (rem/hr) from an irradiated BWR fuel assembly at 1-, 5-, and 10-m perpendicular to the fuel assembly at the center.

Burnup (MWd/MT)	Cooling time after irradiation (yr)							
	1	5	10	15	20	30	40	50
<i>1 m from fuel edge</i>								
20,000	7820	2001	1096	829	690	518	402	316
30,000	10460	3000	1636	1228	1022	768	596	467
<i>5 m from fuel edge</i>								
20,000	627	161	88	67	56	42	33	26
30,000	839	241	132	99	83	62	48	38
<i>10 m from fuel edge</i>								
20,000	164	42	23	17	15	11	8	7
30,000	218	63	34	26	21	16	13	10

Figure 3. Dose rate from a BWR fuel assembly.

Neutron Dose Rates

Dose rates from neutrons and neutron-induced gammas are not included in the estimates in Table 1 because these rates are small compared to the gamma dose for the burnups considered here. The data base in Ref. 2 gives the total photon flux as 6.873×10^{16} photons per second/MTIHM for a Westinghouse 15×15 fuel assembly burned to 30,000 MWd/MT and cooled for one year. The total neutron flux in Ref. 2 for the same conditions

is 2.5×10^8 neutrons per second/MTIHM. In Ref. 4, neutron and gamma-ray flux-to-dose-rate factors are given. Using the largest neutron conversion factor of 2.2×10^{-4} (rem/hr)/(n/cm²·s) and the smallest photon conversion factor of 2.5×10^{-7} (rem/hr)/(photons/cm²·s), we found that the photon dose rate was 3×10^5 higher than the neutron dose rate for this burnup.

Fuel Rod Self-Shielding

We investigated self-shielding of the fuel rods. Properties [including a fuel rod with an outside diameter of 0.011 m (0.42 in.) and

zirconium cladding, a fuel pellet with an outside diameter of 0.009 m (0.37 in.), an active fuel length of 3.65 m (144 in.), and a fuel-smear

density of 10.07 g/cm³ for UO₂] were taken from Ref. 1. The smear-density accounts for the fuel density being 95% of the theoretical density, which is 10.96 g/cm³, and for each fuel pellet stacked in the fuel rod having dished and chamfered ends. From this information, we prepared a model for a single fuel rod to use as input into MicroShield, which calculated the dose rate. The dose rate was calculated for the same PWR fuel irradiated to 30,000 MWd/MT and cooled for one year. The dose point was centered on the vertical fuel rod. The dose rates were 348 rem/hr, 23.6 rem/hr, and 6.08 rem/hr at 1-, 5-, and 10-m separations in the air between the dose point and the fuel rod edge.

The Westinghouse 15 × 15 fuel assembly has 204 fuel rods, 20 guide tubes for control rods, and an instrument guide tube in the center of the

assembly. Multiplying the single rod dose rates above by 204 gives dose rates of 71,000 rem/hr, 4810 rem/hr, and 1240 rem/hr, respectively, at 1-, 5-, and 10-m separations in the air between the dose point and the fuel rod edge. These values represent an upper bound for the dose rates with no self-shielding.

Comparison of the dose rate values in Table 1 for one year with the upper-limit dose-rate values above shows that the upper limit values are more than three times larger.

The homogenization of the fuel material over the entire volume of the assembly so that the UO₂ density is 3.2 g/cm³ allows MicroShield to calculate the attenuation of radiation from the fuel in the fuel assembly space. Values in Table 1 include a reasonable estimate of the fuel rod self-shielding for this calculation.

Spent-Fuel Dose-Rate Measurements

Reference 5 presents experimental measurements of dose rates from spent PWR and boiling-water reactor fuel assemblies when the assemblies are in water, in air, and inside a storage cask. (Some measurements for neutron doses outside a cask are also presented.) For conditions similar to those of this study, the experimental

dose rate data are comparable to the calculated results in Table 1.

Modeling of the examples shown in Ref. 5 using the techniques of this report was not attempted because the exact dimensions and conditions of the measurements were not given in this reference.

References

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