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ALARA STUDIES ON SPENT FUEL AND WASTE CASKS*

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ABSTRACT

In this report, some implications of applying the ALARA concept to cask designs for transporting spent fuel, high-level commercial and defense waste, and remote-handled transuranic waste are investigated. The XSDRNPM, one-dimensional radiation transport code, was used to obtain potential shield designs that would yield total dose rates at 1.8 m from the cask surface of 10, 5, and 2 mrem/h. Gamma shields of depleted uranium, lead, and steel were studied, the capacity of the casks was assumed to be 1, 4, or 7 elements or canisters, and the wastes were 1, 3, 5, and 10 yrs old. Depending on the dose rate, the cask empty weights and lifetime transportation costs were estimated.

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ALARA STUDIES ON SPENT FUEL AND WASTE CASKS

Introduction

A study has been completed at Sandia Laboratories in which the impact of applying the ALARA concept to the hardware used in transporting spent fuel and commercial and defense wastes was investigated. The ALARA concept pertains to the philosophy of limiting radiation exposure to "as low as is reasonably achievable." The manner in which this concept was applied in this study is an evaluation of the additional shielding necessary to decrease the acceptable dose rate of 10 mrem/h at 1.8 m (6 ft)[1] from the accessible surface of the transportation package to 5 or 2 mrem/h.

Spent Fuel and Waste Description

Commercial reactor spent fuel and the following three types of waste were considered: high-level commercial waste (HLCW), high-level defense waste (HLDW), and remote-handled transuranic waste (RH-TRU). In all cases, the SANDIA-ORIGEN code[2] was used to obtain the radiation source strengths and power-generation rates associated with the spent fuel and wastes.

Spent Fuel

The spent fuel considered was from pressurized water reactors (PWRs) and had experienced a typical irradiation sequence involving 5-yr residence in the reactor with three separate burn cycles, a capacity factor of 80%, and a total burnup of 15,000 MW days per assembly. The initial enrichment of the fuel was assumed to be 3.3% ^{235}U by weight. Table 1 lists the radiation and thermal characteristics of such fuel for 1, 3, 5, and 10 yr since discharge from the reactor.

High-Level Commercial Waste

HLCW results from the chemical processing of commercial reactor spent fuel. Three specific HLCW types are generally possible: present-generation (once through) HLCW, uranium-recycle HLCW, and uranium-plutonium HLCW:[3]

- Present-generation HLCW results by reprocessing enriched uranium fuel that has been used once in the reactor. The uranium and plutonium thus extracted are not used to make fresh commercial reactor-fuel rods.
- Uranium-recycle HLCW is obtained by reprocessing spent fuel that contains uranium previously extracted for recycling.
- Uranium-plutonium HLCW results from the chemical separation of spent fuel containing both recycled uranium and plutonium.

Each HLCW type has distinct radiation and thermal characteristics. Present generation and uranium recycle wastes are quite similar. Uranium-plutonium recycle waste is more radioactive than either present generation or uranium recycle waste.

The HLCW considered here is present-generation HLCW. This waste is assumed to contain 0.5% of the uranium and plutonium and 100% of the fission products and other transuranics originally in the unprocessed spent fuel. To obtain the waste considered, HLCW anticipated from reprocessing spent fuel from pressurized-water and boiling-water reactors was mixed in a ratio of 2:1 by volume respectively, representing the current proportions of commercial reactor types in this country. The resultant HLCW is assumed solidified in a borosilicate-glass matrix. In this matrix, the waste obtained by reprocessing 1 megagram (Mg) heavy metal equivalent of spent fuel is incorporated into 0.085 m^3 (3 ft^3) of glass. Steel cylinders that are 31 cm (12 in) in diameter and 3 m (10 ft) long are filled to 2.4 m (8 ft) with this glass product. The container with glass, weighs approximately 750 kg. Table 2 indicates the radiation source strengths and thermal characteristics of HLCW at 1, 3, 5, and 10 yr since discharge of the source spent fuel from the reactor.

High-Level Defense Waste

HLDW is a by-product of reprocessed spent fuel from military reactors supporting the nation's defense programs. Large quantities of this waste are in temporary storage at the Savannah River Plant near Aiken, SC; the Hanford Reservations near Richland, WA; and the Idaho National Engineering Laboratory (INEL) near Idaho Falls, ID. Present waste forms include salts, sludges, liquid, and calcine. In some instances the waste age is roughly 30 yr; such waste has correspondingly low radiation levels. In designing transportation hardware, however, radiation and thermal characteristics of HLDW to be generated in the future provide a more appropriate design basis since such waste will emit considerably more radiation and heat.

In this study the HLDW described in Reference 4 was considered. This waste, which will be generated at the Savannah River Plant, is the "hottest" defense waste expected in the future. Table 3 lists the radiation and thermal characteristics assumed for this waste for up to 10 yr of cooling. Like HLCW, HLDW may be vitrified and contained in steel canisters. For present purposes, the waste is assumed to be in canisters identical to the HLCW container previously described.

Remote-Handled Transuranic Waste

The last waste considered in this study is RH-TRU, which is difficult to characterize because of considerable disagreement as to what will constitute RH-TRU. It is generally agreed that RH-TRU includes any radioactive waste that has a surface dose rate greater than 200 mrem/h and does not fit into some other category of waste (such as HLDW). Though the amount of RH-TRU currently on hand is limited, considerable quantities will be generated as nuclear facilities are decommissioned for disposal in the future.

For the purposes of this study, the most current definition and physical description of this waste provided by the Waste Isolation Pilot Plant (WIPP)[5] was used. An RH-TRU container acceptable at the WIPP may be 61 cm (2 ft) in diameter, 4.6 m (15 ft) long, weigh 3200 kg (7000 lb), and have a maximum surface dose rate of 100 rem/h. The radiation and thermal characteristics of RH-TRU with such a dose rate are given in Table 4.

Table 5 summarizes the physical dimensions, assumed weights, and thermal outputs for variously aged wastes and spent fuel.

Calculations and Results

The feasibility of applying the ALARA concept in cask design was assessed by first obtaining shield designs that complied with the 10-mrem/h dose rate requirement and then by determining how much additional shielding was necessary to decrease this dose rate by 50% and 80%. This procedure was followed for wastes and spent fuel of 1, 3, 5, and 10-yr age and for casks with one, four, or seven element or canister capacities.

The cask shield designs considered were developed around a framework (Figure 1) with a 2.5-cm-thick steel inner wall, a gamma shield zone of variable thickness, a 5.0-cm-thick steel structural wall, and a neutron shield zone of variable thickness if such a shield was necessary. Table 6 gives the cavity diameters of the casks used for the spent fuel and for three types of waste and their capability to contain one, four, or seven fuel assemblies or waste canisters. The cavity diameters were obtained by requiring a 2.5-cm clearance between the cask sidewall and waste containers or fuel assemblies and between individual containers or assemblies. In each case an aluminum basket was used to support the contents inside the cavity. If the cask carried four canisters or assemblies a square arrangement of the payload was employed inside the basket. A central assembly or canister surrounded by six others was used for the seven-element casks.

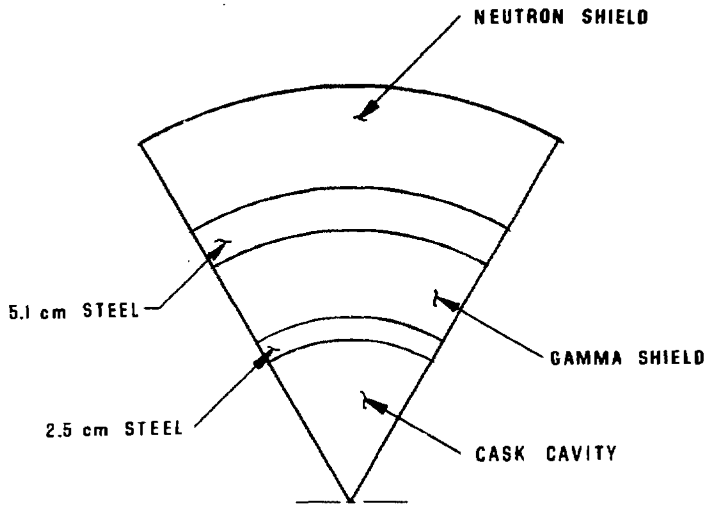

Figure 1. Computer Model of the Cask Framework

The gamma shield materials evaluated included steel, depleted uranium, and lead. Water was the only neutron shield investigated. Table 7 lists the densities and compositions assumed for each of these materials as well as those of other materials, including concrete, a potential matrix material for RH-TRU waste. This material was used in the shielding calculations involving RH-TRU because the radiation spectrum used in this case corresponded to RH-TRU in concrete. The other wastes and the spent fuel assemblies were modeled as radiation-emitting voids in the casks, thus yielding conservative results for shield thicknesses by neglecting self-shielding.

XSDRNPM, a one-dimensional radiation transport code[6], was used to estimate the thicknesses of the neutron and gamma shield materials necessary to obtain 10, 5, and 2 mrem/h at 1.8 m from the cask surface. In general, the primary gamma flux caused the greater fraction of the total dose rate at the 10 mrem/h level. The neutron and the secondary gamma contribution to the total dose rate was much more significant at lower dose rates, particularly at 2 mrem/h. In order to obtain some consistency in designs involving both neutron and gamma shield materials (designs for HLCW and spent fuel), the criteria given in Table 8 designating acceptable primary gamma and neutron-secondary gamma contributions to the total dose rate were adopted. In most instances, adherence to these criteria resulted in reasonably balanced shield designs.

Only one-dimensional, radiation transport calculations were performed. The results of such calculations were shown to be in excellent agreement with multidimensional and Monte Carlo approaches. Also, the simple cask models used in this study do not warrant a more detailed analysis. The calculations were performed using an 11-group, P1 primary gamma cross-section set and a coupled 19-neutron, 13-secondary gamma P1 cross-section set. The energy structure of these cross-section sets and the corresponding flux-to-dose-rate conversion factors used are described in Reference 3. The calculations were performed in cylindrical geometry using an S_6 quadrature.

The results are tabulated in Tables 9 to 20. Tables 9 to 11 pertain to possible spent-fuel cask shield designs using, respectively, depleted uranium, lead, and steel. The results are presented as pairs (00/00) representing, respectively, the thickness of the gamma shield material and of the neutron shield zone. Values are provided for spent-fuel elements 1, 3, 5, and 10 yr since discharge from the reactor and for casks having a capacity of one, four, and seven elements and which yield total dose rates at 1.8 m from the cask surface of 10, 5, and 2 mrem/h. Tables 12 to 14 give comparable results for HLCW; Tables 15 to 17 for HLDW; and Tables 18 to 20 for possible RH-TRU cask shield designs. Only the thickness of the required gamma shield is given in the last six tables; the neutron sources for HLDW and RH-TRU are of such magnitude as to provide little contribution to the total dose rate. No neutron shield is necessary beyond the shielding provided by the cask gamma shield for HLDW and RH-TRU.

Uncertainties in these results include such difficulties as dose conversion factors, multidimensional effects, code convergence criteria, radiation source definition, and material cross-sections. Uncertainties in cross-section values probably provide the greatest contribution to the current problem uncertainties. It is estimated that these results are accurate to within ±0.5 cm in the thickness of the gamma shield zones and a few cm for the water shield thickness.

Tables 21 through 24 provide estimates for the radii of spent-fuel and waste casks. These estimates are based on the shield thicknesses given in Tables 9 to 20. The estimates do not include the height of cooling fins that may be necessary in some designs such as the short, cooled spent-fuel and HLCW casks, but probably not in the HLDW and RH-TRU casks. Typical cooling fins might be 8 cm high, adding 16 cm to the overall diameter. The diameter is important because the transportation-imposed limitation is about 2.4 m (8 ft) as an upper bound on this dimension. Allowing for cooling fins, those radii that would be unacceptably large are circled in the tables; only a few spent fuel and HLCW cask designs are thus excluded.

Tables 25 to 28 show how the weight of the empty casks would increase if the dose rate requirement of 10 mrem/h at 1.8 m from the cask surface was to be reduced to 5 or 2 mrem/h by increasing the shield thickness (see Tables 9 to 20 for thicknesses). Such weight increases lead to higher cost for materials, construction, and transportation. Each table presents the increase required for a different waste. The data are entered in pairs (00/00) for each particular material constituting the gamma shield, indicating the percentage of weight increase for 5 and 2 mrem/h, respectively. In addition, the information is categorized by age of the waste and the capacity of the cask.

For spent fuel, regardless of age or gamma shield material, the weight increases approximately 8% for a 50% decrease in dose rate (5 mrem/h) and 20% for an 80% (2 mrem/h) decrease. For HLCW, the weight increase depends considerably on its age and on the gamma shield material, probably because this waste needs more neutron shielding then spent fuel and the gamma shield materials themselves vary widely in their capability to shield against neutrons. For instance, for a 50% decrease in dose rate, uranium requires 8% to 17% weight increase, lead requires 12% to 24%, and steel requires 8% to 10%. For an 80% decrease, the differences in increased weight are even more scattered: uranium - 20% to 39%; lead - 24% to 79%; and steel - 21% to 26%. The tables show similar differences for HLDW and RH-TRU.

Tables 29 to 32 contain estimates of the total weights, in Mg, of empty casks for the various types of waste. For each particular gamma shield material, the weights are presented in sets of three, each set representing the required weight for 10, 5, and 2 mrem/h shielding The information is further divided by the age of the waste and the capacity of the cask. The maximum weight of a loaded cask is probably limited by transportation and handling requirements to about 120 Mg. None of the casks described in this study would exceed this weight when loaded.

Estimates of the cask weight can be used to obtain estimates of the lifetime transportation costs of the casks. Based on information contained in Reference 7, the truck haulage fee for spent-fuel casks is approximately 4.4 cents/Mg-km and the rail haulage fee is about 9.3 cents/Mg-km (in 1978 dollars). For present purposes the same fees may be assumed for the transport of the other waste types. Assuming a roundtrip of 3200 km (2000 mi), a truck cask could complete about 40 and a rail cask about 15 roundtrips per year.

The cost estimates, obtained using these assumptions, are given in Tables 33 to 36. The costs are presented in sets of three (00/00/00) representing the lifetime transportation costs for casks with shield material required to limit dose rates to 10, 5, and 2 mrem/h, respectively. It was assumed that casks with a capacity of one fuel assembly or waste canister would go by truck and those with a greater capacity by rail. Depending on the age of the waste and the capacity of the cask, the heavier 2-mrem/h casks would cost about $1 000 000 more to operate than the corresponding 10-mrem/h casks. Casks using lead and steel for gamma shield materials would cost several hundred thousand dollars more to operate than those using uranium. Such transportation cost increases may not be appreciable over a 20-yr lifetime. The higher transportation costs for lead, and especially steel casks, over depleted uranium casks may also be more than offset by the anticipated savings in material and fabrication costs for the former casks.

Conclusion

Some of the cask shield dimensions determined as necessary to satisfy 10, 5, or 2 mrem/h dose rate conditions lead to unacceptably large diameter casks, but only for a few spent-fuel and HLCW cask designs. Applying the ALARA concept to cask design results in roughly a 10% increase in a spent-fuel or waste cask empty weight if the cask shield design is intended to allow a maximum dose rate of 5 mrem/h at 1.8 m from the cask surface rather than the current standard of 10 mrem/h. If the dose-rate goal is decreased further to 2 mrem/h, the corresponding empty cask weight penalty increases by another 10% or more. However, these higher cask weights result in only a few hundred thousand or a couple million dollars increase in the estimated cask lifetime transportation costs. Such additional costs for similar casks using different gamma shield materials may be offset by probable decreased costs in material and fabrication if common materials such as steel, cast iron, or lead are used in future casks in place of depleted uranium or other exotic materials.

Table 1

Spent-Fuel Radiation Characteristics Per Assembly

Mean Energy (MeV)	Gamma Spectrum (photons/s) 1-Yr Old	3-Yr Old	5-Yr Old	10-Yr Old
3.25	6.9 + 6	5.6 + 6	5.2 + 6	4.3 + 6
2.75	2.4 + 13	3.3 + 12	4.6 + 11	5.1 + 9
2.38	2.5 + 12	6.3 + 11	1.6 + 11	5.2 + 9
1.99	6.6 + 13	1.1 + 13	2.0 + 12	2.8 + 10
1.55	1.4 + 14	6.2 + 13	3.0 + 13	5.3 + 12
1.10	3.8 + 14	2.3 + 14	1.7 + 14	9.7 + 13
0.63	1.2 + 16	5.6 + 15	3.4 + 15	1.6 + 15
0.30	2.1 + 13	9.3 + 12	1.0 + 13	1.3 + 13
Total	1.3 + 16	5.9 + 15	3.6 + 15	1.8 + 15
Neutron Yield (n/s)	2.2 + 8	1.7 + 8	1.6 + 8	1.3 + 8
Total Decay Heat (Wth)	5000	1700	970	580

Table 2

High-Level Commercial Waste Radiation Characteristics Per Litre of Waste

Mean Energy (MeV)	Gamma Spectrum (photons/s) 1-Yr Old	3-Yr Old	5-Yr Old	10-Yr Old
3.25	1.6 + 5	1.3 + 5	1.2 + 5	1.0 + 5
2.75	5.4 + 11	7.4 + 10	1.0 + 10	1.2 + 8
2.38	5.7 + 10	1.4 + 10	3.6 + 9	1.2 + 8
1.99	1.4 + 12	2.5 + 11	4.4 + 10	6.1 + 8
1.55	3.3 + 12	1.4 + 12	6.8 + 11	1.2 + 11
1.10	8.8 + 12	5.5 + 12	4.0 + 12	2.3 + 12
0.63	2.8 + 14	1.3 + 14	9.1 + 13	3.9 + 13
0.30	3.6 + 11	5.2 + 10	2.9 + 10	9.3 + 9
Total	2.9 + 14	1.4 + 14	8.5 + 13	4.2 + 13
Neutron Yield (n/s)	5.1 + 6	4.0 + 6	3.7 + 6	3.1 + 6
Total Decay Heat (Wth)	110	37	20	12

Table 3

High-Level Defense Waste Radiation Characteristics
Per Litre of Waste

Mean Energy (MeV)	Gamma Spectrum (photons/s) 1-Yr Old	3-Yr Old	5-Yr Old	10-Yr Old
3.25	3.6 + 1	3.5 + 1	3.4 + 1	3.1 + 1
2.75	4.0 + 7	1.9 + 8	3.6 + 8	6.3 + 8
2.38	2.8 + 7	7.2 + 6	1.8 + 6	5.9 + 4
1.99	2.0 + 9	3.4 + 8	6.5 + 7	1.2 + 7
1.55	2.0 + 10	9.9 + 9	5.0 + 9	9.5 + 8
1.10	1.2 + 11	9.5 + 10	7.8 + 10	5.0 + 10
0.63	3.9 + 12	3.2 + 12	2.7 + 12	2.2 + 12
0.30	2.4 + 9	2.9 + 9	3.6 + 9	5.0 + 9
Total	4.1 + 12	3.3 + 12	2.8 + 12	2.2 + 12
Neutron Yield (n/s)	9.7 + 3	8.7 + 3	8.1 + 3	7.5 + 3
Total Decay Heat (Wth)	1.3	1.1	0.99	0.84

Table 4

RH-TRU Waste Radiation Characteristics Per Litre of Waste

Mean Energy (MeV)	Gamma Spectrum (photons/s) 1-Yr Old	3-Yr Old	5-Yr Old	10-Yr Old
3.25	4.3 - 1	4.3 - 1	4.3 + 1	4.3 + 1
2.75	1.8 + 5	4.5 + 4	1.2 + 4	3.7 + 2
2.38	1.1 + 6	2.7 + 5	6.9 + 4	2.2 + 3
1.99	1.4 + 6	3.6 + 5	9.2 + 4	3.0 + 3
1.55	4.5 + 6	1.1 + 6	2.9 + 5	9.3 + 3
1.10	1.4 + 10	1.1 + 10	8.5 + 9	4.8 + 9
0.63	3.2 + 9	2.6 + 9	2.3 + 9	2.0 + 9
0.30	2.8 + 7	3.0 + 7	3.2 + 7	3.6 + 7
Total	1.7 + 10	1.3 + 10	1.1 + 10	6.8 + 9
Neutron Yield (ns)	3.2 + 1	3.3 + 1	3.3 + 1	3.4 + 1
Total Decay Heat (Wth)	7.6-2	7.1-2	6.8-2	5.9-2

Table 5

Physical Parameters of Spent Fuel and Waste

Cask	Physical Dimensions	Weight (kg)	Power Generation Rate (Wth) 1-Yr Old	3-Yr Old	5-Yr Old	10-Yr Old
PWR Spent Fuel	21.7-cm dia 420-cm length	660	5000	1700	970	580
High-Level Commercial Waste Canister	30.5-cm dia 305-cm length	750	20000	6600	3600	2100
High-Level Defense Waste Canister	30.5-cm dia 305-cm length	750	230	200	180	150
Remotely Handled TRU Waste Container	61-cm dia 460-cm length	3200	100	95	90	80

Table 6

Cask Cavity Dimensions and Capacities

Cask	Cask Cavity Dia (cm)	Cask Capacity (Number of assemblies or canisters)
PWR Spent Fuel	39	1
	75	4
	94	7
High-Level Commercial Waste	39	1
	07	4
	107	7
High-Level Defense Waste	39	1
	87	4
	107	7
Remote Handled TRU Waste	66	1
	137	4
	193	7

Table 7

Material Specifications

Material	Density (g/cm^3)	Composition (atoms/barn-cm)	
Steel	7.9	C	0.00032
		Si	0.00169
		Cr	0.0174
		Mn	0.00173
		Fe	0.0579
		Ni	0.0081
Lead	11.4	Pb	0.0330
Depleted Uranium	19.0	U	0.0483
Concrete	2.3	H	0.0137
		C	0.00012
		O	0.0458
		Al	0.00175
		Si	0.0166
		Ca	0.00152
		Fe	0.00035
Aluminum	2.7	Al	0.0602
Air	0.0013	N	0.00004
		O	0.00001
Water	1.0	H	0.0669
		O	0.0334

Table 8

Acceptable Primary Gamma and Neutron-Secondary Gamma Dose Rate Contributions

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Primary Gamma (mrem/h)	Neutron-Secondary Gamma (mrem/h)
10	7.0 $\pm$2.0	3.0 $\mp$2.0
5	3.5 $\pm$1.0	1.5 $\mp$1.0
2	1.5 $\pm$0.5	0.5 $\mp$0.5

Table 9

Depleted Uranium Spent-Fuel Cask: Gamma and Neutron Shield Thicknesses

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Fuel Age (yr)	Number of Fuel Assemblies Per Cask (Thicknesses in cm)		
		1 (U/H_2O)	4 (U/H_2O)	7 (U/H_2O)
10	1	8.5/16.0	9.0/18.0	9.5/18.0
	3	7.0/15.0	7.5/16.0	8.0/16.0
	5	6.0/15.0	6.5/14.0	7.0/15.0
	10	5.0/13.0	5.0/17.0	5.5/16.0
5	1	9.0/21.0	10.0/18.0	10.5/18.0
	3	7.5/20.0	8.0/20.0	8.5/22.0
	5	6.5/18.0	7.0/18.0	7.5/19.0
	10	5.5/15.0	5.5/20.0	6.0/19.0
2	1	10.0/25.0	11.0/20.0	11.5/23.0
	3	8.5/20.0	9.0/23.0	9.5/27.0
	5	7.5/20.0	8.0/22.0	8.5/24.0
	10	6.0/20.0	6.5/20.0	6.5/26.0

Table 10

Lead Spent-Fuel Cask: Gamma and Neutron Shield Thicknesses

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Fuel Age (yr)	Number of Fuel Assemblies Per Cask (Thicknesses in cm)		
		1 Pb/cm H_2O)	4 (Pb/cm H_2O)	7 (Pb/cm H_2O)
10	1	15.5/18.0	16.5/20.0	17.5/20.0
	3	13.0/15.0	13.5/20.0	14.5/20.0
	5	11.0/25.0	12.0/16.0	12.5/19.0
	10	9.0/15.0	9.5/18.0	10.5/17.0
5	1	16.0/25.0	17.5/25.0	18.5/27.0
	3	13.5/22.0	15.0/20.0	15.5/25.0
	5	12.0/20.0	13.0/20.0	13.5/25.0
	10	10.0/17.0	11.0/18.0	11.5/21.0
2	1	18.0/26.0	19.5/32.0	20.5/38.0
	3	15.5/21.0	17.0/26.0	17.5/35.0
	5	13.5/21.0	14.5/26.0	15.0/35.0
	10	11.0/22.0	12.5/25.0	13.0/30.0

Table 11

Steel Spent-Fuel Cask: Gamma and Neutron Shield Thicknesses

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Fuel Age (yr)	Number of Fuel Assemblies Per Cask (Thicknesses in cm)		
		1 (steel/H_2O)	4 (steel/H_2O)	7 (steel/H_2O)
10	1	25.0/20.0	26.5/20.0	28.0/19.0
	3	21.0/21.0	22.5/19.0	24.0/17.0
	5	19.5/17.0	20.5/18.0	21.5/18.0
	10	17.5/16.0	18.0/19.0	19.0/19.0
5	1	27.5/18.0	28.5/21.0	30.0/21.0
	3	23.0/20.0	24.5/19.0	26.0/18.0
	5	21.5/16.0	22.5/17.0	23.5/18.0
	10	19.0/17.0	19.5/20.0	20.5/20.0
2	1	30.0/20.0	31.0/24.0	32.5/25.0
	3	25.5/20.0	27.0/21.0	28.5/21.0
	5	23.5/18.0	24.5/20.0	26.0/19.0
	10	21.0/18.0	21.5/22.0	22.5/23.0

Table 12

Depleted Uranium, High-Level Commercial Waste Cask: Gamma and Neutron Shield Thicknesses

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Waste Age (yr)	Number of Waste Canisters Per Cask (Thicknesses in cm)		
		1 (U/H_2O)	4 (U/H_2O)	7 (U/H_2O)
10	1	10.5/19.0	11.5/20.0	12.0/23.0
	3	9.0/17.0	10.0/18.0	10.5/21.0
	5	8.0/25.0	9.0/27.0	9.5/20.0
	10	6.0/19.0	7.0/19.0	7.5/22.0
5	1	11.5/19.0	13.5/20.0	14.0/24.0
	3	10.0/18.0	12.0/19.0	12.5/23.0
	5	9.0/16.0	10.0/21.0	10.5/26.0
	10	7.0/19.0	8.0/21.0	8.5/27.0
2	1	12.5/23.0	15.5/27.0	16.0/37.0
	3	11.0/21.0	14.0/25.0	14.5/35.0
	5	10.5/21.0	12.0/26.0	12.5/38.0
	10	8.0/23.0	10.0/23.0	10.5/37.0

Table 13

Lead High-Level Commercial Waste Cask:
Gamma and Neutron Shield Thicknesses

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Waste Age (yr)	Number of Waste Canisters Per Cask (Thicknesses in cm)		
		1 (Pb/H_2O)	4 (Pb/H_2O)	7 (Pb/H_2O)
10	1	19.0/23.0	20.0/34.0	22.0/39.0
	3	16.5/20.0	17.5/29.0	19.5/34.0
	5	14.5/19.0	16.0/26.0	18.0/32.0
	10	12.5/17.0	14.0/23.0	16.0/28.0
5	1	21.0/25.0	23.0/42.0	26.0/52.0
	3	18.0/24.0	20.0/38.0	23.0/47.0
	5	16.5/21.0	17.5/37.0	20.5/46.0
	10	14.5/18.0	16.0/32.0	19.0/42.0
2	1	23.0/32.0	30.0/56.0	30.0/74.0
	3	19.0/31.0	27.0/52.0	27.0/70.0
	5	17.5/29.0	25.0/50.0	25.0/69.0
	10	15.5/26.0	24.0/48.0	24.0/65.0

Table 14

Steel High-Level Commercial Waste Cask:
Gamma and Neutron Shield Thicknesses

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Waste Age (yr)	Number of Waste Canisters Per Cask (Thicknesses in cm)		
		1 ($steel/H_2O$)	4 ($steel/H_2O$)	7 ($steel/H_2O$)
10	1	29.0/30.0	30.5/32.0	32.0/33.0
	3	25.0/28.0	26.5/28.0	28.0/29.0
	5	23.0/25.0	24.5/25.0	25.5/27.0
	10	21.0/22.0	22.0/23.0	23.0/25.0
5	1	31.0/32.0	32.5/36.0	34.0/37.0
	3	27.0/28.0	28.5/33.0	30.0/33.0
	5	25.0/25.0	26.5/27.0	27.5/30.0
	10	23.0/21.0	24.0/24.0	25.0/28.0
2	1	33.0/39.0	35.5/40.0	37.0/44.0
	3	29.0/35.0	31.0/37.0	33.0/40.0
	5	27.0/30.0	29.0/32.0	30.5/38.0
	10	25.0/25.0	26.5/30.0	28.0/36.0

Table 15

Depleted Uranium High-Level Defense Waste Cask Shield Thicknesses

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Waste Age (yr)	Number of Waste Canisters Per Cask (Thicknesses in cm)		
		1	4	7
10	1	5.0	5.5	6.0
	3	4.5	5.0	5.5
	5	4.5	5.0	5.5
	10	4.0	4.5	5.0
5	1	6.0	6.5	7.0
	3	5.5	6.0	6.5
	5	5.0	5.5	6.0
	10	4.5	5.5	6.0
2	1	6.5	7.5	8.0
	3	6.0	7.0	7.5
	5	6.0	6.5	7.5
	10	5.5	6.5	7.0

Table 16

Lead High-Level Defense Waste Cask: Shield Thicknesses

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Waste Age (yr)	Number of Waste Canisters Per Cask (Thicknesses in cm)		
		1	4	7
10	1	9.5	10.5	11.5
	3	8.5	9.5	10.5
	5	8.5	9.0	10.0
	10	7.5	8.5	9.5
5	1	10.5	12.0	13.0
	3	10.0	11.0	12.0
	5	9.5	10.5	11.5
	10	8.5	10.0	11.0
2	1	12.5	14.0	16.0
	3	11.5	13.5	15.0
	5	11.0	12.5	14.5
	10	10.5	12.0	14.0

Table 17

Steel High-Level Defense Waste Cask:
Shield Thicknesses

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Waste Age (yr)	Number of Waste Canisters Per Cask (Thicknesses in cm)		
		1	4	7
10	1	18.5	19.5	20.5
	3	18.0	19.0	20.0
	5	17.5	18.5	19.5
	10	17.0	18.0	19.0
5	1	20.0	21.0	22.5
	3	19.5	20.5	21.5
	5	19.0	20.0	21.0
	10	18.5	19.5	20.5
2	1	22.0	23.5	25.0
	3	21.5	22.5	24.0
	5	21.0	22.0	2[illegible].5
	10	20.5	21.5	23.0

Table 18

Depleted Uranium RH-TRU Waste Cask:
Shield Thicknesses

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Waste Age (yr)	Number of Waste Canisters Per Cask (Thicknesses in cm)		
		1	4	7
10	1	3.0	3.0	3.0
	3	2.5	3.0	3.0
	5	2.5	3.0	3.0
	10	2.0	2.5	2.5
5	1	3.5	3.5	3.5
	3	3.0	3.5	3.5
	5	3.0	3.5	3.5
	10	2.5	3.0	3.0
2	1	4.0	4.5	4.5
	3	4.0	4.0	4.0
	5	3.5	4.0	4.0
	10	3.0	3.5	3.5

Table 19

Lead RH-TRU Waste Cask: Shield Thicknesses

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Waste Age (yr)	Number of Waste Canisters Per Cask (Thicknesses in cm)		
		1	4	7
10	1	5.5	6.0	6.0
	3	5.0	5.5	5.5
	5	4.5	5.5	5.5
	10	4.0	4.5	4.5
5	1	6.5	7.0	7.0
	3	6.0	6.5	6.5
	5	5.5	6.0	6.5
	10	5.0	5.5	5.5
2	1	7.5	8.0	8.0
	3	7.0	7.5	8.0
	5	7.0	7.5	7.5
	10	6.0	6.5	7.0

Table 20

Steel RH-TRU Waste Cask: Shield Thicknesses

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Waste Age (yr)	Number of Waste Canisters Per Cask (Thicknesses in cm)		
		1	4	7
10	1	10.0	11.0	11.5
	3	9.5	10.5	11.0
	5	9.0	10.0	10.0
	10	8.0	9.0	9.0
5	1	12.0	12.5	13.0
	3	11.0	12.0	12.5
	5	10.5	11.5	12.0
	10	9.5	10.5	10.5
2	1	14.0	15.0	15.0
	3	13.5	14.5	14.5
	5	13.0	13.5	14.0
	10	11.5	12.5	12.5

Table 21

Estimated Radii of Spent-Fuel Casks

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Fuel Age (yr)	Number of Fuel Assemblies per Cask (Radii in cm) 1			4			7		
		U	Pb	Steel	U	Pb	Steel	U	Pb	Steel
10	1	52	61	72	72	82	92	82	92	102
	3	49	55	69	69	79	87	79	89	96
	5	48	63	64	66	73	84	77	86	94
	10	45	51	61	67	73	82	76	82	93
5	1	57	68	73	73	88	95	83	100	106
	3	55	63	70	73	80	89	85	95	99
	5	52	59	65	70	78	85	81	93	96
	10	48	54	63	71	74	85	80	87	95
2	1	62	71	77	76	97	100	89	113	112
	3	56	64	73	77	88	93	91	107	104
	5	55	62	69	75	86	90	87	105	100
	10	53	60	66	72	83	89	87	98	100

Table 22

Estimated Radii of High-Level Commercial Waste Casks

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Waste Age (yr)	Number of Waste Assemblies per Cask (Radii in cm) 1			4			7		
		U	Pb	Steel	U	Pb	Steel	U	Pb	Steel
10	1	57	69	86	83	105	114	96	122	126
	3	53	64	80	79	98	106	93	115	118
	5	60	61	75	87	93	101	91	111	114
	10	52	57	70	77	88	96	91	105	109
5	1	56	73	90	85	116	120	99	139	132
	3	55	69	82	82	109	113	97	131	124
	5	52	65	77	82	105	105	98	128	119
	10	53	60	71	80	99	99	97	122	114
2	1	63	82	99	94	137	127	114	165	142
	3	59	77	91	90	130	119	111	158	134
	5	59	74	84	89	126	112	112	155	130
	10	58	69	77	84	123	108	109	150	125

Table 23

Estimated Radii of High-Level Defense Waste Casks

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Waste Age (yr)	Number of Waste Assemblies per Cask (Radii in cm) 1			4			7		
		U	Pb	Steel	U	Pb	Steel	U	Pb	Steel
10	1	32	37	46	57	62	71	67	73	82
	3	32	36	45	56	61	70	67	72	81
	5	32	36	45	56	60	70	67	71	81
	10	31	35	44	56	60	69	66	71	80
5	1	33	38	47	58	63	72	68	74	84
	3	33	37	47	57	62	72	68	73	83
	5	32	37	46	57	62	71	67	73	82
	10	32	36	46	57	61	71	67	72	82
2	1	34	40	49	59	65	75	69	77	86
	3	33	39	49	58	65	74	69	76	85
	5	33	38	48	58	64	73	69	76	85
	10	33	38	48	58	63	73	68	75	84

Table 24

Estimated Radii of Remotely Handled Transuranic Waste Casks

Nominal Dose Rate at 1.8 m From Cask Exterior (mrem/h)	Waste Age (yr)	Number of Waste Assemblies per Cask (Radii in cm) 1			4			7		
		U	Pb	Steel	U	Pb	Steel	U	Pb	Steel
10	1	44	46	51	79	82	87	107	110	116
	3	43	46	50	79	82	87	107	110	115
	5	43	45	50	79	82	86	107	110	114
	10	43	45	49	79	81	85	107	109	113
5	1	44	47	53	80	83	89	108	111	117
	3	44	47	52	80	83	88	108	111	117
	5	44	46	51	80	82	88	108	111	116
	10	43	46	50	79	82	87	107	110	115
2	1	45	48	55	81	84	91	109	112	119
	3	45	48	54	80	84	91	108	112	119
	5	44	48	54	80	84	90	108	112	118
	10	44	47	52	80	83	89	108	111	117

Table 25

Spent-Fuel Cask Estimated Percentage Increase in Empty Weight:
To Achieve 50% and 80% Reduction in 10 mrem/h Dose Rate at 1.8 m

Spent-Fuel	One-Assembly Capacity Cask			Four-Assembly Capacity Cask			Seven-Assembly Capacity Cask		
Age yr)	U*	Pb*	Steel*	U	Pb	Steel	U	Pb	Steel
1	9/22	8/22	9/22	9/19	8/24	8/19	8/19	9/26	8/19
3	10/21	9/22	8/20	8/20	9/25	8/20	9/21	9/27	8/20
5	9/23	12/25	9/21	8/22	9/24	8/19	8/22	10/27	8/19
10	9/21	10/24	9/20	9/21	11/28	8/18	8/20	10/27	7/18

*Gamma shield material

Table 26

High-Level Commercial Waste Cask: Estimated Percentage Increase in Empty
Weight to Achieve 50% and 80% Reduction in 10 mrem/h Dose Rate at 1.8 m

Waste Age	One-Canister Capacity Cask			Four-Canister Capacity Cask			Seven-Canister Capacity Cask		
(yr)	U	Pb	Steel	U	Pb	Steel	U	Pb	Steel
1	8/20	12/28	9/22	15/34	18/60	8/20	14/35	23/53	8/21
3	10/22	12/24	8/22	17/37	18/64	10/21	16/39	22/56	9/22
5	11/31	14/28	9/22	11/32	15/66	9/21	12/36	20/57	9/24
10	11/27	15/29	8/21 R	11/33	17/79	8/23	13/39	24/67	9/26

Table 27

High-Level Defense Waste Cask: Estimated Percentage Increase in Empty Weight to Achieve 50% and 80% Reduction in 10 mrem/h Dose Rate at 1.8 m

Waste Age	One-Canister Capacity Cask			Four-Canister Capacity Cask			Seven-Canister Capacity Cask		
(yr)	U	Pb	Steel	U	Pb	Steel	U	Pb	Steel
1	14/22	9/27	8/20	13/25	11/26	7/19	12/24	10/31	9/20
3	15/23	14/28	8/20	13/27	12/32	7/17	12/25	11/33	7/18
5	8/23	9/23	9/20	7/20	12/29	7/17	6/25	11/34	7/18
10	8/24	10/30	9/21	14/29	13/30	7/17	13/27	12/35	7/19

Table 28

Remotely Handled Waste Cask: Estimated Percentage Increase in Empty Weight to Achieve 50% and 80% Reduction in 10 mrem/h Dose Rate at 1.8 m

Waste Age	One-Canister Capacity Cask			Four-Canister Capacity Cask			Seven-Canister Capacity Cask		
(yr)	U	Pb	Steel	U	Pb	Steel	U	Pb	Steel
1	9/18	11/22	14/29	8/26	10/19	9/25	8/25	9/19	9/20
3	9/29	11/22	11/29	8/17	10/20	9/25	8/17	10/25	9/21
5	9/19	12/30	11/30	8/17	5/20	10/23	8/17	10/20	12/25
10	10/21	12/25	12/28	9/18	11/22	10/24	9/18	11/27	10/23

Table 29

Estimated Weights of Empty Spent-Fuel Casks

Fuel Assemblies per Cask	Fuel Age (yr)	Gamma Shield Material (Weights in Mg)* U	Pb	Steel
1	1	23/25/28	28/31/35	36/39/44
	3	20/22/24	24/25/29	31/33/37
	5	17/19/22	21/23/25	27/30/34
	10	15/16/18	17/19/22	25/27/30
4	1	40/44/47	47/51/58	56/61/67
	3	35/37/41	40/44/50	48/52/57
	5	31/34/37	35/39/44	45/47/53
	10	26/29/32	31/34/39	40/43/47
7	1	50/55/60	59/64/74	69/75/82
	3	44/47/53	50/55/64	59/64/71
	5	39/43/48	45/49/56	55/58/65
	10	34/36/41	39/43/49	49/53/58

*Weights in sets of three (00/00/00) representing 10, 5, and 2 mrem/h

Table 30

Estimated Weights of Empty High-Level Commercial Waste Casks

Waste Canisters per Cask	Waste Age (yr)	Gamma Shield Material (Weights in Mg) U	Pb	Steel
1	1	20/22/25	25/29/33	33/35/39
	3	17/19/22	22/25/27	27/30/34
	5	15/17/21	19/22/25	25/27/30
	10	14/15/17	16/19/22	22/25/27
4	1	40/45/54	48/57/77	55/59/65
	3	35/41/48	42/49/69	47/52/57
	5	33/36/43	38/44/64	43/46/52
	10	27/31/36	34/40/61	39/42/47
7	1	50/57/67	63/76/95	66/71/80
	3	45/52/62	55/67/86	57/63/70
	5	41/45/55	51/61/80	53/57/65
	10	35/39/48	45/56/76	47/52/60

Table 31

Estimated Weights of Empty High-Level Defense Waste Casks

Waste Canisters per Cask	Waste Age (yr)	Gamma Shield Material (Weights in Mg)		
		U	Pb	Steel
1	1	10/11/12	12/13/15	16/18/20
	3	9/10/11	11/12/14	16/17/19
	5	9/10/11	11/12/14	15/17/19
	10	8/9/10	10/11/13	15/16/18
4	1	20/23/25	24/26/30	30/33/36
	3	19/22/25	22/25/29	30/32/35
	5	19/20/23	21/24/27	29/31/34
	10	18/20/23	20/23/26	28/30/34
7	1	26/29/32	30/33/39	37/41/45
	3	25/27/31	28/31/37	36/39/43
	5	25/26/31	27/30/36	35/38/43
	10	23/26/29	26/29/35	35/37/42

Table 32

Estimated Weights of Empty Remotely Handled Transuranic Waste Casks

Waste Canisters per Cask	Waste Age (yr)	Gamma Shield Material (Weights in Mg)		
		U	Pu	Steel
1	1	16/17/19	17/19/22	21/25/27
	3	15/16/19	16/18/20	20/23/26
	5	15/16/17	15/17/20	20/22/25
	10	14/15/16	15/16/18	18/20/24
4	1	31/34/39	35/38/42	42/45/52
	3	31/34/36	34/36/40	40/45/51
	5	31/34/36	34/35/40	39/43/48
	10	29/31/34	30/34/36	36/40/45
7	1	44/47/55	48/53/57	58/64/70
	3	44/47/51	46/51/57	56/62/68
	5	44/47/51	46/51/55	54/60/66
	10	40/44/47	42/46/53	50/55/62

Table 33

Estimated Lifetime Transportation Costs of Spent-Fuel Casks

Fuel Assemblies per Cask	Fuel Age (yr)	Gamma Shield Material (Costs (in $ millions))*		
		U	Pb	Steel
1	1	2.6/2.8/3.2	3.2/3.5/4.0	4.1/4.4/5.0
	3	2.3/2.5/2.7	2.7/2.8/3.3	3.5/3.7/4.2
	5	1.9/2.2/2.5	2.4/2.6/2.8	3.1/3.4/3.8
	10	1.7/1.8/2.1	1.9/2.2/2.5	2.8/3.1/3.4
4	1	3.7/4.1/4.3	4.3/4.7/5.3	5.2/5.6/6.1
	3	3.3/3.4/3.8	3.7/4.1/4.6	4.4/4.6/5.2
	5	2.9/3.2/3.4	3.3/3.6/4.1	4.2/4.3/4.9
	10	2.5/2.7/3.0	2.9/3.2/3.6	3.7/4.0/4.3
7	1	4.7/5.2/5.6	5.5/6.0/6.9	6.4/7.0/7.6
	3	4.2/4.4/5.0	4.7/5.2/6.0	5.5/6.0/6.6
	5	3.7/4.1/4.5	4.3/4.6/5.2	5.2/5.4/6.1
	10	3.3/3.4/3.9	3.7/4.1/4.6	4.6/5.0/5.4

*In sets of 3 (00/00/00) representing costs for casks required for dose rates of 10, 5, and 2 mrem/h.

Table 34

Estimated Lifetime Transportation Costs of High-Level Commercial Waste Casks

Waste Canisters per Cask	Waste Age (yr)	Gamma Shield Material (Costs (in $ millions))		
		U	Pb	Steel
1	1	2.3/2.5/2.8	2.8/3.3/3.7	3.7/4.0/4.4
	3	1.9/2.2/2.5	2.5/2.8/3.1	3.1/3.4/3.9
	5	1.7/1.9/2.4	2.2/2.5/2.8	2.8/3.1/2.6
	10	1.6/1.7/1.9	1.8/2.2/2.5	2.5/2.8/3.1
4	1	3.7/4.2/5.0	4.5/5.3/7.1	5.1/5.4/6.0
	3	3.3/3.8/4.5	3.9/4.5/6.3	4.4/4.8/5.3
	5	3.1/3.4/4.0	3.6/4.1/5.9	4.0/4.3/4.8
	10	2.6/2.9/3.4	3.2/3.7/5.6	3.6/3.9/4.4
7	1	4.7/5.4/6.3	5.9/7.1/8.8	6.2/6.6/7.4
	3	4.3/4.9/5.8	5.2/6.3/8.0	5.4/5.9/6.5
	5	3.9/4.3/5.2	4.8/5.7/7.4	5.0/5.4/6.1
	10	3.4/3.7/4.6	4.3/5.3/7.1	4.5/4.9/5.6

Table 35

Estimated Lifetime Transportation Costs of High-Level Defense Waste Casks

Waste Canisters per Cask	Waste Age (yr)	Gamma Shield Material (Costs (in $ millions)) U	Pb	Steel
1	1	1.2/1.3/1.4	1.4/1.5/1.7	1.8/2.1/2.3
	3	1.1/1.2/1.3	1.3/1.4/1.6	1.8/1.9/2.2
	5	1.1/1.2/1.3	1.3/1.4/1.6	1.7/1.9/2.2
	10	0.9/1.1/1.2	1.2/1.3/1.5	1.7/1.8/2.1
4	1	1.9/2.2/2.4	2.3/2.5/2.8	2.8/3.1/3.4
	3	1.8/2.1/2.4	2.1/2.4/2.7	2.8/3.0/3.[illegible]
	5	1.3/1.9/2.2	2.0/2.3/2.6	2.7/2.9/3.2
	10	1.8/1.9/2.2	1.9/2.2/2.5	2.7/2.8/3.2
7	1	2.6/2.8/3.1	2.9/3.2/3.7	3.6/3.9/4.3
	3	2.5/2.7/3.0	2.8/3.0/3.6	3.5/3.7/4.1
	5	2.5/2.6/3.3	2.7/2.9/3.5	3.4/3.7/4.1
	10	2.3/2.6/2.8	2.6/2.8/3.4	3.4/3.6/4.0

Table 36

Estimated Lifetime Transportation Costs of Remotely Handled Transuranic Waste Casks

Waste Canisters per Cask	Waste Age (yr)	Gamma Shield Material (Costs (in $ millions)) U	Pb	Steel
1	1	2.0/2.1/2.3	2.1/2.3/2.6	2.5/3.0/3.2
	3	1.9/2.0/2.3	2.0/2.2/2.4	2.4/2.8/3.1
	5	1.9/2.0/2.1	1.9/2.1/2.4	2.4/2.6/3.0
	10	1.7/1.9/2.0	1.9/2.0/2.2	2.2/2.4/2.9
4	1	3.4/3.6/4.1	3.7/4.0/4.4	4.4/4.6/5.3
	3	3.4/3.6/3.8	3.6/3.8/4.2	4.2/4.6/5.2
	5	3.4/3.6/3.8	3.6/3.7/4.2	4.1/4.4/4.9
	10	3.2/3.4/3.6	3.3/3.6/3.8	3.8/4.2/4.6
7	1	5.0/5.2/6.0	5.3/5.8/6.1	6/2/6.8/7.3
	3	5.0/5.2/5.6	5.1/5.6/6.1	6.0/6.6/7.1
	5	5.0/5.2/5.6	5.1/5.6/6.0	5.9/6.4/6.9
	10	4.6/5.0/5.2	4.8/5.1/5.8	5.5/6.0/6.6

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