PHOENIX MEMORIAL LABORATORY

MEMORANDUM REPORT NO. 4

Calculation of Radiation Dose Rates From Fission Products In The Ford Nuclear Reactor

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INTRODUCTION

Calculations are given for estimating the gamma-radiation dose rate due to an unshielded core in the empty pool of the FNR. The calculations were made in order to estimate consequences of an accident which would cause the water to drain out of the pool. The calculations are based on the methods of Stephenson.*

The equations were programmed in the MAD language for use on The University of Michigan IBM-7090 computer. The programs are given in Appendices A and B.

The assumptions made in the approach are:

1. The reactor is a point source.
2. The fission product inventory is due to 2 MW operation for 10^7 seconds.
3. The reactor has been shut down for 10 minutes.
4. Radiation outside the direct beam is due to single scattering from: 1) the pool walls, 2) the building walls, 3) the building ceiling and 4) the building air.
5. Air absorption and pair production may be neglected.

GENERAL EQUATIONS FOR SLAB SCATTERING

Consider a mono-energetic gamma beam of intensity I_o and cross-sectional area A_b, incident on a unit slab. See Figure 1. Assume Σ_1 and Σ_2 to be the total macroscopic cross sections of the slab material for the incident and scattered radiation, I_o and I. At a distance t below the surface of a slab of density ρ, the mass of a small scattering element dt as seen by I_o is ρ Sec θ_1 dt and the radiation **intensity** at the depth t is:

$$I_t = I_o e^{-\Sigma_1 t \operatorname{Sec} \theta_1} \tag{1}$$

* Stephenson, R., "Introduction to Nuclear Engineering", (pgs. 193-200) McGraw-Hill, New York, 1954

Similarly the fraction of the scattered radiation reaching the surface is

$$e^{-\Sigma_2 t \operatorname{Sec} \theta_2} \qquad (2)$$

If we now assume the scattering phenomena to be adequately described by the Klein-Nishina formula we may write:

$$I = \frac{N A_b \operatorname{Sec} \theta_1}{C^2} \frac{d\sigma}{d\Omega} \int_0^t e^{-(\Sigma_1 \operatorname{Sec} \theta_1 + \Sigma_2 \operatorname{Sec} \theta_2) t} \, dt \qquad (3)$$

where I is the intensity at a detector located a distance C from the scattering slab, N is the electron density of the slab and $\frac{d\sigma}{d\Omega}$ is the differential Klein-Nishina cross section.

$$\text{Since } \frac{d\sigma}{d\Omega} = \frac{r_o^2}{2} \left(P - P^2 \operatorname{Sin}^2 \phi + P^3 \right) \qquad (4)$$

$$\text{where } P = \frac{E}{E_o} = \frac{1}{1 + \frac{E_o(1 - \cos \phi)}{.511}} \qquad (5)$$

where E_o is the incident gamma energy, E is the scattered gamma energy and ϕ is the scattering angle.

After integrating and simplifying (3) becomes:

$$I = \frac{N A_b}{C^2} \left[\frac{1 - e^{-\left(\frac{\Sigma_1}{\cos \theta_1} + \frac{\Sigma_2}{\cos \theta_2}\right) t}}{\Sigma_1 + \Sigma_2 \left(\frac{\cos \theta_1}{\cos \theta_2}\right)} \right] \frac{d\sigma}{d\Omega} \qquad (6)$$

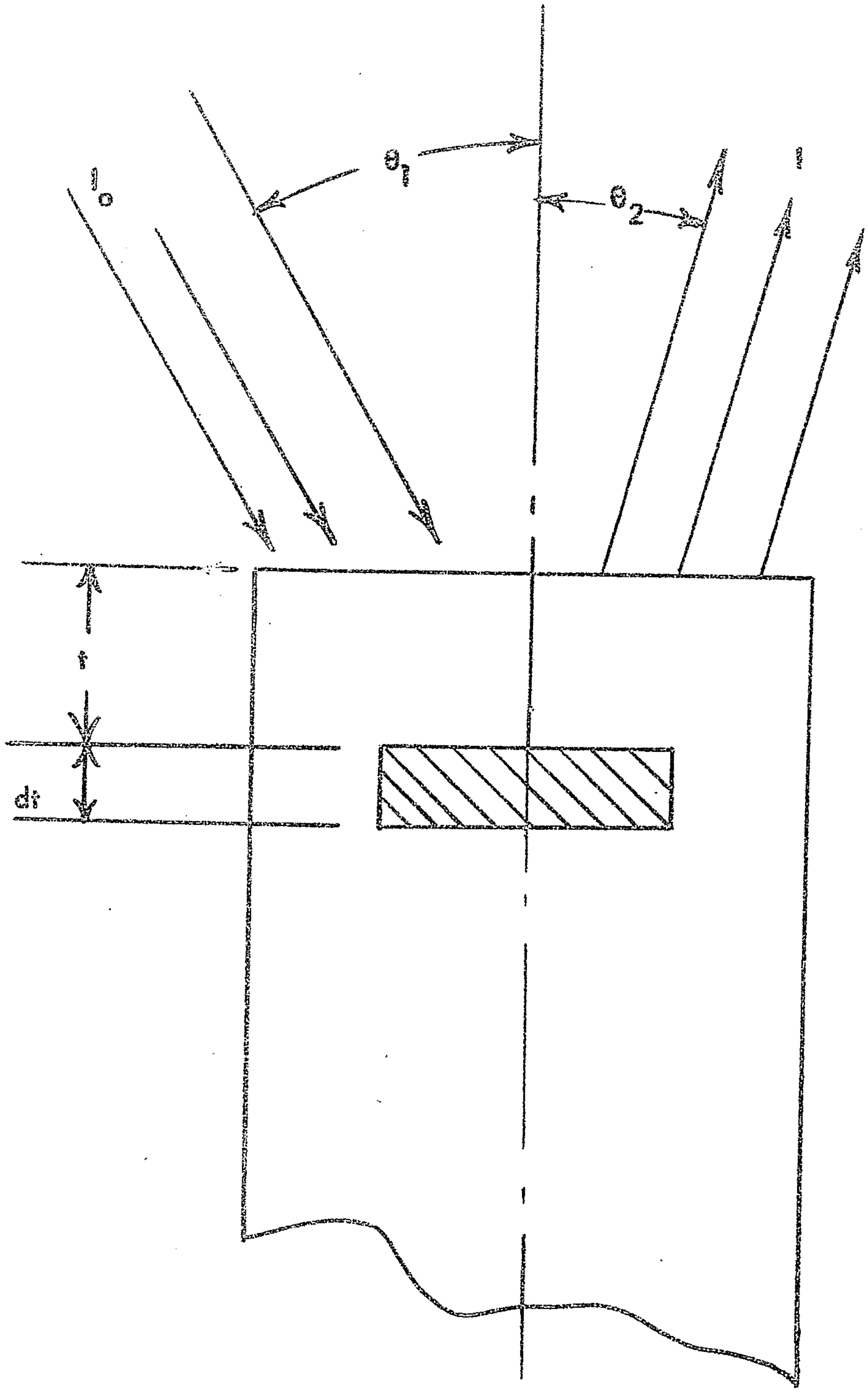

Figure 1

Using the approximate expression (page 184, Stephenson):

$$\text{Dose Rate } (r/hr.) \cong 1.86 \times 10^{-6}\, E\, I \qquad (7)$$

for E ~ .07 Mev to ~3 Mev, the dose rate may be calculated by evaluating (6) at any detector location of interest where I is the number of photons per cm^2 per sec. The difficulty in applying equation (6) is the requirement that the scattering source approximate a point source. Since the detector is 20 to 30 feet from the scattering planes, this requirement is satisfied by dividing all the scattering walls into 20 cm x 20 cm squares and summing the contribution from each square. This is the calculation carried out by the program shown in Appendix A.

GENERAL EQUATION FOR AIR SCATTERING

The air scattering problem is simplified by neglecting absorption in air which also tends to compensate for the error in neglecting secondary scattering. However, the calculation is more laborious because of the necessity of volumetric integration. The equation used here is:

$$I = \frac{N\,S \quad dx\,dy\,dz}{4\pi\, d_1^2 \quad C^2}\;\frac{d\,\sigma}{d\,\Omega} \qquad (8)$$

and the new symbols are S = source strength in gammas per second, d_1 = distance from source to scattering volume dx dy dz. For this calculation the unit volume selected was 50 cm x 50 cm x 50 cm. This calculation was performed with the aid of the program shown in Appendix B.

SOURCE CHARACTERISTICS

The source characteristics were taken from Blomeke and Todd* where four energy groups are given. The maximum energy was used for each energy group. The source characteristics for the assumed power history are given in Table 1.

Table 1 - Source Characteristics

Group	Energy (Mev)	S (photons/sec)
I	.25	3.51×10^{16}
II	1.0	7.39×10^{16}
III	1.7	2.21×10^{16}
IV	3.0	0.70×10^{16}

* ORNL-2127, Part I Volume 2, "Uranium-235 Fission-Product Production As A Function Of Thermal Neutron Flux, Irradiation Time, And Decay Time." J. O. Blomeke and Mary F. Todd

RESULTS

Using equation (7) and the source values shown in Table 1, the gamma dose rate in the direct beam at the reactor bridge was estimated to be 9100 r/hr. In addition, estimates were made for the delayed neutron contribution to the dose rate in the direct beam. The results indicate that neutron dose rate is less than 100 mrem/hr.

Using the computer program shown in Appendices A and B, calculations for scattered radiation dose rates were performed for two detector locations. The location labeled "Inside Building" in Table 2 is considered to be representative of locations of interest in the reactor building. This location is 6 feet above the operating floor at the west wall of the reactor building. Contributions to the dose rate at this location are as follows: the interior south wall of the reactor building; the inside edge of the reactor pool wall; the ceiling of the reactor building and the interior north wall of the reactor building. The dose rate contribution from these individual scattering planes is indicated in the following table.

The location labeled "Outside Building" is considered to be a typical location of interest. The point lies 10 feet to the west of the building at the operating floor elevation which is 10 feet above the ground level.

In addition to the wall scattering contribution, the contribution from radiations scattered by the air in the reactor building is also presented in the table of results.

Table 2 - Radiation Dose Rates

Scattering Source	Dose Rate (r/hr) Inside Building	Dose Rate (r/hr) Outside Building
Air	41.0	7.8
South Wall	13.3	7.5
Ceiling	8.8	5.1
North Wall	14.8	8.7
Pool Walls	82.3	0.0
TOTAL	160.2	29.1

* Note

The calculations for the detector located exterior to the building have neglected the presence of the reactor building walls which are concrete 12 inches thick. This is a tenth thickness value for 3 Mev gammas, hence a reduction in the dose rates by a factor of 10 is considered to be conservative.

APPENDIX A

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E MAD, PRINT OBJECT , PUNCH OBJECT, DUMP , EXECUTE

962 VERSION) PROGRAM LISTING ... ... ...

   READ DATA
   PRINT RESULTS DELX,DELY,DELZ,XD, YD, ZD, ZF, YW, WP, KON,CASE
   WHENEVER CASE.E.1
   XI = CX1
   K1 = CX1 * CX1
   K2 = CX1
   D1 = DELY
   D2 = DELZ
   DC = XD
   DELI = DELY
   DELJ = DELZ
   OR WHENEVER CASE.E.2
   XI = CX2
   K1 = CX2 * CX2
   K2 = CX2
   D1 = DELY
   D2 = DELZ
   DC = XD
   DELI = DELY
   DELJ = DELZ
   OR WHENEVER CASE.E.3
   ZI = CZ
   K1 = CZ * CZ
   K2 = CZ
   D1 = DELX
   D2 = DELY
   DC = ZD
   DELI = DELX
   DELJ = DELY
   OR WHENEVER CASE.E.4
   YI = CY
   K1 = CY * CY
   K2 = CY
   D1 = DELX
   D2 = DELZ
   DC = YD
   JMIN = ZF- (ZD-ZF ) * WP/.ABS. ( YD- YW)
   DELI = DELX
   DELJ = DELZ
   OTHERWISE
   TRANSFER TO STOP
   END OF CONDITIONAL
   INTERNAL FUNCTION F.(D1,D2,K1,V1,V2 ) = D1*D2*K1/(SQRT.(K1+
 2 V1*V1 ) * SQRT. ( K1+ V2*V2 ))
   INTERNAL FUNCTION CO1T. (K2) =.ABS. ( K2 / SB )
   INTERNAL FUNCTION CO2T. (K2, DC) =.ABS. (K2-DC)/SC
   TDR = 0.0
   THROUGH LOOP,FOR VALUES OF EI = 0.25, 1.0, 1.7, 3.0
   DOSI = 1
   WHENEVER EI .E. 0.25
   XCT1 = .270
   S= 3.51E16
   OR WHENEVER EI .E. 1.0
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XCT1 = .1492
S = 7.39E16
OR WHENEVER  EI .E. 1.70
XCT1 = .120
S = 2.21E16
OR WHENEVER EI .E. 3.00
XCT1 = .0853
S = 0.70E16
END OF CONDITIONAL
THROUGH FIRST,FOR I = IMIN, DELI, I .G. IMAX
THROUGH FIRST,FOR J= JMIN, DELJ, J .G. JMAX
WHENEVER CASE.E.1 .OR. CASE.E.   2
YI = I
ZI = J
OR WHENEVER CASE.E.3
XI = I
YI = J
OR WHENEVER CASE.E.4
XI = I
ZI = J
OTHERWISE
TRANSFER TO STOP
END OF CONDITIONAL
A = XD *XD+ YD*YD+ ZD*ZD
B = XI*XI + YI*YI+ ZI*ZI
C= (XD-XI) * (XD-XI)+(YD-YI)*(YD-YI)
1   +(ZD-ZI) * ( ZD-ZI)
SB = SQRT. (B)
SC = SQRT. (C)
C2B = 2.0 * SB * SC
COS1 = (A-B-C) / C2B
SIN21 = 1.0 - COS1 * COS1
P = 1.0/ (1.0+EI* (1.0-COS1) / 0.511 )
DKN= .0237 * ( P -P*P* SIN21 + P .P. 3.0)
V1 = I
V2 = J
AB = F. (D1, D2, K1, V1, V2   )
CO1 = CO1T.(K2)
CO2 = CO2T. (K2, DC)
E = P * EI
WHENEVER E .G . 0.00 .AND. E .L. 0.10 , XCT2 = .397
WHENEVER E .GE. 0.10 .AND. E .L. 0.15 , XCT2 = .327
WHENEVER E .GE. 0.15 .AND. E .L. 0.20 , XCT2 = .291
WHENEVER E .GE. 0.20 .AND. E .L. 0.30 , XCT2 = .251
WHENEVER E .GE. 0.30 .AND. E .L. 0.40 , XCT2 = .2242
WHENEVER E .GE. 0.40 .AND. E .L. 0.50 , XCT2 = .2045
WHENEVER E .GE. 0.50 .AND. E .L. 0.60 , XCT2 = .1889
WHENEVER E .GE. 0.60 .AND. E .L. 0.80 , XCT2 = .1659
WHENEVER E .GE. 0.80 .AND. E .L. 1.00 , XCT2 = .1492
WHENEVER E .GE. 1.00 .AND. E .L. 1.25 , XCT2 = .1332
WHENEVER E .GE. 1.25 .AND. E .L. 1.50 , XCT2 = .1215
WHENEVER E .GE. 1.50 .AND. E .L. 2.00 , XCT2 = .1046
WHENEVER E .GE. 2.00 .AND. E .L. 3.00 , XCT2 = .0853
WHENEVER E .GE. 3.00 .AND. E .L. 9.00 , XCT2 = .060
IBC = S / ( 6.28 * 2.0 * C * B)
NUM = 1.0 - EXP.(( -XCT1/CO1 -XCT2/CO2 )* T)
DEN = XCT1 + XCT2* CO1/ CO2
GAMI = KON*AB*(NUM/DEN)*DKN*IBC
WHENEVER I.E.IMIN .AND.J.E.JMIN, PRINT RESULTS EI, I,J,GAMI,
1 CASE
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APPENDIX B

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$COMPILE MAD, PRINT OBJECT, PUNCH OBJECT, EXECUTE, DUMP

MAD (16 APR 1962 VERSION) PROGRAM LISTING ... ... ...

IN      READ DATA
        PRINT RESULTS XD,YD,ZD,DELI, DELJ, DELK, IMAX, IMIN, JMAX,
       1 JMIN, KMAX, KMIN
        TDR = 0.0
        THROUGH LOOP,FOR VALUES OF EI = 0.25, 1.0, 1.7, 3.0
        WHENEVER EI .E. 0.25, S = 3.51E16
        WHENEVER EI .E. 1.00, S = 7.39E16
        WHENEVER EI .E. 1.70, S = 2.21E16
        WHENEVER EI .E. 3.00, S = 0.70E16
        DOSI = 0.0
        THROUGH FIRST,FOR XI = IMIN, DELI, XI .G. IMAX
        THROUGH FIRST,FOR YI = JMIN, DELJ, YI .G. JMAX
        THROUGH FIRST,FOR ZI = KMIN, DELK, ZI .G. KMAX
        A = XD*XD + YD*YD + ZD*ZD
        B = XI *XI + YI*YI + ZI*ZI
        C= (XD-XI)*(XD-XI ) + (YD-YI) * (YD-YI)+(ZD-ZI)*(ZD-ZI)
        SB = SQRT. (B)
        SC = SQRT. (C)
        C2B = 2.0 * SB * SC
        COS1 = ( A- B- C) / C2B
        SIN21 = 1.0 - COS1 * COS1
        P = 1.0 / (1.0+EI *(1.0-COS1)/0.511 )
        E = P * EI
        DKN = 0.0237 * ( P-P*P*SIN21 + P .P. 3.0 )
        GAMI = 4.77E-05 * S * DKN *DELI*DELJ*DELK/ (B*C )
        WHENEVER XI.E.IMIN.AND.YI.E.JMIN.AND.ZI.E.KMIN,PRINT RESULTS
       1 EI , XI, YI, ZI, GAMI
FIRST   DOSI = DOSI + 1.86E-06 * E * GAMI
        PRINT RESULTS EI, DOSI, XD, YD, ZD
LOOP    TDR = TDR + DOSI
        PRINT RESULTS TDR, XD, YD, ZD
        TRANSFER TO IN
STOP    END OF PROGRAM

THE FOLLOWING NAMES HAVE OCCURRED ONLY ONCE IN THIS PROGRAM.
COMPILATION WILL CONTINUE.

STOP
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