Determination of the Gamma-Ray Skyshine Dose Contribution in a Loss Of Shielding Accident

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ABSTRACT

The goal of this research is to determine the gamma-ray dose contribution from skyshine. In a transportation accident involving the loss of lead gamma shielding, first responders to the accident will be exposed to both direct gamma radiation streaming from the exposed spent nuclear fuel and atmospherically reflected gamma radiation. The reflected radiation is referred to as skyshine and should contribute minimally to the overall dose; however, when there is minimal shielding above the exposed source, skyshine at large distances from the source must be considered. The program SKYDOSE developed by Shultis and Faw evaluates the gamma-ray skyshine dose from a point, isotropic, polyenergetic, gamma-photon source. Assuming an infinite black wall shielding all direct radiation, the model assumes a first responder is located at varying distances from the wall. Skyshine doses are calculated both through SKYDOSE’s integral line-beam method and an approximate approach prescribed by the National Council of Radiation Protection and Measurements. Initial results from SKYDOSE indicate nearly equivalent dose rates from either direct or skyshine radiation at nine meters from the wall, which seemed unusual and not readily explained. NCRP methodology, however, yields skyshine dose rates which are drastically smaller than direct dose rates at the same distance. Further investigation using the program MicroSkyshine®, which allows a variety of source configurations, suggests skyshine contributes minimally to dose in a loss-of-shielding accident.

INTRODUCTION and OBJECTIVE

In order to estimate the risks and possible consequences of the transportation of radioactive-material, a computer code called RADTRAN was developed in 1977 [1]. RADTRAN is used to assess risks from a transportation accident as well as the risks from incident-free transportation. In the near future, RADTRAN 6.0 will incorporate the capability to calculate doses received by both first responders and the general public for an incident where the transportation cask lead gamma shielding is compromised.

Various devastating worst-case accident scenarios could involve the spent nuclear fuel (SNF) cask impacting a stationary object or being fully engulfed in an extremely high temperature long duration fire. Either scenario could lead to degradation in the lead gamma shielding. In a severe impact, the lead would deform due to the force of the impact. In an engulfing fire, the lead could yield and flow away due to the low melting point. In either case, the void can potentially expose the fuel and is referred to as slump. Figure 1 represents an example of lead slump as a result of a high speed impact.

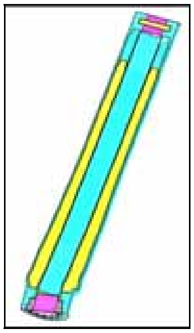

Fig. 1. Finite Element Analysis for a Lead-Shielded Truck Cask involved in 144.8 km/hr corner impact without Impact Limiters [2].

To evaluate the potential radiological impact of a Loss-of-Shielding (LOS) accident, an LOS model was developed and incorporated into RADTRAN [2]. Previous work has explored the direct dose received in a LOS accident at varying radial and axial positions from a spent fuel cask [2, 3]. However, the dose contribution from gamma-ray skyshine had not been considered. The goal of this research is to determine the gamma-ray dose contribution from skyshine.

In a transportation accident involving the loss of lead gamma shielding, first responders to the accident will be exposed to both direct gamma radiation streaming from the exposed SNF and atmospherically reflected gamma radiation. The reflected radiation is referred to as skyshine and should contribute minimally to the overall dose; however, when there is minimal shielding above the exposed source, skyshine at large distances from the source must be considered [4].

Three separate methods were employed to determine the skyshine dose in a hypothetical accident scenario. For a first approximation, the computer code SKYDOSE developed by Shultis and Faw was used. Secondly, an analytical approximation using a recommendation from the National Council of Radiation Protection and Measurements (NCRP) was used to compare the SKYDOSE estimates. Finally, Grove Software’s computer code MicroSkyshine® 2.0 was used to evaluate a more refined model and provided results more consistent with expected values.

SYSTEM PARAMETERS

Any one of the previously mentioned modeling approaches requires some initial information to perform the analysis. With this in mind, the type of accident scenario was defined as a LOS accident in which a SNF stainless steel-lead-stainless steel (S.S.-Pb-S.S.) rail cask was transported through an urban environment. This indicates that when the rail car stops, it is located in a commercial urban district shielded on both sides by buildings. Before proceeding any further, it should be noted what type of SNF rail cask is being used and some applicable dimensions. Information on SNF rail casks was obtained from NUREG/CR-6672 [5]. The report provides pertinent cask dimensions for various S.S.-Pb-S.S. rail casks, as well as suggesting values for a generic rail cask. For the purposes of this research, the generic dimensions were used, converted to metric units, and are presented below in Table I.

Table I. Generic SNF Steel-Lead-Steel Rail Cask Parameters [5]

Outside Diameter (m)	Cavity Diameter (m)	Lead Wall Thickness (m)	Cask Length (m)
2.032	1.651	0.1143	5.08

For skyshine all models used, each assumes that the shielding medium is a black wall or box, meaning all incident radiation on that surface is fully attenuated. Therefore, the shielding material thickness is dimensionless.

No account of how the lead gamma shielding was lost is considered, only the fact that approximately 5 % slump occurred in the shielding. Therefore, assuming the lead slump occurs along the length of the cask and equally circumferentially, 0.254 cm of fuel is exposed in the accident. This length of exposed fuel, combined with the cask cavity diameter from Table I, was used to determine the percent volume of fuel exposed, 3.3%. This value is crucial in determining the activity of exposed fuel. Activity values for 15 year cooled Pressurized Water Reactor (PWR) SNF were obtained from the Yucca Mountain Final Environmental Impact Statement [6]. This Curie content per isotope was multiplied by 24 to account for the number of individual assemblies present in the generic SNF rail cask. Also, all isotope activities were multiplied by a factor of 0.033 to account for 3.3% of the total fuel volume exposed. The difference in unshielded and shielded activity is also reported below. It should also be noted that only isotopes which emitted gamma-rays were considered. Table II presents the activity content used for modeling.

Other distance parameters necessary for modeling are the distance from source to wall and the wall height. The distance from source to wall was assumed to be 30 meters based on the default value used in RADTRAN [1]. The average urban building height was chosen as12 meters. Finally, the maximum first responder distance was assigned as 0.25 miles (400 meters) from the wall (again, the shielding from buildings is assumed to be an infinite black wall). Also, the simulated first responder is assumed to be 1.83 meters tall (6 feet). These two values, distance from the wall and responder height, determine the detector placement for dose determination.

Table II. Radionuclide Activity Inventory for 24 PWR assemblies, shielded and unshielded

Isotope	Activity (Ci)	Total Activity for 24 Assemblies (Ci)	Total Unshielded Activity for 24 Assemblies (Ci)	Total Shielded Activity for 24 Assemblies (Ci)
Ac-227	1.30E-05	3.12E-04	1.03E-05	3.02E-04
Am-241	1.50E+03	3.60E+04	1.19E+03	3.48E+04
Am-242m	7.20E+00	1.73E+02	5.70E+00	1.67E+02
Am-243	2.00E+01	4.80E+02	1.58E+01	4.64E+02
Ba-137m	5.20E+04	1.25E+06	4.12E+04	1.21E+06
Cl-36	6.30E-03	1.51E-01	4.99E-03	1.46E-01
Cm-242	5.90E+00	1.42E+02	4.67E+00	1.37E+02
Cm-243	1.30E+01	3.12E+02	1.03E+01	3.02E+02
Cm-244	1.80E+03	4.32E+04	1.43E+03	4.18E+04
Cm-245	2.90E-01	6.96E+00	2.30E-01	6.73E+00
Cm-246	9.10E-02	2.18E+00	7.21E-02	2.11E+00
Co-60 Structure	1.10E+03	2.64E+04	8.71E+02	2.55E+04
Co-60 CRUD	8.80E+00	2.11E+02	6.97E+00	2.04E+02
Cs-134	7.20E+02	1.73E+04	5.70E+02	1.67E+04
Eu-154	1.50E+03	3.60E+04	1.19E+03	3.48E+04
Eu-155	2.20E+02	5.28E+03	1.74E+02	5.11E+03
Fe-55	4.00E+01	9.60E+02	3.17E+01	9.28E+02
I-129	2.20E-02	5.28E-01	1.74E-02	5.11E-01
Kr-85	2.20E+03	5.28E+04	1.74E+03	5.11E+04
Nb-93m	1.90E+01	4.56E+02	1.50E+01	4.41E+02
Nb-94	8.10E-01	1.94E+01	6.42E-01	1.88E+01
Ni-59	1.90E+00	4.56E+01	1.50E+00	4.41E+01
Np-237	2.50E-01	6.00E+00	1.98E-01	5.80E+00
Pa-231	3.30E-05	7.92E-04	2.61E-05	7.66E-04
Pm-147	1.70E+03	4.08E+04	1.35E+03	3.95E+04
Pu-238	2.60E+03	6.24E+04	2.06E+03	6.03E+04
Pu-239	1.80E+02	4.32E+03	1.43E+02	4.18E+03
Pu-240	3.10E+02	7.44E+03	2.46E+02	7.19E+03
Pu-242	1.50E+00	3.60E+01	1.19E+00	3.48E+01
Sb-125	1.20E+02	2.88E+03	9.50E+01	2.78E+03
Sm-151	2.40E+02	5.76E+03	1.90E+02	5.57E+03
Sn-126	3.70E-01	8.88E+00	2.93E-01	8.59E+00
Tc-99	9.10E+00	2.18E+02	7.21E+00	2.11E+02
Th-230	9.90E-05	2.38E-03	7.84E-05	2.30E-03
U-232	2.40E-02	5.76E-01	1.90E-02	5.57E-01
U-233	3.20E-05	7.68E-04	2.53E-05	7.43E-04
U-234	6.70E-01	1.61E+01	5.31E-01	1.55E+01
U-235	8.80E-03	2.11E-01	6.97E-03	2.04E-01
U-236	1.90E-01	4.56E+00	1.50E-01	4.41E+00
U-238	1.40E-01	3.36E+00	1.11E-01	3.25E+00

System Diagram

Using the parameters determined in the previous section, a schematic of the problem is easily constructed. Figure 2 on the following page illustrates the problem setup.

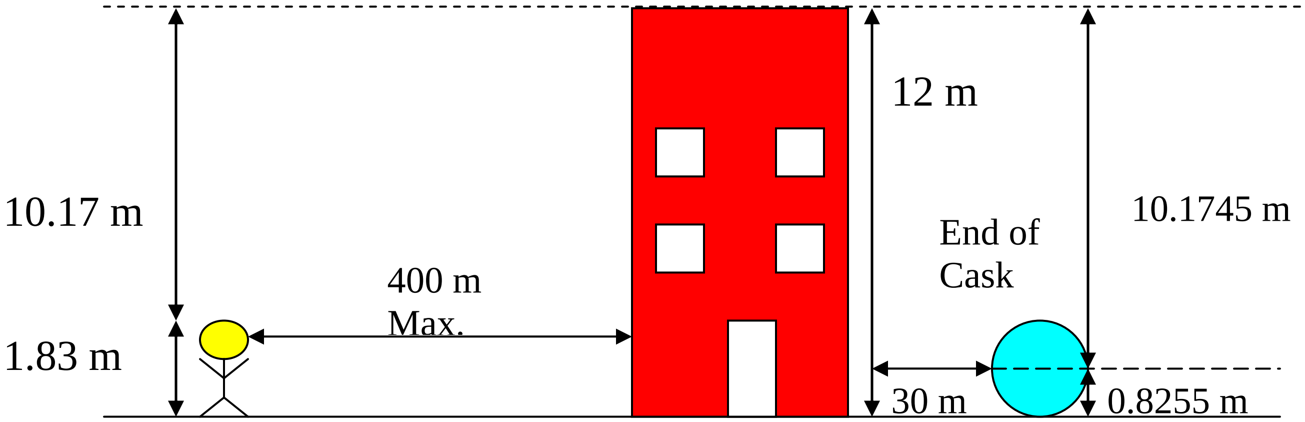

Fig. 2. System parameters schematic

ANALYSIS

When this research first began, the only model available to estimate gamma-ray skyshine was the code SKYDOSE. When unreasonable dose rates were obtained using SKYDOSE, an approximate analytical approach from NCRP was used to compare results. However, neither method corroborated the other so a commercially developed code, MicroSkyshine® 2.0 was used to determine the dose to a first responder. In the following section, a brief discussion of the results from SKYDOSE and the NCRP method is presented, along with a more exhaustive explanation of the final method using MicroSkyshine® 2.0.

Solution Using SKYDOSE

The program SKYDOSE developed by Shultis and Faw evaluates the gamma-ray skyshine dose from a point, isotropic, polyenergetic, gamma-photon source [7]. Assuming an infinite black wall shielding all direct radiation, the code places a detector at varying distances from the wall. The skyshine dose is approximated using the integral line-beam skyshine method from the line-beam response function [4, 7].[1]

In this treatment, only the unshielded portion of the rail cask was modeled and the dose obtained is for one SNF assembly. The system parameters presented above were used in SKYDOSE. The results for various distances are presented in Table III.

As Table III indicates, the skyshine dose rate is extremely high at a distance of only 39 meters from the source. Comparing this value to the direct unshielded dose rate for the same source and geometry as simulated in MicroShield® 7.01, it is difficult to believe that at 39 meters skyshine contributes to almost $^{1}/_{12}$ of the total dose. With these unexpectedly high values, another approach was sought to either confirm or deny the results.

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[1] For a more detailed explanation of the theory and derivation behind the integral line-beam skyshine method, refer to reference 4 and 7.

Table III. SKYDOSE Calculated Skyshine Dose

Distance from Source (m)	Distance from wall (m)	SKYDOSE Skyshine (mrem/hr)	MicroShield Point Dose w/Buildup (mrem/hr)
39	9	1021.4	12290
107.3	77.3	224.7	1752
204.9	174.9	49.9	
302.4	272.4	13.8	
400	370	4.2	26.27

NCRP Skyshine Approximation for Medical Accelerator

The closest analytical approximation available for skyshine was a method prescribed by NCRP Report No. 51 in which it calculates the photon component of skyshine for an 18 MeV accelerator using Equation 1 [8].

$$B_{xs} = (4.02E-06)\frac{\overset{*}{D}_x d_i^2 d_s^2}{\overset{*}{D}_{IO}\,\Omega^{1.3}} \qquad \text{(Eq. 1)}$$

where:

$\overset{*}{D}_x$ = photon dose equivalent rate at ground level outside the shield (nSv sec^{-1})

d_s = distance from isocenter of the point where dose equivalent rate is $\overset{*}{D}_x$

d_i = distance from x-ray target to point 2 meters above roof

$\overset{*}{D}_{IO}$ = x-ray dose rate at 1 meter from target (cGy sec^{-1})

Ω = solid angle of radiation beam

B_{xs} = roof shielding transmission ratio (1 if no ceiling shield)

Some important assumptions must be stated before using this approach. First, the equation is only good up to approximately 107 meters and the accuracy degrades rapidly at larger distances. Second, no roof shielding is used. This is done to match the problem setup using SKYDOSE. Third, the results are multiplied by a 5.3 correction factor to account for the difference between measured and calculated results [8]. Finally, the initial dose rate, $\overset{*}{D}_{IO}$, was determined using MicroShield® 7.01 to be 366,200 mrem/hr at 1 meter. Performing the calculations, the dose rate at 39 and 107.3 meters was found and is presented in Table IV.

Table IV. NCRP Method Analytical Results

Distance from Source (m)	NCRP No. 51 Skyshine (mrem/hr)
39	1.18
107.3	0.157

The results presented in Table IV are three orders of magnitude less than the results obtained using SKYDOSE. The continued inconsistency warranted a third and final approach using MicroSkyshine® 2.0.

Skyshine Determination using MicroSkyshine® 2.0

Grove Software's MicroSkyshine® 2.0 is a commercial, vastly updated version of the older program SKYDOSE. As in the case of SKYDOSE, MicroSkyshine® 2.0 uses the integral line-beam skyshine method from the line-beam response function [9]. Therefore, the approximation technique is very similar; however, MicroSkyshine® 2.0 allows the user to define much more extensive source and source to detector geometries. Of the various source geometries available, a horizontal cylinder volume source behind a wall was chosen. Modeling the source volume as a cylinder is a slight approximation since the fuel assemblies are actually square and arranged in a lattice structure that approximates a cylinder. However, at increasing distances, the source appears cylindrical. Again, the source is assumed to be behind an infinite black wall, approximating the buildings shielding the first responders. Figure 3 shows the configuration for the problem as viewed from the side and above.

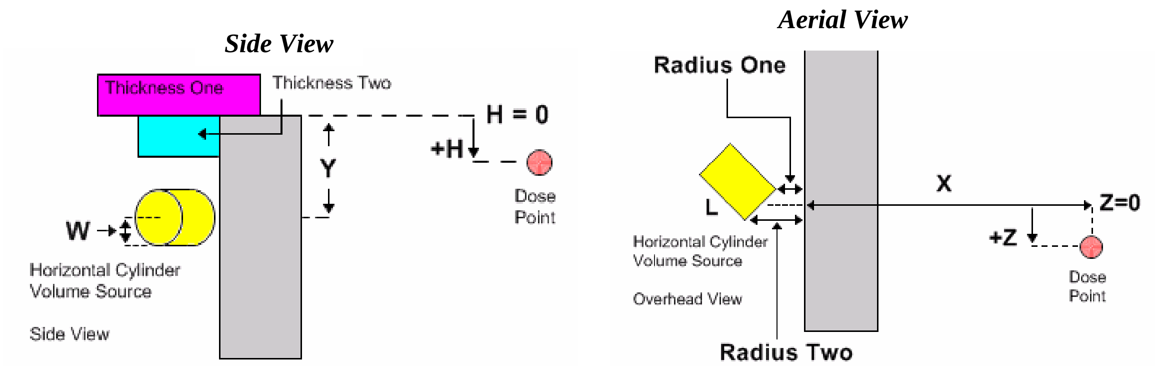


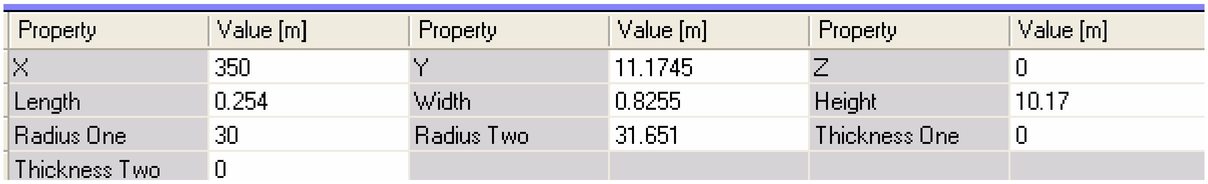
Fig. 3. Generic side and aerial view of problem geometry as presented in MicroSkyshine® 2.0

The problem must be further partitioned into two cases. Case 1 represents the unshielded slumped portion of the fuel. Case 2 represents the remaining length of the cask that is still shielded and minimally contributing to skyshine dose.

Case I: 3.3% Unshielded Cask Volume from 5% Slump

Since this case is modeled as an unshielded source, it is not necessary to have the top shield present as represented with the pink and blue squares in the side view of Figure II. Additionally, the source cylinder is parallel to the wall at a distance of 30 meters. Initial values derived from the earlier section on system parameters were input into MicroSkyshine® 2.0. These values are listed below in Table V.

Table V. Case I Input Values

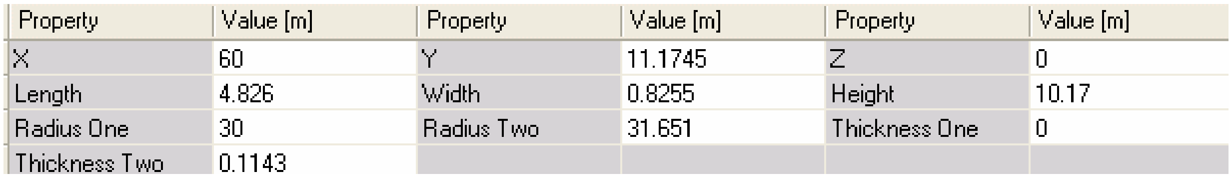


Property	Value [m]	Property	Value [m]	Property	Value [m]
X	350	Y	11.1745	Z	0
Length	0.254	Width	0.8255	Height	10.17
Radius One	30	Radius Two	31.651	Thickness One	0
Thickness Two	0				

Case II: 96.7% Shielded Cask Volume

In this case, it is necessary to have the top shield present as represented by the blue square (Thickness Two) in Figure II. This is necessary because the skyshine dose from the remaining 4.826 meters of shielded cask must be accounted. In MicroSkyshine® 2.0 there is no method of wrapping a shield material around the source; therefore, it was approximated that the shield was a 0.1143 meter thick lead slab. This is a conservative assumption because the thickest portion of the annular lead enclosing the fuel is 0.1143 meters. Initial values derived from the earlier section on system parameters were input into MicroSkyshine® 2.0. These values are listed below in Table VI.

Table VI. Case II Input Values



Property	Value [m]	Property	Value [m]	Property	Value [m]
X	60	Y	11.1745	Z	0
Length	4.826	Width	0.8255	Height	10.17
Radius One	30	Radius Two	31.651	Thickness One	0
Thickness Two	0.1143				

RESULTS

A source file used in Case I and II was created using the activities from Table II. The numerical quadrature for integration of the point kernel was chosen as "32 – Most Accurate". The radial, circumferential, and length segments were all set to 15. Both Case I and II were run for first responder distances from the wall ranging from 10 to 400 meters. It should be noted that MicroSkyshine® 2.0 reports the exposure [mRoentgen/hour] and not dose rate. Therefore, the results were multiplied by 0.88 and a quality factor of 1 to convert to mrem/hour [10]. The results for Case I and II and the combined dose rate are presented in Table VII and graphed in Figure 4.

Table VII. Case I and II Results and Combined Dose Rate for 10 to 400 Meters

3.3% total volume exposed fuel, 5% slump, no shielding			97.6% shielded fuel w/0.1134m lead			
Distance [m] (Wall to Detector)	**Exposure [mR/hr]**	**Dose Rate [mrem/hr]**	**Distance [m] (Wall to Detector)**	**Exposure [mR/hr]**	**Dose Rate [mrem/hr]**	**Total Dose Rate [mrem/hr]**
10	5.72E+00	5.04E+00	10	1.22E-02	1.07E-02	5.05E+00
20	4.49E+00	3.95E+00	20	9.64E-03	8.48E-03	3.96E+00
30	3.60E+00	3.17E+00	30	7.79E-03	6.86E-03	3.18E+00
40	2.94E+00	2.59E+00	40	6.40E-03	5.63E-03	2.59E+00
50	2.43E+00	2.14E+00	50	5.32E-03	4.68E-03	2.14E+00
60	2.03E+00	1.79E+00	60	4.47E-03	3.93E-03	1.79E+00
80	1.44E+00	1.27E+00	80	3.21E-03	2.82E-03	1.27E+00
100	1.05E+00	9.21E-01	100	2.35E-03	2.07E-03	9.23E-01
120	7.71E-01	6.78E-01	120	1.75E-03	1.54E-03	6.80E-01
140	5.74E-01	5.05E-01	140	1.31E-03	1.15E-03	5.06E-01
150	4.97E-01	4.37E-01	150	1.14E-03	1.00E-03	4.38E-01
160	4.31E-01	3.80E-01	160	9.92E-04	8.73E-04	3.80E-01
180	3.26E-01	2.87E-01	180	7.56E-04	6.65E-04	2.88E-01
200	2.49E-01	2.19E-01	200	5.79E-04	5.10E-04	2.19E-01
220	1.90E-01	1.67E-01	220	4.46E-04	3.92E-04	1.68E-01
240	1.46E-01	1.29E-01	240	3.45E-04	3.03E-04	1.29E-01
250	1.29E-01	1.13E-01	250	3.03E-04	2.67E-04	1.13E-01
260	1.13E-01	9.94E-02	260	2.67E-04	2.35E-04	9.97E-02
280	8.76E-02	7.71E-02	280	2.08E-04	1.83E-04	7.73E-02
300	6.81E-02	5.99E-02	300	1.62E-04	1.43E-04	6.01E-02
320	5.32E-02	4.68E-02	320	1.27E-04	1.12E-04	4.69E-02
340	4.16E-02	3.66E-02	340	9.95E-05	8.75E-05	3.67E-02
350	3.68E-02	3.24E-02	350	8.81E-05	7.76E-05	3.25E-02
360	3.26E-02	2.87E-02	360	7.81E-05	6.88E-05	2.88E-02
380	2.57E-02	2.26E-02	380	6.15E-05	5.41E-05	2.26E-02
400	2.02E-02	1.78E-02	400	4.85E-05	4.27E-05	1.79E-02

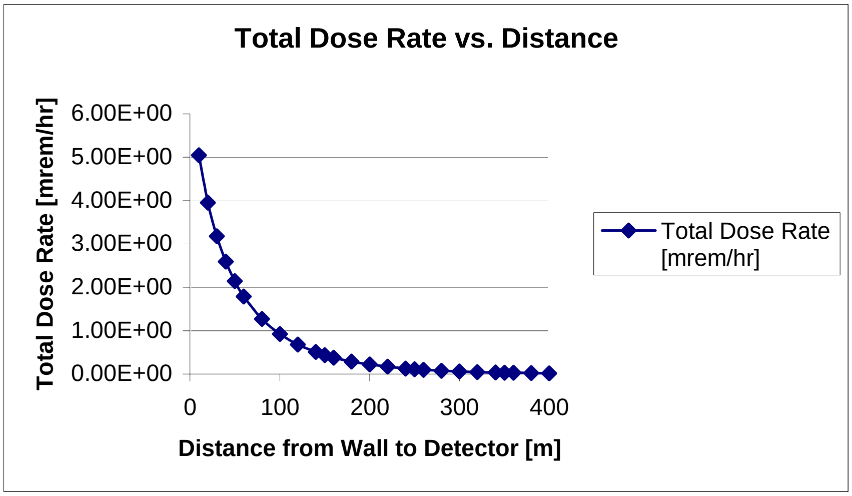


Fig. 4. Total Dose Rate for Case I and II versus Detector Distance from Wall

CONCLUSION

First, the initial discrepancy between the SKYDOSE model and the NCRP analytical method should be discussed. While the NCRP method is strictly applicable to medical accelerators, it still gave a good approximation of skyshine dose magnitude. The results confirmed doubts that the SKYDOSE doses should not be as high as reported in Table III. In retrospect, the SKYDOSE computer model is only as good as the user defined initial values for source-detector geometry and source activity. The large doses probably arose from erroneous values of source activity that did not account for 24 PWR fuel assemblies or for the fraction of fuel exposed due to slump. With that in mind, this report makes no attempt to confirm the validity of the SKYDOSE approach and was not revisited once MicroSkyshine® 2.0 simulations were performed.

Second, the MicroSkyshine® 2.0 derived dose rates are more in-line with expected values. From Table VII and Figure III we see the collective dose rate decreases exponentially over increasing distance. Also the dose rate ranges from 5.05 mrem/hr at 10 meters to 0.0179 mrem/hr at 400 meters which indicates that even if the first responders are located near the commercial buildings, they could remain below the 5 rem annual occupational limit [10]. Since skyshine dose can be maintained well below regulatory standards, this report recommends that skyshine need not be considered because of its minimal dose contribution in the LOS accident.

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