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CONCEPTUAL DESIGN OF LARGE SPENT FUEL SHIPPING CASKS FOR OLDER PWR FUEL*

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INTRODUCTION

Today, much of the spent fuel stored at various reactor sites is already 5-10 years old. Because less neutron and gamma shielding is required, shipping casks designed for such fuel could be expanded to carry significantly larger payloads than those currently in use, without adding appreciably to the overall weight. The purpose of this study was to identify realistic designs for large rail casks which have been optimized for the shipment of 2-, 3-, 5-, 7-, and 10-year-old PWR fuel assemblies.

To generate and evaluate the various designs, extensive use was made of the SCOPE program which was developed by Computer Sciences at Oak Ridge National Laboratory (ORNL) as an inexpensive scoping code for Shipping Cask Optimization and Parametric Evaluation (1,2). Using tabulated shielding thicknesses specified by the user, and a fixed set of optimal packing arrangements, the code will "design" a cask to carry a single fuel assembly, and then increment the number of assemblies until one of the design limits, such as the overall weight, is exceeded. For each design, the code will calculate the steady-state temperature distribution throughout the cask and perform a complete 1-D space/time transient thermal analysis following a postulated half-hour fire.

Using the SCOPE program, a wide range of conceptual designs were evaluated at minimal cost. About 100 cases of potential interest are presented below.

BASIC DESIGN PHILOSOPHY

The object of this study was to optimize a series of large rail casks designed to carry spent PWR fuel assemblies. Typically, such casks can be expected to weigh ∿91 tonnes, although there is some latitude in the maximum allowable weight. Lead (Pb), Iron (Fe), and depleted uranium metal (U) were considered as primary shielding materials. In each case, a borated-water neutron shield was also used, as shown in Fig. 1. Assuming that the total radiation dose rate 3.05 m from the cask centerline was not to exceed 10 mrem/hr, the relative amount of neutron and gamma shielding used in each case was optimized for the shipment of 2-, 3-, 5-, 7-, and 10-year-old PWR spent fuel.

The key physical features of those casks considered in this study are illustrated in Fig. 1. Depending on the amount of decay heat that must be dissipated, the cask may or may not have fins (casks with forced circulation cooling systems were not considered in this study). In each case, the cask has an inner shell, a gamma shield, an outer shell, a neutron shield, and an outside liner. The inner and outer shells and the outside liner were all assumed to be stainless-steel. The thicknesses of these components varied, however, depending on the type of cask (cf. Table 1). The length of the cavity inside the cask (435.9 cm) was chosen so as to accommodate a 4.2-m PWR fuel assembly while leaving an additional 15.9-cm space for an internal axial shock absorber.

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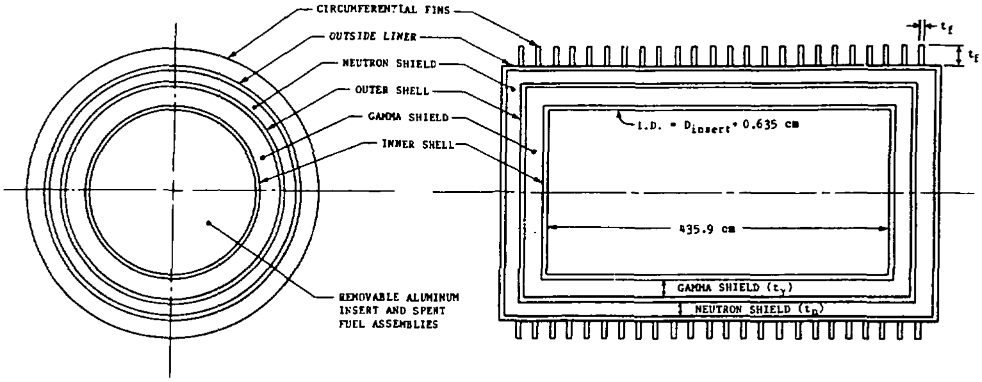

Note:

1) The removable aluminum insert containing the spent fuel is more fully illustrated in Fig. 2.
2) The thicknesses of the components were assumed to be the same in the axial and radial directions.
3) Actual dimensions of the various components depend on the type of cask, as noted in Table 1.
4) Sketch not drawn to scale; many casks had 45-50 fins; center-to-center spacing was 10 centimeters.
5) When calculating the net weight, the fins were assumed to extend outward from the outer shell.

Fig. 1. Overview of a typical spent fuel shipping cask with external cooling fins.

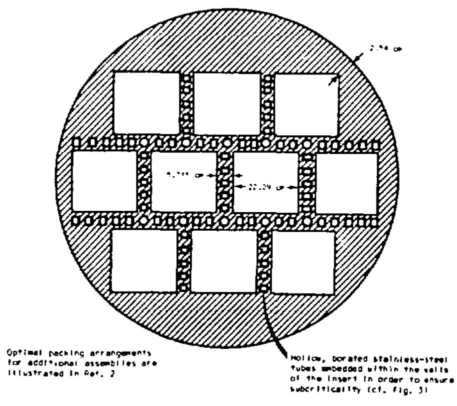

Fig. 2. Inherently subcritical, removable aluminum insert designed to hold 10 PWR fuel assemblies.

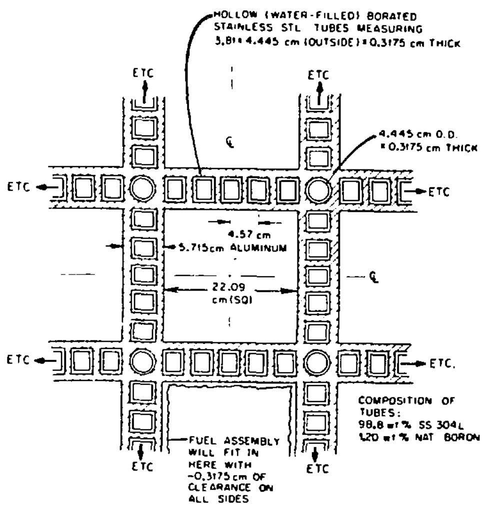

Fig. 3. Details regarding the use (and placement) of hollow, borated stainless-steel tubes within the wall-forming structure of the insert used to separate fuel assemblies and ensure subcriticality.

Inside the cask, the fuel assemblies are separated by means of an aluminum insert, as illustrated in Fig. 2. Each of the square holes shown in Fig. 2 measures 22.09 cm x 22.09 cm and can accommodate most typical PWR fuel assemblies with ~0.32-cm clearance on all four sides. Other insert configurations capable of holding additional fuel assemblies were also considered (cf. Appendix B of Ref. 2). Indeed, those illustrated in Ref. 2 were considered "optimal" insofar as they minimized the diameter of the circular cavity required to enclose any given number of square assemblies. Given the spatial configuration, the size of the square holes (22.09 cm x 22.09 cm), and the thickness of the compartment walls between the fuel assemblies (5.715 cm), the outside diameter of the insert and/or the inside diameter of the cask can be calculated.

In addition to physically separating the fuel assemblies, the insert must provide a low-resistance path by which the decay heat may be carried away from the innermost assemblies and, secondly, it must provide an inherently passive means of ensuring subcriticality under the most reactive conditions conceivable. These requirements are each discussed further in subsequent sections. To prevent possible leakage of radioactive contaminants in the event of an accident, it was assumed that the spent fuel would be shipped dry, with only air as the primary coolant.

SHIELDING

On a volumetric basis, the neutron shield in each case was assumed to consist of 28.5% water (1.0 g/cc), 66.0% ethylene glycol (1.11 g/cc; $HOCH_2CH_2OH$) and 5.5% potassium tetraborate (1.74 g/cc; $K_2B_4O_7 \cdot 8H_2O$) made with natural boron. By weight, this common mixture of water and antifreeze contains ~1% boron.

Considerable effort was spent in determining the relative amount of neutron and gamma shielding that should be used in each case so as to minimize the overall weight of the loaded cask (2). Given the age of the spent fuel and the type of cask (Pb, Fe, or U), the thickness of the gamma shield can be held constant while a zone-width search calculation is performed to determine the corresponding amount of neutron shielding that would yield a total dose rate of 10 mrem/hr at a point 3.05 m from the cask's centerline. This procedure was repeated many times for gamma shields of different thicknesses in order to identify the optimal n/γ split for each type of cask as a function of the spent fuel's decay time.

Once the optimal n/γ splits were established, extensive tables of neutron and gamma shielding requirements were compiled for each material as a function of the age of the fuel and the number of assemblies in the cask (2). Pertinent results are summarized in Table 1. Used in conjunction with the other structural components described in Table 1, these optimized shield dimensions will ensure a dose rate of 10 mrem/hr at a point 3.05 m from the centerline. As in the optimization study, these estimates are based on a series of one-dimensional S_8P_3 discrete ordinates calculations using the XSDRNPM code (3) and the DLC-23/CASK coupled cross-section library (4) having 22 neutron and 18 gamma groups.

HEAT TRANSFER

As noted previously, the SCOPE code will calculate the steady-state temperature distribution throughout the cask and perform a complete 1-D space/time transient thermal analysis following its exposure to a postulated half-hour fire as prescribed in 10CFR71, Appendix B (5). A summary description of the heat transfer analysis performed by the code is provided below. Additional details may be found in Refs. 1 and 2.

Steady-State Thermal Analysis

Knowing the decay heat load that must be dissipated to the environment, the temperature on the surface of the cask can be calculated in an iterative fashion using an expression of the form:

$$Q = A \left\{ \sigma\varepsilon \left(T_{surf}^4 - T_{amb}^4 \right) + C \left(T_{surf} - T_{amb} \right)^{4/3} \right\}$$

where σ is the Stefan-Boltzmann constant, ε is the surface emissivity of the cask, C is a semiempirical constant determined by McAdams (6), and A is the outside surface area (excluding the ends of the cask).* Note that the first term in this expression accounts for radiation heat transfer while the second term accounts for natural convection from a horizontal cylinder in air. Since existing regulations require that the cask be capable of sustained operation with an ambient temperature of 54°C (347°K), that value is used in the above equation as the code numerically iterates to determine T_{surf}. If the surface temperature is found to be less than 121°C, a finless cask design is assumed. In those cases where fins are required to reduce the outside surface temperature to 121°C, a separate numerical search is conducted to determine the particular fin dimensions which could satisfy this criteria while minimizing the overall weight of the loaded cask (2). In all the cases considered in this study, the circumferential fins shown in Fig. 1 were assumed to be stainless-steel and spaced on a 10-cm pitch.

The temperature distribution inside the cask itself may be calculated assuming simple heat conduction through the various components. The neutron shield, however, must be treated in a slightly different manner. Because the borated water is trapped inside a long horizontal cylindrical annulus, large kidney-shaped convective loops often develop and are responsible for transporting much of the decay heat in this region. Based on a number of experiments, Liu, Mueller, and Landis (7) have developed an expression for the effective thermal conductivity of the fluid (k_e) which depends on the inside and outside radius of the region, the average temperature of the fluid, the ΔT across the region, and the flow regime as characterized by the Grashof and Prandtl numbers. Knowing the decay heat load, the temperature drop across the neutron shield may be calculated in an iterative fashion using their expression for the effective thermal conductivity. (See Ref. 2 for additional details.)

Across the thin (0.32-cm) air gap between the cavity insert and the inner shell of the cask, radiation and conduction serve as the primary modes of heat transfer. Knowing the decay heat load and the temperature on the inside surface of the inner shell, the ΔT across this gap is then calculated in an iterative fashion.

In addition to physically separating the fuel assemblies, the use of an aluminum insert, as shown in Fig. 2, provides a low-resistance thermal conduction path by which the decay heat may be carried outward, away from the innermost assemblies. Instead of being surrounded by other hot fuel assemblies (all of which may be emitting substantial amounts of decay heat), the innermost assemblies are, in fact, surrounded by a relatively cool aluminum surface. The SCOPE code solves the 2-D heat conduction problem throughout the entire insert to determine the heat flow through each section of the honeycombed structure and the temperature at corresponding nodes.

The last parameter of interest is the surface temperature of the hottest fuel pin in the innermost fuel assembly. Knowing the temperature of the surrounding insert and the amount of decay heat emanating from the particular assembly, we can calculate this temperature in an iterative fashion using the Wooten-Epstein equation (8). This semi-theoretical, semiempirical equation accounts for both radiation and convection from a single fuel assembly in a horizontal enclosure.

Accident/Post-Accident Transient Thermal Analysis

To determine the transient thermal effects of the hypothetical half-hour fire defined in 10CFR71, the SCOPE code solves the actual time-dependent, finite-differenced, one-dimensional heat transfer equations for the entire cask. (To account for the relatively large heat capacity of the aluminum insert without adding undue complexity to the problem, the insert has been modeled as a solid annular region just inside the inner shell. It should also be noted that the small gap between the inner shell and the insert has been maintained, as has the overall cross-sectional area of the insert.) At each time step, the resulting spatial equations are solved using matrix factorization. The steady-state temperature distribution used as the initial condition at the start of the transient assumes that the neutron shield has long-since been rendered void as a result

*In this scoping design study, it was assumed that the cask would normally be sheltered from the direct rays of the sun by means of an opaque covering over a large, light-weight frame structure surrounding the entire cask. Notes regarding the effect of direct solar heating under steady-state, accident, and post-accident conditions may be found in Ref. 2.

of the 9-m drop test.* The postulated fire, having a flame temperature of 802°C, is then assumed to last for 30 minutes. Because the thermal transient peaks in some components long after the external fire has been extinguished, this analysis follows the transient for 12 full hours. Numerical results for the transient thermal analysis package used in the SCOPE code have been benchmarked against HEATING-5 results (2,9) with good agreement. Using a similar 1-D model, the two sets of results were generally within ±1°C at all spatial points during the entire transient. To conservatively estimate the maximum temperature at points inside the cask cavity (i.e., in the insert and the fuel), the maximum temperature rise in the insert, as given by the simplified 1-D model, is added to the maximum steady-state value given by the detailed 2-D analysis. Likewise, the maximum fuel pin clad temperature is also recalculated at this elevated temperature.

CRITICALITY

Most spent fuel shipping casks are loaded under water. Inadvertent loading of the cask with fresh fuel (or fuel with very little accumulated burnup) is then typically taken as the most reactive condition considered in the licensing application. Should casks be designed to carry large numbers of fuel assemblies, as might be the case for long-cooled spent fuel, the problem of ensuring subcriticality becomes more difficult. The approach used here (2,10) relies on the use and placement of hollow, borated stainless-steel tubes within the walls of the aluminum insert between the fuel assemblies, as shown in Fig. 3. Given an infinite array of infinitely long PWR fuel assemblies @ 3.4 wt % ^{235}U, this flooded configuration was found to be safely subcritical with $k_{eff} = 0.916 \pm 0.003$. Even at 3.9 wt % ^{235}U, this configuration was safely subcritical with $k_{eff} = 0.941 \pm 0.003$. These criticality calculations were performed using the KENO-IV Monte Carlo code (11) as implemented in the CSAS2 analytic sequence of the SCALE system for Standardized Computer Analyses for Licensing Evaluation (12). In each case, the SCALE 27-group ENDF-IV cross-section library was used, with the homogenized cell-averaged cross-section data being weighted as noted in Ref. 12. Use of this inherently subcritical insert design in all of the casks studied, preempted the need for a separate analysis of each cask, and lent an important degree of credibility to the designs that finally evolved.

RESULTS AND CONCLUSIONS

The purpose of this study was to develop new conceptual designs for lead, iron, and uranium-shielded spent fuel casks which have been optimized for the shipment of 2-, 3-, 5-, 7-, or 10-year-old PWR spent fuel assemblies. Using the SCOPE program in conjunction with the optimized shielding data described above, a wide range of conceptual cask designs were evaluated at minimal cost. SCOPE output for those cases of potential interest is presented in Table 1. Each line of output gives the age of the spent fuel (in years); the number of assemblies in the cask; the materials used for the insert, gamma shield, and neutron shield; the thickness of the gamma shield and the neutron shield; the overall weight of the loaded cask; and some characteristic dimensions [including the inside diameter of the cask, the outside diameter of the cask (including fins, if required), the overall exterior length of the cask, and the length and thickness of the fins (if required)]. It also gives the steady-state temperature on the outside surface of the cask, on the innermost surface of the gamma shield, at the hottest point inside the insert, and on the surface of the hottest fuel pin. Finally, it presents the maximum transient temperature calculated in the gamma shield, in the insert, and on the surface of the hottest fuel pin during or after the postulated 30-minute fire.

Since many design limits are not absolutely rigid, this rather extensive table shows a number of cases on either side of the nominal 91-tonne (200,000 lbm) weight limit. The utility of this "extra" information becomes apparent when one notes that the inside diameter of a cask (and hence its overall weight) is a nonuniform function of the number of assemblies in the cask. Thus, for example, while there may be very little difference in the overall weight of the casks designed to carry 16, 17, or 18 assemblies, one

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*This scenario differs from that in most Safety Analysis Reports for Packages (SARP's) in that they assume the temperature distribution throughout the cask at the start of the hypothetical fire to be the same as the steady-state distribution under normal operating conditions. The SCOPE code is capable of analyzing thermal transients on either basis.

Table 1
SCOPE Results for a Number of Cases of Potential Interest

FUEL AGE	NO. ASSY	MATERIALS: INSRT	MATERIALS: GAM. SHLD	MATERIALS: NEUT SHLD	THICKNESS IN CENTM.: GAM. SHLD	THICKNESS IN CENTM.: NEUT SHLD	CASK WEIGHT: TONNES	KEY DIMENSIONS IN CENTIMETERS: ID	OD	LENGTH	FIN HT.	FIN THK.	STEADY STATE TEMPERATURES IN DEG.C: FUEL PIN	INSRT MATL	GAMMA SHLD	CASK SURF	MAX FIRE-TEST TEMPERATURES IN DEG.C: FUEL PIN	INSRT MATL	GAMMA SHLD
10.0	15	AL	PB	H2O	9.75	10.24	77.70	141.7	203.2	497.3	0.0	0.0	177	132	86	82	249	206	199
10.0	16	AL	PB	H2O	9.80	10.24	88.50*	157.2	218.9	497.6	0.0	0.0	181	135	86	82	248	205	198
10.0	18	AL	PB	H2O	9.91	10.21	89.18*	157.2	219.2	497.6	0.0	0.0	187	142	89	84	259	217	205
10.0	19	AL	PB	H2O	9.96	10.31	92.99*	162.1	224.3	498.1	0.0	0.0	188	143	90	86	261	218	207
10.0	21	AL	PB	H2O	10.08	10.49	93.85*	162.1	224.8	498.6	0.0	0.0	194	149	93	88	271	229	213
10.0	22	AL	PB	H2O	10.11	10.54	99.20*	169.2	232.2	498.9	0.0	0.0	196	152	93	88	271	229	213
10.0	13	AL	FE	H2O	23.19	9.35	78.88	132.1	205.0	508.5	0.0	0.0	171	124	82	78	230	186	175
10.0	14	AL	FE	H2O	23.27	9.35	85.77	141.7	214.6	508.8	0.0	0.0	172	126	82	79	230	186	176
10.0	15	AL	FE	H2O	23.34	9.35	86.09	141.7	214.6	508.8	0.0	0.0	175	129	84	81	236	192	179
10.0	16	AL	FE	H2O	23.42	9.35	97.57*	157.2	230.4	509.0	0.0	0.0	178	133	84	80	237	193	178
10.0	18	AL	FE	H2O	23.55	9.35	98.29*	157.2	230.6	509.3	0.0	0.0	185	140	87	83	247	204	186
10.0	18	AL	U	H2O	6.12	8.46	81.37	157.2	204.2	482.9	0.0	0.0	189	144	91	87	264	222	217
10.0	19	AL	U	H2O	6.15	8.53	84.96	162.1	209.3	483.1	0.0	0.0	190	145	92	88	266	224	219
10.0	21	AL	U	H2O	6.22	8.69	85.73	162.1	209.8	483.4	0.0	0.0	196	151	96	91	277	235	226
10.0	22	AL	U	H2O	6.25	8.71	90.81*	169.2	216.9	483.6	0.0	0.0	198	153	96	91	277	235	226
10.0	23	AL	U	H2O	6.27	8.74	95.84*	175.8	223.5	483.6	0.0	0.0	197	153	96	91	275	233	227
10.0	24	AL	U	H2O	6.30	8.76	96.16*	175.8	223.8	483.9	0.0	0.0	200	156	98	93	279	238	229
10.0	25	AL	U	H2O	6.32	8.79	98.02*	178.1	226.1	483.9	0.0	0.0	207	163	99	93	288	247	232
10.0	26	AL	U	H2O	6.32	8.81	98.29*	178.1	226.1	483.9	0.0	0.0	210	166	100	95	293	252	234
7.0	14	AL	PB	H2O	10.46	10.01	80.15	141.7	204.2	498.3	0.0	0.0	194	142	89	85	267	217	206
7.0	15	AL	PB	H2O	10.54	10.03	80.47	141.7	204.5	498.6	0.0	0.0	198	146	91	87	273	224	211
7.0	16	AL	PB	H2O	10.57	10.08	91.53*	157.2	220.2	498.9	0.0	0.0	202	150	91	86	273	224	209
7.0	18	AL	PB	H2O	10.67	10.19	92.22*	157.2	220.5	499.1	0.0	0.0	209	158	94	89	285	237	217
7.0	19	AL	PB	H2O	10.72	10.19	96.12*	162.1	225.6	499.4	0.0	0.0	211	159	96	91	287	239	218
7.0	21	AL	PB	H2O	10.85	10.24	96.93*	162.1	225.8	499.6	0.0	0.0	217	167	99	93	298	251	226
7.0	22	AL	PB	H2O	10.90	10.31	102.42*	169.2	233.2	499.9	0.0	0.0	219	169	99	94	299	252	226
7.0	12	AL	FE	H2O	24.28	9.12	76.34	124.2	198.9	510.7	0.0	0.0	186	132	86	81	248	198	183
7.0	13	AL	FE	H2O	24.36	9.12	82.01	132.1	206.8	510.5	0.0	0.0	190	137	87	82	252	202	185
7.0	14	AL	FE	H2O	24.43	9.12	89.09*	141.7	216.4	510.5	0.0	0.0	192	139	87	83	253	203	186
7.0	15	AL	FE	H2O	24.51	9.12	89.45*	141.7	216.7	510.8	0.0	0.0	196	143	89	84	259	210	191
7.0	16	AL	FE	H2O	24.59	9.12	101.20*	157.2	232.2	510.8	0.0	0.0	199	148	89	84	261	212	189
7.0	15	AL	U	H2O	6.43	8.56	72.71	141.7	189.5	483.6	0.0	0.0	200	148	94	89	279	230	224
7.0	16	AL	U	H2O	6.45	8.59	83.19	157.2	205.2	483.6	0.0	0.0	204	152	94	89	278	230	222
7.0	18	AL	U	H2O	6.50	8.64	83.78	157.2	205.2	483.9	0.0	0.0	211	160	97	92	291	243	229
7.0	19	AL	U	H2O	6.55	8.71	87.45*	162.1	210.3	484.1	0.0	0.0	212	161	98	93	292	245	231
7.0	21	AL	U	H2O	6.63	8.86	88.22*	162.1	210.8	484.6	0.0	0.0	219	169	102	97	304	257	239
7.0	22	AL	U	H2O	6.63	8.89	93.44*	169.2	217.9	484.6	0.0	0.0	222	171	103	97	304	257	239
7.0	23	AL	U	H2O	6.65	8.92	98.57*	175.8	224.8	484.9	0.0	0.0	221	170	103	97	303	256	240
5.0	13	AL	PB	H2O	11.15	10.34	76.11	132.1	196.6	500.4	0.0	0.0	226	163	97	92	306	247	223
5.0	14	AL	PB	H2O	11.20	10.34	82.96	141.7	206.5	500.6	0.0	0.0	228	165	98	92	306	247	224
5.0	15	AL	PB	H2O	11.25	10.36	83.32	141.7	206.5	500.6	0.0	0.0	233	170	101	94	314	255	229
5.0	16	AL	PB	H2O	11.30	10.34	94.66*	157.2	222.3	500.6	0.0	0.0	239	176	100	94	316	258	228
5.0	18	AL	PB	H2O	11.40	10.34	95.30*	157.2	222.3	500.9	0.0	0.0	248	186	104	98	329	272	237
5.0	19	AL	PB	H2O	11.46	10.46	99.34*	162.1	227.6	501.4	0.0	0.0	249	187	106	99	331	274	239
5.0	12	AL	FE	H2O	25.45	9.07	79.42	124.2	200.9	512.6	0.0	0.0	218	153	93	88	286	225	200
5.0	13	AL	FE	H2O	25.53	9.07	85.23	132.1	209.0	512.6	0.0	0.0	223	159	94	89	291	231	203
5.0	14	AL	FE	H2O	25.60	9.04	92.49*	141.7	218.7	512.8	0.0	0.0	226	162	96	90	292	233	204
5.0	15	AL	FE	H2O	25.68	9.04	92.85*	141.7	218.9	512.8	0.0	0.0	231	167	98	92	299	240	209
5.0	16	AL	FE	H2O	25.76	9.04	104.92*	157.2	234.4	513.1	0.0	0.0	236	173	98	92	303	244	208
5.0	15	AL	U	H2O	6.88	8.46	75.07	141.7	190.2	484.4	0.0	0.0	236	173	104	98	320	262	243
5.0	16	AL	U	H2O	6.91	8.46	85.82	157.2	205.7	484.4	0.0	0.0	241	179	103	98	322	264	241
5.0	18	AL	U	H2O	6.96	8.51	86.45*	157.2	206.0	484.6	0.0	0.0	250	188	108	102	335	278	250
5.0	19	AL	U	H2O	7.01	8.59	90.22*	162.1	211.1	484.9	0.0	0.0	251	190	109	103	337	281	252
5.0	21	AL	U	H2O	7.09	8.76	90.99*	162.1	211.6	485.4	0.0	0.0	259	199	114	107	350	294	261
5.0	22	AL	U	H2O	7.09	8.74	96.30*	169.2	218.4	485.4	0.0	0.0	262	202	114	107	351	296	261
5.0	23	AL	U	H2O	7.11	8.74	101.51*	175.8	225.3	485.4	0.0	0.0	261	201	116	108	349	294	262
3.0	12	AL	PB	H2O	12.50	10.64	75.52	124.2	192.3	503.7	0.0	0.0	314	220	121	111	405	319	269
3.0	13	AL	PB	H2O	12.55	10.67	81.28	132.1	200.2	503.9	0.0	0.0	323	231	122	112	413	329	272
3.0	14	AL	PB	H2O	12.62	10.67	88.45*	141.7	209.8	503.9	0.0	0.0	326	234	124	114	414	331	274
3.0	15	AL	PB	H2O	12.67	10.69	88.81*	141.7	210.1	504.2	0.0	0.0	333	242	128	117	424	342	281
3.0	16	AL	PB	H2O	12.73	10.72	100.74*	157.2	225.8	504.4	0.0	0.0	344	254	127	117	431	351	279
3.0	10	AL	FE	H2O	27.13	9.58	79.42	117.9	198.9	516.9	0.0	0.0	299	204	109	101	373	285	234
3.0	11	AL	FE	H2O	27.30	9.60	84.59	124.2	205.7	517.4	0.0	0.0	302	206	112	103	377	289	239
3.0	12	AL	FE	H2O	27.48	9.63	85.23	124.2	206.2	517.7	0.0	0.0	309	216	116	107	387	301	247
3.0	13	AL	FE	H2O	27.56	9.63	91.31*	132.1	214.1	517.9	0.0	0.0	319	226	118	108	396	311	251
3.0	14	AL	FE	H2O	27.64	9.63	98.97*	141.7	223.8	517.9	0.0	0.0	322	229	119	109	399	314	252
3.0	14	AL	U	H2O	7.65	8.99	79.33	141.7	192.8	486.9	0.0	0.0	329	238	129	119	422	339	288
3.0	15	AL	U	H2O	7.67	9.07	81.51	141.7	203.2	487.2	5.1	0.63	323	231	114	104	431	349	308
3.0	16	AL	U	H2O	7.70	9.09	92.90*	157.2	218.7	487.2	5.1	0.63	333	243	113	103	437	356	305
3.0	18	AL	U	H2O	7.77	9.09	93.53*	157.2	218.9	487.4	5.1	0.63	346	256	119	108	453	374	317
3.0	19	AL	U	H2O	7.80	9.12	97.52*	162.1	224.0	487.4	5.1	0.63	347	257	121	109	456	377	319
3.0	21	AL	U	H2O	7.90	9.17	98.43*	162.1	224.3	487.7	5.1	0.63	357	269	126	113	471	394	329

Table 1 (cont.)

2.0	9	AL	PB	H20	13.28	10.41	73.35	117.9	186.9	504.7	0.0	0.0	392	266	133	121	481	367	292
2.0	10	AL	PB	H20	13.41	10.49	75.98	117.9	197.4	505.2	5.1	0.63	391	264	119	106	496	383	314
2.0	11	AL	PB	H20	13.51	10.64	81.06	124.2	204.5	505.7	5.1	0.63	393	266	123	108	499	387	320
2.0	12	AL	PB	H20	13.64	10.79	81.65	124.2	205.0	506.2	5.1	0.63	403	278	127	112	512	402	330*
2.0	13	AL	PB	H20	13.69	10.79	87.68*	132.1	212.9	506.5	5.1	0.63	416	293	129	114	523	417	333*
2.0	14	AL	PB	H20	13.74	10.77	95.25*	141.7	222.5	506.5	5.1	0.63	420	299	131	116	526	420	335*
2.0	15	AL	PB	H20	13.82	10.77	95.57*	141.7	222.8	506.5	5.1	0.63	428	309	156	118	537	433	344*
2.0	16	AL	PB	H20	13.87	10.77	108.09*	157.2	238.3	506.7	5.1	0.63	445	329	135	118	551	449	341*
2.0	8	AL	FE	H20	28.40	9.80	77.07	110.0	194.1	519.9	0.0	0.0	373	243	123	112	449	330	261
2.0	9	AL	FE	H20	28.60	9.83	83.37	117.9	202.4	520.4	0.0	0.0	387	259	127	116	464	348	268
2.0	10	AL	FE	H20	28.78	9.88	84.05	117.9	202.9	520.7	0.0	0.0	398	273	133	120	478	364	279
2.0	11	AL	FE	H20	28.96	9.93	91.67*	124.2	220.0	521.2	5.1	0.63	388	261	118	104	478	364	293
2.0	12	AL	FE	H20	29.11	9.96	92.31*	124.2	220.2	521.7	5.1	0.63	398	273	122	107	491	379	302
2.0	13	AL	FE	H20	29.21	9.96	98.70*	132.1	228.3	521.7	5.1	0.63	411	288	124	109	504	395	306
2.0	13	AL	U	H20	8.25	9.30	77.79	132.1	195.1	488.7	5.1	0.63	418	296	135	119	531	426	348
2.0	14	AL	U	H20	8.28	9.32	84.91	141.7	205.0	488.9	5.1	0.63	422	301	136	121	533	428	350
2.0	15	AL	U	H20	8.31	9.32	85.64	141.7	210.1	488.9	7.6	0.63	428	308	136	120	546	442	363
2.0	16	AL	U	H20	8.36	9.32	97.48*	157.2	225.6	488.9	7.6	0.63	444	328	136	119	558	458	359
2.0	17	AL	U	H20	8.38	9.32	98.25*	157.2	230.9	488.9	10.2	0.63	450	335	137	120	569	471	371
2.0	18	AL	U	H20	8.41	9.32	99.88*	157.2	236.0	489.2	12.7	0.79	456	341	138	120	580	483	381
[a] 2.0	9	AL	PB	H20	13.28	10.41	76.43	117.9	189.5	507.2	0.0	0.0	392	265	132	120	479	365	285
2.0	10	AL	PB	H20	13.41	10.49	79.11	117.9	199.9	507.7	5.1	0.63	391	264	119	106	494	381	306
2.0	11	AL	PB	H20	13.51	10.64	84.37	124.2	207.0	508.3	5.1	0.63	392	266	122	107	497	384	306
2.0	12	AL	PB	H20	13.64	10.79	84.96	124.2	207.5	508.8	5.1	0.63	402	278	127	111	506	399	321
2.0	13	AL	PB	H20	13.69	10.79	91.17*	132.1	215.4	509.0	5.1	0.63	416	293	129	113	522	414	324
2.0	14	AL	PB	H20	13.74	10.77	98.93*	141.7	225.0	509.0	5.1	0.63	420	299	131	114	524	418	326*
2.0	15	AL	PB	H20	13.82	10.77	99.29*	141.7	225.3	509.0	5.1	0.63	428	309	136	117	535	431	334*

a) For added thermal protection, a 6.35-cm outer shell was used in lieu of the 5.08-cm outer shell.

Note:

1) Pb casks have a 3.81-cm inner shell, a 5.08-cm outer shell, and a 1.905-cm outside liner.
2) Fe casks have a 0.9525-cm inner shell, a 0.9525-cm outer shell, and a 1.905-cm outside liner
3) U-metal casks have a 1.905-cm inner shell, a 5.08-cm outer shell, and a 1.905-cm outside liner.
4) External cooling fins, when required, were assumed to be stainless-steel unless noted otherwise.
5) An asterisk (*) is used to flag any parameter that is close to or over the nominal design limit.

designed to carry 14 or 15 assemblies would weigh considerably less, while one designed to carry 19, 20, or 21 assemblies would weigh considerably more. Because of the "magic numbers" associated with the various packing arrangements, the rigid enforcement of one weight limit as opposed to another may have very little impact on the estimated capacity of some casks while at the same time having a severe impact on the estimated capacity of others. With the aid of Table 1, each cask can be evaluated on a case-by-case basis.

Ultimately, however, one must eventually answer the basic question: "How many 2-, 3-, 5-, 7-, or 10-year-old PWR fuel assemblies could actually be shipped in a Pb, Fe, or U-shielded cask?" Based on the information in Table 1, and assuming 89.8 tonnes as the maximum allowable weight for the loaded cask, Table 2a shows the estimated capacity of each type of cask as a function of cooling time. Assuming that a slightly heavier cask could be tolerated, the estimated capacity of 10 of these 15 designs could be adjusted upward - some by as many as three assemblies. Table 2b, for example, shows the estimated capacity for each type of cask as a function of cooling time assuming a slightly higher weight limit of 93.9 tonnes. In either case, it appears that optimized cask designs could be developed which could carry as many as 15-18 five-year-old PWR fuel assemblies or as many as 18-21 ten-year-old PWR fuel assemblies.

Table 2a
Optimal Pb, Fe, and U-Metal Cask Designs vs
Decay Time of Spent Fuel (Wt < 89.81 tonnes)

FUEL AGE	GAMMA SHIELD	NO.OF ASSYS	LOADED WT (TONNES)	CASKID (CM)	GSHLD (CM)	NSHLD (CM)	L-FIN (CM)	T-FIN (CM)
10	PB	18	89.18	157.2	9.91	10.21	—	—
7	PB	15	80.47	141.7	10.54	10.03	—	—
5	PB	15	83.32	141.7	11.25	10.36	—	—
3	PB	15	88.81	141.7	12.67	10.69	—	—
2	PB	12[a]	84.96	124.2	13.64	10.80	5.08	0.64
10	FE	15	86.09	141.7	23.34	9.35	—	—
7	FE	15	89.45	141.7	24.51	9.12	—	—
5	FE	13	85.23	132.1	25.53	9.07	—	—
3	FE	12	85.23	124.2	27.48	9.63	—	—
2	FE	10	84.05	117.9	28.78	9.88	—	—
10	U	21	85.73	162.1	6.22	8.69	—	—
7	U	21	88.22	162.1	6.63	8.86	—	—
5	U	18	86.45	157.2	6.96	8.51	—	—
3	U	15	81.51	141.7	7.67	9.07	5.08	0.64
2	U	15	85.64	141.7	8.31	9.32	7.62	0.64

a) For added thermal protection, a 6.35-cm outer shell was used in lieu of a 5.08-cm outer shell.

Table 2b

Optimal Pb, Fe, and U-Metal Cask Designs vs
Decay Time of Spent Fuel (Wt < 93.89 tonnes)

FUEL AGE	GAMMA SHIELD	NO.OF ASSYS	LOADED WT (TONNES)	CASKID (CM)	GSHLD (CM)	NSHLD (CM)	L-FIN (CM)	T-FIN (CM)
10	PB	21	93.85	162.1	10.08	10.49	--	--
7	PB	18	92.22	157.2	10.67	10.19	--	--
5	PB	15	83.32	141.7	11.25	10.36	--	--
3	PB	15	88.81	141.7	12.67	10.69	--	--
2	PB	13[a]	91.17	132.1	13.69	10.80	5.08	0.64
10	FE	15	86.09	141.7	23.34	9.35	--	--
7	FE	15	89.45	141.7	24.51	9.12	--	--
5	FE	15	92.85	141.7	25.68	9.04	--	--
3	FE	13	91.31	132.1	27.56	9.63	--	--
2	FE	12	92.31	124.2	29.11	9.96	5.08	0.64
10	U	22	90.81	169.2	6.25	8.71	--	--
7	U	22	93.44	169.2	6.63	8.89	--	--
5	U	21	90.99	162.1	7.09	8.76	--	--
3	U	18	93.53	157.2	7.77	9.09	5.08	0.64
2	U	15	85.64	141.7	8.31	9.32	7.62	0.64

a) For added thermal protection, a 6.35-cm outer shell was used in lieu of a 5.08-cm outer shell.

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