Rough Calculations: Dose Emanating from Bottom of Tipped-Over Cask

This calculation attempts to estimate the gamma dose emanating from the bottom of a single tipped-over HI-STORM 100 cask. To do this, I will attempt to calculate the dose rate at the bottom of an unshielded MPC container, given the dose rate at the bottom of a HI-TRAC transfer cask. Once this has been estimated, I will estimate the dose rate on the outside of the bottom of a HI-STORM cask which has been tipped over. I will first calculate the dose rate due to Co-60, then for fuel gammas (assuming all the dose is from Cs-137).

According to the SAR for the HI-STORM 100 cask, the dose rate adjacent to the bottom of a HI-TRAC transfer cask filled with design-basis fuel is 3058.38 mrem/hour. The "fuel gamma" dose rate at the same point is 238.28 mrem/hour. From drawings of the HI-TRAC contained in the HI-STORM SAR, this dose rate is after passing through shielding (2.75 inches of steel and approximately 1 inch of lead, in addition to the meter of air). To calculate the dose before attenuation by the shielding, the following equation is used, solving for D_o.

$$D(x) = D_0 \times e^{-\lambda_s x}$$

The shielding coefficient λ_s can be calculated with the tenth-value layer as follows:

λ_s (1/cm) = ln10/tenth-value layer

Table 1: Tenth Value Layers of Radionuclides

Radionuclide	Gamma Energy	Tenth-value layer			Shielding coefficient		
		Concrete	Steel	Lead	Concrete	Steel	Lead
	(MeV)	(cm)	(cm)	(cm)	(1/cm)	(1/cm)	(1/cm)
Cs-137	0.66	15.7	5.3	2.1	0.1467	0.4345	1.0965
Co-60	1.17, 1.33	20.6	6.9	4.0	0.1118	0.3337	0.5756

1). Co-60

A). Inside Dose Calculation

As was previously mentioned, the dose rate at the bottom of a HI-TRAC cask due to CO-60 was given as 3058.38 mrem/hour adjacent to the cask. Using the above shielding coefficients for steel and lead (ignoring any attenuation in air), we obtain the following value for the dose rate inside the shielding.

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$$\dot{D}_{inside} = \frac{D_{outside}}{e^{-(\lambda_L T_L + \lambda_{st} T_{st})}};$$

where the thickness of steel and lead were previously given (2.75 inches and 1 inch, respectively).

Using these values, we obtain a dose rate inside the shielding of **135,748.5 mrem/hour.**

B). Annulus Area Calculation

A central assumption in this calculation is that the majority of the gamma ray dose emanating from the bottom of the cask will travel through the annulus which, under normal conditions, allows for convective heat transfer. The annulus creates a ring in which it is possible for streams of radiation to pass through without being shielded by any concrete, with the only shielding being provided by the steel baseplate, estimated to be 3 inches thick.

The formula for calculating the area of an annulus is as follows:

$A = \pi(r_o^2 - r_i^2)$;

In this case, r_o = 36.75 inches and r_i = 34.1875 inches, based on drawings in the HI-STORM SAR.

Using these numbers, the area of the annulus is calculated to be 571 in^2.

Next, we need to estimate what percentage of the source term is able to stream through this annulus. As a bounding case, we take the percentage of area occupied by the annulus when compared to the area of the bottom of the HI-STORM that is considered part of the source term. This is bounding because we assume that the entire radiation dose is contained in the area bounded by the outer diameter of the annulus, thus arriving at the maximum fractional area for the annulus.

The area bounded by the outer radius (36.75 inches) is 4243 in^2. Therefore the annulus occupies 13.45% of this area.

C). Computation of Dose outside HI-STORM Annulus

We need to make and assumption regarding the fraction of radiation that can emanate directly through the annulus. As a first approximation, we make the assumption that 13.45% of the radiation emanating from the MPC container travels directly through the annulus, unencumbered by any concrete. This is an overestimate, since the MPC container stops at the inner radius of the annulus, meaning that there is no direct path through it. Therefore, as a second approximation, we reduce the area by a factor of 10.

Next, we recomputed the dose rate, this time on the outside of the HI-STORM cask, after passing through approximately 3 inches of steel. From the previous table, the shielding coefficient for Co-60 through steel is .3337 cm^{-1}. The shielding coefficient for Co-60 in air is 7.12e-5 cm^{-1}, which will be applied to obtain a dose rate at 1 meter from the bottom of the cask. The results are provided below for both cases (13.45% and 1.345% of the radiation emanating through the annulus, respectively.)

Table 2: Tipped-Over Cask Dose Rate from Co-60

Case	% of source term unshielded by concrete	Dose Rate inside shielding (mrem/hr)	Dose rate at 1 meter outside HI-STORM bottom (mrem/hour)
1	13.45	18,258	1426
2	1.345	1,825.8	142.6

D). Estimate of dose at site boundary assuming a line of casks overturning

If a line of casks overturn, we can estimate the dose at the boundary assuming a line source. The largest "line source" would consist of 80 casks overturning, creating a line 1,520 feet (463.3 meters). If we assume all 80 tip over so their bottoms are perpendicular to and facing the site boundary, we can estimate a linear source term for the two cases analyzed above as follows:

Table 3: Development of Line Source Term for Co-60

Case	Single Cask Dose rate @ 1 meter (mrem/hour)	Linear Source term (mrem/meter-hour)
1	1426	246.2
2	142.6	24.62

The dose rate from a linear source term decreases linearly with distance by the following formula:

$I_2 = I_1\theta/h$;

Where theta is the angle in the following diagram. In this case, theta =.79 rad, or approximately 45 degrees and h is equal to 555 meters.

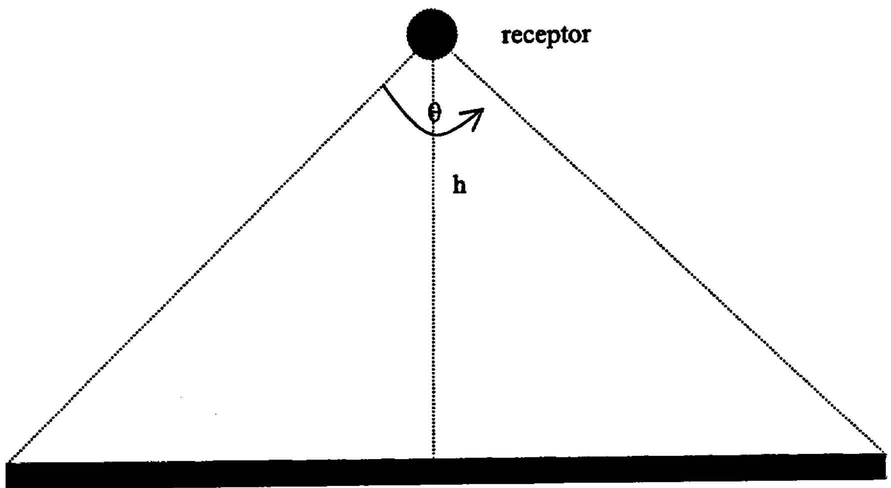

Figure 1: Explanation of angle in line source calculation

Using this formula, we obtain the following dose rates at the site boundary for the two cases.

Table 4: Dose Rate at Controlled Area Boundary from Co-60; No Attenuation in Air

Case	Dose Rate @ 555 meters		
	mrem/hour	mrem/year, 2000 hours/year	mrem/year, 8760 hours/year
1	.35	701	3070
2	.035	70.1	307

However, we did not take into account the shielding by the steel of the casks in this calculation. Therefore, we will discount value using Beer's Law, correcting for the broad-beam geometry.

$I/I_o = Be^{-ut}$

In this case, μ=7.12e-5 cm^{-1} for Co-60 through air and the buildup factor is approximately 6.7 (based on values from table 6.5.1 of *Handbook of Health Physics and Radiological Health*. Using this results in a reduction by a factor of .133. Thus, the final dose rate due to the postulated line source is given as:

Table 5: Dose Rate at Controlled Area Boundary from Co-60

Case	Dose Rate @ 555 meters, assuming attenuation in air		
	mrem/hour	mrem/year, 2000 hours/year	mrem/year, 8760 hours/year
1	.047	93.6	410
2	.0047	9.36	41.0

2). Cs-137

A). Inside Dose Calculation

The fuel gamma dose rate at the bottom of a HI-TRAC cask was given in the HI-STORM SAR as 238.28 mrem/hour adjacent to the cask. Using the above shielding coefficients for steel and lead (ignoring any attenuation in air), we obtain the following value for the dose rate inside the shielding.

$$D_{inside} = \frac{D_{outside}}{e^{-(\lambda_L T_L + \lambda_{st} T_{st})}};$$

where the thickness of steel and lead were previously given (2.75 inches and 1 inch, respectively).

Using these values, we obtain a dose rate inside the shielding of **80,301.1 mrem/hour.**

B). Annulus Area Calculation

A central assumption in this calculation is that the majority of the gamma ray dose emanating from the bottom of the cask will travel through the annulus which, under normal conditions, allows for convective heat transfer. The annulus creates a ring in which it is possible for streams of radiation to pass through without being shielded by any concrete, with the only shielding being provided by the steel baseplate, estimated to be 3 inches thick.

The formula for calculating the area of an annulus is as follows:

$A = \pi(r_o^2 - r_i^2)$;

In this case, r_o = 36.75 inches and r_i = 34.1875 inches, based on drawings in the HI-STORM SAR.

Using these numbers, the area of the annulus is calculated to be 571 in^2.

Next, we need to estimate what percentage of the source term is able to stream through this annulus. As a bounding case, we take the percentage of area occupied by the annulus when compared to the area of the bottom of the HI-STORM that is considered part of the source term. This is bounding because we assume that the entire radiation dose is contained in the area bounded by the outer diameter of the annulus, thus arriving at the maximum fractional area for the annulus.

The area bounded by the outer radius (36.75 inches) is 4243 in^2. Therefore the annulus occupies 13.45% of this area.

C). Computation of Dose outside HI-STORM Annulus

We need to make and assumption regarding the fraction of radiation that can emanate directly through the annulus. As a first approximation, we make the assumption that 13.45% of the radiation emanating from the MPC container travels directly through the annulus, unencumbered by any concrete. This is an overestimate, since the MPC container stops at the inner radius of the annulus, meaning that there is no direct path through it. Therefore, as a second approximation, we reduce the area by a factor of 10.

Next, we recomputed the dose rate, this time on the outside of the HI-STORM cask, after passing through approximately 3 inches of steel. From the previous table, the shielding coefficient for Cs-137 through steel is .4345 cm^{-1}. The shielding coefficient for Cs-137 in air is 9.31e-5 cm^{-1}, which will be applied to obtain a dose rate at 1 meter from the bottom of the cask. The results are provided below for both cases (13.45% and 1.345% of the radiation emanating through the annulus, respectively.)

Table 6: Tipped-Over Cask Dose Rate from Cs-137

Case	% of source term unshielded by concrete	Dose Rate inside shielding (mrem/hr)	Dose rate at 1 meter outside HI-STORM bottom (mrem/hour)
1	13.45	10,801	391
2	1.345	1,825.8	39.1

3). Estimate of dose at site boundary assuming a line of casks overturning

If a line of casks overturn, we can estimate the dose at the boundary assuming a line source. The largest "line source" would consist of 80 casks overturning, creating a line 1,520 feet (463.3 meters). If we assume all 80 tip over so their bottoms are perpendicular to and facing the site boundary, we can estimate a linear source term for the two cases analyzed above as follows:

Table 7: Development of Line Source Term for Cs-137

Case	Single Cask Dose rate @ 1 meter (mrem/hour)	Linear Source term (mrem/meter-hour)
1	394	67.5
2	39.4	6.75

The dose rate from a linear source term decreases linearly with distance by the following formula:

$I_2 = I_1\theta/h$;

Using this formula, we obtain the following dose rates due to Cs-137 at the site boundary for the two cases.

Table 8: Dose Rate at Controlled Area Boundary from Cs-137; No Attenuation in Air

Case	Dose Rate @ 555 meters		
	mrem/hour	mrem/year, 2000 hours/year	mrem/year, 8760 hours/year
1	.097	194	849
2	.0097	19.4	84.9

However, we did not take into account the shielding by the steel of the casks in this calculation. Therefore, we will discount value using Beer's Law, correcting for the broad-beam geometry.

$I/I_o = Be^{-ut}$

In this case, μ=9.67e-5 cm^{-1} for Cs-137 through air and the buildup factor is approximately 10 (based on values from table 6.5.1 of *Handbook of Health Physics and Radiological Health*. Using this results in a reduction by a factor of .049. Thus, the final Cs-137 dose rate due to the postulated line source is given as:

Table 9: Dose Rate at Controlled Area Boundary from Cs-137

Case	Dose Rate @ 555 meters, assuming attenuation in air		
	mrem/hour	mrem/year, 2000 hours/year	mrem/year, 8760 hours/year
1	.0048	9.52	41.7
2	.00048	0.952	4.17

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dding up the doses from Co-60 and Cs-137, we obtain the following dose rates at the controlled area boundary"

Table 10: Estimated Dose Rate at Controlled Area Boundary, Multiple Cask Tip-Over

Case	Dose Rate @ 555 meters, assuming attenuation in air		
	mrem/hour	mrem/year, 2000 hours/year	mrem/year, 8760 hours/year
1	.05	103	451
2	.005	10.3	45.1