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CALCULATIONS OF THE SKYSHINE GAMMA-RAY DOSE RATES FROM INDEPENDENT SPENT FUEL STORAGE INSTALLATIONS (ISFSI) UNDER WORST CASE ACCIDENT CONDITIONS

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ABSTRACT

Calculations of the skyshine gamma-ray dose rates from three spent fuel storage pools under worst case accident conditions have been made using the discrete ordinates code DOT-IV and the Monte Carlo code MORSE and have been compared to those of two previous methods. The DNA 37N-21G group cross-section library was utilized in the calculations, together with the Claiborne-Trubey gamma-ray dose factors taken from the same library. Plots of all results are presented. It was found that the dose was a strong function of the iron thickness over the fuel assemblies, the initial angular distribution of the emitted radiation, and the photon source near the top of the assemblies.

INTRODUCTION

Transport calculations of the gamma radiation emanating from three ISFSI configurations have been made assuming worst case accident conditions. The resulting fluxes were folded with the Claiborne-Trubey gamma-ray dose factors[1] to obtain dose rates at various distances from the installations. These calculations were performed using the two- and three-dimensional codes DOT-IV[2] and MORSE.[3] Cross sections and dose factors were taken from the DNA 37N-21G library.[1] The results are presented as plots and in tables and, where appropriate, are compared with those from Kreger[4] and Anderson.[5] (Anderson's calculations were made at only one ground range, 100 m.)

CONFIGURATIONS

All configurations had a pool capacity of 5000 metric tons of uranium (MTU), no cover over the pool, and no water in the pool. The pool walls and floors were concrete of 0.9144 m thickness. The models used in the calculations were called the Kreger ISFSI,[4] the G. E. Morris configuration 1,[6] and the G. E. Morris configuration 2.[6] The Kreger ISFSI was a rectangular spent fuel pool 20 m wide and 40 m long. The homogenized spent fuel racks-fuel assembly extended the width and length of the pool and the height was 4.2 m. The top of the pool was 6.1 m above the top of the racks. The lip of the pool was at ground level.

The G. E. Morris configuration 1 was a pool with inside dimensions of 25.38 m width and 51.28 m length. The 25.38-m-wide walls were 8.99 m high and their lips were level with the ground. The 51.28-m-long walls were 9.82 m high with their lips extended 0.83 m above ground. The homogenized spent fuel racks-fuel assembly was 4.27 m high and had a 0.61 m air gap between it and the concrete walls. A variation of this configuration without the 0.83 m lip extension was also used.

The G. E. Morris configuration 2 was the same as configuration 1 except that the fuel was 6.1 m from the top of the ground instead of 4.72 m thus increasing the depth of the pool, and there was no concrete lip extension above ground level.

For the two-dimensional DOT-IV cases, all spent fuel racks-fuel assembly configurations were approximated with cylindrical geometry; the volume and surface area of the fuel was the same as for the rectangular configurations.

SOURCES AND RESPONSES

The gamma-ray source terms (photons/sec) for various growth-decay periods were taken from Refs. 4 and 6 and, using flat weighting, were reformatted into the DNA gamma-ray group structure as shown in Table 1. Since there were no source gamma-rays above 3.0 MeV, only source terms for Groups 8-21 are shown in the table.

Table 1. Source and Response Terms

Gamma-Ray Group	Upper E (MeV)	Kreger ISFSI Sources: 1/2 yr decay 33,000 MWD/MT[a] (photons/sec)	Kreger ISFSI Sources: 1 yr decay 33,000 MWD/MT (photons/sec)	G. E. Morris Configuration Sources, 1 yr decay: 33,000 MWD/MT (photons/sec)	G. E. Morris Configuration Sources, 1 yr decay: 40,000 MWD/MT (photons/sec)	C/T Dose Factors[b] (Rads/photons/cm^2)
[c] 8	3.0+0[d]	8.30+15	6.00+15	1.246+15	1.627+15	1.09-9
9	2.5+0	6.11+17	4.03+17	7.825+15	1.019+16	9.59-10
10	2.0+0	6.48+17	4.13+17	7.785+17	8.865+17	8.13-10
11	1.5+0	3.33+18	2.75+18	6.057+16	7.945+16	6.41-10
12	1.0+0	5.84+19	1.77+19	3.112+18	4.104+18	4.82-10
13	7.0-1	1.18+20	3.42+19	3.823+18	5.048+18	3.60-10
14	4.5-1	5.97+19	4.49+19	1.073+20	1.394+20	2.48-10
15	3.0-1	5.50+19	4.35+19	6.111+18	7.087+18	1.64-10
16	1.5-1	0	0	2.038+18	2.362+18	1.01-10
17	1.0-1	0	0	1.222+18	1.417+18	7.44-11
18	7.0-2	0	0	1.022+18	1.187+18	7.73-11
19	4.5-2	0	0	6.128+17	7.120+17	1.17-10
20	3.0-2	0	0	4.075+17	5.002+17	2.23-10
21	2.0-2[e]	0	0	6.304+17	8.203+17	6.26-10

[a] MWD/MT = Mega Watt-Days/Metric Ton.

[b] Claiborne-Trubey dose factors.

[c] Gamma-ray groups above Group 8 contained no source.

[d] Read as 3.0×10^0.

[e] Lower E boundary for last group is 1.0-2 MeV.

CROSS SECTIONS

The P_3 cross sections were taken from the DNA 37N-21G library. The fuel, fuel cladding, rack cladding, rack shield, and air were all homogenized as indicated in Ref. 4. Final compositons are shown in Table 2.

CODES

One set of calculations was performed using an S-8 quadrature with two-dimensional DOT-IV, the latest of the DOT[7] computer codes which was developed in the mid sixties. This code uses the method of discrete ordinates to describe the transport of neutral particles in cylindrical geometry according to the Boltzmann transport equation. The particle fluence is a function of five variables, viz., energy with one variable, spatial position with two variables and direction with two variables. A multigroup approximation is used for the energy variable. In this approximation, all particles traveling with energies within a given group interact according to cross-section data appropriately averaged over the energy range of each group. Solutions to the transport equation require integration over the angular variable. This is performed in DOT by mechanical quadrature composed of discrete directions and point weights. Finally, the spatial dimension is divided into intervals. From this discrete system, the particle balances are calculated for each discrete cell.

The other set of calculations was performed with the three-dimensional code MORSE,[3] which was also developed in the mid sixties. This code uses random sampling to estimate the solution of the Boltzmann transport equation. The history of a particle is therefore represented as a sequence of statistical events. Several sophisticated sampling techniques are employed in the code to reduce the statistical error and running time.

Table 2. ISFSI Compositions (Atoms/b-cm)

Element	Kreger Fuel[a]	Morris Fuel[a]	Ground	Concrete	Iron[d]	Air
H	--	--	9.770-3	1.065-2	--	--
B-10	1.252-3[b]	--	--	--	--	--
B-11	5.396-3	--	--	--	--	--
C	1.662-3	1.922-5	--	1.310-4	--	--
N	1.569-5	9.753-6	--	--	--	2.573-5
O	1.021-2	4.912-3	3.480-2	4.084-4	--	9.599-6
Na	--	--	--	1.071-3	--	--
Mg	--	--	--	1.620-4	--	--
Al	--	--	4.880-3	2.822-3	--	--
Si	--	7.091-5	1.160-2	1.322-2	--	--
P	--	8.554-6	--	--	--	--
S	--	1.617-6	--	--	--	--
Ar	1.305-7	--	--	--	--	2.139-7
K	--	--	--	8.280-4	--	--
Ca	--	--	--	2.426-3	--	--
Cr	--	1.833-4	--	--	--	--
Mn	--	7.199-5	--	--	--	--
Fe	3.392-3	2.459-3	--	5.428-3	8.409-2	--
Ni	--	3.856-4	--	--	--	--
Zr	--	1.472-3	--	--	--	--
Mo	3.400-3[c]	2.537-5	--	--	--	--
U-235	--	7.943-5	--	--	--	--
U-238	5.103-3	2.373-3	--	--	--	--

[a]Homogenized to include fuel, cladding, rack cladding, rack shield, and air.

[b]Read as 1.252×10^{-3}.

[c]Substituted for Zr in Kreger Fuel, Zr cross sections were unavailable when Kreger calculations were made.

[d]Used to simulate the rack, grid plates and plugs above the fuel.

The DOT and MORSE codes are the two- and three-dimensional calculational methods utilized to analyze neutron and gamma-ray transport in reactor shielding and air/ground scenarios at ORNL. The personnel involved in the calculations have a minimum of nine years-per-man experience with the codes.

The two codes have been used in much previous air-over-ground work.[8-11] As an indication of the reliability of the codes and the calculational procedures, the maximum difference between measured and calculated values for the HENRE experiment is approximately a factor of two.[8] On the other hand, previous and current work in reactor shielding[12-16] has demonstrated the ability to produce excellent results. Monte Carlo calculations, when compared to measured values,[15] agree to within 20% in most cases. DOT calculations for concrete[16] are no greater than a factor of two over measured values and are mostly within 30%.

RESULTS

The ground ranges given in the tables and figures are measured from the centerline of the configurations.

Figure 1 and Table 3 show a comparison of the dose rates obtained by ORNL and NRC[4] for the Kreger ISFSI. Most points are in fairly good agreement.

Figures 2 and 3 and Table 4 show the results of supplemental MORSE calculations in which iron of various thicknesses was added to the top of the fuel to simulate the upper portion of the fuel racks. As an additional DOT calculation, the dose rate 1 cm above a single assembly for various thicknesses of iron is shown in Table 5. These results indicate that the dose rate is very dependent upon the amount of iron above the fuel.

Table 3. Skyshine Dose Rates (Rads/hr) Using Various Calculational Methods for the Kreger ISFSI with the 1/2 Year Source

Ground Range (m)	ORNL DOT	ORNL MORSE	KREGER NRC ANISN/G[4]
21.9	1402.0	--	--
25	--	668.9(7.4)[a]	740.0
28	644.0	--	--
50	--	--	370.0
100	--	--	160.0
150	--	--	65.0
181	42.2	--	34.0
200	--	35.2(14.7)	16.0
211	30.5	--	--
250	--	--	--
275	--	--	12.0
300	--	--	8.8
350	--	--	4.5
389	5.7	--	--
400	--	4.8(12.8)	2.6
418	4.4	--	--

[a]Read as 668.9 ± 7.4%.

Table 4. MORSE Calculations of Skyshine Dose Rates (Rads/hr) for the Kreger ISFSI with Iron Shields above the Fuel

Ground Range (m)	Iron Thickness (cm)					
	0.0		4.5		7.5	
	1/2 yr source	1 yr source	1/2 yr source	1 yr source	1/2 yr source	1 yr source
25	668.9(7.4)[a]	199.5(11.8)	88.9(10.1)	36.0(12.9)	26.7(11.2)	12.9(29.4)
200	35.2(14.7)	10.1(4.8)	3.6(7.5)	1.2(10.4)	0.8(8.0)	0.3(12.0)
400	4.8(12.8)	1.4(14.0)	0.4(8.5)	0.2(19.0)	0.1(15.4)	0.03(22.6)

[a]Read as 668.9 ± 7.4%.

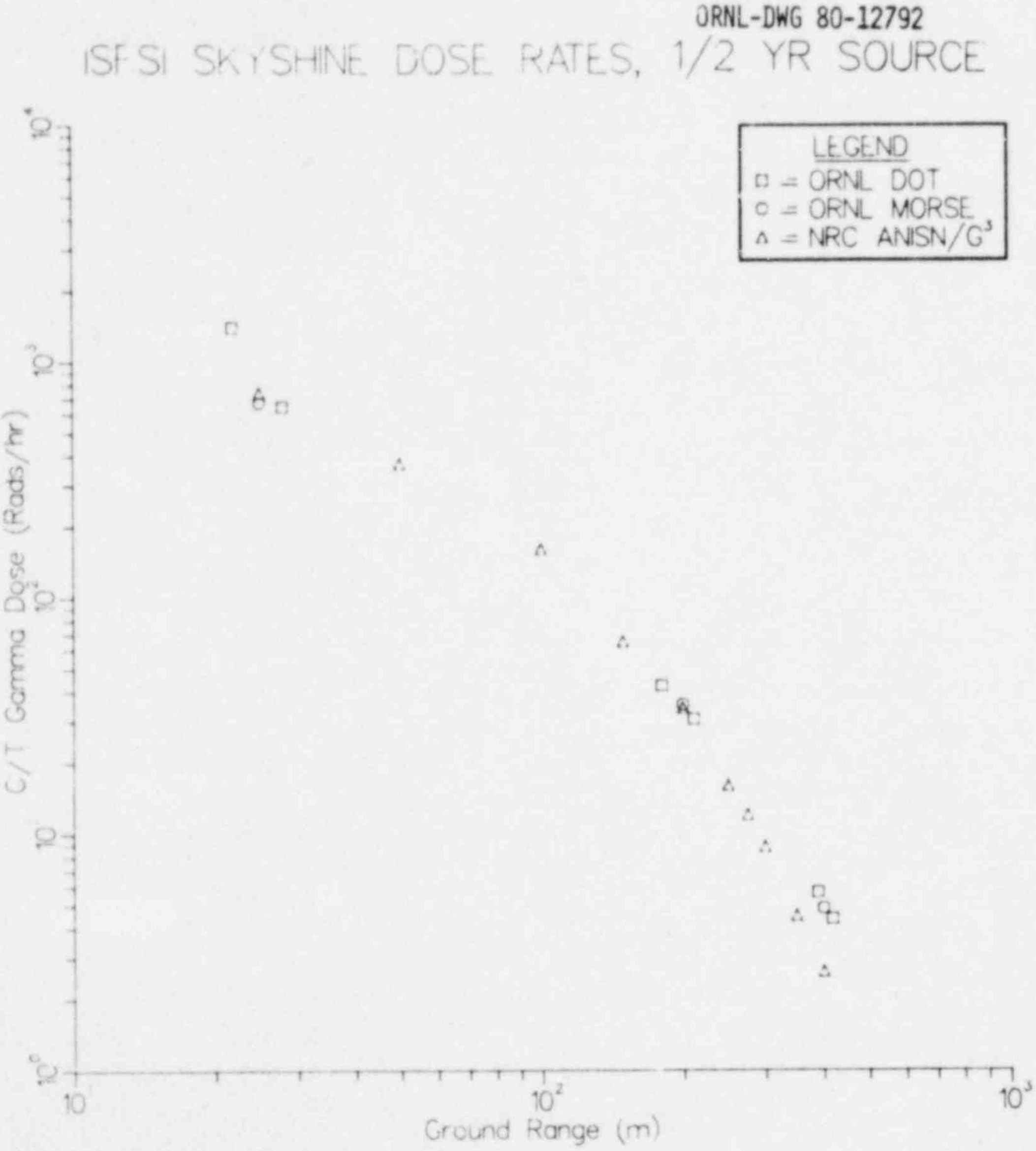

Fig. 1. Claiborne-Trubey doses from three calculational methods are plotted versus ground range for the Kreger ISFSI with a one-half year decay source for 33,000 MWD/MT.

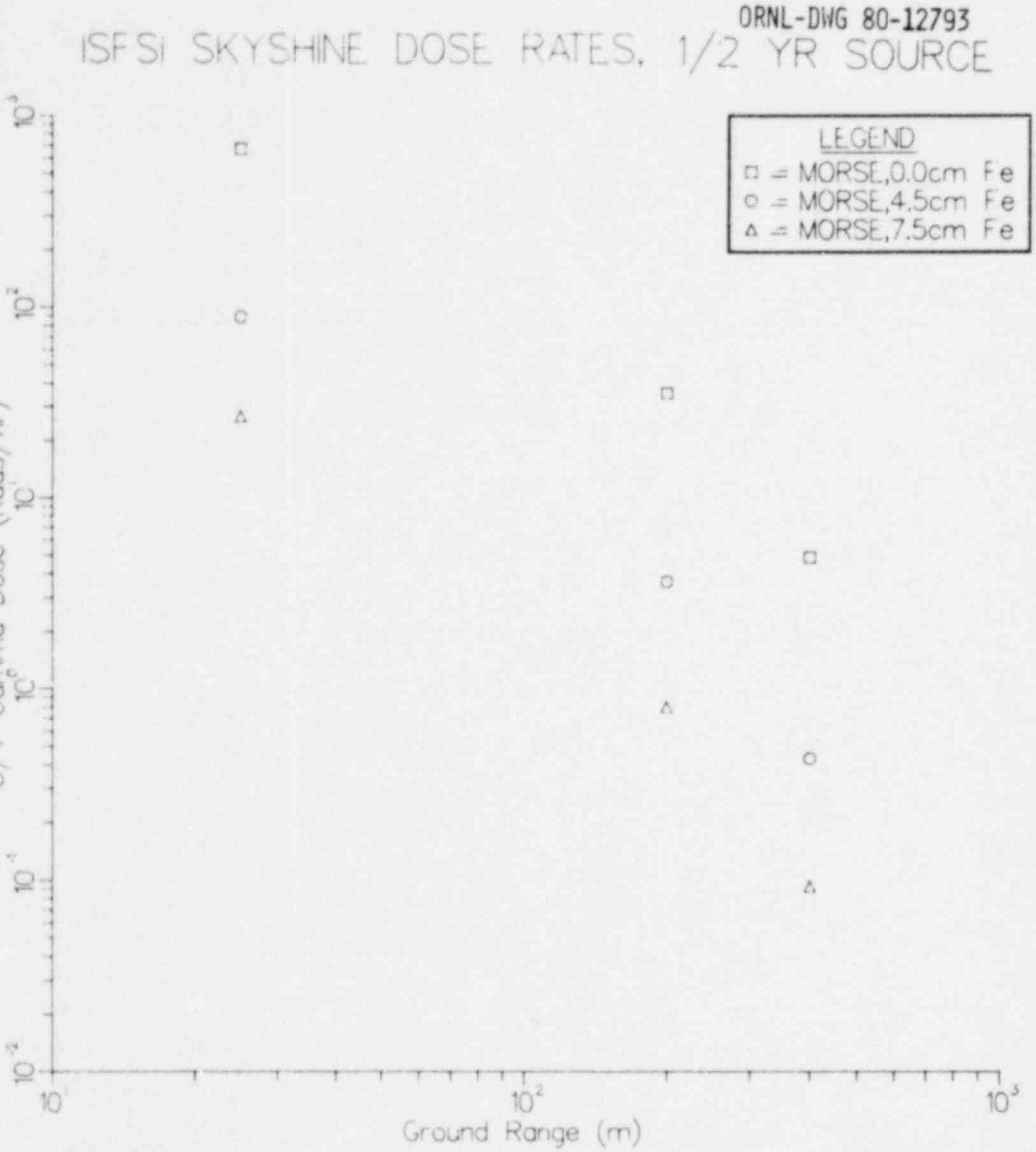

Fig. 2. Claiborne-Trubey doses through three thicknesses of iron are plotted versus ground range for the Kreger ISFSI. The MORSE code used a one-half year decay source for 33,000 MWD/MT.

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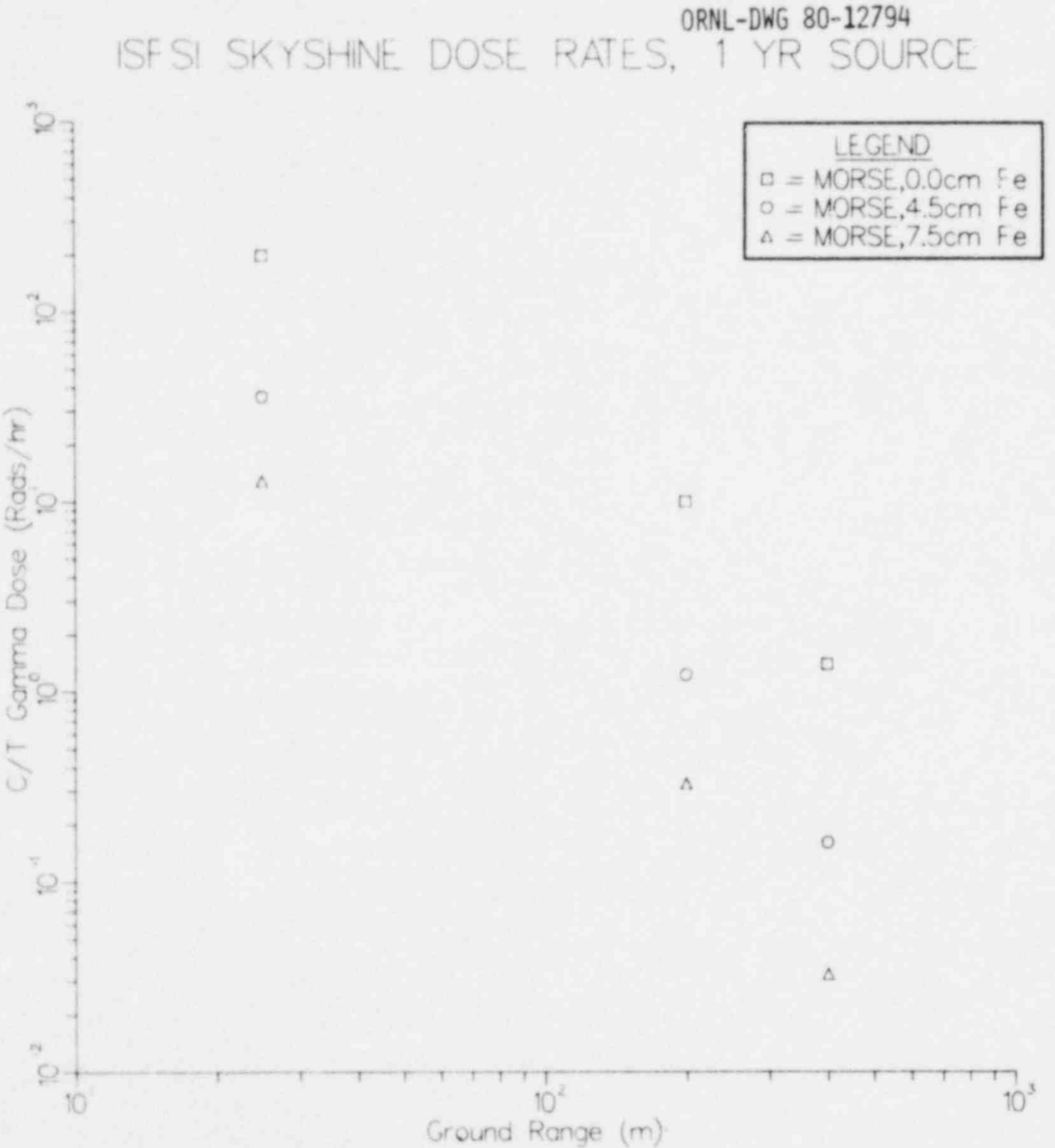

Fig. 3. Claiborne-Trubey doses through three thicknesses of iron are plotted versus ground range for the Kreger ISFSI. The MORSE code used a one year decay source for 33,000 MWD/MT.

Table 5. ISFSI Single Element Dose Rate 1 cm Above Top, One Yr Source

Fe Thickness (cm)	C/T Dose (Rads/hr)
0	2.62 + 4
4.5	2.02 + 3
7.5	5.02 + 2

At a ground range of 100 m, the dose rates for the three calculations in Fig. 1 were approximately 200 rads/hr. From Figs. 2 and 3, it is seen that the ratio of dose rates from the 1/2 year source to the dose rate from the one year source is about 3 to 1. Anderson's calculation[5] using the one year source gave approximately 35-65 mr/hr at 100 m, which differs from the present calculational values by nearly three orders of magnitude. Possible explanations for these discrepancies are given in the conclusions.

Tables 6 and 7 and Figs. 4 through 11 show the dose rates for the G. E. Morris configurations. The sharp dip and rise in the dose as the ground range increases is due to the detector position moving through the concrete lip extension of configuration 1.

The statistical errors on the MORSE results vary from 4% at close ground ranges to 25% at the long ground ranges. A maximum of 1000 batches with 400 particles (photons) per batch were used in the MORSE calculations. Reduction of the statistical error at long ground ranges would require more batches.

CONCLUSIONS

In general, the differences between the Kreger, Anderson, and present results were probably due more to variations in the assumptions than in the methods employed. Two of the most significant assumptions which led to higher dose rates for the Kreger and ORNL calculations were:

1) Direction of emerging photon source. Gamma radiation emitted isotropically from the top of the fuel contributed more to the dose than gamma radiation emitted anisotropically in the vertical direction. The Kreger and ORNL calculations indicate less anisotropy than Anderson's calculations.

2) Thickness of iron at the top of the fuel. Varying the thickness of the iron (which simulates the rack, grid plates, and plugs over the assemblies) affects the magnitude of the dose rate tremendously. The Kreger and ORNL calculations contained no iron over the fuel; conversely, the Anderson and the supplemental ORNL iron-over-fuel calculations contained the iron.

Due to the sensitivity of the dose rate to the various assumptions made, further investigations should be initiated to obtain more realistic answers. For example, are there streaming paths between the fuel modules which enhance the dose? Because of the tremendous self shielding of the homogeneous fuel mixture, the overwhelming majority of the photon source comes from the top one-half meter of the fuel. Therefore, how large an effect does variation in axial burnup have on the source term? Ultimate verification of the modeling assumptions, data, and methods employed would require comparison with measurements taken at a storage facility.

Table 6. Skyshine Dose Rates (Rads/hr) Using the DOT and MORSE Codes for the G. E. Morris ISFSI. The G. E. Morris Source Was Used with the Kreger Fuel Composition.

Ground Range (m)	Configuration 1[a]				Configuration 2			
	30,000 MWD		40,000 MWD		30,000 MWD		40,000 MWD	
	DOT	MORSE	DOT	MORSE	DOT	MORSE	DOT	MORSE
0.51	1.55+4[b]	--	2.00+4	--	1.43+4	--	1.84+4	--
9.67	1.51+4	--	1.95+4	--	1.36+4	--	1.76+4	--
19.84	9.60+3	--	1.24+4	--	8.37+3	--	1.08+4	--
21.0	5.59+3	--	7.20+3	--	6.88+3	--	8.89+3	--
21.62	2.15+1	--	2.73+1	--	2.62+3	--	3.37+3	--
25.0	2.02+2	--	2.62+2	--	4.22+2	--	5.47+2	--
50.0	--	4.88+1(18.3)[c]	--	1.05+2(5.3)	--	7.36+1(5.2)	--	8.31+1(4.0)
59.5	7.01+1	--	9.08+1	--	6.81+1	--	8.82+1	--
90.5	4.17+1	--	5.41+1	--	4.05+1	--	5.26+1	--
121.5	2.59+1	--	3.37+1	--	2.52+1	--	3.27+1	--
152.5	1.67+1	--	2.17+1	--	1.63+1	--	2.11+1	--
200.0	1.02+1	5.57+0(11.4)	1.32+1	8.66+0(6.1)	9.99+0	7.90+0(12.8)	1.29+1	9.86+0(11.5)
250.5	5.34+0	--	6.94+0	--	5.20+0	--	6.75+0	--
316.5	2.74+0	--	3.55+0	--	2.67+0	--	3.46+0	--
349.5	2.00+0	--	2.58+0	--	1.94+0	--	2.51+0	--
400.0	1.34+0	1.20+0(25.6)	1.74+0	1.12+0(11.9)	1.30+0	9.80-1(22.6)	1.69+0	9.20-1(9.5)
445.9	8.11-1	--	1.04+0	--	7.85-1	--	1.02+0	--
505.7	4.70-1	--	6.07-1	--	4.56-1	--	5.89-1	--
565.5	2.74-1	--	3.53-1	--	2.65-1	--	3.42-1	--
625.3	1.56-1	--	2.02-1	--	1.52-1	--	1.95-1	--

[a] This set of calculations includes the concrete extension above ground level.

[b] Read as 1.55×10^4.

[c] Read as $4.88 \times 10^1 \pm 18.3\%$.

Table 7. Skyshine Dose Rates (Rads/hr) Using the DOT Code for the G. E. Morris ISFSI. The Morris Source Was Used with the Morris Fuel Composition.

Ground Range (m)	Configuration 1[a]		Configuration 2	
	33,000 MWD	40,000 MWD	33,000 MWD	40,000 MWD
0.51	2.96+4[b]	3.81+4	2.74+4	3.53+4
9.67	2.89+4	3.72+4	2.62+4	3.37+4
19.84	1.78+4	2.29+4	1.60+4	2.06+4
21.0	1.44+4	1.86+4	1.31+4	1.69+4
21.62	5.64+3	7.72+3	4.89+3	6.30+3
25.0	9.28+2	1.19+3	7.91+2	1.02+3
59.5	1.43+2	1.85+2	1.31+2	1.70+2
90.5	8.50+1	1.10+2	7.78+1	1.01+2
121.5	5.27+1	6.81+1	4.86+1	6.29+1
152.5	3.41+1	4.42+1	3.14+1	4.07+1
200.0	2.08+1	2.70+1	1.91+1	2.48+1
250.5	1.09+1	1.41+1	9.99+0	1.30+1
316.5	5.60+0	7.26+0	5.13+0	6.62+0
349.5	4.70+0	5.27+0	3.72+0	4.82+0
400.0	2.74+0	3.55+0	2.51+0	3.24+0
445.9	1.65+0	2.14+0	1.51+0	1.95+0
505.7	9.60-1	1.24+0	8.76-1	1.13+0
565.5	5.61-1	7.26-1	5.10-1	6.55-1
625.3	3.22-1	4.14-1	2.91-1	3.75-1

[a]The concrete extension above ground level on configuration 1 was removed from this set of calculations.

[b]Read as 2.96×10^4.

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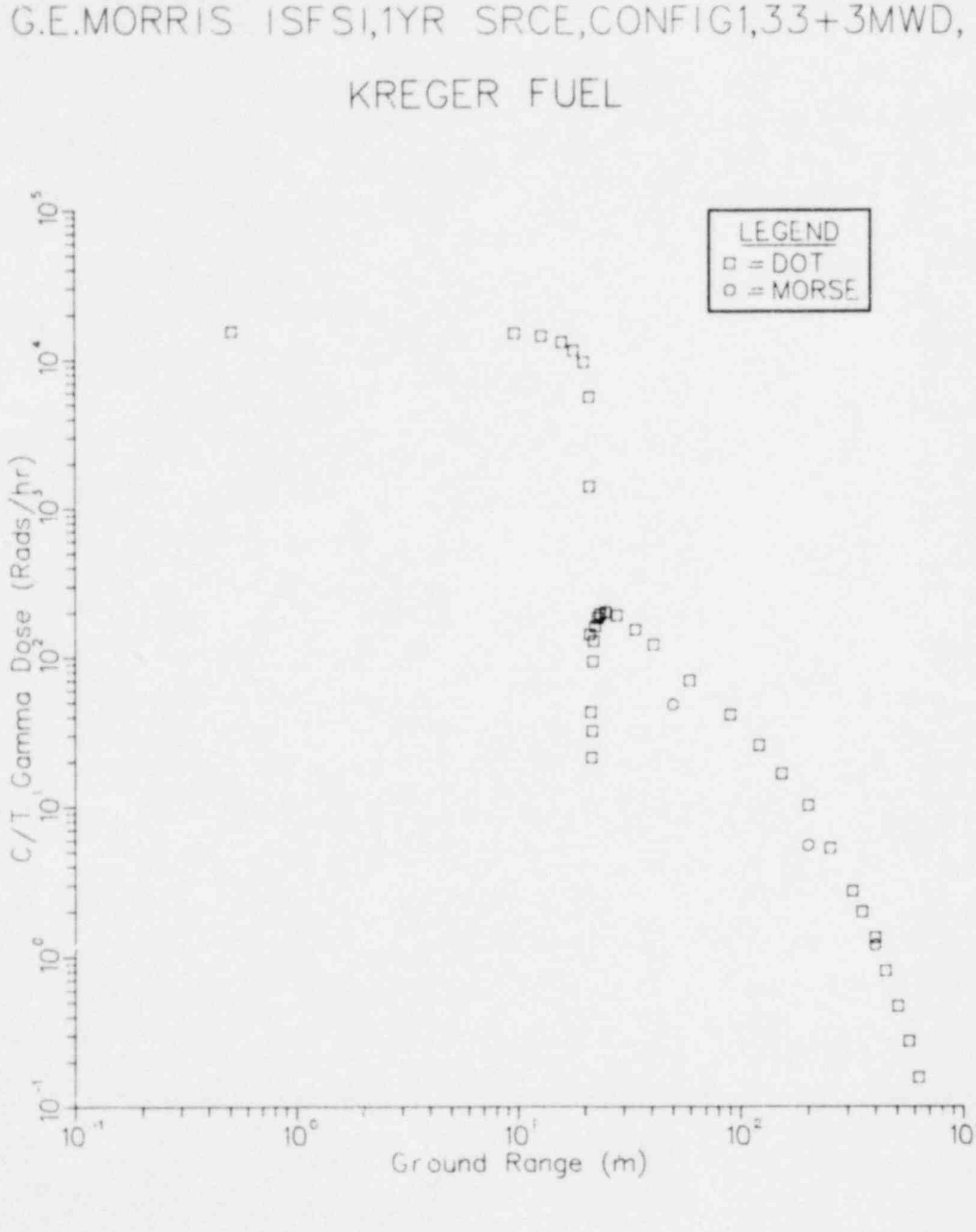

Fig. 4. Claiborne-Trubey doses from two calculational methods are plotted versus ground range from the center of configuration 1 (with the lip extension). The two methods used the one year G. E. Morris decay source with the Kreger fuel composition for 33,000 MWD/MT.

ORNL-DWG 80-12796

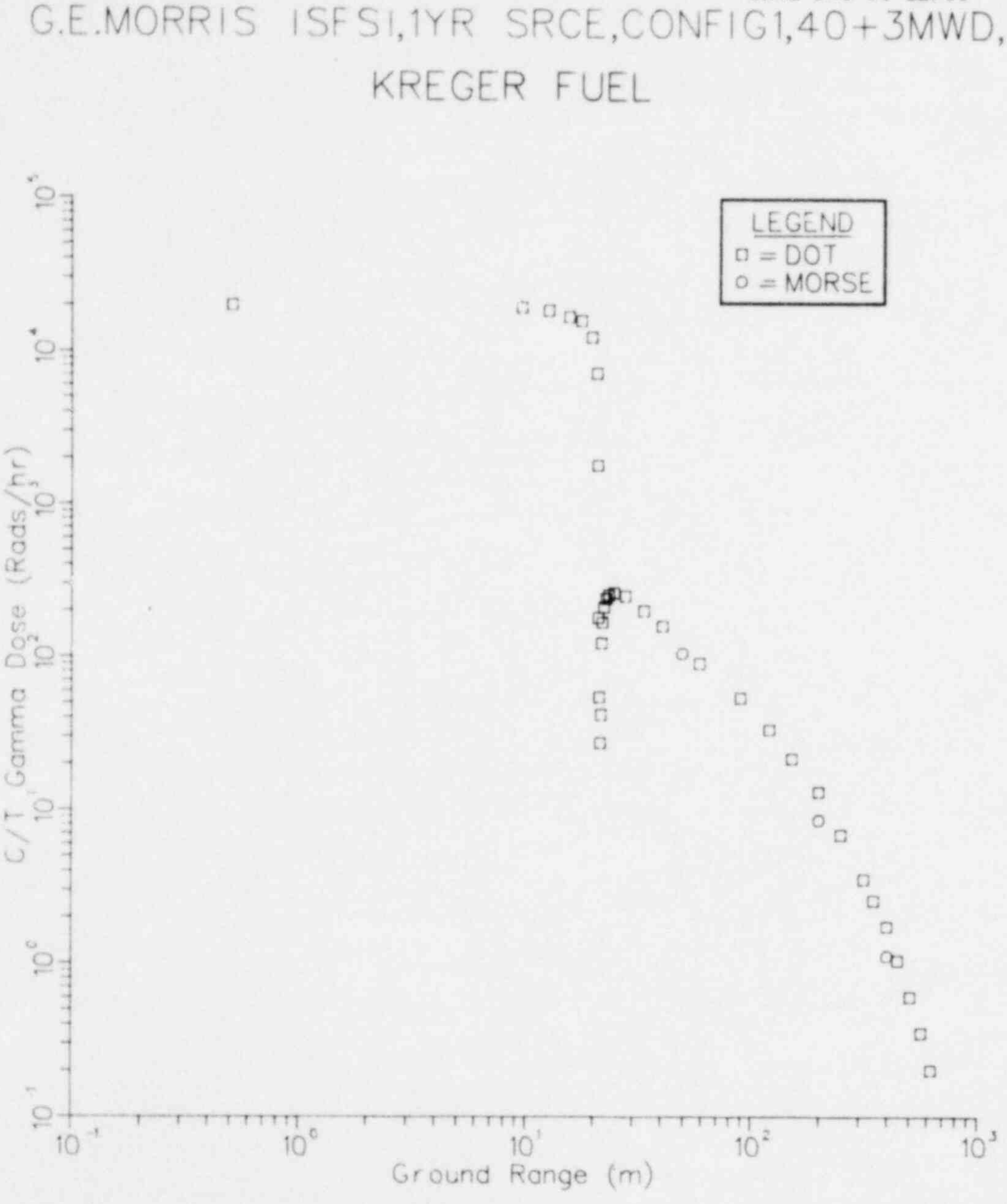

Fig. 5. Claiborne-Trubey doses from two calculational methods are plotted versus ground range from the center of configuration 1 (with the lip extension). The two methods used the one year G. E. Morris decay source with the Kreger fuel composition for 40,000 MWD/MT.

ORNL-DWG 80-12797

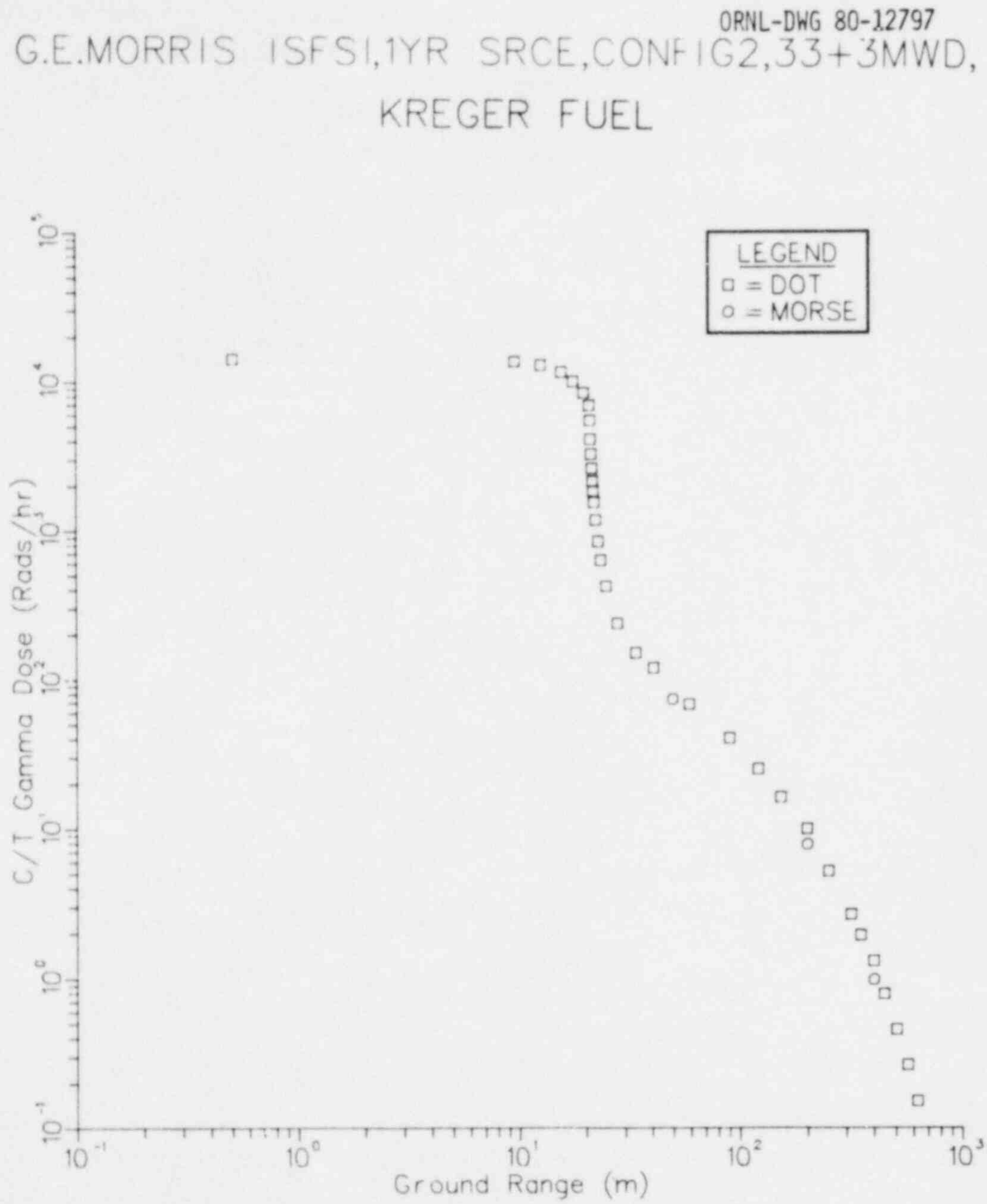

Fig. 6. Claiborne-Trubey doses from two calculational methods are plotted versus ground range from the center of configuration 2. The two methods used the one year G. E. Morris decay source with the Kreger fuel composition for 33,000 MWD/MT.

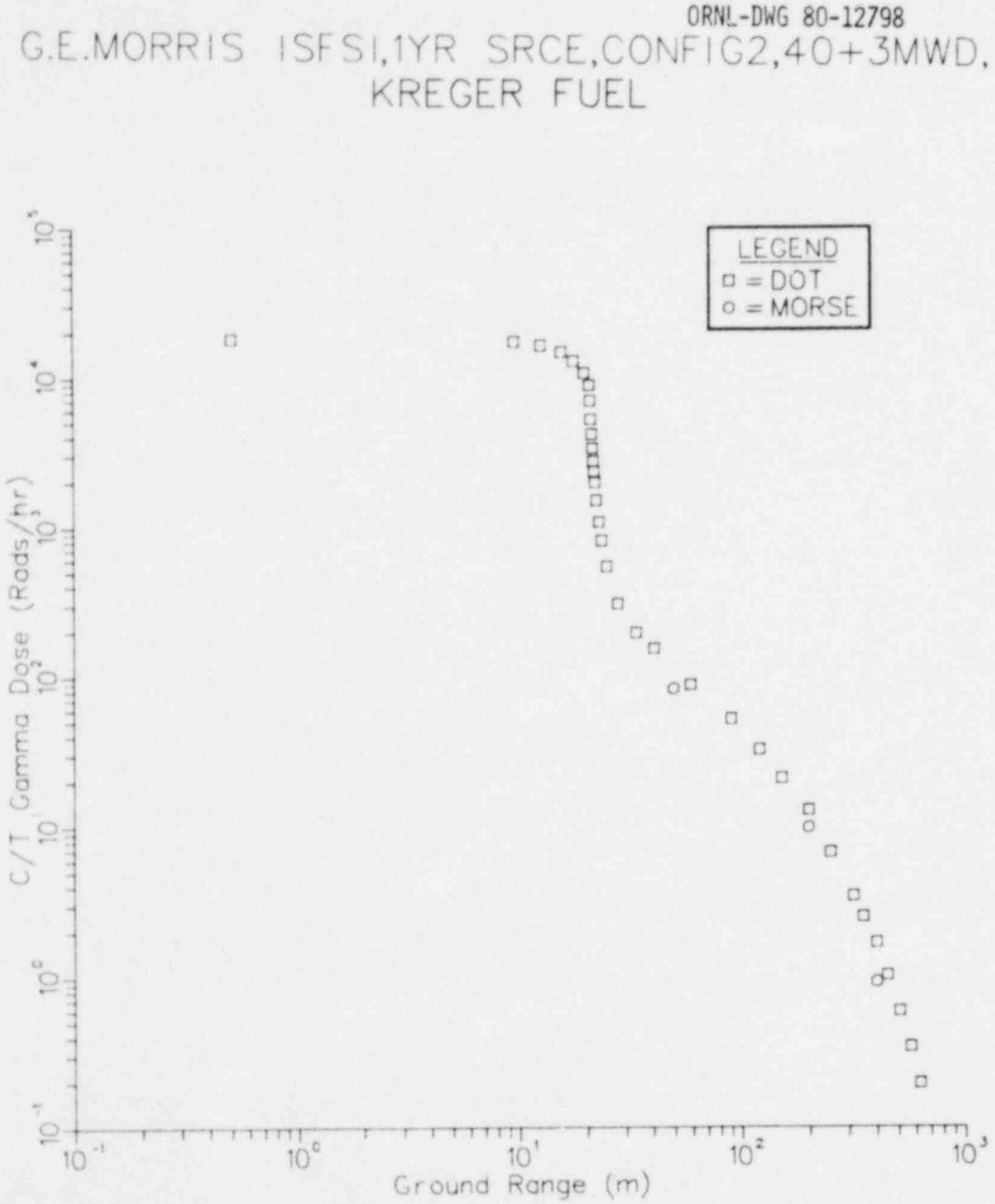

Fig. 7. Claiborne-Trubey doses from two calculational methods are plotted versus ground range from the center of configuration 2. The two methods used the one year G. E. Morris decay source with the Kreger fuel composition for 40,000 MWD/MT.

ORNL-DWG 80-12799

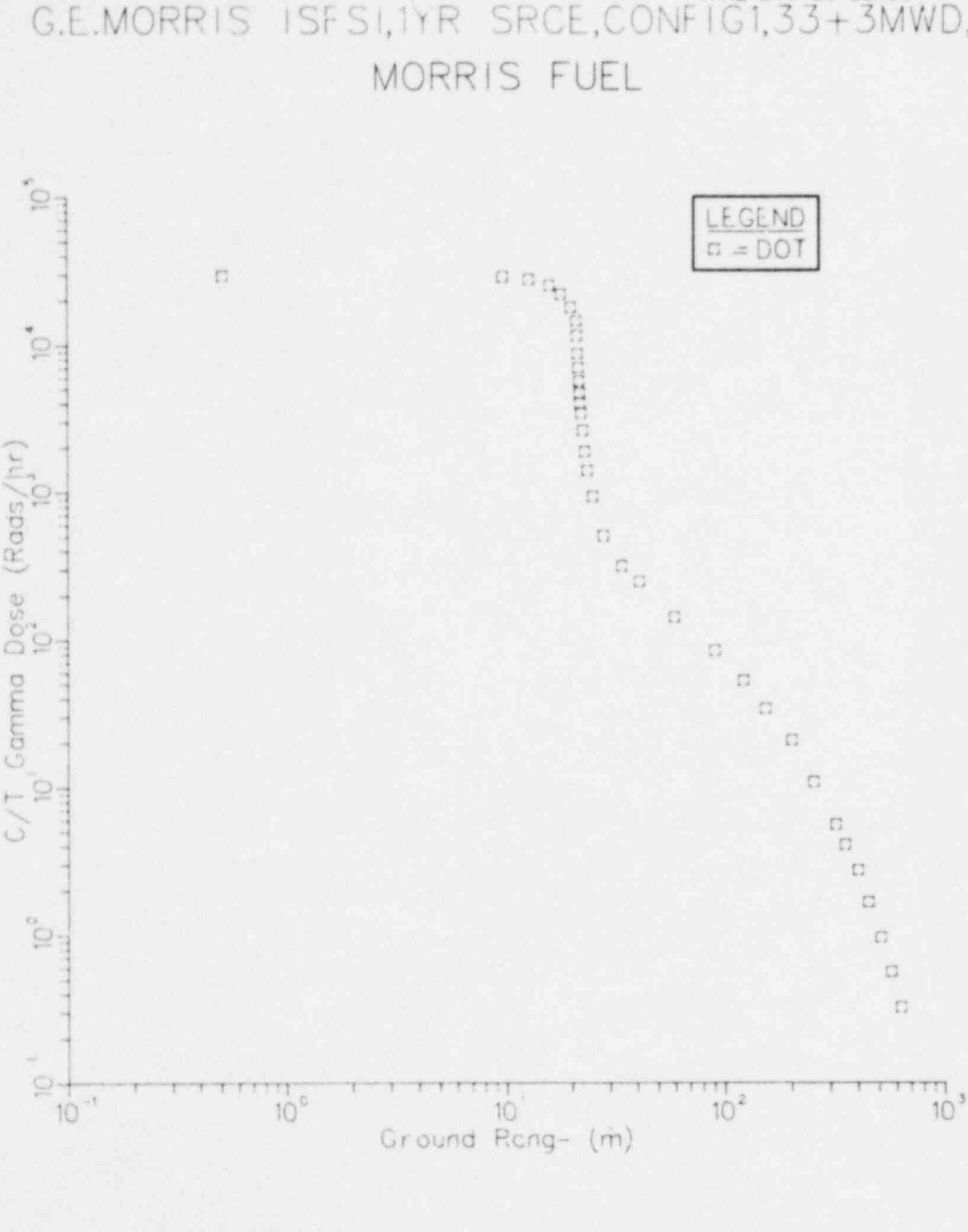

Fig. 8. Claiborne-Trubey doses from the DOT calculational method are plotted versus ground range from the center of configuration 1 (no lip extension above ground). The two methods used the one year G. E. Morris decay source with the G. E. Morris fuel composition for 33,000 MWD/MT.

ORNL-DWG 80-12800

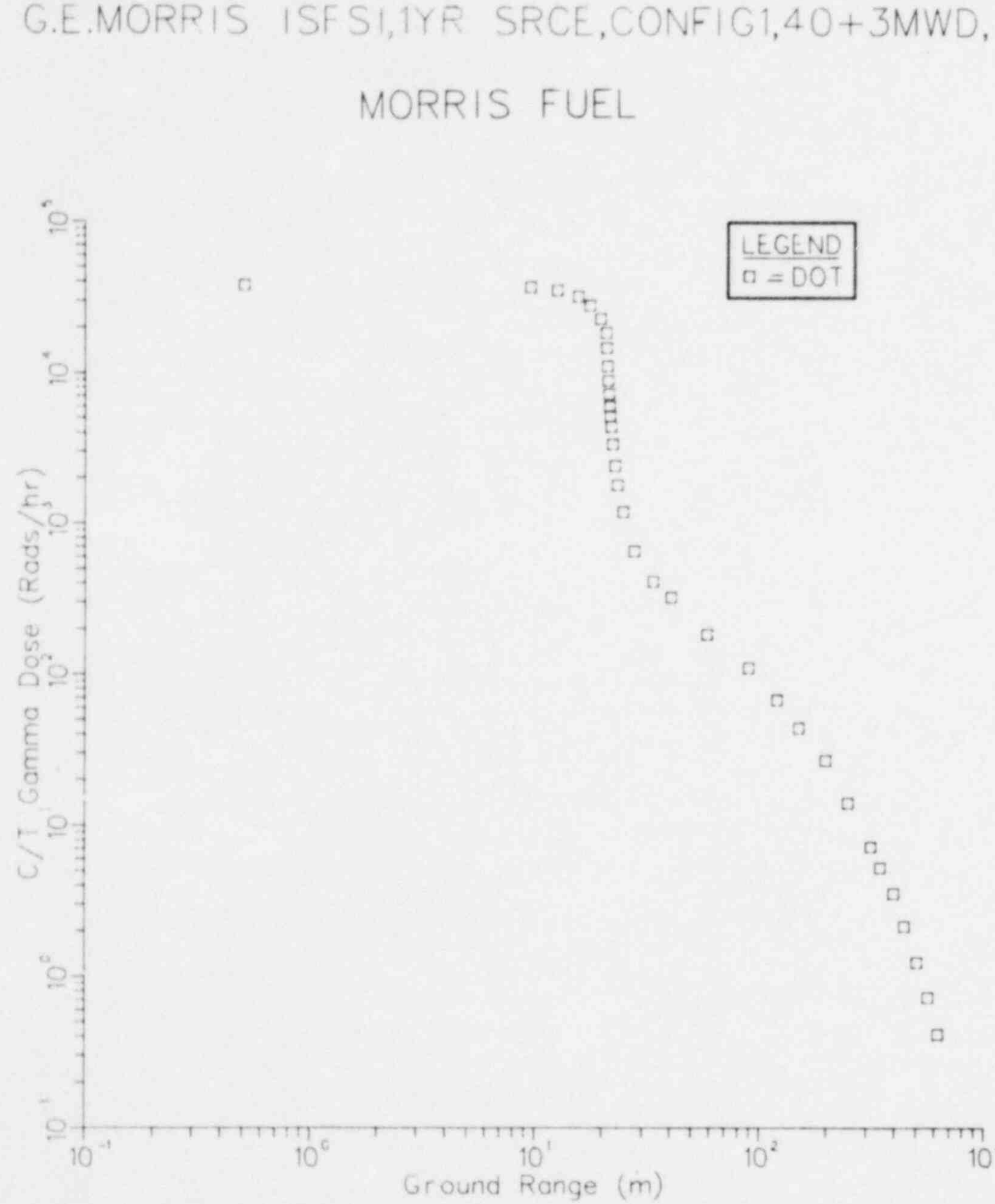

Fig. 9. Claiborne-Trubey doses from the DOT calculational method are plotted versus ground range from the center of configuration 1 (no lip extension above ground). The two methods used the one year G. E. Morris decay source with the G. E. Morris fuel composition for 40,000 MWD/MT.

ORNL-DWG 80-12801

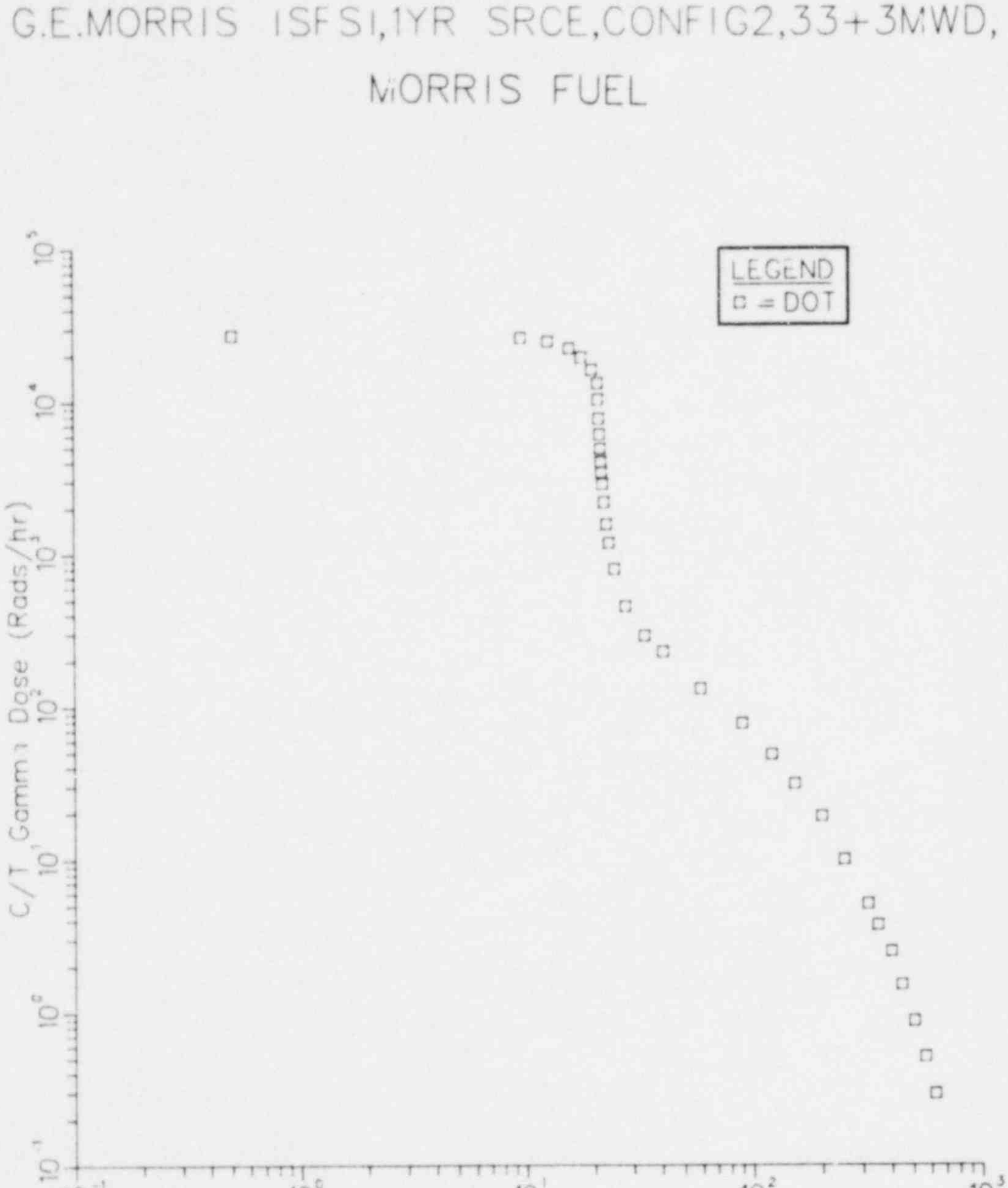

Fig. 10. Claiborne-Trubey doses from the DOT calculational method are plotted versus ground range from the center of configuration 2. The two methods used the one year G. E. Morris decay source with the Kreger fuel composition for 33,000 MWD/MT.

ORNL-DWG 80-12802

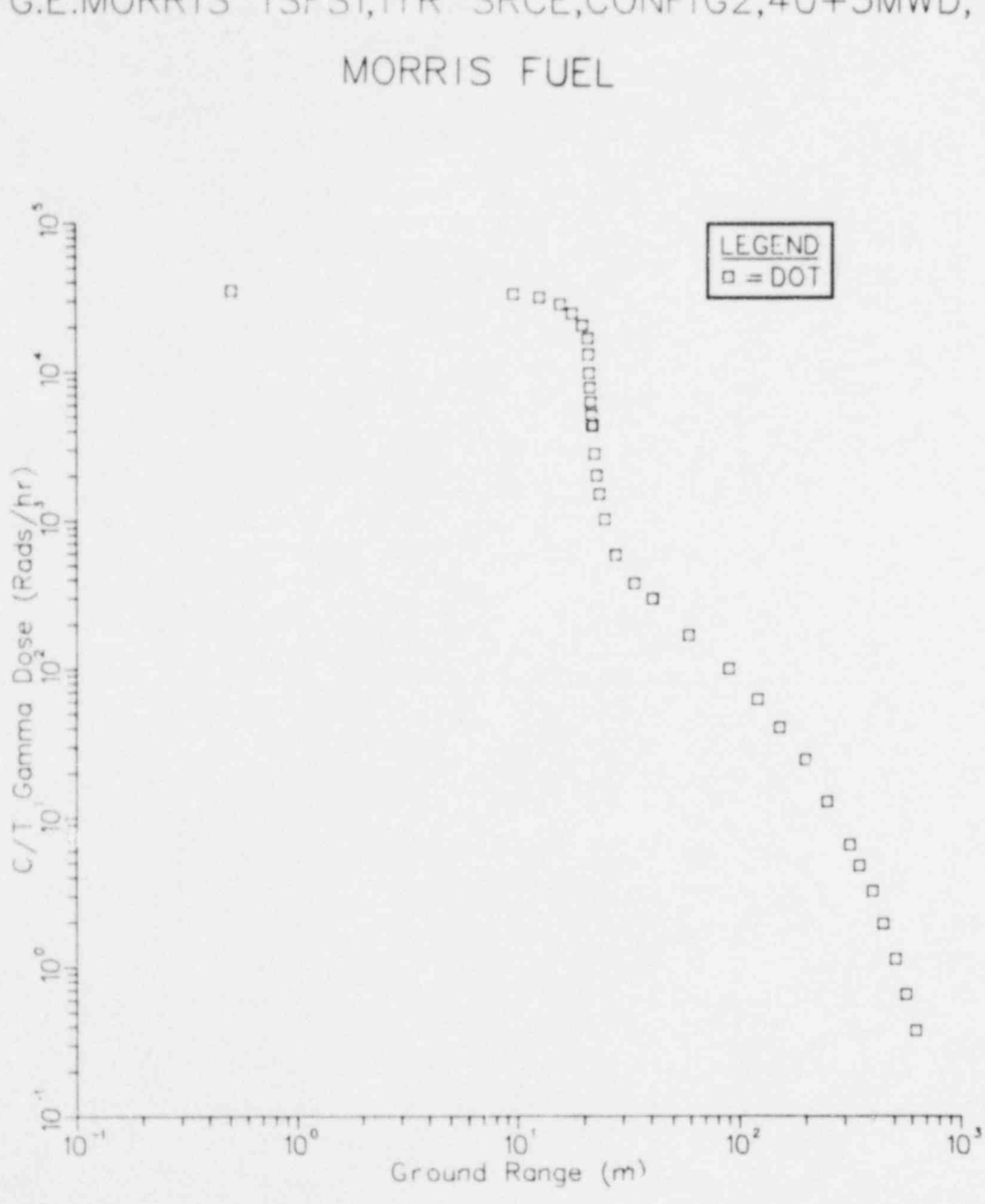

Fig. 11. Claiborne-Trubey doses from the DOT calculational method are plotted versus ground range from the center of configuration 2. The two methods used the one year G. E. Morris decay source with the Kreger fuel composition for 40,000 MWD/MT.

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