MAGI PROJECT 7145

DOSE DELIVERED TO THE HAND

OF

ON

24 MAY 1976

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1. INTRODUCTION

Mathematical Applications Group, Inc. (MAGI) has performed a series of Monte Carlo calculations for the Consolidated Edison Company (Con Ed), to assess the biological dose delivered to the hand of during the incident of 24 May 1976 at the Indian Point No. 2 facility.

The sections which follow describe the calculations performed and the results achieved.

2. GEOMETRIC CONFIGURATION

The geometry used in the Monte Carlo calculations was as shown in Figure 1.

A stainless steel rod (OD=.385", ID=.268") protrudes 2' from a water bath. At the 1' level, the rod is surrounded by a gloved hand. The hand is 4" high (OD=3", ID=.4546") and is completely enclosed by the glove which is .0348" thick.

The hand is assumed to be tissue. The final results are not sensitive to the dimensions of the hand, since the hand is "optically thin"; i.e., doubling the hand volume would essentially double the neutron path lengths (and thus the flux) thereby leaving the energy deposition per unit volume unchanged. The glove has no appreciable effect upon the gamma radiation and has only the slight geometric effect of displacing the hand by 0.0348" from the rod. For convenience, the glove was given the same chemical composition as water.

The atomic concentrations of the stainless steel rod and the hand are given in Table 1.

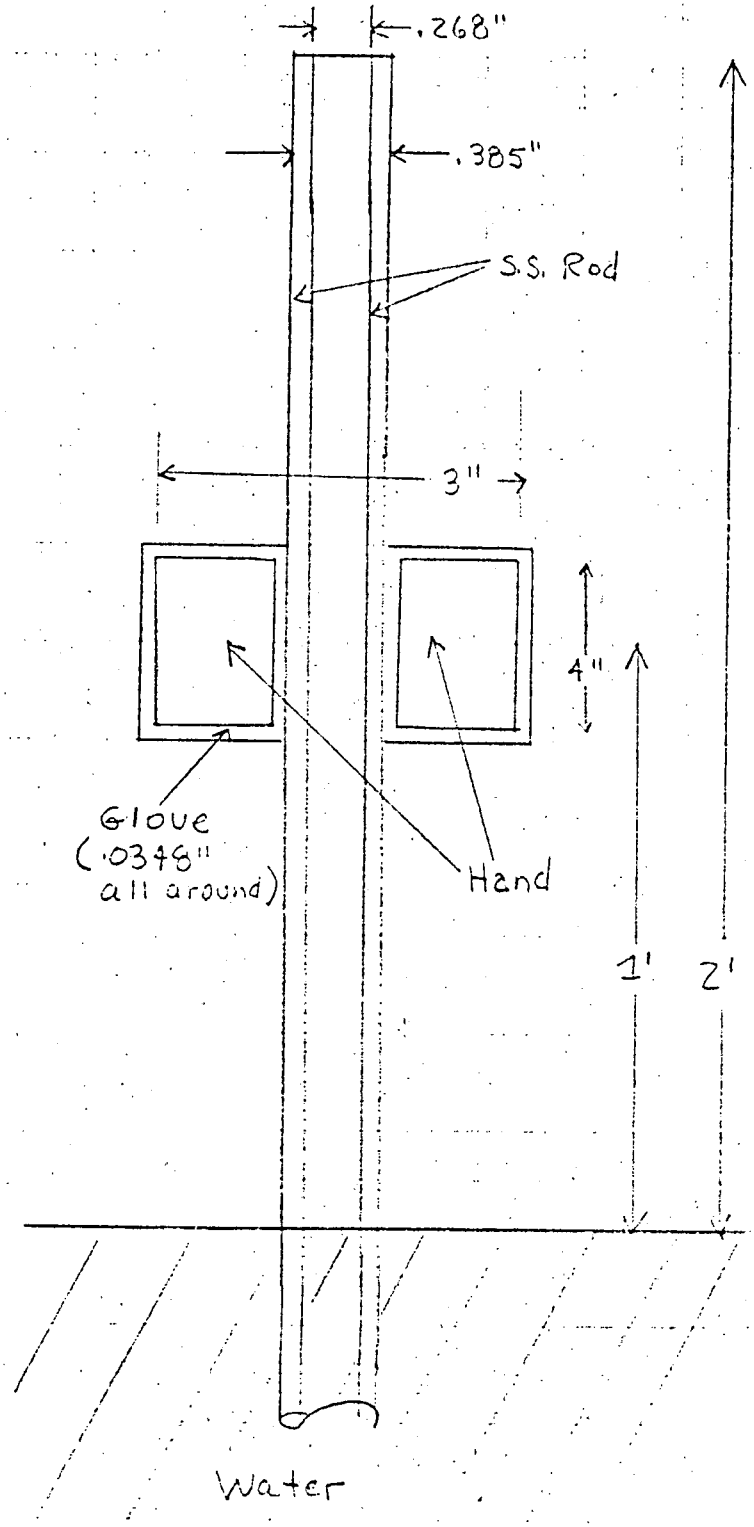


Figure 1

GEOMETRIC CONFIGURATION
(not to scale)

TABLE 1

ATOMIC CONCENTRATIONS

MATERIAL	NUCLIDE	ATOMIC DENSITY (atoms/barn·cm)
Stainless Steel	Iron	0.06175
Stainless Steel	Chromium	0.01676
Stainless Steel	Nickel	0.00882
Tissue	Hydrogen	0.0598
Tissue	Oxygen	0.0245
Tissue	Carbon	0.00903
Tissue	Nitrogen	0.00129

3. GAMMA RADIATION SOURCES

It was assumed that the rod was uniformly radioactive. Nine prominent gamma ray lines were identified by Con Ed and these are displayed in Table 2 along with preliminary estimates of the source strength terms (also provided by Con Ed).

Since the source strengths were provided on a preliminary basis only, separate Monte Carlo calculations (see below) were performed for each gamma ray line and the results which were obtained were on a per source particle basis. Subsequently, these results were each folded with the corresponding source strengths, and then summed over all nine lines, to obtain the estimate of the dose to the hand.

TABLE 2

GAMMA RAY SOURCES

GAMMA RAY LINE (MeV)	RADIOACTIVE ISOTOPE	SOURCE STRENGTH* (MeV/cm·sec)
0.19	Fe-59	5.51 + 7**
0.32	Cr-51	1.31 + 10
0.511	Co-58	2.09 + 10
0.81	Co-58	1.11 + 11
1.10	Fe-59	6.07 + 9
1.17	Co-60	1.18 + 10
1.29	Fe-59	5.37 + 9
1.33	Co-60	1.34 + 10
1.64	Co-58	1.12 + 9

*At time 5 days after shutdown

**Read: 5.51×10^7

4. MONTE CARLO CALCULATIONS

Separate calculations were performed with the SAM-CE Monte Carlo code[1] for each of the nine identified gamma ray lines. In order to speed convergence of the Monte Carlo calculations, spatial and angular importance sampling were employed to emphasize those gamma ray histories which intercept the hand.

SAM-CE calculated the flux in the hand, as a function of energy, and then applied an energy-dependent gamma flux-to-tissue dose conversion factor[2] to obtain tissue dose. Both uncollided and total doses were determined for each gamma ray line. The statistical uncertainty of the results were approximately $\pm$5%.

The results are given for each line, in Table 3. They are also plotted, for both uncollided and total dose, in Figure 2 wherein a simple linear relationship between dose and source energy is clearly visible. This will eliminate the need for additional Monte Carlo calculations should other prominent gamma ray lines be identified in the future.

TABLE 3

MONTE CARLO RESULTS

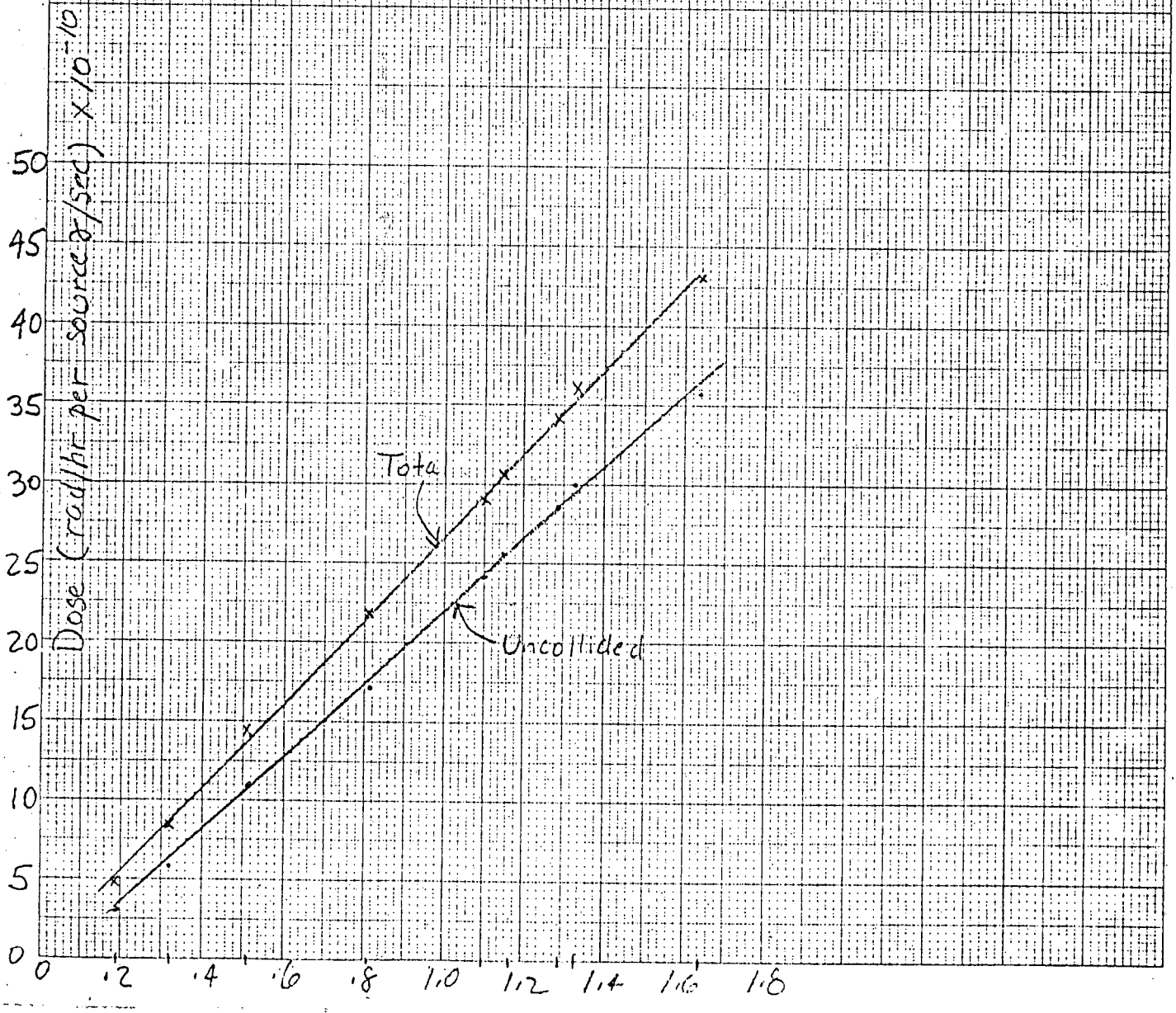
GAMMA RAY LINE (MeV)	DOSE (rad/hr per sourceγ/sec)* Uncollided	Total	RATIO: Uncollided-to-Total
0.19	.301 -9 (5)**	.480 -9 (6)	.63
0.32	.567 -9 (4)	.838 -9 (5)	.68
0.511	.110 -9 (4)	.144 -8 (4)	.76
0.81	.173 -8 (5)	.220 -8 (5)	.79
1.10	.242 -8 (5)	.291 -8 (5)	.83
1.17	.257 -8 (5)	.307 -8 (6)	.84
1.29	.286 -8 (5)	.342 -8 (5)	.82
1.33	.300 -8 (5)	.362 -8 (5)	.83
1.64	.358 -8 (4)	.432 -8 (4)	.83

*Note: Divide by 3600 sec/hr to obtain dose in units of rad/source γ as in Table 4.

**Read: $0.301 \times 10^{-9} \pm 5\%$

Figure 2

DOSE AS A FUNCTION OF SOURCE ENERGY



5. DETERMINATION OF THE HAND DOSE

The source strengths provided by Con Ed, S_ℓ, are in units of MeV/cm·sec at time 5 days after shutdown. These can be converted to the ten-second source strengths, $S_{10\text{-sec}}$ (γ particles), at time 54 days, as follows:

1) Radioactive Decay - The half-life in days, $T_{1/2}$, is given in Table 4 for each line. These are related to the decay constant, λ (days^{-1}) by $\lambda = \ell n\ (2)/T_{1/2}$. The relative source strength at time 54 days is then:

$$S_\ell(54 \text{ days}) = S_\ell(5 \text{ days}) \cdot \exp[-\lambda(54-5)]$$

2) Particle Emission - The conversion of source strength from MeV to source particles is accomplished by a simple $(E_0)^{-1}$ conversion factor, where E_0 is the source energy in MeV.

3) Total Length - Mulitplication by 60.96 cm (2 feet) converts the source strengths from a per centimeter basis to a total length basis.

4) Irradiation Time - It is conservatively assumed that the rod and hand were in the position of Figure 1 during the entire 10 second interval*. Hence, the source strengths per sec are converted to 10-second source strengths by a multiplication factor of 10.

Combining items 1-4, above, the source terms are obtained by:

$$S_{10\text{-sec}}(\text{source photons}) = \frac{S_\ell x e^{-49\lambda}}{E_0} \times 609.6$$

The results are given in Table 4. (The customary unit of biological dose, the rem, is used, where one rad of gamma radiation corresponds to a biological dose of one rem[3]. Hence the rad-to-rem conversion factor is unity).

Table 4 shows that the total 10-second dose to the hand, based upon the preliminary source strengths provided by Con Ed is ∿54 rem. The 0.81 MeV line from Co-58 dominates the problem, accounting for ∿59% of the total dose to the hand.

*Actually, during this 10 second period, the 2 foot section of originally exposed rod was being shoved under water, with the hand probably reaching the water level after about 5 seconds. This will be examined below.

TABLE 4

DOSE TO HAND

GAMMA RAY LINE (MeV)	DOSE PER SOURCE γ (rem/source γ)	$T_{1/2}$ (days)	λ (day^{-1})	$\frac{609.6e^{-49\lambda}}{E_0}$ (cm·sec/MeV)	S_ℓ (MeV/cm·sec)	$S_{10\text{-sec}}$ (source γ)	DOSE TO HAND (rem)
.19	1.33 -13*	44.6	.01554	1498.	5.51 + 7	8.25 + 10	0.01
.32	2.33 -13	27.7	.02502	559.	1.37 + 10	7.66 + 12	1.78
.511	4.00 -13	71.3	.00972	741.	2.09 + 10	1.55 + 13	6.19
.81	6.11 -13	71.3	.00972	467.	1.11 + 11	5.18 + 13	31.67
1.10	8.08 -13	44.6	.01554	259.	6.07 + 9	1.57 + 12	1.27
1.17	8.53 -13	5.27 years	3.60×10^{-4}	512.	1.18 + 10	6.04 + 12	5.15
1.29	9.50 -13	44.6	.01554	221.	5.37 + 9	1.19 + 12	1.13
1.33	1.006 -12	5.27 years	3.60×10^{-4}	450.	1.34 + 10	6.03 + 12	6.07
1.64	1.20 -12	71.3	.00972	231.	1.12 + 9	2.59 + 11	.31

*Read: 1.33×10^{-13}

TOTAL DOSE = 53.58 rem

6. SOURCE GEOMETRIC CONFIGURATION

In order to assess the degree of conservatism provided by assuming that the rod and hand were in the position of Figure 1 for the entire 10 second period, a second set of calculations were run for the point in the time history when the lower part of the hand reached the water level (i.e., the rod protruded 1'2" from the water bath). The results are displayed in Table 5.

It is seen that the dose contributions from the gamma lines below 1 MeV are essentially unchanged. For these softer gamma rays most of the contribution is from the 4" section held by the hand. For the source energies above 1 MeV, lateral contributions (i.e., from other parts of the rod) contribute to the total dose and these are significantly attenuated by the presence of more water.

However, when the results are combined with the preliminary source strengths and summed over all nine gamma lines, the net effect of lowering the rod is a small decrease in the hand dose rate by a factor of $\sim 50.3/53.6 = 0.94$.

If it is assumed that at the end of the ten second period (rod completely under all water) the dose has decreased by an additional factor of 0.94, then the dose at this time would be $\sim$47.2 rem.

Therefore, the best estimate of the 10 second hand dose is of the order of 50 rem. This result can be refined with improved estimates of the source strengths of the identified gamma rays lines.

TABLE 5

EFFECT OF ROD POSITION ON HAND DOSE

GAMMA RAY LINE (MeV)	DOSE (rad/hr per sourceγ/sec) ROD 2' ABOVE WATER	ROD 1'2" ABOVE WATER
0.19	.480 -9 (6)*	.475 -9 (7)
0.32	.838 -9 (5)	.877 -9 (6)
0.511	.144 -8 (4)	.151 -8 (5)
0.81	.220 -8 (5)	.205 -8 (8)
1.10	.291 -8 (5)	.271 -8 (5)
1.17	.307 -8 (6)	.289 -8 (5)
1.29	.342 -8 (5)	.292 -8 (5)
1.33	.362 -8 (5)	.305 -8 (6)
1.64	.432 -8 (4)	.390 -8 (6)
HAND DOSE (Calculations not shown)	53.6 rem	50.3 rem

*Read: $0.480 \times 10^{-9} \pm 6\%$

7. REFERENCES

1. M. O. Cohen, et al., "SAM-CE: A Three Dimensional Monte Carlo Code for the Solution of the Forward Neutron and Forward and Adjoint Gamma Ray Transport Equations - Revision D", MR-7021, Rev. D (Oct. 1975).

2. B. J. Henderson, "Conversion of Neutron or Gamma Ray Flux to Absorbed Dose Rate", XDC 59-8-179, p. 18 (Aug. 1959).

3. H. Goldstein, "Fundamental Aspects of Reactor Shielding", Addison-Wesley Publishing Co., Inc., p. 27 (1959).