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NAC-1 Cask Dose Rate Calculations for LWR Spent Fuel

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Abstract: A Nuclear Assurance Corporation nuclear fuel transport cask, NAC-1, is being considered as a transport and storage option for spent nuclear fuel located in the B-Cell of the 324 Building. The loaded casks will be shipped to the 200 East Area Interim Storage Area for dry interim storage. Several calculations were performed to assess the photon and neutron dose rates. This report describes the analytical methods, models, and results of this investigation.

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NAC-1 Cask Dose-Rate Calculations for LWR Spent Fuel

HNF-3016, Rev. 0

RJ Migliore
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NAC-1 Cask Dose-Rate Calculations for LWR Spent Fuel

1.0 Introduction

A Nuclear Assurance Corporation (NAC) nuclear fuel transport cask, NAC-1, is being considered as a transport and storage option for spent nuclear fuel located in the B-Cell of the 324 Building. Five casks will each contain a single spent fuel assembly from a pressurized water reactor (PWR). A sixth "consolidated" cask will contain individual rods pulled from two spent fuel assemblies of a boiling water reactor (BWR), along with some PWR rods. The loaded casks will be shipped to the 200 East Area Interim Storage Area (200 Area ISA) for dry interim storage.

Several calculations were performed to assess the photon and neutron dose rates for three separate cases: i) single cask with no lid, ii) single cask with lid, and iii) all six casks in a storage array. Dose rates were calculated for a number of locations to provide a technical basis for meeting the limits in both the storage Safety Analysis Report (SAR) and transportation Safety Analysis Report for Packaging (SARP). These limits affect the transport, handling, and storage of the casks. This report describes the analytical methods, models, and results of this investigation. Potential accident scenarios are beyond the scope of this document and were not analyzed.

2.0 Method

The photon and neutron dose rates outside the NAC-1 cask were estimated using the MCNP code (Reference 1). MCNP is a general purpose, continuous energy, three dimensional, coupled neutron-photon Monte Carlo transport code system developed at Los Alamos National Laboratory. MCNP is an industry standard code that has been used for shielding calculations. MCNP allows geometrical modeling in as much detail as the user deems necessary. The physics model employed in MCNP accounts for neutron multiplication in the fuel. The code was executed on a Hewlett-Packard workstation.

The source strength for both the neutron and photon source in the spent fuel was generated using the ORIGEN2 code (Reference 2), an isotopic depletion and decay computer program. The photon source strength for the irradiated stainless steel fuel assembly end fittings was estimated from laboratory measurements for an irradiated stainless steel sample from a burnable poison rod assembly (BPRA) (Reference 3).

The computer programs have utilized Pacific Northwest National Laboratory's software quality assurance process as defined in the Standards-Based Management System.

3.0 Model

The geometry of the model, associated source terms, and model variations made to calculate the dose rate information are described in the following sections. Selected input files are presented in Appendix A.

3.1 Geometry

The NAC-1 cask was modeled as concentric annuli surrounding a parallelepiped fuel assembly with stainless steel end fittings on each end, as described in Table 1 and shown graphically in Figure 1. Dimensions and tolerances were obtained from References 4 and 5. The cask was modeled to lie on its side (long edge horizontal), with the underside of the cask approximately 9 cm from the underside of the isocontainer. The cask will be on its side for both transportation and storage.

To provide a conservative dose rate estimate, minimum cask dimensions were used when the tolerances were known. The fuel assembly was located inside a stainless steel canister, with the bottom end fitting of the fuel assembly resting against the lower end of this canister. This canister is inside the cask. The canister lid had a small cylindrical cavity 2.54 cm across and approximately 5.7 cm deep. This cavity is located in the middle of the outer surface of the lid and was modeled explicitly. Because the inner cavity of the cask is longer than the fuel assembly, there is an air gap at the upper end of the canister. The end regions of the cask were modeled as stainless steel plates covered with balsa wood impact limiters. The cask neutron shield was modeled as a void. The entire cask was surrounded by a steel isocontainer. The main function of the isocontainer is to protect the cask from the weather. Credit for shielding was taken for all components of the model.

The model was slightly different for the consolidated cask. Since the rods will be removed from the BWR and PWR assemblies, there will be no end fittings in the consolidated cask. Also, although the BWR fuel rods are somewhat longer than the PWR fuel rods, for modeling purposes all of the fuel in this cask was assumed to be the length of the BWR rods.

The MCNP input did not model each fuel rod explicitly, because this would have made the model unnecessarily complex. To simplify the geometry, a fuel assembly was modeled as a solid fuel-filled parallelepiped of uniform density. The outer dimensions of this “fuel box” correspond to the outer dimensions of the fuel assembly. The density of the fuel in the fuel box was appropriately adjusted from the true density so that the total mass of uranium in the model matched the total mass in the assembly.

As with the fuel, the geometry of the upper and lower end fittings was too complicated to model exactly. It was assumed that the end fittings had the same side dimensions of the fuel and a length of 10 cm. The densities of the “smeared” end fittings were selected so that the masses of the end fittings in the model matched the estimated true masses of the end fittings. The exact masses of the end fittings were not known. The masses modeled were the largest masses found

in a reference book for this type of assembly so that the calculations would be conservative (Reference 6).

3.2 Source Terms

Table 2 lists the characteristics of the various spent fuel assemblies. Note that Assembly D047 contains 126 of its original rods (ATM-104) and 13 rods from another assembly (ATM-106). Therefore, different rods in that assembly had different enrichments, decay times, burnups, etc. ORIGEN2 calculations were made to estimate the decay heat rate, neutron and photon source terms, and radionuclide content for each assembly as of June 1996. It was determined that Assembly D047 from the Calvert Cliffs PWR will generate the highest dose rates. Assembly D047 has the highest curium-244 concentration, which is the principal contributor (about 90%) to the neutron dose rate. Therefore, assembly D047 is the bounding case. For a full description of the source terms for these fuel assemblies, see Reference 7.

Although assembly D047 is the bounding case, the top end fitting had been removed. Because the casks containing Point Beach fuel had intact top end fittings, this top end fitting source strength was modeled in the D047 assembly so that D047 results would be bounding in all cases. The additional source was removed from D047 in the multiple cask array model (Section 3.3).

The neutron source in the fuel was modeled as a distributed source. The source was not uniformly distributed; the concentration was highest in the middle and lower at the ends. This uneven neutron source distribution was modeled explicitly in MCNP. There is no neutron source in the end fittings.

The photon source in both the fuel and end fittings was assumed to be uniformly distributed. ORIGEN2 was used to calculate the photon source in the fuel. However, ORIGEN2 could not be used to calculate the photon source in the end fittings because the end fittings were located outside the active region of the core. Instead, the photon source strength for the end fittings was estimated from laboratory measurements for an irradiated stainless steel sample from a BPRA (Reference 3). The BPRA data were adjusted to account for differing irradiation and decay times to estimate the cobalt-60 source strength for the end fittings. It was assumed that cobalt-60 was the only nuclide in the end fittings that would result in any measurable dose rate.

3.3 Variations to the Model

One model was not able to generate all of the needed dose rate information, so three variations to the basic model were developed. In all cases, ANSI/ANS 1991 flux-to-dose rate conversion factors were used (Ref. 8). The cask is lying on its side in all of these exposure scenarios.

No cask lid. This model estimated the dose rate to a radworker as the top lid of the canister is bolted down. The cask lid is removed, while the canister lid is still present. Assembly D047 was modeled because this was the bounding case.

Single cask. The single cask model estimated the dose rates on the surface of the cask, and several meters away from the cask. These dose rates are important for transportation and handling. It was assumed that the underside of the isocontainer was located 1 m from the ground, which was modeled as silicon dioxide. Again, assembly D047 was modeled because this was the bounding case.

Array of casks, 1.2 m (4 ft)¹ apart. All 6 casks were placed in an array with a separation distance of 1.2 m between the isocontainers. The 1.2 m separation distance was selected to allow routine maintenance between the isocontainers. Other separation distances were not investigated.

This dose rate calculation is important for the long-term storage of the fuel assemblies. The most radioactive fuel assembly was placed near the center of the array so that it would be partially shielded by the other casks. Likewise, the least radioactive fuel assemblies were placed at the ends of the array. The layout, from left to right, is H07, D101, consolidated, D047, H12, and H25. (H07, H12, and H25 were modeled identically and thus are interchangeable in the array). The source strength in each individual cask was modeled explicitly in MCNP. The isocontainers rest on a concrete pad surrounded by earth. The concrete pad and surrounding earth are modeled as silicon dioxide.

Because this arrangement takes credit for shielding of the most radioactive fuel assembly by the adjacent casks, it should not be considered conservative. A conservative arrangement would have the most radioactive fuel assembly at the end of the array to maximize the dose rate. However, it is reasonable to model the casks with the most radioactive fuel assembly in the center because the risk that the casks would be arranged in an improper order is within acceptable limits.

4.0 Results

Results for the three models are presented in the following sections. The relative uncertainty (i.e., plus or minus one standard deviation) is reported for each dose rate calculation. Because MCNP is a Monte Carlo code, results must be interpreted as falling within a range of values. There is a 68% probability that the true dose rate will fall within one standard deviation and a 95% probability that the true dose rate will fall within two standard deviations.

4.1 No Cask Lid (Bounding Case)

The results for the no cask lid model are presented in Table 3 and graphically in Figure 2. Dose rates were calculated at the center of the canister lid and approximately 14 cm off-center at varying distances from the lid. The 14 cm off-center position was selected to approximate the location a worker would stand while bolting on the lid. Note that the off-center dose rates are much lower than the centerline dose rates. A hole in the top center of the lid contributes to this effect. Both neutrons and photons contribute to the dose rates, although photons are the dominant contributors, comprising over 90% of the dose rate at all measured locations.

¹In this document, equivalent dimensions are given in feet if this unit is the "natural" unit of the quantity.

Photons in the fuel and in the top end fitting both contribute to this dose rate. The dominant contributor to the dose rate in the top end fitting is cobalt-60 (about 70%) and in the fuel it is cesium-137 (about 30%). The half-lives of these nuclides are approximately 5 and 30 years, respectively. Because of this difference in half-life, the dose rate will drop approximately 35% over the next 5 years as the cobalt-60 undergoes one half-life of decay. After that time, the dose rate will drop more slowly, as the longer half-life cesium-137 begins to dominate.

4.2 Single Cask Model (Bounding Case)

The results for the single cask model are given in Table 4 and shown graphically in Figure 3. Dose rates were calculated at various points along the cask and isocontainer, including at the midplane, upper and lower isocontainer ends, and miser fire valves. At the ends of the isocontainer, dose rates were calculated 2, 4, 5, and 6 m from the ends, at 0, 1, 2, and 3 m to the right of the centerline.

The transportation dose rate limit on the surface of the isocontainer is 200 mrem/hr. The maximum calculated dose rate on the isocontainer surface is 38 mrem/hr, which is well within the limit. The Hanford on-site limit for the truck driver transporting the cask is 5 mrem/hr, and the Department of Transportation limit is 2 mrem/hr. The maximum dose rate at least 2 m from the end of the isocontainer is 1.6 mrem/hr, which is below both of these limits. There is also a 10 mrem/hr limit 2 m from the side of the isocontainer. Because the maximum calculated dose rate at 2 m is 8.7 mrem/hr, the dose rates for the bounding case are below all applicable limits.

Both neutrons and photons contribute to these dose rates, although neutrons are the dominant contributors, comprising over 90% of the dose rate at all measured locations. Because the primary contributor to the neutron dose rate is curium-244, the dose rates will decrease with time as the curium-244 decays. The half-life of curium-244 is approximately 18 years.

4.3 Storage Array Model

Results for the storage array model are presented in Tables 5 and 6 and graphically in Figures 4 and 5. Dose rates were calculated at multiple locations, including 30.5 m (100 ft) and 42.7 m (140 ft) from the top and bottom of the isocontainers (at various locations along the array), and 42.7 m (140 ft) and 61.0 m (200 ft) from the right- and left-most boundaries of the array. Dose rates were also calculated at 2 and 4 m from the ends of the array, at 2, 4, and 6 m from the right and left of D047. Figure 4 indicates the position of these dose rate locations. All six casks contribute to these dose rates.

Note that Figure 4 presents more dose rates than Tables 5 and 6, because Table 5 lists only the maximum values 30.5 m and 42.7 m from the ends of the isocontainers. These maximum values are presented in boldface in Figure 4. The maximum dose rates at 30.5 m and 42.7 m tended to be past the right and left boundaries of the array because of the additional contributions from particles coming out the sides of the casks.

All of the dose rates at 42.7 m were less than 0.05 mrem/hr. The dose rates away from the array are not extremely sensitive to the separation distance, so the operators have some leeway when positioning the casks.

At times, routine maintenance activities could dictate the removal of an impact limiter (the casks will be stored with the impact limiters intact). The dose rate at the end of the cask with the impact limiter removed was not calculated for any of the casks in the storage array model. However, the dose rate between the cask lid and upper impact limiter was calculated in the single cask model, and the dose rate in the storage array would not be expected to be more than 25% higher than the single cask value (1.6 mrem/hr). Also, the dose rates under the isocontainers were not calculated. It may be inferred from geometrical considerations that these dose rates would be similar to the dose rates calculated at the sides of the isocontainers.

Both neutrons and photons contribute to these dose rates, although neutrons are the dominant contributors, comprising about 95% of the dose rate at all locations. Because the primary contributor to the neutron dose rate is curium-244, the dose rates will decrease with time as the curium-244 decays.

5.0 References

1. Radiation Safety Information Computational Center. 1997. *MCNP-4B General Monte Carlo N-Particle Transport Code*, CCC-660. Oak Ridge National Laboratory. Oak Ridge, TN.
2. Croff, A.G. 1980. *A User's Manual for the ORIGEN2 Computer Code*. ORNL/TM-7175, Oak Ridge National Laboratory, Oak Ridge, TN.
3. Migliore, R.J., et. al. 1994. *Non-Fuel Assembly Components: 10 CFR 61.55 Classification for Waste Disposal*. PNL-10103, Pacific Northwest Laboratory, Richland, WA.
4. Nuclear Fuel Services drawing number E10080, Rev. 2, sheets 1-4.
5. PNNL Drawing number H-3-304087, sheets 1-3.
6. Saling, J.J. 1986. *Nuclear Fuel Data*, WTSD-TME-148, Westinghouse Electric Corporation, Madison, PA.
7. Jenquin, U.P. 1996. *Inventory of LWR Spent Nuclear Fuel in the 324 Building*, PNNL-11273, Pacific Northwest National Laboratory, Richland, WA.
8. ANSI/ANS-6.1.1-1991. Neutron and Gamma Ray Fluence-to-Dose Factors. American Nuclear Society. La Grange Park, IL.

Table 1. NAC Cask Model Description

Region	Dimension (cm)	Material
Fuel (side width)	20.64	Fuel Smear
Gap (outer radius)	15.24	Air
Canister (outer radius)	16.27	Stainless Steel
Gap (outer radius)	16.51	Air
Inner Shell (outer radius)	17.30	Stainless Steel
Lead Shielding (outer radius) Note: the top 76.2 cm of lead is slightly thinner than the rest	30.34 (upper part of cask) 33.51 (lower part of cask)	Lead
Shielding Barrier (outer radius) Note: the top 63.5 cm of this barrier has a different inner and outer radius than the rest, but the same thickness	33.51 (upper part of cask) 36.68 (lower part of cask)	Stainless Steel
Neutron Shielding (outer radius)	47.63	Vacuum
Outer Shell (outer radius)	48.05	Stainless Steel
Fuel (length)	349.0 (PWR) 371.0 (BWR)	UO ₂
Fuel Assembly End Fittings (length)	10.0	Stainless Steel
Gap (top of fuel to canister lid)	51.37 (PWR) 49.37 (BWR)	Air
Canister Lid (max thickness) Note: There is a cavity in the center of the lid 2.54 cm across and 5.7 cm deep	15.24	Stainless Steel
Cask Upper Lid (thickness)	19.33	Stainless Steel
Upper Impact Limiter (thickness)	30.48	Balsa Wood
Canister Lower End (thickness)	15.24	Stainless Steel
Cask Lower Lid (thickness)	21.29	Stainless Steel
Lower Impact Limiter (thickness)	20.32	Balsa Wood
Isocontainer Outer Dimensions	244 x 244 x 610	Steel
Isocontainer Wall (thickness)	0.2	Steel

Table 2. Characterization of Spent Fuel in 324 Building (Reference 7)

Assembly ID	D047	D101	H07, H12, H25	Consolidated Fuel Rods
Reactor	Calvert Cliffs	Calvert Cliffs	Point Beach	Cooper and Calvert Cliffs
Relative Source Strength: Neutrons	1 (absolute: 2.22×10^8 n/s)	0.37	0.36	0.41
Relative Source Strength: Photons in Fuel	1 (absolute: 2.36×10^{15} p/s)	0.87	1.02	0.87
Relative Source Strength: Photons in Top End Fitting	0	0	1 (absolute: 9.9×10^{11} p/s)	0
Relative Source Strength: Photons in Bottom End Fitting	1 (absolute: 1.14×10^{12} p/s)	0.60	0.74	0
ATM No.	ATM-104/106	ATM-103	NA	ATM-105/108*
Mass U, Kg	308.2	372.1	401.1	407.3
No. of Rods	126/13	168	179	112
Burnup, GWD/MTU	41.8/42.7	30.7	32.9	28*
Discharge Date	4-17-82/10-18-80	10-18-80	10-09-81	5-21-82*
Decay Time, yr	14.2/15.7	15.7	14.7	14.1*
Initial Enrichment, wt%	3.04/2.45	2.72	3.19	2.50* (average)
Rod Mass, KgU	2.215/2.244	2.215	2.241	3.89*

* Information applicable to Cooper only

Table 3. Dose Rates for the “No Cask Lid” Exposure Scenario (Bounding Case)

Location	Dose Rate (mrem/hr)	
	Center	Off-center
Top of Canister Lid (surface)	790 +/- 3%	298 +/- 4%
30 cm (1 ft) from Top of Canister Lid	170 +/- 5%	104 +/- 2%
61 cm (2 ft) from Top of Canister Lid	71 +/- 4%	55 +/- 2%
91 cm (3 ft) from Top of Canister Lid	38 +/- 5%	35 +/- 3%
122 cm (4 ft) from Top of Canister Lid	26 +/- 6%	24 +/- 4%

Table 4. Dose Rates for Single Cask Exposure Scenario (Bounding Case)

Location	Dose Rate (mrem/hr)			
Midplane of Cask (surface)	114 +/- 0.4%			
Midplane of Isocontainer (surface)	38 +/- 3%			
Upper Cask Lid (surface)	1.4 +/- 8%			
Upper Impact Limiter (surface)	0.72 +/- 15%			
Upper Miser Fire Valve	4.8 +/- 2%			
Upper End of Isocontainer, center (surface)	1.2 +/- 8%			
Upper Edge of Isocontainer (surface)	2.8 +/- 5%			
Lower Cask Lid (surface)	5.0 +/- 4%			
Lower Impact Limiter (surface)	1.6 +/- 9%			
Lower Miser Fire Valve	2.7 +/- 2%			
Lower End of Isocontainer, center (surface)	1.8 +/- 5%			
Lower Edge of Isocontainer (surface)	4.5 +/- 3%			
	1 m right	2 m right	5 m right	10 m right
Midplane from Isocontainer	15.5 +/- 0.5%	8.7 +/- 0.7%	2.6 +/- 1%	0.72 +/- 2%
	0 m right	1 m right	2 m right	3 m right
2 m from top end of Isocontainer	0.78 +/- 2%	0.90 +/- 2%	1.1 +/- 2%	1.2 +/- 2%
4 m from top end of Isocontainer	0.38 +/- 3%	0.40 +/- 3%	0.51 +/- 2%	0.56 +/- 2%
5 m from top end of Isocontainer	0.29 +/- 4%	0.30 +/- 3%	0.37 +/- 3%	0.41 +/- 3%
6 m from top end of Isocontainer	0.20 +/- 3%	0.23 +/- 3%	0.26 +/- 3%	0.31 +/- 3%
2 m from bottom end of Isocontainer	1.0 +/- 2%	1.2 +/- 2%	1.4 +/- 2%	1.6 +/- 2%
4 m from bottom end of Isocontainer	0.49 +/- 3%	0.50 +/- 2%	0.60 +/- 2%	0.69 +/- 2%
5 m from bottom end of Isocontainer	0.35 +/- 3%	0.35 +/- 3%	0.42 +/- 2%	0.47 +/- 3%
6 m from bottom end of Isocontainer	0.25 +/- 3%	0.27 +/- 4%	0.29 +/- 3%	0.35 +/- 3%

Table 5. Dose Rates for Storage Array Exposure Scenario

Location	Dose Rate (mrem/hr)			
Top 30.5 m (100 ft) Maximum	0.076 +/- 4%			
Top 42.7 m (140 ft) Maximum	0.036 +/- 5%			
Bottom 30.5 m (100 ft) Maximum	0.081 +/- 4%			
Bottom 42.7 m (140 ft) Maximum	0.036 +/- 5%			
2 m right of array	3.8 +/- 2%			
4 m right of array	1.6 +/- 3%			
42.7 m (140 ft) right of array	0.040 +/- 4%			
42.7 m (140 ft) left of array	0.038 +/- 4%			
61.0 m (200 ft) right of array	0.015 +/- 5%			
61.0 m (200 ft) left of array	0.018 +/- 10%			
	Left		Right	
Cask 1, Midplane	41 +/- 2%		58 +/- 2%	
Cask 2, Midplane	49 +/- 2%		53 +/- 2%	
Cask 3, Midplane	50 +/- 2%		70 +/- 2%	
Cask 4, Midplane	138 +/- 1%		133 +/- 1%	
Cask 5, Midplane	69 +/- 2%		50 +/- 2%	
Cask 6, Midplane	60 +/- 2%		43 +/- 2%	
	Top End	Bottom End	Midplane Left	Midplane Right
Isocontainer 1	2.6 +/- 4%	3.9 +/- 4%	17 +/- 3%	24 +/- 2%
Isocontainer 2	1.9 +/- 5%	2.9 +/- 4%	24 +/- 2%	26 +/- 2%
Isocontainer 3	3.1 +/- 4%	4.8 +/- 3%	26 +/- 2%	36 +/- 2%
Isocontainer 4	2.4 +/- 4%	4.0 +/- 4%	55 +/- 2%	53 +/- 2%
Isocontainer 5	2.8 +/- 4%	4.6 +/- 3%	36 +/- 2%	26 +/- 3%
Isocontainer 6	1.2 +/- 7%	1.7 +/- 5%	24 +/- 2%	17 +/- 3%

Table 6. Two and Four Meter Dose Rates for Storage Array Exposure Scenario

Location	Dose Rate (mrem/hr)						
	-6 m	-4 m	-2 m	0 m (centerline of D047)	2 m	4 m	6 m
2 m from top of Isocontainers	1.8 +/- 2%	2.1 +/- 2%	2.1 +/- 2%	1.8 +/- 2%	2.1 +/- 2%	1.9 +/- 2%	1.4 +/- 3%
4 m from top of Isocontainers	1.2 +/- 3%	1.2 +/- 3%	1.2 +/- 3%	1.1 +/- 3%	1.2 +/- 3%	1.1 +/- 3%	0.94 +/- 3%
2 m from bottom of Isocontainers	2.4 +/- 2%	2.8 +/- 2%	2.9 +/- 2%	2.4 +/- 2%	2.8 +/- 2%	2.5 +/- 2%	1.9 +/- 2%
4 m from bottom of Isocontainers	1.5 +/- 3%	1.7 +/- 2%	1.5 +/- 2%	1.4 +/- 3%	1.5 +/- 3%	1.4 +/- 3%	1.2 +/- 3%

Figure 1. Cask Model

Figure 2. Dose Rates For No Cask Lid
Exposure Scenario (Bounding Case)
(mrem/hr)

Figure 3. Dose Rates for Single Cask Exposure Scenario (Bounding Case) (mrem/hr)

Figure 4. Dose Rates for Storage Array Exposure Scenario (mrem/hr)

Note: Numbers inside the isocontainer are dose rates on the right and left sides of the casks.

Figure 5. Dose Rates for Storage Array Exposure Scenario
(close up) (mrem/hr)

Appendix A

MCNP Input Files for Select Cases

Three input files are included in this appendix. The first is for the single cask (no top lid) with a photon source. The second is for the single cask (top lid present) with the neutron source. The third is for the storage array with the neutron source.

MCNP Input for Single Cask Model, No Lid, Photons

```

Gamma top, single cask, no top, FWR
c
999 0 -220:224:-210:214:-231:230 $Empty Universe
c
c air
c 100 5 -1.197e-3 220 -224 108 -230 103 -211 $top
101 5 -1.197e-3 220 -224 108 -230 211 -212
102 5 -1.197e-3 220 -224 108 -230 212 -213
103 5 -1.197e-3 220 -224 108 -230 213 -214
c
200 5 -1.197e-3 220 -224 108 -230 210 -215 $bottom
201 5 -1.197e-3 220 -224 108 -230 215 -216
202 5 -1.197e-3 220 -224 108 -230 216 -217
203 5 -1.197e-3 220 -224 108 -230 217 -100
c
250 5 -1.197e-3 100 -103 108 -230 220 -104 $sides
251 5 -1.197e-3 100 -103 108 -230 107 -221
252 5 -1.197e-3 100 -103 108 -230 221 -222
253 5 -1.197e-3 100 -103 108 -230 222 -223
254 5 -1.197e-3 100 -103 108 -230 223 -224
255 5 -1.197e-3 100 -103 111 -230 104 -107
c
300 5 -1.197e-3 220 -224 200 -108 210 -214 $air under truck
301 7 -1.4 220 -224 231 -200 210 -214 $dirt
c
c Cask with source
c
400 4 -2.682 -12 13 -14 15 21 -22 $ Fuel Cavity
401 2 -2.27 -12 13 -14 15 22 -121 $ Top nozzle
402 2 -1.32 -12 13 -14 15 120 -21 $ Bottom nozzle
403 5 -1.197e-3 -12 13 -14 15 121 -122 $ Air
404 5 -1.197e-3 120 -122 -13 -16 $ Air around fuel
405 5 -1.197e-3 120 -122 12 -16
406 5 -1.197e-3 120 -122 13 -12 14 -16
407 5 -1.197e-3 120 -122 13 -12 -15 -16
408 2 -7.82 120 -122 16 -17 $ Canister
409 2 -7.82 146 -120 -17 $ Bottom canister
410 2 -7.82 145 -146 -17 $ Bottom canister
411 2 -7.82 144 -145 -17 $ Bottom canister
412 2 -7.82 143 -144 -17 $ Bottom canister
413 2 -7.82 142 -143 -17 $ Bottom canister
414 2 -7.82 141 -142 -17 $ Bottom canister
415 2 -7.82 140 -141 -17 $ Bottom canister
416 2 -7.82 2 -140 -17 $ Bottom canister
417 2 -7.82 122 -123 -17 $ Top canister
418 2 -7.82 123 -124 -17 $ Top canister
419 2 -7.82 124 -125 -17 $ Top canister
420 2 -7.82 125 -127 -17 $ Top canister
421 2 -7.82 127 -128 -17 $ Top canister
422 2 -7.82 128 -129 -17 126 $ Top canister
423 2 -7.82 129 -130 -17 126 $ Top canister
424 2 -7.82 130 -3 -17 126 $ Top canister
425 5 -1.197e-3 128 -3 -126 $ Air in lid
426 5 -1.197e-3 2 -3 -5 17 $ Air
427 2 -7.8200 2 -3 5 -6 $ SS Inner Shell
c
c lead goes in here
428 2 -7.8200 76 -77 181 -3 $ SS Inner Water Shell (top)
429 2 -7.8200 77 -7 181 -3 $ SS Inner Water Shell (top)
430 2 -7.8200 2 -180 7 -8 $ SS Inner Water Shell (bottom)
431 3 -0.0001 180 -3 7 -8 $ Water void (small)
432 3 -0.0001 2 -3 8 -9 $ Water void
433 2 -7.8200 2 -3 9 -10 $ SS Outer Water Shell
c
434 6 -0.144 4 -19 -10 $ Top impact limiter
435 6 -0.176 18 -1 -10 $ Bottom impact limiter
c
c stainless steel on bottom
30 2 -7.82 -10 40 -2
31 2 -7.82 -10 39 -40
32 2 -7.82 -10 38 -39

```

```

33 2 -7.82 -10 37 -38
34 2 -7.82 -10 36 -37
35 2 -7.82 -10 35 -36
36 2 -7.82 -10 34 -35
37 2 -7.82 -10 33 -34
38 2 -7.82 -10 32 -33
39 2 -7.82 -10 31 -32
40 2 -7.82 -10 1 -31
c no lid
50 5 -1.187e-3 3 -232 -10
51 5 -1.187e-3 232 -19 -10
52 5 -1.187e-3 19 -233 105 -106 109 -110
53 5 -1.187e-3 233 -102 105 -106 109 -110
54 5 -1.187e-3 103 -234 220 -224 108 -230
55 5 -1.187e-3 234 -235 220 -224 108 -230
56 5 -1.187e-3 235 -211 220 -224 108 -230
c lead shielding
70 1 -11.3 2 -3 6 -70
71 1 -11.3 2 -3 70 -71
72 1 -11.3 2 -3 71 -72
73 1 -11.3 2 -3 72 -73
74 1 -11.3 2 -3 73 -74
75 1 -11.3 2 -3 74 -75
76 1 -11.3 2 -3 75 -76
77 1 -11.3 2 -181 76 -77
78 1 -11.3 2 -181 77 -7
c isocontainer
80 5 -1.197e-3 19 -102 105 -106 109 -110 $stop
81 5 -1.197e-3 101 -18 105 -106 109 -110 $bottom
82 5 -1.187e-3 18 -19 105 -106 109 -110 10 $side
83 5 -1.187e-3 104 -107 108 -111 102 -103 $stop
84 2 -7.82 104 -107 108 -111 100 -101 $bottom
85 2 -7.82 101 -102 104 -105 109 -110 $side
86 2 -7.82 101 -102 106 -107 109 -110 $side
87 2 -7.82 101 -102 104 -107 108 -109 $side
88 2 -7.82 101 -102 104 -107 110 -111 $side

1 pz 2.84
2 pz 24.1300
3 pz 474.98
c 4 pz 494.31
5 c/z 0 -64.57 16.51 $ Inside I.R
6 c/z 0 -64.57 17.30 $ SS Shell O.R.
7 c/z 0 -64.57 33.51 $ Lead O.R.
8 c/z 0 -64.57 36.68 $ SS Shell O.R.
9 c/z 0 -64.57 47.63 $ Water O.R.
10 c/z 0 -64.57 48.05 $ Outer Shell O.R.
12 py -54.25
13 py -74.89
14 px 10.32
15 px -10.32
16 c/z 0 -64.57 15.24
17 c/z 0 -64.57 16.27
18 pz -17.48
19 pz 524.79
21 pz 49.37
22 pz 398.37
c
31 pz 4.02
32 pz 6.03
33 pz 8.04
34 pz 10.05
35 pz 12.06
36 pz 14.07
37 pz 16.08
38 pz 18.09
39 pz 20.1
40 pz 22.1
c
50 pz 476.89
51 pz 478.79

```



```

c      52      pz  480.70
c      53      pz  482.60
c      54      pz  484.51
c      55      pz  486.41
c      56      pz  488.32
c      57      pz  490.22
c      58      pz  492.3
c
70     c/z  0  -64.57  19.10
71     c/z  0  -64.57  20.90
72     c/z  0  -64.57  22.70
73     c/z  0  -64.57  24.50
74     c/z  0  -64.57  26.30
75     c/z  0  -64.57  28.10
76     c/z  0  -64.57  30.34
77     c/z  0  -64.57  31.70
c      isocontainer
100    pz  -53.34
101    pz  -53.14
102    pz  556.06
103    pz  556.26
104    px  -121.92
105    px  -121.72
106    px  121.72
107    px  121.92
108    py  -121.92
109    py  -121.72
110    py  121.72
111    py  121.92
c
120    pz  39.37
121    pz  408.37
122    pz  459.74
123    pz  461.645
124    pz  463.55
125    pz  465.455
126    c/z  0  -64.57  1.27
127    pz  467.36
128    pz  469.265
129    pz  471.17
130    pz  473.075
140    pz  26.035
141    pz  27.94
142    pz  29.845
143    pz  31.75
144    pz  33.655
145    pz  35.56
146    pz  37.456
c
180    pz  411.48
181    pz  398.78
200    py  -220
c      surfaces for air in the single cask problem
210    pz  -653
211    pz  756
212    pz  956
213    pz  1056
214    pz  1156
215    pz  -553
216    pz  -453
217    pz  -253
220    px  -1122
221    px  222
222    px  322
223    px  622
224    px  1122
230    py  1000
231    py  -500
232    pz  505.46
233    pz  535.94
234    pz  566.42

```

```

235 pz 596.9
c
c tally surfaces for single cask problem
c
c 24 c/x -64.57 223.87 3
c 25 c/x -64.57 223.87 5
c 27 c/z 0 -64.57 5
c 80 c/x -64.57 389.08 5 $for Co tally
c 82 pz 228.87 $for midplane fuel
c 83 pz 218.87 $for midplane fuel
c 85 1 cx 5 $for Co tally
c 86 2 cx 5 $for bottom Co tally
c 87 c/x -64.57 30.08 5 $for bottom Co tally
c 500 c/z 0 -64.57 50 $2/4/5/6 m top
c 501 c/z 100 -64.57 50 $2/4/5/6 m top
c 502 c/z 200 -64.57 50 $2/4/5/6 m top
c 503 c/z 300 -64.57 50 $2/4/5/6 m top
c 510 c/x -64.57 223.87 50 $1/2/5/10 m right
511 c/z 0 -64.57 2.5 $1/2/3/4' from can
c 512 c/z 15.2 -64.57 3 $1/2/3/4' from can, off center
513 c/z 0 -64.57 5 $1/2/3/4' from can
c 514 c/z 15.2 -64.57 5 $1/2/3/4' from can, off center
515 c/z 0 -64.57 13.27 $1/2/3/4' from can
c 520 pz 479
c 521 pz 469
c 522 py -39.57
c 523 py -89.57
c 524 px 111.92

m1 82000. 1.0000 $ Lead
m2 26000. -0.6613 $ SS-304
    6000. -0.0008
    25000. -0.0200
    14000. -0.0100
    24000. -0.2000
    28000. -0.1050
    7000. -0.0010
    27000. -0.0012
m3 1000. 0.0669 $ Water
    8000. 0.0335
m4 92000. -1 $ Fuel
    8000 -0.1344
    40000 -0.2215

c -----
c Total 294930.
m5 7000 -75.55 $ air
    8000 -23.13
m6 1000 -0.0622 $ balsa wood
    6000 -0.4445
    8000 -0.4934
m7 14000 -0.467 $ "dirt" (silicon dioxide)
    8000 -0.533
c *tr1 0 -64.57 389.08 45 135 90
c *tr2 0 -64.57 30.08 45 135 90
print -85
c
c tallies
c
fc342 Canister lid
f342:p 3
fs342 -511 -515 -17
fm342 1.36e12
sd342 19.6 1r 278.41 1r
c
fc352 1' from Canister lid
f352:p 232
fs352 -511 -515 -17
fm352 1.36e12
sd352 19.6 1r 278.41 1r
c
fc362 2' from Canister lid

```

```

f362:p      233
fs362      -513 -515 -17
fm362      1.36e12
sd362      78.54 1r 278.41 1r
c
fc372      3' from Canister lid
f372:p      234
fs372      -513 -515 -17
fm372      1.36e12
sd372      78.54 1r 278.41 1r
c
fc382      4' from Canister lid
f382:p      235
fs382      -513 -515 -17
fm382      1.36e12
sd382      78.54 1r 278.41 1r
c
c
c
mode        p
prdm        1e8 1e6 1 2
nps         20000000
imp:p       0 256 2r 1 11r $big air
            1 1 1 1 1 4r $fuel and around fuel
            1 7r $bot can
            2 4 8 16 32 64 128 256 1r $stop can
            1 8r $rest of cask
            1 10r $bottom ss
            256 6r $stop air (no ss)
            1 8r $lead
            1 1 256 1 4r $iso
sdef         cel=401 erg=dl pos 0 -64.57 403.37 rad=d2
            ext=d3 axs=0 0 1
si2         14.6
si3         5.0
c            Photon source
c            E, MeV      photons/s
#            si1        spl
            1           d
            1.1732      6.8e11
            1.3325      6.8e11
c            =====
c            Total      1.36e12
c
c            E, MeV      mR/hr/cmy/s
c            de0         df0
#            0.010      2.211e-5
            0.013      4.407e-5
            0.016      6.450e-5
            0.020      8.578e-5
            0.025      1.037e-4
            0.030      1.152e-4
            0.040      1.291e-4
            0.060      1.473e-4
            0.080      1.669e-4
            0.100      1.907e-4
            0.15       2.709e-4
            0.20       3.702e-4
            0.25       4.676e-4
            0.30       5.625e-4
            0.40       7.439e-4
            0.60       1.076e-3
            0.80       1.375e-3
            1.0       1.647e-3
            1.2       1.899e-3
            1.5       2.247e-3
            2.0       2.770e-3
            2.5       3.244e-3
            3.0       3.685e-3
            4.0       4.503e-3
            5.0       5.271e-3

```

6.0	6.012e-3
8.0	7.463e-3
10.0	8.919e-3
12.0	1.041e-2

MCNP Input for Single Cask Model, Neutrons

Neutron, without water, with top impact limiter, single cask

```

c
999 0 -220:224:-210:214:-231:230 $Empty Universe
c
c air
100 5 -1.197e-3 220 -224 108 -230 103 -211 $top
101 5 -1.197e-3 220 -224 108 -230 211 -212
102 5 -1.197e-3 220 -224 108 -230 212 -213
103 5 -1.197e-3 220 -224 108 -230 213 -214
c
200 5 -1.197e-3 220 -224 108 -230 210 -215 $bottom
201 5 -1.197e-3 220 -224 108 -230 215 -216
202 5 -1.197e-3 220 -224 108 -230 216 -217
203 5 -1.197e-3 220 -224 108 -230 217 -100
c
250 5 -1.197e-3 100 -103 108 -230 220 -104 $sides
251 5 -1.197e-3 100 -103 108 -230 107 -221
252 5 -1.197e-3 100 -103 108 -230 221 -222
253 5 -1.197e-3 100 -103 108 -230 222 -223
254 5 -1.197e-3 100 -103 108 -230 223 -224
255 5 -1.197e-3 100 -103 111 -230 104 -107
c
300 5 -1.197e-3 220 -224 200 -108 210 -214 $air under truck
301 7 -1.4 220 -224 231 -200 210 -214 $dirt
c
c Cask with source
c
400 4 -2.682 -12 13 -14 15 21 -22 $ Fuel Cavity
401 2 -2.27 -12 13 -14 15 22 -121 $ Top nozzle
402 2 -1.32 -12 13 -14 15 120 -21 $ Bottom nozzle
403 5 -1.197e-3 -12 13 -14 15 121 -122 $ Air
404 5 -1.197e-3 120 -122 -13 -16 $ Air around fuel
405 5 -1.197e-3 120 -122 12 -16
406 5 -1.197e-3 120 -122 13 -12 14 -16
407 5 -1.197e-3 120 -122 13 -12 -15 -16
408 2 -7.82 120 -122 16 -17 $ Canister
409 2 -7.82 146 -120 -17 $ Bottom canister
410 2 -7.82 145 -146 -17 $ Bottom canister
411 2 -7.82 144 -145 -17 $ Bottom canister
412 2 -7.82 143 -144 -17 $ Bottom canister
413 2 -7.82 142 -143 -17 $ Bottom canister
414 2 -7.82 141 -142 -17 $ Bottom canister
415 2 -7.82 140 -141 -17 $ Bottom canister
416 2 -7.82 2 -140 -17 $ Bottom canister
417 2 -7.82 122 -123 -17 $ Top canister
418 2 -7.82 123 -124 -17 $ Top canister
419 2 -7.82 124 -125 -17 $ Top canister
420 2 -7.82 125 -127 -17 $ Top canister
421 2 -7.82 127 -128 -17 $ Top canister
422 2 -7.82 128 -129 -17 126 $ Top canister
423 2 -7.82 129 -130 -17 126 $ Top canister
424 2 -7.82 130 -3 -17 126 $ Top canister
425 5 -1.197e-3 128 -3 -126 $ Air in lid
426 5 -1.197e-3 2 -3 -5 17 $ Air
427 2 -7.8200 2 -3 5 -6 $ SS Inner Shell
c
lead goes in here
428 2 -7.8200 76 -77 181 -3 $ SS Inner Water Shell (top)
429 2 -7.8200 77 -7 181 -3 $ SS Inner Water Shell (top)
430 2 -7.8200 2 -180 7 -8 $ SS Inner Water Shell (bottom)
431 3 -0.0001 180 -3 7 -8 $ Water void (small)
432 3 -0.0001 2 -3 8 -9 $ Water void
433 2 -7.8200 2 -3 9 -10 $ SS Outer Water Shell
434 6 -0.144 4 -19 -10 $ Top impact limiter
435 6 -0.176 18 -1 -10 $ Bottom impact limiter
c
stainless steel on bottom
30 2 -7.82 -10 40 -2
31 2 -7.82 -10 39 -40
32 2 -7.82 -10 38 -39
33 2 -7.82 -10 37 -38

```

34	2	-7.82	-10	36	-37	
35	2	-7.82	-10	35	-36	
36	2	-7.82	-10	34	-35	
37	2	-7.82	-10	33	-34	
38	2	-7.82	-10	32	-33	
39	2	-7.82	-10	31	-32	
40	2	-7.82	-10	1	-31	
c	stainless steel on top					
50	2	-7.82	-10	3	-50	
51	2	-7.82	-10	50	-51	
52	2	-7.82	-10	51	-52	
53	2	-7.82	-10	52	-53	
54	2	-7.82	-10	53	-54	
55	2	-7.82	-10	54	-55	
56	2	-7.82	-10	55	-56	
57	2	-7.82	-10	56	-57	
58	2	-7.82	-10	57	-58	
59	2	-7.82	-10	58	-4	
c	lead shielding					
70	1	-11.3	2	-3	6	-70
71	1	-11.3	2	-3	70	-71
72	1	-11.3	2	-3	71	-72
73	1	-11.3	2	-3	72	-73
74	1	-11.3	2	-3	73	-74
75	1	-11.3	2	-3	74	-75
76	1	-11.3	2	-3	75	-76
77	1	-11.3	2	-181	76	-77
78	1	-11.3	2	-181	77	-7
c	isocontainer					
80	5	-1.197e-3	19	-102	105	-106 109 -110 \$top
81	5	-1.197e-3	101	-18	105	-106 109 -110 \$bottom
82	5	-1.187e-3	18	-19	105	-106 109 -110 10 \$side
83	2	-7.82	104	-107	108	-111 102 -103 \$top
84	2	-7.82	104	-107	108	-111 100 -101 \$bottom
85	2	-7.82	101	-102	104	-105 109 -110 \$side
86	2	-7.82	101	-102	106	-107 109 -110 \$side
87	2	-7.82	101	-102	104	-107 108 -109 \$side
88	2	-7.82	101	-102	104	-107 110 -111 \$side
1	pz	2.84				
2	pz	24.1300				
3	pz	474.98				
4	pz	494.31				
5	c/z	0	-64.57	16.51	\$	Inside I.R.
6	c/z	0	-64.57	17.30	\$	SS Shell O.R.
7	c/z	0	-64.57	33.51	\$	Lead O.R.
8	c/z	0	-64.57	36.68	\$	SS Shell O.R.
9	c/z	0	-64.57	47.63	\$	Water O.R.
10	c/z	0	-64.57	48.05	\$	Outer Shell O.R.
12	py	-54.25				
13	py	-74.89				
14	px	10.32				
15	px	-10.32				
16	c/z	0	-64.57	15.24		
17	c/z	0	-64.57	16.27		
18	pz	-17.48				
19	pz	524.79				
21	pz	49.37				
22	pz	398.37				
c						
31	pz	4.02				
32	pz	6.03				
33	pz	8.04				
34	pz	10.05				
35	pz	12.06				
36	pz	14.07				
37	pz	16.08				
38	pz	18.09				
39	pz	20.1				
40	pz	22.1				
c						

50	pz	476.89	
51	pz	478.79	
52	pz	480.70	
53	pz	482.60	
54	pz	484.51	
55	pz	486.41	
56	pz	488.32	
57	pz	490.22	
58	pz	492.3	
c			
70	c/z	0	-64.57 19.10
71	c/z	0	-64.57 20.90
72	c/z	0	-64.57 22.70
73	c/z	0	-64.57 24.50
74	c/z	0	-64.57 26.30
75	c/z	0	-64.57 28.10
76	c/z	0	-64.57 30.34
77	c/z	0	-64.57 31.70
c			
	isocontainer		
100	pz	-53.34	
101	pz	-53.14	
102	pz	556.06	
103	pz	556.26	
104	px	-121.92	
105	px	-121.72	
106	px	121.72	
107	px	121.92	
108	py	-121.92	
109	py	-121.72	
110	py	121.72	
111	py	121.92	
c			
120	pz	39.37	
121	pz	408.37	
122	pz	459.74	
123	pz	461.645	
124	pz	463.55	
125	pz	465.455	
126	c/z	0	-64.57 1.27
127	pz	467.36	
128	pz	469.265	
129	pz	471.17	
130	pz	473.075	
140	pz	26.035	
141	pz	27.94	
142	pz	29.845	
143	pz	31.75	
144	pz	33.655	
145	pz	35.56	
146	pz	37.456	
c			
180	pz	411.48	
181	pz	398.78	
200	py	-220	
c	surfaces	for air in the single cask problem	
210	pz	-653	
211	pz	756	
212	pz	956	
213	pz	1056	
214	pz	1156	
215	pz	-553	
216	pz	-453	
217	pz	-253	
220	px	-1122	
221	px	222	
222	px	322	
223	px	622	
224	px	1122	
230	py	1000	
231	py	-500	
c			

```

c      tally surfaces for single cask problem
c
24      c/x  -64.57  223.87  3
25      c/x  -64.57  223.87  5
27      c/z    0      -64.57  5
80      c/x  -64.57  389.08  5  $for Co tally
82      pz   228.87          $for midplane fuel
83      pz   218.87          $for midplane fuel
85      1  cx  5            $for Co tally
86      2  cx  5            $for bottom Co tally
87      c/x  -64.57  30.08  5  $for bottom Co tally
500     c/z    0      -64.57  50  $2/4/5/6 m top
501     c/z  100     -64.57  50  $2/4/5/6 m top
502     c/z  200     -64.57  50  $2/4/5/6 m top
503     c/z  300     -64.57  50  $2/4/5/6 m top
510     c/x  -64.57  223.87  50  $1/2/5/10 m right
511     c/z    0      -64.57  10
512     c/z    0      -64.57  15
520     pz   479
521     pz   469
522     py  -39.57
523     py  -89.57
524     px  111.92

m1      82000.    1.0000    $ Lead
m2      26000.    -0.6613    $ SS-304
        6012.     -0.0008
        25055.    -0.0200
        14000.    -0.0100
        24000.    -0.2000
        28000.    -0.1050
        7014.     -0.0010
        27059.    -0.0012
m3      1001.     0.0669    $ Water
        8016.     0.0335
m4      95241.    -252.7    $ Fuel Smear
        95243.    -64.28
        63154.    -5.8
        53129.    -71.50
        93237.    -183.8
        94238.    -78.39
        94239.    -1574.
        94240.    -841.4
        94241.    -238.1
        43099.    -286.9
        92234.    -48.17
        92235.    -1330.
        92236.    -1227.
        92238.    -288800.
        8016.     -39164
        40000.    -64546

c      -----
c      Total  294930+39164+64546.
m5      7014     -75.55    $ air
        8016     -23.13
m6      1001     -0.0622    $ balsa wood
        6012     -0.4445
        8016     -0.4934
m7      14000    -0.467     $ "dirt" (silicon dioxide)
        8016     -0.533

*tr1    0  -64.57  389.08  45  135  90
*tr2    0  -64.57  30.08  45  135  90
print   -85
c
c      tallies
c
fc32     Midplane of fuel box
f32:n    14
fs32     -24
fm32     2.22e8
sd32     28.27  1r

```



```

c
fc42      Midplane of canister
f42:n     17
fs42      -24
fm42      2.22e8
sd42      56.54 1r
c
fc52      Midplane of cask
f52:n     10
fs52      -25
fm52      2.22e8
sd52      157.08 1r
c
fc62      Top of cask (surface of impact limiter)
f62:n     19
fs62      -511
fm62      2.22e8
sd62      314.16 1r
c
fc72      Bottom of cask (surface of impact limiter)
f72:n     18
fs72      -511
fm72      2.22e8
sd72      314.16 1r
c
fc102     Top of cask (surface of SS)
f102:n    4
fs102     -511
fm102     2.22e8
sd102     314.16 1r
c
fc112     Bottom of cask (surface of SS)
f112:n    1
fs112     -511
fm112     2.22e8
sd112     314.16 1r
c
fc122     Dose at top side of cask (by Co source, if present), perp to face
f122:n    10
fs122     -80
fm122     2.22e8
sd122     157.08 1r
c
fc132     Dose at top of cask (for Co), perp to corner
f132:n    10
fs132     -85
fm132     2.22e8
sd132     157.08 1r
c
fc142     Dose at top of cask (for Co), all the way around
f142:n    10
fs142     +121 -22
fm142     2.22e8
sd142     3032.6 2r
c
fc152     Dose at middle of cask, all the way around
f152:n    10
fs152     +82 -83
fm152     2.22e8
sd152     3032.6 2r
c
fc182     Dose at top of isocontainer
f182:n    103
fs182     -512
fm182     2.22e8
sd182     706.86 1r
c
fc192     Dose at bottom of isocontainer
f192:n    100
fs192     -512
fm192     2.22e8

```

```

sd192      706.86  1r
c
fc202      Dose at midplane of isocontainer
f202:n     104
fs202      -25
fm202      2.22e8
sd202      78.54  1r
c
fc212      Dose towards top of isocontainer (for Co)
f212:n     104
fs212      -80
fm212      2.22e8
sd212      78.54  1r
c
fc222      Dose at bottom side of cask (by Co source, if present), perp to face
f222:n     10
fs222      -87
fm222      2.22e8
sd222      157.08  1r
c
fc232      Dose at bottom of cask (for Co), perp to corner
f232:n     10
fs232      -86
fm232      2.22e8
sd232      157.08  1r
c
fc242      Dose at bottom of cask (for Co), all the way around
f242:n     10
fs242      +21 -120
fm242      2.22e8
sd242      3032.6  2r
c
fc252      Dose towards bottom of isocontainer (for Co)
f252:n     107
fs252      -87
fm252      2.22e8
sd252      78.54  1r
c
fc262      2m from top of iso
f262:n     211
fs262      -500 -501 -502 -503
fm262      2.22e8
sd262      7854  4r
c
fc272      4m from top of iso
f272:n     212
fs272      -500 -501 -502 -503
fm272      2.22e8
sd272      7854  4r
c
fc282      5m from top of iso
f282:n     213
fs282      -500 -501 -502 -503
fm282      2.22e8
sd282      7854  4r
c
fc292      6m from top of iso
f292:n     214
fs292      -500 -501 -502 -503
fm292      2.22e8
sd292      7854  4r
c
fc302      1m from right of iso
f302:n     221
fs302      -510
fm302      2.22e8
sd302      7854  1r
c
fc312      2m from right of iso
f312:n     222
fs312      -510

```

```

fm312      2.22e8
sd312      7854 1r
c
fc322      5m from right of iso
f322:n     223
fs322      -510
fm322      2.22e8
sd322      7854 1r
c
fc332      10m from right of iso
f332:n     224
fs332      -510
fm332      2.22e8
sd332      7854 1r
c
c
fc342      2m from bottom of iso
f342:n     217
fs342      -500 -501 -502 -503
fm342      2.22e8
sd342      7854 4r
c
fc352      4m from bottom of iso
f352:n     216
fs352      -500 -501 -502 -503
fm352      2.22e8
sd352      7854 4r
c
fc362      5m from bottom of iso
f362:n     215
fs362      -500 -501 -502 -503
fm362      2.22e8
sd362      7854 4r
c
fc372      6m from bottom of iso
f372:n     210
fs372      -500 -501 -502 -503
fm372      2.22e8
sd372      7854 4r
c
c
fc382      Bottom miser fire (bottom IL side)
f382:n     10
fs382      1 -18
fm382      2.22e8
sd382      6134.8 2r
c
fc392      Top miser fire (Top IL side)
f392:n     10
fs392      520 -521
fm392      2.22e8
sd392      3019 2r
c
fc402      Bottom iso edge
f402:n     100
fs402      522 -523 -524 107
fm402      2.22e8
sd402      500 4r
c
fc412      Top iso edge
f412:n     103
fs412      522 -523 -524 107
fm412      2.22e8
sd412      500 4r
c
mode       n
prdmp      1e8 5e5 1 2
nps        5000000
imp:n      0 1 90r
sdef       cel=400 erg=d1 pos 0 -64.57 49.37 rad=d2
           ext=d3 axs=0 0 1

```

sp1	-3	0.9060	3.848		
si2		14.6			
si3	a	0.0	3.4	6.9	10.3
		20.7	27.6	34.5	44.8
		280.0	300.7	311.1	321.4
		335.2	338.7	343.8	349.0
sp3		0.026	0.026	0.055	0.108
		0.342	0.547	0.677	0.827
		1.000	0.827	0.677	0.436
		0.148	0.077	0.038	0.038

Total Source = 2.22e8 n/sec

c	E, MeV	mR/hr/cm ² /s
c	da0	df0
c		
#		
	1.00E-07	0.0016
	1.00E-06	0.0017
	1.00E-05	0.0016
	1.00E-04	0.0015
	1.00E-03	0.0014
	1.00E-02	0.0016
	2.00E-02	0.0020
	3.00E-02	0.0026
	5.00E-02	0.0039
	7.50E-02	0.0056
	1.00E-01	0.0073
	1.50E-01	0.0106
	2.00E-01	0.0139
	3.00E-01	0.0200
	4.00E-01	0.0255
	6.00E-01	0.0353
	8.00E-01	0.0437
	1.00E+00	0.0509
	1.50E+00	0.0656
	2.00E+00	0.0769
	2.50E+00	0.0861
	3.00E+00	0.0938
	4.00E+00	0.1062
	5.00E+00	0.1161
	6.00E+00	0.1244
	8.00E+00	0.1379
	1.00E+01	0.1491
	1.20E+01	0.1590

MCNP Input for Storage Array, Neutrons

```

neutron, without water, with top impact limiter, 4' spacing
c
c Universe 0
c
999 0 221:-218:114:-209:213:-214 $Empty Universe
998 0 -112 113 -114 115 -116 117 fill=1
c
c Air and Dirt
c
300 5 -1.197e-3 115 -114 113 -112 116 -210 $top air
301 5 -1.197e-3 115 -114 113 -112 210 -211
302 5 -1.197e-3 115 -114 113 -112 211 -212
303 5 -1.197e-3 115 -114 218 -221 212 -213
c
310 5 -1.197e-3 115 -114 113 -112 217 -117 $bottom air
311 5 -1.197e-3 115 -114 113 -112 216 -217
312 5 -1.197e-3 115 -114 113 -112 215 -216
314 5 -1.197e-3 115 -114 218 -221 214 -215
c
320 5 -1.197e-3 115 -114 218 -225 215 -212 $left air
321 5 -1.197e-3 115 -114 225 -223 215 -212
322 5 -1.197e-3 115 -114 223 -113 215 -212
323 5 -1.197e-3 115 -114 112 -219 215 -212 $right air
324 5 -1.197e-3 115 -114 219 -220 215 -212
325 5 -1.197e-3 115 -114 220 -222 215 -212
326 5 -1.197e-3 115 -114 222 -224 215 -212
327 5 -1.197e-3 115 -114 224 -221 215 -212
c
330 7 -1.4 209 -115 218 -221 214 -213 $dirt
c
c Universe 1: The 6x1 lattice
c
997 0 -118 119 -182 183 185 -184 u=1 lat=1
fill=0:5 0:0 0:0 2 2 3 2 2 2
c
c Universe 2: FWR Cask with source
c
400 4 -2.682 -12 13 -14 15 21 -22 u=2 $ Fuel Cavity
401 2 -2.27 -12 13 -14 15 22 -121 u=2 $ Top nozzle
402 2 -1.32 -12 13 -14 15 120 -21 u=2 $ Bottom nozzle
403 5 -1.197e-3 -12 13 -14 15 121 -122 u=2 $ Air
404 5 -1.197e-3 120 -122 -13 -16 u=2 $ Air around fuel
405 5 -1.197e-3 120 -122 12 -16 u=2
406 5 -1.197e-3 120 -122 13 -12 14 -16 u=2
407 5 -1.197e-3 120 -122 13 -12 -15 -16 u=2
408 2 -7.82 120 -122 16 -17 u=2 $ Canister
409 2 -7.82 146 -120 -17 u=2 $ Bottom canister
410 2 -7.82 145 -146 -17 u=2 $ Bottom canister
411 2 -7.82 144 -145 -17 u=2 $ Bottom canister
412 2 -7.82 143 -144 -17 u=2 $ Bottom canister
413 2 -7.82 142 -143 -17 u=2 $ Bottom canister
414 2 -7.82 141 -142 -17 u=2 $ Bottom canister
415 2 -7.82 140 -141 -17 u=2 $ Bottom canister
416 2 -7.82 2 -140 -17 u=2 $ Bottom canister
417 2 -7.82 122 -123 -17 u=2 $ Top canister
418 2 -7.82 123 -124 -17 u=2 $ Top canister
419 2 -7.82 124 -125 -17 u=2 $ Top canister
420 2 -7.82 125 -127 -17 u=2 $ Top canister
421 2 -7.82 127 -128 -17 u=2 $ Top canister
422 2 -7.82 128 -129 -17 126 u=2 $ Top canister
423 2 -7.82 129 -130 -17 126 u=2 $ Top canister
424 2 -7.82 130 -3 -17 126 u=2 $ Top canister
425 5 -1.197e-3 128 -3 -126 u=2 $ Air in lid
426 5 -1.197e-3 2 -3 -5 17 u=2 $ Air
427 2 -7.8200 2 -3 5 -6 u=2 $ SS Inner Shell
c
c lead goes in here
428 2 -7.8200 76 -77 181 -3 u=2 $ SS Inner Water Shell (top)

```

```

429 2 -7.8200 77 -7 181 -3 u=2 $ SS Inner Water Shell (top)
430 2 -7.8200 2 -180 7 -8 u=2 $ SS Inner Water Shell (bottom)
431 3 -0.0001 .180 -3 7 -8 u=2 $ Water void (small)
432 3 -0.0001 2 -3 8 -9 u=2 $ Water void
433 2 -7.8200 2 -3 9 -10 u=2 $ SS Outer Water Shell
434 6 -0.144 4 -19 -10 u=2 $ Top impact limiter
435 6 -0.176 18 -1 -10 u=2 $ Bottom impact limiter

c stainless steel on bottom
30 2 -7.82 -10 40 -2 u=2
31 2 -7.82 -10 39 -40 u=2
32 2 -7.82 -10 38 -39 u=2
33 2 -7.82 -10 37 -38 u=2
34 2 -7.82 -10 36 -37 u=2
35 2 -7.82 -10 35 -36 u=2
36 2 -7.82 -10 34 -35 u=2
37 2 -7.82 -10 33 -34 u=2
38 2 -7.82 -10 32 -33 u=2
39 2 -7.82 -10 31 -32 u=2
40 2 -7.82 -10 1 -31 u=2

c stainless steel on top
50 2 -7.82 -10 3 -50 u=2
51 2 -7.82 -10 50 -51 u=2
52 2 -7.82 -10 51 -52 u=2
53 2 -7.82 -10 52 -53 u=2
54 2 -7.82 -10 53 -54 u=2
55 2 -7.82 -10 54 -55 u=2
56 2 -7.82 -10 55 -56 u=2
57 2 -7.82 -10 56 -57 u=2
58 2 -7.82 -10 57 -58 u=2
59 2 -7.82 -10 58 -4 u=2

c lead shielding
70 1 -11.3 2 -3 6 -70 u=2
71 1 -11.3 2 -3 70 -71 u=2
72 1 -11.3 2 -3 71 -72 u=2
73 1 -11.3 2 -3 72 -73 u=2
74 1 -11.3 2 -3 73 -74 u=2
75 1 -11.3 2 -3 74 -75 u=2
76 1 -11.3 2 -3 75 -76 u=2
77 1 -11.3 2 -181 76 -77 u=2
78 1 -11.3 2 -181 77 -7 u=2

c isocontainer
80 5 -1.197e-3 19 -102 105 -106 109 -110 u=2 $top
81 5 -1.197e-3 101 -18 105 -106 109 -110 u=2 $bottom
82 5 -1.187e-3 18 -19 105 -106 109 -110 10 u=2 $side
83 2 -7.82 104 -107 108 -111 102 -103 u=2 $top
84 2 -7.82 104 -107 108 -111 100 -101 u=2 $bottom
85 2 -7.82 101 -102 104 -105 109 -110 u=2 $side
86 2 -7.82 101 -102 106 -107 109 -110 u=2 $side
87 2 -7.82 101 -102 104 -107 108 -109 u=2 $side
88 2 -7.82 101 -102 104 -107 110 -111 u=2 $side
89 5 -1.187e-3 107 -104 -111 -108 -103 -100 u=2 $air

c
c Universe 3: BWR Cask with source
c
500 4 -2.682 -12 13 -14 15 120 -204 u=3 $ Fuel Cavity
503 5 -1.197e-3 -12 13 -14 15 204 -122 u=3 $ Air
504 5 -1.197e-3 120 -122 -13 -16 u=3 $ Air around fuel
505 5 -1.197e-3 120 -122 12 -16 u=3
506 5 -1.197e-3 120 -122 13 -12 14 -16 u=3
507 5 -1.197e-3 120 -122 13 -12 -15 -16 u=3
508 2 -7.82 120 -122 16 -17 u=3 $ Canister

c
c on the bottom canister, I am decreasing the density by 33% because the
c bottom is modeled as 6" instead of the true 4"
c
509 2 -5.21 146 -120 -17 u=3 $ Bottom canister
510 2 -5.21 145 -146 -17 u=3 $ Bottom canister
511 2 -5.21 144 -145 -17 u=3 $ Bottom canister
512 2 -5.21 143 -144 -17 u=3 $ Bottom canister
513 2 -5.21 142 -143 -17 u=3 $ Bottom canister
514 2 -5.21 141 -142 -17 u=3 $ Bottom canister

```

515	2	-5.21	140	-141	-17		u=3	\$ Bottom canister
516	2	-5.21	2	-140	-17		u=3	\$ Bottom canister
517	2	-7.82	122	-123	-17		u=3	\$ Top canister
518	2	-7.82	123	-124	-17		u=3	\$ Top canister
519	2	-7.82	124	-125	-17		u=3	\$ Top canister
520	2	-7.82	125	-127	-17		u=3	\$ Top canister
521	2	-7.82	127	-128	-17		u=3	\$ Top canister
522	2	-7.82	128	-129	-17	126	u=3	\$ Top canister
523	2	-7.82	129	-130	-17	126	u=3	\$ Top canister
524	2	-7.82	130	-3	-17	126	u=3	\$ Top canister
525	5	-1.197e-3	128	-3	-126		u=3	\$ Air in lid
526	5	-1.197e-3	2	-3	-5	17	u=3	\$ Air
527	2	-7.8200	2	-3	5	-6	u=3	\$ SS Inner Shell
c lead goes in here								
528	2	-7.8200	76	-77	181	-3	u=3	\$ SS Inner Water Shell (top)
529	2	-7.8200	77	-7	181	-3	u=3	\$ SS Inner Water Shell (top)
530	2	-7.8200	2	-180	7	-8	u=3	\$ SS Inner Water Shell (bottom)
531	3	-0.0001	180	-3	7	-8	u=3	\$ Water void (small)
532	3	-0.0001	2	-3	8	-9	u=3	\$ Water void
533	2	-7.8200	2	-3	9	-10	u=3	\$ SS Outer Water Shell
534	6	-0.144	4	-19	-10		u=3	\$ Top impact limiter
535	6	-0.176	18	-1	-10		u=3	\$ Bottom impact limiter
c stainless steel on bottom								
540	2	-7.82	-10	40	-2		u=3	
541	2	-7.82	-10	39	-40		u=3	
542	2	-7.82	-10	38	-39		u=3	
543	2	-7.82	-10	37	-38		u=3	
544	2	-7.82	-10	36	-37		u=3	
545	2	-7.82	-10	35	-36		u=3	
546	2	-7.82	-10	34	-35		u=3	
547	2	-7.82	-10	33	-34		u=3	
548	2	-7.82	-10	32	-33		u=3	
549	2	-7.82	-10	31	-32		u=3	
550	2	-7.82	-10	1	-31		u=3	
c stainless steel on top								
555	2	-7.82	-10	3	-50		u=3	
556	2	-7.82	-10	50	-51		u=3	
557	2	-7.82	-10	51	-52		u=3	
558	2	-7.82	-10	52	-53		u=3	
559	2	-7.82	-10	53	-54		u=3	
560	2	-7.82	-10	54	-55		u=3	
561	2	-7.82	-10	55	-56		u=3	
562	2	-7.82	-10	56	-57		u=3	
563	2	-7.82	-10	57	-58		u=3	
564	2	-7.82	-10	58	-4		u=3	
c lead shielding								
570	1	-11.3	2	-3	6	-70	u=3	
571	1	-11.3	2	-3	70	-71	u=3	
572	1	-11.3	2	-3	71	-72	u=3	
573	1	-11.3	2	-3	72	-73	u=3	
574	1	-11.3	2	-3	73	-74	u=3	
575	1	-11.3	2	-3	74	-75	u=3	
576	1	-11.3	2	-3	75	-76	u=3	
577	1	-11.3	2	-181	76	-77	u=3	
578	1	-11.3	2	-181	77	-7	u=3	
c isocontainer								
580	5	-1.197e-3	19	-102	105	-106 109 -110	u=3	\$top
581	5	-1.197e-3	101	-18	105	-106 109 -110	u=3	\$bottom
582	5	-1.187e-3	18	-19	105	-106 109 -110 10	u=3	\$side
583	2	-7.82	104	-107	108	-111 102 -103	u=3	\$top
584	2	-7.82	104	-107	108	-111 100 -101	u=3	\$bottom
585	2	-7.82	101	-102	104	-105 109 -110	u=3	\$side
586	2	-7.82	101	-102	106	-107 109 -110	u=3	\$side
587	2	-7.82	101	-102	104	-107 108 -109	u=3	\$side
588	2	-7.82	101	-102	104	-107 110 -111	u=3	\$side
589	5	-1.187e-3	107	-104	111	-108	103	-100 u=3 \$air
1 pz 2.84								
2 pz 24.1300								
3 pz 474.98								
4 pz 494.31								

5	c/z	0	-64.57	16.51	\$ Inside I.R
6	c/z	0	-64.57	17.30	\$ SS Shell O.R.
7	c/z	0	-64.57	33.51	\$ Lead O.R.
8	c/z	0	-64.57	36.68	\$ SS Shell O.R.
9	c/z	0	-64.57	47.63	\$ Water O.R.
10	c/z	0	-64.57	48.05	\$ Outer Shell O.R.
12	py		-54.25		
13	py		-74.89		
14	px		10.32		
15	px		-10.32		
16	c/z	0	-64.57	15.24	
17	c/z	0	-64.57	16.27	
18	pz		-17.48		
19	pz		524.79		
21	pz		49.37		
22	pz		398.37		
c					
31	pz		4.02		
32	pz		6.03		
33	pz		8.04		
34	pz		10.05		
35	pz		12.06		
36	pz		14.07		
37	pz		16.08		
38	pz		18.09		
39	pz		20.1		
40	pz		22.1		
c					
50	pz		476.89		
51	pz		478.79		
52	pz		480.70		
53	pz		482.60		
54	pz		484.51		
55	pz		486.41		
56	pz		488.32		
57	pz		490.22		
58	pz		492.3		
c					
70	c/z	0	-64.57	19.10	
71	c/z	0	-64.57	20.90	
72	c/z	0	-64.57	22.70	
73	c/z	0	-64.57	24.50	
74	c/z	0	-64.57	26.30	
75	c/z	0	-64.57	28.10	
76	c/z	0	-64.57	30.34	
77	c/z	0	-64.57	31.70	
c					
	isocontainer				
100	pz		-53.34		
101	pz		-53.14		
102	pz		556.06		
103	pz		556.26		
104	px		-121.92		
105	px		-121.72		
106	px		121.72		
107	px		121.92		
108	py		-121.92		
109	py		-121.72		
110	py		121.72		
111	py		121.92		
c					
	"real" ones to work with				
112	px		1950.7199		
113	px		-121.9199		
114	py		2999.9999		
115	py		-121.9999		
116	pz		556.2599		
117	pz		-53.3399		
c					
118	px		182.88		
119	px		-182.88		
c					
120	pz		39.37		


```

121 pz 408.37
122 pz 459.74
123 pz 461.645
124 pz 463.55
125 pz 465.455
126 c/z 0 -64.57 1.27
127 pz 467.36
128 pz 469.265
129 pz 471.17
130 pz 473.075
140 pz 26.035
141 pz 27.94
142 pz 29.845
143 pz 31.75
144 pz 33.655
145 pz 35.56
146 pz 37.456
c
180 pz 411.48
181 pz 398.78
182 py 3000
183 py -122
184 pz 600
185 pz -60
c
204 pz 410.37 $for BWR
c
c surfaces for air
c
209 py -400
210 pz 756.26
211 pz 956.26
212 pz 3604
213 pz 4823
214 pz -4320.54
215 pz -3101.34
216 pz -453.34
217 pz -253.34
218 px -6218
219 px 2150.72
220 px 2350.72
221 px 8047
222 px 4999
223 px -3170
224 px 6218
225 px -4389
c
c tally surfaces
c
96 c/x -64.57 223.87 15 $for right/left iso
97 c/x -64.57 223.87 10 $for right/left cask
302 c/z -1829 30 150 $P-5
303 c/z -1463 30 150 $P-4
304 c/z -1097 30 150 $P-3
305 c/z -731.5 30 150 $P-2
306 c/z -365.8 30 150 $P-1
307 c/z 0 30 150 $P1
308 c/z 365.8 30 150 $P2
309 c/z 731.5 30 150 $P3
310 c/z 1097 30 150 $P4
311 c/z 1463 30 150 $P5
312 c/z 1829 30 150 $P6
313 c/z 2195 30 150 $P7
314 c/z 2560 30 150 $P8
315 c/z 2926 30 150 $P9
316 c/z 3292 30 150 $P10
317 c/z 3658 30 150 $P11
318 c/z 4023 30 150 $P12
319 c/z 4389 30 150 $P13
320 c/z 4755 30 150 $P14
321 c/z 5120 30 150 $P15

```

```

351 c/z 297 -64.57 50 $2/4 m top
352 c/z 497 -64.57 50 $2/4 m top
353 c/z 697 -64.57 50 $2/4 m top
354 c/z 897 -64.57 50 $2/4 m top
355 c/z 1097 -64.57 50 $2/4 m top, D047
356 c/z 1297 -64.57 50 $2/4 m top
357 c/z 1497 -64.57 50 $2/4 m top
358 c/z 1697 -64.57 50 $2/4 m top
359 c/z 1897 -64.57 50 $2/4 m top
360 c/x -64.57 423.87 50 $2/4 m right
361 c/x -64.57 223.87 50 $2/4 m right
362 c/x -64.57 23.87 50 $2/4 m right
363 c/x 80 1209 200 $200' side
364 c/x 80 209.58 200 $200' side
365 c/x 80 -791 200 $200' side
400 c/z 0 -64.57 30 Stop/bottom iso P1
401 c/z 365.8 -64.57 30 Stop/bottom iso P2
402 c/z 731.5 -64.57 30 Stop/bottom iso P3
403 c/z 1097 -64.57 30 Stop/bottom iso P4
404 c/z 1463 -64.57 30 Stop/bottom iso P5
405 c/z 1829 -64.57 30 Stop/bottom iso P6

m1 82000. 1.0000 $ Lead
m2 26000. -0.6613 $ SS-304
    6012. -0.0008
    25055. -0.0200
    14000. -0.0100
    24000. -0.2000
    28000. -0.1050
    7014. -0.0010
    27059. -0.0012
m3 1001. 0.0669 $ Water
    8016. 0.0335
m4 95241. -252.7 $ Fuel Smear
    95243. -64.28
    63154. -5.8
    53129. -71.50
    93237. -183.8
    94238. -78.39
    94239. -1574.
    94240. -841.4
    94241. -238.1
    43099. -286.9
    92234. -48.17
    92235. -1330.
    92236. -1227.
    92238. -288800.
    8016 -39164
    40000 -64546

c -----
c Total 294930+39164+64546.
m5 7014 -75.55 $ air
    8016 -23.13
m6 1001 -0.0622 $ balsa wood
    6012 -0.4445
    8016 -0.4934
m7 14000 -0.467 $ "dirt" (silicon dioxide)
    8016 -0.533

print -85
c
c tallies
c
fc12 Top 140' Doses
f12:n 213
fs12 -302 -303 -304 -305 -306 -307 -308 -309 -310 -311
    -312 -313 -314 -315 -316 -317 -318 -319 -320 -321
fm12 6.32e8
sd12 70686 20r
c
c
fc22 Bottom 140' Doses

```

```

f22:n      214
fs22       -302 -303 -304 -305 -306 -307 -308 -309 -310 -311
           -312 -313 -314 -315 -316 -317 -318 -319 -320 -321
fm22       6.32e8
sd22       70686 20r
c
c
fc32       Top 100' Doses
f32:n      212
fs32       -302 -303 -304 -305 -306 -307 -308 -309 -310 -311
           -312 -313 -314 -315 -316 -317 -318 -319 -320 -321
fm32       6.32e8
sd32       70686 20r
c
c
fc42       Bottom 100' Doses
f42:n      215
fs42       -302 -303 -304 -305 -306 -307 -308 -309 -310 -311
           -312 -313 -314 -315 -316 -317 -318 -319 -320 -321
fm42       6.32e8
sd42       70686 20r
c
c
fc62       Top of Isocontainer
f62:n      116
fs62       -400 -401 -402 -403 -404 -405
fm62       6.32e8
sd62       2827 6r
c
c
fc72       Bottom of Isocontainer
f72:n      117
fs72       -400 -401 -402 -403 -404 -405
fm72       6.32e8
sd72       2827 6r
c
c
fc82       Left of Isocontainer (0 0 0)
f82:n      113
fs82       -96
fm82       6.32e8
sd82       707 1r
c
c
fc92       Left of Isocontainer (1 0 0)
f92:n      (104<997[1 0 0]<998)
fs92       -96
fm92       6.32e8
sd92       707 1r
c
c
fc102      Left of Isocontainer (2 0 0)
f102:n     (104<997[2 0 0]<998)
fs102      -96
fm102      6.32e8
sd102      707 1r
c
c
fc112      Left of Isocontainer (3 0 0)
f112:n     (104<997[3 0 0]<998)
fs112      -96
fm112      6.32e8
sd112      707 1r
c
c
fc122      Left of Isocontainer (4 0 0)
f122:n     (104<997[4 0 0]<998)
fs122      -96
fm122      6.32e8
sd122      707 1r
c
c
fc132      Left of Isocontainer (5 0 0)
f132:n     (104<997[5 0 0]<998)
fs132      -96
fm132      6.32e8
sd132      707 1r

```

```

c
c
fc142      Right of Isocontainer (0 0 0)
f142:n     (107<997[0 0 0]<998)
fs142      -96
fm142      6.32e8
sd142      707 1r
c
fc152      Right of Isocontainer (1 0 0)
f152:n     (107<997[1 0 0]<998)
fs152      -96
fm152      6.32e8
sd152      707 1r
c
fc162      Right of Isocontainer (2 0 0)
f162:n     (107<997[2 0 0]<998)
fs162      -96
fm162      6.32e8
sd162      707 1r
c
fc172      Right of Isocontainer (3 0 0)
f172:n     (107<997[3 0 0]<998)
fs172      -96
fm172      6.32e8
sd172      707 1r
c
fc182      Right of Isocontainer (4 0 0)
f182:n     (107<997[4 0 0]<998)
fs182      -96
fm182      6.32e8
sd182      707 1r
c
fc192      Right of Isocontainer (5 0 0)
f192:n     112
fs192      -96
fm192      6.32e8
sd192      707 1r
c
c
fc262      2m from bottom of Isocontainer
f262:n     217
fs262      -351 -352 -353 -354 -355 -356 -357 -358 -359
fm262      6.32e8
sd262      7854 9r
c
fc272      4m from bottom of Isocontainer
f272:n     216
fs272      -351 -352 -353 -354 -355 -356 -357 -358 -359
fm272      6.32e8
sd272      7854 9r
c
fc282      2m from top of Isocontainer
f282:n     210
fs282      -351 -352 -353 -354 -355 -356 -357 -358 -359
fm282      6.32e8
sd282      7854 9r
c
fc292      4m from top of Isocontainer
f292:n     211
fs292      -351 -352 -353 -354 -355 -356 -357 -358 -359
fm292      6.32e8
sd292      7854 9r
c
c
fc302      2m from Right of Array
f302:n     219
fs302      -360 -361 -362
fm302      6.32e8
sd302      7854 3r
c
fc312      4m from Right of Array

```

```

f312:n      220
fs312      -360 -361 -362
fm312      6.32e8
sd312      7854 3r
c
c
fc322      200' from Right of Array
f322:n      221
fs322      -363 -364 -365
fm322      6.32e8
sd322      125664 3r
c
c
fc332      200' from Left of Array
f332:n      218
fs332      -363 -364 -365
fm332      6.32e8
sd332      125664 3r
c
c
fc342      100' from Right of Array
f342:n      222
fs342      -363 -364 -365
fm342      6.32e8
sd342      125664 3r
c
c
fc352      100' from Left of Array
f352:n      223
fs352      -363 -364 -365
fm352      6.32e8
sd352      125664 3r
c
c
fc362      140' from Right of Array
f362:n      224
fs362      -363 -364 -365
fm362      6.32e8
sd362      125664 3r
c
c
fc372      140' from Left of Array
f372:n      225
fs372      -363 -364 -365
fm372      6.32e8
sd372      125664 3r
c
c
c
fc482      Cask (0 0 0)
f482:n      (10<997[0 0 0]<998)
fs482      -97
fm482      6.32e8
sd482      628 1r
c
c
fc492      Cask (1 0 0)
f492:n      (10<997[1 0 0]<998)
fs492      -97
fm492      6.32e8
sd492      628 1r
c
c
fc502      Cask (2 0 0)
f502:n      (10<997[2 0 0]<998)
fs502      -97
fm502      6.32e8
sd502      628 1r
c
c
fc512      Cask (3 0 0)
f512:n      (10<997[3 0 0]<998)
fs512      -97
fm512      6.32e8
sd512      628 1r
c
c
fc532      Cask (4 0 0)
f532:n      (10<997[4 0 0]<998)
fs532      -97
fm532      6.32e8

```

```

sd532      628 1r
c
fc542      Cask (5 0 0)
f542:n     (10<997[5 0 0]<998)
fs542      -97
fm542      6.32e8
sd542      628 1r
c
c
mode        n
prdmpr     1e8 5e5 1 2
nps        5000000
imp:n      0 1 168r
sdef       cel=d4 erg=d1 pos 0 -64.57 39.37 rad=d2
           ext=fcel=d5 axs=0 0 1
sp1        -3      0.9060      3.848
si2         14.6
si3         a      10.0      13.4      16.9      20.3      23.8
           30.7      37.6      44.5      54.8      72.1
           290.0     310.7     321.1     331.4     340.0
           345.2     348.7     353.8     359.0
sp3         0.026     0.026     0.055     0.108     0.200
           0.342     0.547     0.677     0.827     1.000
           1.000     0.827     0.677     0.436     0.264
           0.148     0.077     0.038     0.038
si13        a      0.0      3.6      7.3      10.9      14.7
           22.0     29.3     36.7     47.6     66.0
           297.7     319.7     330.7     341.7     350.8
           356.3     360.1     365.5     371.0
sp13        0.026     0.026     0.055     0.108     0.200
           0.342     0.547     0.677     0.827     1.000
           1.000     0.827     0.677     0.436     0.264
           0.148     0.077     0.038     0.038
si4         1 998:997(0 0 0):400 998:997(1 0 0):400 998:997(2 0 0):500
           998:997(3 0 0):400 998:997(4 0 0):400 998:997(5 0 0):400
sp4         0.362 0.367 0.410 1.0 0.362 0.362
ds5         s 3 3 13 3 3 3
c           Total Source = 6.32e8 n/sec
c
c
#           E, MeV      mrem/hr/cm^2/s
           de0         dE0
           1.00E-07      0.001605
           1.00E-06      0.001724
           1.00E-05      0.001646
           1.00E-04      0.001479
           1.00E-03      0.001397
           1.00E-02      0.001640
           2.00E-02      0.002045
           3.00E-02      0.002622
           5.00E-02      0.003897
           7.50E-02      0.005565
           1.00E-01      0.007255
           1.50E-01      0.01060
           2.00E-01      0.01385
           3.00E-01      0.01995
           4.00E-01      0.02553
           6.00E-01      0.03534
           8.00E-01      0.04369
           1.00E+00      0.05093
           1.50E+00      0.06557
           2.00E+00      0.07690
           2.50E+00      0.08608
           3.00E+00      0.09378
           4.00E+00      0.1062
           5.00E+00      0.1161
           6.00E+00      0.1244
           8.00E+00      0.1379
           1.00E+01      0.1491
           1.20E+01      0.1590

```

Appendix B

QA Package for NAC Cask Dose Rate Calculations

QA Package for NAC Cask Dose Rate Calculations

Geometry Assumptions/Approximations

1. Every detail of the cask was not modeled. The model was constructed to adequately simulate the shielding properties of the cask while keeping it as simple as possible. Dimensions were obtained from References 1 and 2.
2. The fuel was smeared. Individual rods were not modeled. The smeared fuel included the cladding.
3. The end fittings were smeared. It was assumed that they were 10 cm long.
4. The masses of the end fittings were approximated based information found in Reference 3.
5. It was assumed that the bottom of the canister containing consolidated fuel will be 4" thick, as opposed to 6" thick for the PWR fuel. However, to simplify the model, a 6" bottom was modeled in all cases, with the steel density reduced by 1/3 for the consolidated canister.
6. The thicknesses of the top and bottom cask lids do not match the true thicknesses of the lids because some additional steel was added. The reason is that there is a 0.109 inch thick sheet of stainless steel on the outer surface of the top impact limiter, and a 0.50 inch thick sheet of stainless steel on the outer surface of the bottom impact limiter. Rather than model these sheets separately, they were simply added to the thickness of the lids, which were 7.5 inches and 7.88 inches for the top and bottom, respectively.
7. Minimum tolerances were used (when known) so that the calculated dose rates would be conservative. Minimum tolerances were used on both the lead shield and the stainless steel cask lids. Tolerances were obtained from References 1 and 2.

Source Terms

All source terms used in the model were obtained from Reference 4.

Dose Rate Approximations/Corrections in Array Model

An approximation was made to calculate the dose rates on the sides of the cask in the array model. Because the outer surface of the cask was a cylinder, the dose rate tally cutting surface, which was also a cylinder, intersected the cask in two locations. Therefore, the dose rate computed was for the average combined dose rate on both the right and left sides of the casks.

However, we wanted the dose rates on the right and left sides separately, not combined. Since there were also tallies on the right and left sides of the isocontainers (the isocontainers were not cylinders), we assumed that the ratio of the left and right dose rates on the isocontainer would be the same as the ratios of the left and right sides of the cask. This assumption allowed us to extract approximate values for the dose rates on the cask.

Materials

References for the more uncommon materials used in the model are given below.

Stainless steel: The composition and density is from Reference 5.

Fuel: The isotopes used to represent the fuel in the MCNP calculations are a subset of the complete set of isotopes, which is provided in Reference 4. The subset of nuclides chosen represent almost 99%, by mass, of the total.

In addition to the actinides and select fission products, the oxygen in the fuel and the zirconium clad were also smeared. The density of the smeared fuel was computed based upon the total mass and volume.

The density of the fuel was computed for assembly D047 and used for every other assembly in the array calculation. This simplification is conservative because the other casks had a higher fuel smear density. A lower fuel density will provide less shielding.

Balsa wood: The density of the balsa wood impact limiters is given in Reference 1. The chemical composition was assumed to be that of wood (cellulose), $C_6H_{10}O_5$ (Reference 6).

Earth and concrete: The surrounding earth and concrete pad the isocontainers were placed on were assumed to be silicon dioxide (silica), SiO_2 , at 80% theoretical density. The density was taken from Reference 7.

Version of Code and Code QA

All calculations were carried out using MCNP Version 4B. Software quality assurance and configuration management was performed based on the policies and procedures outlined in Battelle's Standards Based Management System (SBMS). The SBMS procedures provide information on the requirements and procedures necessary for the quality assurance and configuration management activities. The code was executed on the HP workstation "RSA8."

File Descriptions

Typically, four different runs were made for each problem because there were four different sources in the problem: neutrons in the fuel, and photons in the fuel, top end fitting, and bottom end fitting. (No run was made for the "no cask top lid" model for the photons in the bottom end fitting because the dose rate would have been negligible).

Because of the thickness of the lead and stainless steel, variance reduction became difficult for the calculations with photons (because it was difficult for them to penetrate the shielding material). For both the single cask and array models, two models were run for the photons in the

fuel: one model tallied the dose rates out the sides of the cask, while the other model tallied the dose rate out the ends of the cask.

All of the input and output files are located on workstation RSA8, in the directory:
/files0/home/d30855/nac-1

The file names and their descriptions are provided in Table B-1.

Table B-1. Input and Output Filenames

File Name	Description
	Single Cask Problem
1cnf.i	Input file for single cask problem, neutron source
1cnf.o	Output file for 1cnf.i
1cnf.t	Tally output file for 1cnf.i
1cgf.i1	Input file for single cask problem, gamma source in fuel, variance reduction out sides of cask only
1cgf.o1	Output file for 1cgf.i1
1cgf.t1	Tally output file for 1cgf.i1
1cgf.i2	Input file for single cask problem, gamma source in fuel, variance reduction out ends of cask only
1cgf.o2	Output file for 1cgf.i2
1cgf.t2	Tally output file for 1cgf.i2
1cgt.i	Input file for single cask problem, gamma source in top end fitting
1cgt.o	Output file for 1cgt.i
1cgt.t	Tally output file for 1cgt.i
1cgb.i	Input file for single cask problem, gamma source in bottom end fitting
1cgb.o	Output file for 1cgb.i
1cgb.t	Tally output file for 1cgb.i
	No Cask Lid Problem
1lnf.i	Input file for no cask lid problem, neutron source
1lnf.o	Output file for 1lnf.i
1lnf.t	Tally output file for 1lnf.i
1nlgf.i	Input file for no cask lid problem, gamma source in fuel
1nlgf.o	Output file for 1nlgf.i
1nlgf.t	Tally output file for 1nlgf.i
1nlgt.i	Input file for no cask lid problem, gamma source in top end fitting
1nlgt.o	Output file for 1nlgt.i
1nlgt.t	Tally output file for 1nlgt.i
	Cask Array Problem
6cnf.i	Input file for cask array problem, neutron source
6cnf.o	Output file for 6cnf.i
6cnf.t	Tally output file for 6cnf.i
6cgf.i1	Input file for cask array problem, gamma source in fuel, variance reduction out ends of cask only
6cgf.o1	Output file for 6cgf.i1
6cgf.t1	Tally output file for 6cgf.i1
6cgf.i2	Input file for cask array problem, gamma source in fuel, variance reduction out sides of cask only
6cgf.o2	Output file for 6cgf.i2
6cgf.t2	Tally output file for 6cgf.i2
6cgt.i	Input file for cask array problem, gamma source in top end fittings
6cgt.o	Output file for 6cgt.i
6cgt.t	Tally output file for 6cgt.i
6cgb.i	Input file for cask array problem, gamma source in bottom end fittings
6cgb.o	Output file for 6cgb.i
6cgb.t	Tally output file for 6cgb.i

References

1. Nuclear Fuel Services drawing number E10080, Rev. 2, sheets 1-4.
2. PNNL drawing number H-3-304087, sheets 1-3.
3. Saling, J.J. 1986. *Nuclear Fuel Data*, WTSD-TME-148, Westinghouse Electric Corporation, Madison, PA.
4. Jenquin, U.P. 1996. *Inventory of LWR Spent Nuclear Fuel in the 324 Building*, PNNL-11273, Pacific Northwest National Laboratory, Richland, WA.
5. *Metals Handbook, Ninth Edition*, Volume 3, American Society for Metals, Metals Park, OH.
6. Van Vlack, L.H., 1989. *Elements of Materials Science and Engineering, Sixth Edition*, Addison Wesley, p. 381.
7. Bolz, R.E., et. al., 1973. *CRC Handbook of Applied Engineering Science, 2nd Edition*, CRC Press, Table 1-122, p. 193.

REVIEW CHECKLIST

HNF-3016, Rev. 0

Document Reviewed:

NAC-1 CASK DOSE-RATE CALCULATIONS FOR LWR SPENT FUEL
HNF-3016, Rev. 0

Scope of Review:

Independent Technical Review per attached e-mail

AB Carlson
10/1/98

Yes No NA

☒	☐	☐	* Previous reviews complete and cover analysis, up to scope of this review, with no gaps.
☒	☐	☐	Problem completely defined.
☒	☐	☒	Accident scenarios developed in a clear and logical manner.
☒	☐	☐	Necessary assumptions explicitly stated and supported.
☒	☐	☐	Computer codes and data files documented.
☒	☐	☐	Data used in calculations explicitly stated in document.
☒	☐	☐	Data checked for consistency with original source information as applicable.
☒	☐	☐	Mathematical derivation checked including dimensional consistency of results.
☒	☐	☐	Models appropriate and used within range of validity or use outside range of established validity justified.
☒	☐	☐	Hand calculations checked for errors. Spreadsheet results should be treated exactly the same as hand calculations.
☒	☐	☐	Software input correct and consistent with document reviewed.
☒	☐	☐	Software output consistent with input and with results reported in document reviewed.
☒	☐	☐	Limits/criteria/guidelines applied to analysis results are appropriate and referenced.
☒	☐	☐	Limits/criteria/guidelines checked against references.
☐	☐	☒	Safety margins consistent with good engineering practices.
☐	☐	☒	Conclusions consistent with analytical results and applicable limits.
☒	☐	☐	Results and conclusions address all points required in the problem statement.
☐	☐	☒	Format consistent with appropriate NRC Regulatory Guide or other standards.
☐	☐	☒	* Review calculations, comments, and/or notes are attached.
☒	☐	☐	Document approved.

TODD L MILES
Reviewer (Printed Name and Signature)

9/15/98
Date

* Any calculations, comments, or notes generated as part of this review should be signed, dated and attached to this checklist. Such material should be labeled and recorded in such a manner as to be intelligible to a technically qualified third party.

Carlson, Alan B

HNF-3016, Rev. 0

From: Miles, Todd L [todd.miles@pnl.gov]
Sent: Wednesday, September 30, 1998 4:07 PM
To: Carlson, Alan B
Cc: Jenquin, Urban P
Subject: RE: Review of NAC-1 Cask Dose Rate Calculations for LWR Spent Fuel, HNF-3016 Rev. 0

The Scope of my Review was an "Independent Technical Review."

-----Original Message-----

From: Carlson, Alan B
Sent: Wednesday, September 30, 1998 11:51 AM
To: Miles, Todd L
Cc: Jenquin, Urban P
Subject: Review of NAC-1 Cask Dose Rate Calculations for LWR Spent Fuel, HNF-3016 Rev. 0

Todd,

Tried by phone but couldn't reach you so after discussing things with Urban Jenquin I am attempting to contact you via e-mail.

At my request, Urban Jenquin has updated the subject document and he had also asked for you to provide a review of the document. In looking over the review checklist you completed, I have noticed that you didn't put anything in "Scope of Review" portion of the review checklist. This portion of the checklist needs to be completed.

My preference in completing the "Scope of Review" section is for you to send me an e-mail message stating the scope of your review. I will then enter that wording into the original review checklist and attach your e-mail message to the document.

You may decide on how detailed you want to define the scope. As an example though, Scope of Review for similar types of documents have been as simple as stating "Independent Technical Review".

Please also copy Urban Jenquin on your e-mail so he has a record.

Thanks,
Alan Carlson

DISTRIBUTION SHEET

To	From	Page 1 of 1
Distribution		Date 9/25/98
Project Title/Work Order		EDT No. 625776
NAC-1 Cask Dose-Rate Calculations for LWR Spent Fuel		ECN No. N/A

Name	MSIN	Text With All Attach.	Text Only	Attach./ Appendix Only	EDT/ECN Only
------	------	-----------------------------	-----------	------------------------------	-----------------

A. B. Carlson	R3-73
L. J. Garvin	R3-26
C. R. Hoover	R3-86
U. P. Jenquin (5)	K8-34
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