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Maximizing Allowable Cask Payloads Using Zone-Loading and Cooling Table Specifications

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1. Introduction

Utilities have recently been placing spent fuel into “dual-purpose” canisters, which can be stored on site in a concrete silo, and/or transported to another location (such as a repository) in a transportation cask. The newer dual-purpose canister designs generally have a higher fuel assembly capacity than earlier designs (e.g., 32 vs. 21-24 PWR assemblies). At the same time, the discharge burnup of spent fuel assemblies has been increasing, from typical values of ~35,000 MWd/MTU in the past to ~50,000 or more today. Finally, at many sites, much of the longer cooling time (and lower burnup) fuel in spent fuel pools has already been loaded into dry-fuel storage systems, leaving only “hotter” (higher burnup, lower cooling time) assemblies in the spent fuel pool.

Taken together, these three factors represent a tremendous challenge for dual-purpose canister systems. Newer systems will be required to accommodate a larger number of higher burnup, lower cooling time fuel assemblies. Due to the resulting increases in thermal and radiological source terms from the assembly payload, this will generally result in higher cask system temperatures and cask external dose rates, making it more difficult to meet 10CFR71 and 10CFR72 thermal and radiological requirements. This may result in a significant reduction in the fraction of assemblies remaining in the spent fuel pool that qualify for loading into the dual-purpose canister, for either storage or shipment. One approach to addressing this issue would be to employ advanced, and potentially expensive, engineering features to enhance cask shielding and heat removal capabilities. Another approach involves the strategic loading of fuel assemblies in specific locations within the dual-purpose canister, along with a more rigorous (as opposed to simple and overly conservative) analysis of the specific assembly payload configuration inside the canister. This second approach, which does not involve difficult engineering design and fabrication, and which does not add to the cost of the canister or cask, is the subject of this paper.

Traditional cask licensing analyses simply model a uniform assembly payload (i.e., assemblies with the same burnup, initial enrichment, and cooling time) over the entire canister interior. One, or perhaps a few “design-basis” combinations of burnup, enrichment, and cooling time are analyzed and qualified. All loaded assemblies must be completely bounded by one or more of the analyzed sets of design basis assembly parameters. Effectively, the “hottest” possible assembly is modeled in all loading slots.

This paper discusses two techniques that could greatly increase the number of spent fuel pool assemblies that qualify for storage or transportation, especially when taken together. The first technique, referred to as “zone loading” involves loading relatively “cold” (i.e., long cooling time and/or low burnup) assemblies in the locations around the edge of the canister. The outer assemblies will almost entirely shield the neutron and gamma fluxes from the interior assemblies, reducing their contribution to cask external dose rate to very low levels. This allows much “hotter” assemblies to be loaded in the non-edge locations. The second technique is the use of a fast, automated analytical process to determine the exact cooling time at which all thermal and radiological requirements are met, for a very large array of assembly burnup and initial enrichment combinations. A “cooling table” which lists the required assembly cooling time as a function of assembly burnup and initial enrichment is produced by this analysis procedure.

The use of zone-loading will greatly increase the allowable radiological (and to a lesser extent, thermal) source terms for all assemblies loaded into non-edge canister locations, without significantly reducing the allowable source terms for the edge locations. The cooling table approach adds to this advantage by analyzing all possible combinations of assembly burnup, initial enrichment, and cooling time that would yield acceptable overall thermal and radiological source terms, for both the center and edge regions of the canister interior. This maximizes the number of assembly parameter combinations that are analyzed and qualified for loading, thereby further maximizing the number of individual assemblies that will qualify for loading in the canister. The use of these two techniques will greatly increase the amount of high burnup, relatively low cooling time fuel (which makes up such a large fraction of discharged fuel now and in the future) that can be loaded into a dual-purpose canister/cask.

2. Methodology

BNFL Fuel Solutions (BFS) has developed a process that makes use of both the zone-loading and cooling table techniques. The first step in the process is to perform shielding calculations that determine per-unit-source strength dose rate contributions from various "source zones" in the canister interior, at one or more key dose locations outside the analyzed storage or transportation cask. The calculated per-unit-source strength dose rate contributions are also referred to as „dose rate importances" of each defined source zone. In addition to defining and modeling the canister, cask, and assembly geometries, the source zones and key dose locations must be defined.

Typically the defined source zones consist or two or three radial zones within the canister interior, each containing several loaded assemblies. The first zone includes all the assemblies that are loaded around (or adjacent to) the canister edge. The remaining, canister interior loading locations are defined as the second zone. Sometimes, the small group of (~4) assemblies at the very center of the cask are defined as a third zone. One or more key dose locations, where dose rates are closest to the regulatory limits, are then determined for the analyzed cask geometry using standard ("forward") shielding analyses. These forward analyses are performed for a sample of fuel parameter (burnup, enrichment, cooling time) combinations. The forward analyses account for the effects of assembly axial burnup profiles and activated assembly hardware, which can influence the peak dose locations.

Once the cask configuration is defined and modeled, the source zones are defined, and the key dose rate location(s) is defined, the shielding analyses can be performed. The objective of these calculations is to determine, for each defined source zone, the dose rate contribution per unit source strength at each key dose location. Thus, the shielding analysis results are in terms of mrem/hr (at the key dose location), per particle/sec within each defined source zone (or alternatively, per assembly within each source zone). Note that with this methodology, all assemblies within a given defined source zone are modeled as having the same source strength.

For gammas, the dose rate contributions are calculated separately for each significant energy level/group (i.e., each gamma energy level that contributes measurably to cask exterior dose rates). For neutrons, the overall dose rate contribution from the entire neutron source is determined. A breakdown of dose rate contributions by energy level/group is not necessary for neutrons, since the normalized energy spectrum (which is based on the spontaneous fission spectrum of ^{244}Cf) is virtually invariant for all spent fuel. Thus, neutron dose rate contributions, for any cask configuration and any dose location, scale directly with overall neutron source strength, for all spent fuel burnup levels, initial enrichments, and cooling times.

The shielding analyses described above can be performed using discrete-ordinates shielding codes such as DORT [1], or Monte Carlo shielding codes like MCNP [2]. Within each defined source zone, a spatially uniform gamma or neutron source, with a unit (one particle/sec) source strength is modeled. For gammas, a separate analysis is performed for each significant gamma energy level/group, each modeling a mono-energetic source. For neutrons, a single analysis is performed for each source zone, which models a source with the ^{244}Cf spntaneous-fission neutron energy Watt spectrum. Thus, for each defined source zone, an analysis is performed for the neutrons, and for each significant gamma energy level/group. These runs are then repeated for all other defined source zones.

The per-unit-source-strength dose rate contributions, or "dose rate importances", for each source zone, for each energy group, at each key dose location, are the final result of the shielding analyses. Note that these analysis results are entirely a function of the cask system physical geometry, and are independent of the fuel parameters of the loaded assemblies. For this reason, this set of analyses only needs to be performed once, for any given cask system configuration. Once these shielding analyses are performed, their results can be used (over and over again) to quickly determine cask exterior dose rates for large numbers of cask payloads (and associated sets of fuel parameters), using an automated code process developed by BFS.

The BFS-developed ADSORB code takes the results of the shielding analyses described above, and automatically generates cooling tables (i.e., minimum required cooling times as a function of assembly burnup and initial enrichment) for the fuel payloads of the analyzed cask system configuration. Fuel depletion calculations, using the ORIGEN2 [3] code were performed by BFS to determine assembly heat generation levels, neutron source terms, and energy-dependent gamma source terms as a function of assembly burnup, initial enrichment, and cooling time, for spent PWR and BWR fuel. For each evaluated combination of burnup and enrichment presented in the cooling table, ADSORB accesses the corresponding radiological and thermal source term data from the tabulated ORIGEN2 results, for a wide range of cooling times. It then multiplies the neutron and energy-dependent gamma source strengths by the associated set of dose rate importances produced by the shielding analyses to yield an absolute dose rate, at the key dose location defined in the shielding analyses, and compares it to a (regulatory) dose rate limit entered by the user. ADSORB also compares the assembly heat generation level (from the ORIGEN2 results) and compares it to a specified heat generation limit entered by the user. ADSORB repeats this whole process for several cooling times. It starts at a minimum cooling time of one year, and increases the cooling time until both the dose rate and assembly heat generation requirements are met. This resulting cooling time is placed in the cooling table for the combination of burnup and initial enrichment in question. This entire process is then repeated for all burnup/enrichment combinations shown in the table.

If multiple source zones are defined, ADSORB will perform the dose rate calculation process for each defined source zone. The user must define fractional dose rate limits for each source zone, which sum to the actual regulatory dose rate limit at the dose location in question. Similarly, different assembly heat generation limits for each zone can be defined (e.g., lower limits in one zone will allow higher limits in others).

Although the number of operations (and evaluated fuel paremeter combinations) is large, the mathematical operations performed by ADSORB are limited to simple data extraction and multiplication operations, which are extremely simple and rapid. Note that the fuel depletion (ORIGEN2) calculations are performed beforehand, and are applicable for all PWR and BWR fuel, in any cask system. The shielding analyses are only performed once for a given cask system geometry, and the results are used repeatedly by ADSORB for all the analyzed fuel parameter combinations. ADSORB can produce a full cooling table, for any given cask system, in a matter of seconds. The calculated cooling times are solely a function of the cask system geometry, and the limits on cask external dose rate and assembly heat generation rate that are entered by the user.

3. Case Study

To provide a basic demonstration of the above process, and to illustrate the benefits of zone-loading and cooling tables, an example case is analyzed and presented. A typical 32-element transportation package (illustrated in Figure 1) is analyzed. A typical fuel cell width of 8.8 inches is modeled, with 3/8”-thick steel structural plates between them. Neutron absorber sheets, which contribute little to overall canister-interior shielding, are neglected for this study. A typical radial cask configuration is modeled, with a 5/8” canister shell, a 1.5” cask inner liner, a 3.25” lead gamma shield, a 2.65” cask outer shell, a 6.0” NS4-FR neutron shield, and a 3/18” outer skin (all structural shells consisting of stainless steel).

Three source zones are defined inside the 32-element canister, an edge zone (Zone 1), an intermediate zone (Zone 2), and a central zone (Zone 3), as shown in Figure 1. The intermediate zone is shielded by the edge zone assemblies, and the central zone is shielded by both the middle and edge zone assemblies. The four corner assemblies labeled „Zone 1/2“ in Figure 1 are not rigorously treated in this case study (as is discussed later). A single key dose location is placed a little more than 2 meters from the side of the cask. 10CFR71 regulations give a dose rate limit of 10 mrem/hr anywhere on the vertical planes two meters from the side of the railcar. This is almost always the limiting dose location for rail casks (i.e., where dose rates are closest to their limits).

For this study, the cask geometry described above (and in Figure 1) is analyzed with a 1-D, infinite-cylinder shielding model, which consists of a set of concentric shells. A central cylinder, with an overall area equal to that of four central 8.8-inch-square fuel cells is modeled. Two other annular shells are defined, with overall areas that correspond to the summed area of the assembly fuel cells (8.8”” square) that lie in the middle and edge zones, respectively. To model the effects of the steel basket structure, 3/8-inch-thick stainless steel rings are modeled on the outside of each of the three annular assembly zones. The assembly zones themselves are filled with a homogenous mixture of UO_2 and zirconium. The average UO_2 and zirconium densities that fill these zones are calculated based upon B&W 15x15 fuel assemblies, with a uranium loading 3.27 kg per inch of fuel height, and on the cladding dimensions for that assembly type. This simplified, cylindrical model is illustrated in Figure 2.

This model is sufficient to give a fairly accurate estimate of the per-unit-source dose contributions for the three defined zones of the 32-element canister interior, suiting the purposes of this study. A rigorous 2-D model of the canister interior (explicitly modelling the square assembly volumes) would be necessary, however, to accurately determine the per-unit-source dose contributions for the four corner (“Zone 1/2”) assemblies shown in Figure 1. The dose contributions of these assemblies would be very similar to that of an intermediate-zone assembly for any cask side (0 degree) dose location, but will be somewhere between that of the intermediate- and edge-zone assemblies for a cask corner (45 degree) dose location. The cylindrical model shown in Figure 2 effectively models a fraction of those four corner assemblies in the edge zone, with the rest in the middle zone. The fraction was chosen so that the radial thickness of both the middle and edge zones is very close to 8.8 inches. This yields overall shielding thicknesses very similar to that seen by particles moving out of the cask in a sideways direction.

Shielding analyses are performed using the simple, infinite-height-cylinder geometry shown in Figure 2. A separate shielding analysis (modeling a uniform, mono-energetic source) is performed for each of the significant gamma energy levels in the ORIGEN2 group structure, i.e., 0.575, 0.85, 1.25, 1.75, 2.25, 2.75, and 3.5 MeV. A single, additional run is performed for neutrons, based on the ^{244}Cf Watt energy spectrum. This entire set of runs is repeated for each of the three defined source zones (i.e., the three annular fuel mixture zones shown in Figure 2).

The results of the shielding analyses are presented in the “Dose Rate Importance” columns of Table 1. For neutrons, and for each gamma energy level, the dose rate contributions at the defined dose location are presented in terms of mrem/hr, per particle/sec-assembly, for each of the three defined source zones. These dose rate contributions are multiplied by the per-assembly source strengths (that apply for all assemblies in a given zone) to yield the overall dose rate contribution for each zone. Then the dose rate contributions are summed over the three zones to yield the total calculated dose rate at the defined location.

In addition to the shielding analysis results, Table 1 presents an example of the dose rate calculation (for each of the three defined source zones) which illustrates the benefits of the zone-loading process. A set of fuel parameters (burnup, enrichment, and cooling time) is chosen for each of the three defined source zones. For each set of fuel parameters (and associated zone), the per-assembly gamma and neutron source strengths are presented, alongside the dose rate importances. The dose importances are multiplied by the source strengths and then summed to yield total dose rate contributions from each zone. As the tables show, the three source-zone dose rate contributions sum to just under 10 mrem/hr.

The final step in the process is to produce a cooling table, as opposed to a single specified set of fuel parameters, for each source zone. A set of four cooling tables, produced by the ADSORB code, is shown in Table 2. The first three cooling tables apply for the edge, intermediate, and central zones of the canister interior, respectively. ADSORB requires an allowable overall dose rate contribution (at the dose location) for each zone. For this study, allowable dose rate contributions of 9.0, 0.8, and 0.2 mrem/hr for the edge, intermediate, and central zones, respectively, are chosen. Based on these dose rate limits for each zone, the required cooling time is determined as a function of burnup and initial enrichment, for a wide range of burnup values (30 to 60 GWd/MTU) and a wide range of initial enrichment values (2.5-5.0%). For each analyzed burnup level, the range of enrichment values expected for assemblies of that burnup level is evaluated. The fourth cooling table is based upon a canister where zone-loading is not applied, and thus the same assembly source terms are present in all basket locations. This final cooling table is presented for comparison, to illustrate the benefits of zone-loading.

For this illustrative analysis, thermal issues are not considered (although ADSORB can input heat generation limits, and automatically factors them into the cooling table calculations). Thermal issues may limit the benefits presented here, because whereas radiological source terms may be increased dramatically for non-edge assemblies (due to the near-total self-shielding), thermal source terms may not be increased as much, due to constraints on interior assembly heat generation. Zone loading will still provide a significant benefit for systems that are constrained by overall canister heat load, as opposed to peak individual assembly heat load (such as transport casks, which are often contrained by the peak neutron shield temperature limit, as opposed to temperatures inside the canister). Zone loading would allow significantly higher assembly heat loads in certain zones, given that it is offset by lower heat loads in other zones. This flexibility will maximize the fraction of assemblies that can be accommodated by the cask. In addition, the use of cooling tables will always maximize the number of fuel parameter combinations (and thus, number of assemblies) that qualify for any given assembly heat generation limit.

As the results in Table 2 show, much lower cooling times, and/or higher burnup levels, can be accommodated in the non-edge zones without significantly increasing cask exterior dose rate. The much “hotter” fuel in the central zones is easily offset by a small increase in cooling times in the edge zone. As is seen by comparing the 1st and 4th cooling table sections in Table 2, the cooling times for the assemblies in the edge zone only have to be increased by one year or less, as compared to the uniform-loading case, in order to accommodate much lower cooling times (and higher burnups) in the non-edge zones. Clearly, the zone-loaded canister can accommodate a much greater fraction of current and future spent fuel, especially given the higher fuel burnups that are now common. It is also clear that using cooling tables, as opposed to a simple, defined, limiting set of fuel parameters greatly increases the number of fuel parameter combinations, and therefore the number of fuel assemblies, that will qualify for loading.

4. Evaluation of Canister-Specific Payloads

The methods described could also be used to explicitly evaluate specific canister payloads, thus removing all unnecessary conservatism from the analysis. For a 32-element canister, 32 separate shielding analyses would be performed, to determine the per-unit-source dose rate contribution at the key dose locations for each loaded assembly (i.e., basket location). Once this is done for the cask system in question, simple, rapid calculations using the ADSORB code can be used to determine the gamma and neutron source terms for each assembly location (based on the actual fuel parameters of the loaded assembly), multiply those source terms by the shielding analysis results for that same location, and sum over the 32 locations to yield the actual total dose rate at the dose locations, for the specific canister (and payload) in question. The ADSORB process could then be quickly repeated for all existing loaded canisters, and all their specific payloads. The shielding analyses are only performed once, for the given cask system design, and does not need to be repeated for each individual canister payload. The primary technical challenge with this approach is finding the azimuthal location (around the cask system) where the peak dose occurs (which will vary from payload to payload, as no symmetry exists for actual loaded canisters). This issue is addressed by specifying multiple dose locations (at different azimuthal angles) along with performing multiple ADSORB calculations that consider different payload orientations within the cask geometry (i.e., 90-degree rotations of the payload).

5. Conclusions

The fraction of present-day, high-burnup spent fuel that qualifies for loading into a spent fuel storage or transportation canister/cask may be greatly increased through the use of canister zone loading and “cooling table” fuel specifications. Due to the fact that inner assemblies are almost completely shielded by the assemblies around the edge of the canister, the allowable radiological source strengths for the inner assemblies can be increased dramatically if multiple canister interior source zones are analyzed separately in the licensing-basis shielding analyses. This results in a significant increase in allowable burnup level, and decrease in required cooling time, for the assemblies in these non-edge locations. A further benefit can be obtained by using cooling tables, as opposed to simple, enveloping fuel parameter limits, to specify the fuel parameter limits for each defined source zone. Cooling tables rigorously determine the minimum required cooling time as a function of assembly burnup and initial enrichment, over the complete range of existing burnup and enrichment values for the spent fuel inventory. Cooling tables, determine and qualify all of the fuel parameter combinations that results in acceptable thermal and radiological source terms for each of the defined canister-interior source zones.

6. References

[1] *TORT-DORT-PC: Two- and Three-Dimensional Discrete Ordinates Transport, Version 2.7.3,* RSICC Code Package CCC-543, Radiation Shielding Information Code Center, OakRidge, TN.

[2] *MCNP4B: Monte Carlo N-Particle Transport Code System,* RSICC Code Package CCC-660< Radiation Shielding Information Code Center, Oak Ridge, TN.

[3] *ORIGEN2.1 Isotope Generation and Depletion Code Matrix Exponential Method*, RSICC Code Package CCC-371, Radiation Shielding Information Code Center, OakRidge, TN.

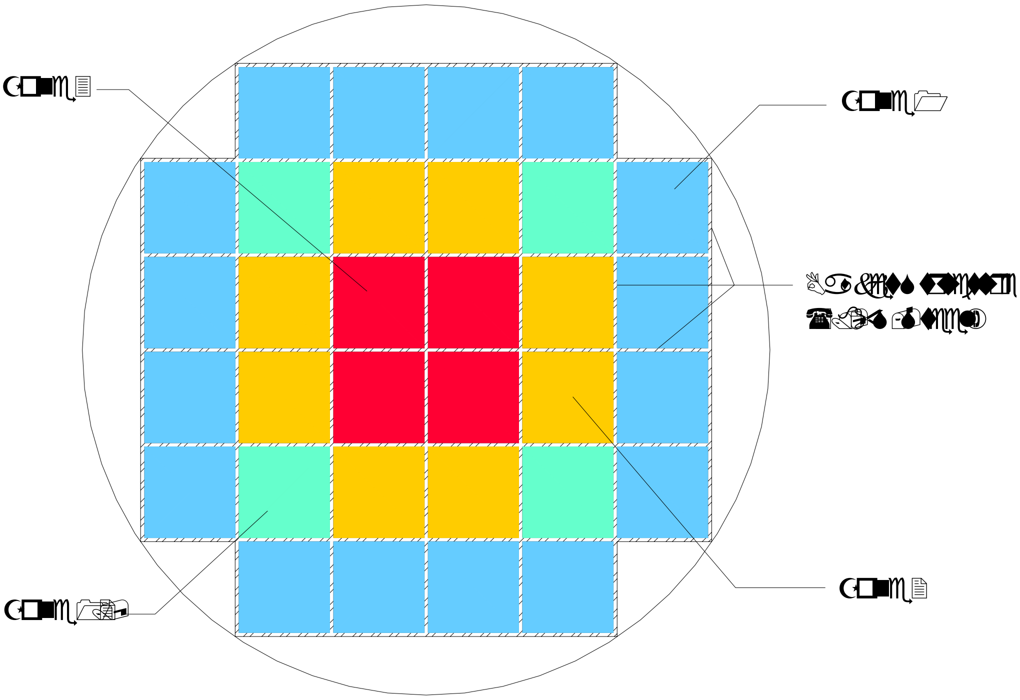

Figure 1 - Typical 32-PWR-Element Cask System Configuration
w/ Three Defined Canister-Interior Source Zones

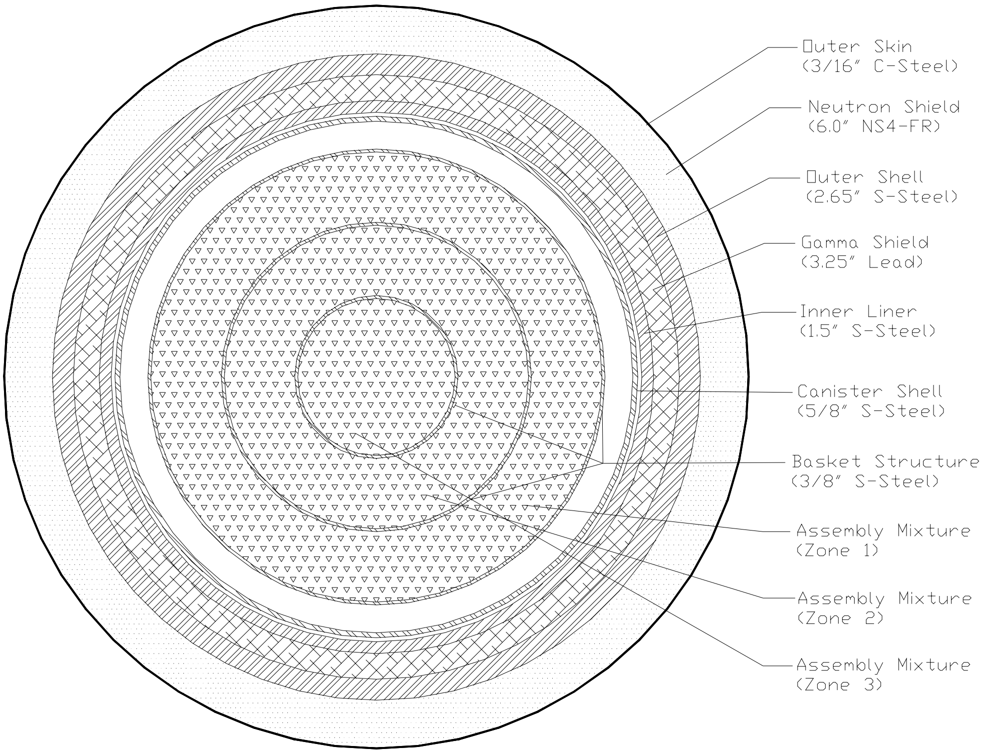

Figure 2 - Simplified Cylindrical Model of 32-Element Cask System

Table 1 - Example Dose Rate Calculation for Zone-Loaded 32-Element Transport Cask

	Edge Zone (50 GWd – 4.0% - 10 yr. Fuel)			Intermediate Zone (50 GWd – 3.5% - 5 yr. Fuel)			Central Zone (60 GWd – 4.0% - 5 yr. Fuel)			
Gamma Energy (MeV)	Dose Rate Response[1]	Source Strength (part/sec)[2]	Dose Rate Contrib. (mrem/hr)	Dose Rate Response[1]	Source Strength (part/sec)[2]	Dose Rate Contrib. (mrem/hr)	Dose Rate Response[1]	Source Strength (part/sec)[2]	Dose Rate Contrib. (mrem/hr)	Total Dose Rate (mrem/hr)
0.575	5.448E-19	2.352E+15	0.00	7.449E-24	3.873E+15	0.00	4.436E-29	4.728E+15	0.00	0.00
0.85	4.743E-16	2.390E+14	0.11	2.801E-19	1.041E+15	0.00	1.523E-22	1.347E+15	0.00	0.11
1.25	3.017E-14	1.950E+14	5.90	1.376E-16	4.122E+14	0.06	5.636E-19	4.893E+14	0.00	5.96
1.75	3.156E-13	2.497E+12	0.79	3.803E-15	5.960E+12	0.02	4.080E-17	7.106E+12	0.00	0.81
2.25	1.021E-12	3.726E+10	0.04	1.872E-14	2.203E+12	0.04	3.022E-16	2.278E+12	0.00	0.08
2.75	2.037E-12	3.008E+09	0.01	4.590E-14	8.686E+10	0.00	9.148E-16	9.471E+10	0.00	0.01
3.5	3.494E-12	3.742E+08	0.00	8.769E-14	1.118E+10	0.00	1.918E-15	1.222E+10	0.00	0.00
Neutron	4.296E-09	4.224E+08	1.82	1.004E-09	6.721E+08	0.67	1.903E-10	1.077E+09	0.20	2.69
Total	-	-	8.66	-	-	0.80	-	-	0.20	9.66

Notes:

1. Taken directly from shielding analysis output. Expressed in terms of mrem/hr (at the key dose location) per particle/sec of source strength in each assembly loaded into the zone in question. Thus, the same source strength is modeled for all assemblies in the zone.
2. Taken from ORIGEN2 results, based on the set of fuel parameters (burnup, enrichment, and cooling time) defined for each zone. Presented in units of particles/sec-assembly. This source strength is analyzed for all assemblies within the zone.

Table 2 - Cooling Tables for Zone-Loaded 32-Element Transportation Cask

(minimum required cooling time vs. burnup and initial enrichment for loaded assemblies)

Edge Zone Assemblies[1]

Burnup (GWd/MTU)	Initial Enrichment (w/o ^{235}U)					
	2.5	3.0	3.5	4.0	4.5	5.0
30	7	6	6	-	-	-
40	-	9	8	7	7	-
50	-	-	11	10	9	8
60	-	-	-	14	13	11

Intermediate Zone Assemblies[1]

Burnup (GWd/MTU)	Initial Enrichment (w/o ^{235}U)					
	2.5	3.0	3.5	4.0	4.5	5.0
30	≤ 5	≤ 5	≤ 5	-	-	-
40	-	≤ 5	≤ 5	≤ 5	≤ 5	-
50	-	-	≤ 5	≤ 5	≤ 5	≤ 5
60	-	-	-	14	9	≤ 5

Central Zone Assemblies[1]

Burnup (GWd/MTU)	Initial Enrichment (w/o ^{235}U)					
	2.5	3.0	3.5	4.0	4.5	5.0
30	≤ 5	≤ 5	≤ 5	-	-	-
40	-	≤ 5	≤ 5	≤ 5	≤ 5	-
50	-	-	≤ 5	≤ 5	≤ 5	≤ 5
60	-	-	-	≤ 5	≤ 5	≤ 5

Uniform Loading Case (all assemblies)[2]

Burnup (GWd/MTU)	Initial Enrichment (w/o ^{235}U)					
	2.5	3.0	3.5	4.0	4.5	5.0
30	6	6	5	-	-	-
40	-	8	7	7	6	-
50	-	-	11	10	9	8
60	-	-	-	14	12	11

Notes:

1. The assembly locations included in each of the three defined source zones are illustrated in Figure 1.
2. The cooling table for a standard, uniformly loaded cask, where zone-loading is not employed, is shown for comparison.