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LOFT GAMMA DENSITOMETER BACKGROUND FLUXES

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LOFT TECHNICAL REPORT
LOFT PROGRAM

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SUMMARY

Background gamma-ray fluxes were calculated at the location of the γ densitometers without integral shielding at both the hot-leg and cold-leg primary piping locations. The principal sources for background radiation at the γ densitometers are ^{16}N activity from the primary piping H_2O and γ radiation from reactor internal sources. The background radiation was calculated by the point-kernel codes QAD-BSA and QAD-P5A. Reasonable assumptions were required to convert the response functions calculated by point-kernel procedures into the gamma-ray spectrum from reactor internal sources. A brief summary of point-kernel equations and theory is included in Appendix A.

CONCLUSIONS AND RECOMMENDATIONS

The principal source of background radiation at the γ densitometers is the ^{16}N activity from the immediate piping that the densitometer is attached to. On the cold leg the heating response due to reactor internal sources is 25 percent of the total background. In the hot leg, the heating response due to reactor background sources is only 10 percent of the total background due to the substantially higher ^{16}N activity. The resultant reactor background gamma spectrum is plotted in Figure 3. The equations and procedures adopted to calculate this γ spectrum from point-kernel response functions are developed in the body of the report. The calculated response due to all ^{16}N activity in piping and machinery adjacent to the pipe the densitometer is mounted on may be normalized to the γ spectrum calculated by detailed Monte Carlo results reported in UCID-17365.

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March 3, 1978

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1.0 STATEMENT OF PROBLEM

Background gamma-ray fluxes at the gamma densitometers arise from two principal sources:

1. Direct-path gamma sources from primary fission gammas and secondary neutron-capture gammas in reactor internals. Of these sources, fluxes arising from secondary neutron capture in the pressure vessel (PV), shield tank inner wall (STIW), and shield tank (ST) H₂O are the principal contributors. The PV and ST constitute an effective shield for sources internal to the PV.
2. ¹⁶N activity in the steam generator and associated piping and pumps arising from the H₂O flowing past the densitometer.

2.0 DISCUSSION

2.1 ¹⁶N Background Flux at the LOFT Cold-Leg Gamma Densitometer

F. J. Wheeler calculated ¹⁶N source densities as a function of flow rates in LTR 129-9⁽¹⁾. Point-kernel fluxes were calculated at four detector-point locations at the cold-leg densitometer using the maximum ¹⁶N source density for 55-MW power. The detector-point locations are shown in Figure 1. The same calculations have been repeated for the densitometer located on the hot leg. These values are reported in Section 2.2.

The variation in source intensity along the axial length of the piping was accurately accounted for in these calculations. Total energy flux at detector locations and heating response in iron was calculated as well as separate contributions from each segment of the primary piping.

No details of the resultant Compton-scattered photon spectrum are given by point-kernel methods. However, the total energy flux from ¹⁶N activity at each detector location can be normalized to the detailed ¹⁶N energy spectrum calculated by Monte Carlo methods reported in UCID-17365⁽²⁾. The Monte-Carlo calculations included only the sources from the 55 inches of piping adjacent to the densitometer. This constitutes 96% of the total gamma flux at detector point 4 and 76% of total gamma flux at detector point 2. Detector point 4 is shielded from the hot-leg piping by the cold-leg pipe itself, whereas

detector point 2 is unshielded. The gamma-ray energy spectrum at detector point 2 should be almost identical to that from the cold-leg sources. Contributions from the hot leg to detector point 4 are only a small perturbation to the spectrum from the cold leg itself.

The gamma energy-flux and gamma heating at the location of the cold-leg gamma densitometer due to ^{16}N decay in the primary coolant loop were calculated with the QAD-BSA⁽³⁾ code. This code includes a general geometry package which allows reasonably accurate models of the loop components to be constructed. The coolant loop was divided into the five components listed in Table I with each component representing a ^{16}N source. A basic model of the reactor vessel and the 139.70 cm (55 in.) straight run section of the cold leg was constructed. Each of the loop components was then modeled and added singly to the basic model for a QAD-BSA calculation. Because of geometry limitations in the code, some of the components had to be further broken down. In all nine such models, subsequent QAD-BSA runs were made. The contributions to the flux from each model were summed and are listed in Table I. The gamma heating results are listed in Table II.

The major assumptions and simplifications used in the QAD-BSA models and calculations are discussed below. All are believed to be conservative.

1. No credit was taken for the shielding value of structural material which may be present between the source volume and the densitometer. The presence of this material may significantly reduce the flux at the densitometer detector.
2. Due to the limited selection of equations for describing surfaces in the QAD-BSA code, the majority of the loop piping was modeled using slabs of steel and water. The source geometry in these regions was limited to a rectangular parallelepiped rather than a more exact cylinder.
3. No credit was taken for the shielding value of the steam generator internals. A small fraction of the internal volume of the steam generator is occupied by the U-tubes, flow separators, and other hardware. The inclusion of this material would slightly increase the self-shielding effect of the steam generator.

TABLE I
 INTEGRAL ENERGY FLUX (MeV/cm² sec) COLD LEG

Source	Detector Numbers			
	1	2	3	4
Hot Leg Piping (PV outlet to SG inlet)	2.377+06	1.580+06	1.263+06	1.386+05
Steam Generator (plenums & tubes)	3.157+05	2.082+05	8.892+04	5.629+04
SG to Pump Piping	1.175+06	9.825+05	8.842+05	7.480+04
Pumps	8.400+04	6.313+04	5.352+02	1.556+03
Cold Leg Piping (pump outlet to PV inlet)	<u>8.816+06</u>	<u>8.685+06</u>	<u>8.489+06</u>	<u>8.355+06</u>
TOTAL	1.277+07	1.152+07	1.073+07	8.626+06

TABLE II
HEATING IN IRON (watts/g) COLD LEG

Source	Detector Number			
	1	2	3	4
Hot Leg Piping	8.211-09	5.848-09	4.675-09	5.130-10
Steam Generator	1.168-09	7.703-10	3.290-10	2.083-10
S.G. to Pump Piping	4.349-09	3.635-09	3.272-09	2.768-10
Pump	3.108-10	2.336-10	1.980-12	5.756-12
Cold Leg Piping	3.262-08	3.214-08	3.141-08	3.091-08
TOTAL	4.666-08	4.263-08	3.969-08	3.191-08
			Reactor Internal	8.5 - 09

Figure 1. Detector locations around LOFT primary coolant inlet pipe.

4. The two primary-coolant pumps were combined into one large pump to facilitate modeling. With respect to the gamma densitometer, the pump closest to the reactor vessel should effectively shield the outer pump, thus combining the two pumps will give a conservative flux estimate.
5. The density variation of the primary coolant water around the circuit was not taken into account. Because of the pressurized nature of the system this variation is not large.

2.2 ^{16}N Background Flux at the LOFT Hot-Leg Gamma Densitometer

The background flux at the LOFT hot-leg gamma densitometer due to gamma decay of ^{16}N in the primary coolant loop water was also calculated. The assumptions and methods used for the calculation were identical to those presented in Section 2.1. Only the location of the detector points was changed. However, the relative locations of the detector points about the coolant pipe were not changed. Thus, Figure 1 is valid for both the hot-leg and cold-leg calculations.

The results of the calculation are given in Table III, in terms of integral energy flux, and Table IV, in terms of heating rates in iron. The background flux at the hot-leg densitometer is about a factor of 2.5 higher than the background flux at the cold-leg densitometer. This is the expected trend since the ^{16}N source in the hot-leg pipe is about two times higher than in the cold-leg pipe. Note that, as in the case of the cold-leg densitometer, the section of piping to which the densitometer is attached is the greatest contributor to the background flux.

2.3 Background Flux Due to Reactor Internal Sources

Reactor background sources as a function of radial distance from the LOFT core axial centerline were calculated by the GAMSORE⁽⁴⁾ code using four-group neutron fluxes determined by the SCAMP⁽⁵⁾ cylindrical S_n transport code. Table V lists the total gamma ray sources determined for each principal region of the LOFT core internals.

TABLE III

INTEGRAL ENERGY FLUX (MeV/cm²-sec) HOT LEG

Source	Detector Number			
	1	2	3	4
Hot Leg Piping (PV outlet to SG inlet)	2.334+07	2.231+07	2.172+07	2.098+07
Steam Generator (plenums and tubes)	3.158+05	2.082+05	8.894+04	5.629+04
SG to Pump Piping	6.844+05	1.289+05	4.878+05	6.806+04
Pumps	4.670+04	3.578+04	3.337+04	4.740+03
Cold Leg Piping (pump outlet to PV inlet)	6.245+05	4.389+05	3.701+05	3.941+04
TOTAL	2.501+07	2.312+07	2.270+07	2.115+07

TABLE IV
HEATING RATE IN IRON (watts/g) HOT LEG

Source	Detector Number			
	1	2	3	4
Hot Leg Piping	8.639-08	8.256-08	8.036-08	7.765-08
Steam Generator	1.168-09	7.703-10	3.290-10	2.083-10
S.G. to Pump Piping	2.532-09	4.769-10	1.805-09	2.518-10
Pump	1.728-10	1.324-10	1.235-10	1.754-10
Cold Leg Piping	2.771-09	1.939-09	1.620-09	1.752-10
TOTAL	9.303-08	8.588-08	8.424-08	7.846-08
Reactor Internal				8.5 - 09

TABLE V

GAMMA SOURCES AT 55 MW

SOURCE REGION	INTEGRAL SOURCE (MeV/sec)
Core	3.452 +19
Flow Skirt	4.163 +18
Stainless Filler	1.135 +18
PV and STIW	4.343 +16
ST H ₂ O	4.091 +15

These sources were determined for a 15-gamma group energy structure with spectra characteristic of the materials in each region. Energy fluxes and detector response as a function of heating in iron were then calculated at three detector locations on the cold-leg gamma densitometer indicated in Figure 2.

Tables VI, VII, and VIII indicate the resultant 15-group energy fluxes and heating response at the three detector locations using the energy absorption buildup factor for iron. The iron buildup factor was chosen as representative of Compton scattering over the last few mean free paths of photon travel from internal source volumes. Even though photons travel through several feet of H₂O before entering the top of the ST, the top of the ST is constructed of three inches of iron.

The reactor internal source spectrum is entirely different from the ¹⁶N activity source spectrum. Simple renormalization of the energy flux from adjacent piping to the Monte Carlo flux spectrum calculated from the cold leg will not be a reasonable approach for the reactor background energy flux. An approach based on what is felt to be reasonable assumptions for obtaining a reactor background photon spectrum at the detector points from the basic point-kernel data in Table VI is outlined in the next section.

A brief description of point-kernel theory and equations is given in Appendix A. Even though some of these assumptions may seem questionable the first time through, we will point out that the response at detector locations from reactor internal sources is only a small percentage of the total response from all sources. This helps to establish a framework for evaluating the assumptions we are required to make.

2.4 Reactor Background Photon Flux Spectrum at Detector Point 5

The reactor background spectrum received at the densitometer without Pb shielding is dominated by the high-energy secondary-neutron capture gammas from the PV and STIW. A significant contribution also accrues from the hydrogen-capture gammas in the ST water. Overall detector response was estimated by calculating heating in iron at the detector location within the framework of the point-kernel method integrated over the source spectra. The following equations give the detector response (watts/gm) in Fe for each source group as calculated by QAD-P5A⁽⁶⁾.

DOSE POINT MAP

Figure 2. Dose point map.

TABLE VI
DETECTOR POINT 5

Energy * Group	Source			
	PV and STIW		ST H ₂ O	
	Uncollided Flux I ₀	Buildup Factor Ba	Uncollided Flux I ₀	Buildup Factor Ba
1	4.95 + 4	3.31		
2	3.59 + 5	3.94		
3	3.68 + 4	4.55		
4	2.094 + 4	5.405		
5	1.045 + 4	6.74		
6	9.09 + 2	8.31	2.78 + 1	7.09
7	1.37 + 3	9.83	1.21 + 1	8.43
8	3.55 + 2	12.1	5.82 + 3	10.4
9	4.63 + 1	15.62	1.45 + 3	13.5
10	10.6	21.05	0.091	18.2
11	1.38	30.8	0.014	26.6
12	0.085	50.4		

Heating in Fe

8.223×10^{-9} watts/gm

Heating in Fe

2.66×10^{-10} watts/gm

Heating from filler source = 7.174×10^{-12} watts/gm

Total Heating = 8.5×10^{-9} watts/gm

* contribution from groups below 12 negligible.

TABLE VII
DETECTOR POINT 9

Energy Group	Source			
	PV and STIW		ST H ₂ O	
	Uncollided Flux 10^0	Buildup Factor Ba	Uncollided Flux 10^0	Buildup Factor Ba
1	5.96 + 4	3.32		
2	4.25 + 5	3.96		
3	4.29 + 4	4.58		
4	2.38 + 4	5.45		
5	1.15 + 4	6.81		
6	7.75 + 2	8.41	2.96 + 1	7.14
7	1.43 + 3	9.97	1.28 + 1	8.49
8	3.6 + 2	12.3	6.13 + 3	10.5
9	45.1	15.9	1.51 + 3	13.61
10	9.88	21.5	0.094	18.4
11	1.23	31.5	0.015	27.0

Heating in Fe

Heating in Fe

 9.72×10^{-9} watts/gm 2.81×10^{-10} watts/gmHeating from filler source = 1.75×10^{-11} watts/gmTotal Heating = 1.02×10^{-8} watts/gm

TABLE VIII
DETECTOR POINT 6

Energy Group	Source			
	PV and STIW		ST H ₂ O	
	Uncollided Flux 10^{10}	Buildup Factor Ba	Uncollided Flux 10^{10}	Buildup Factor Ba
1	4.58 + 4	3.38		
2	3.16 + 5	4.04		
3	3.11 + 4	4.68		
4	1.67 + 4	5.59		
5	7.70 + 3	7.01		
6	6.28 + 2	8.68	1.47 + 1	7.54
7	8.89 + 2	10.31	6.11	8.97
8	2.14 + 2	12.75	2.79 + 3	11.1
9	25.4	16.5	6.46 + 2	14.4
10	5.2	22.4	0.037	19.5
11	0.60	33.0		

Heating in Fe
 7.34×10^{-9} watts/gm

Heating in Fe
 1.336×10^{-10} watts/gm

Heating from filler source = 4.07×10^{-11} watts/gm

Total Heating = 7.52×10^{-9} watts/gm

$$R_g(\text{watts/gm}) = [K I_o^0 B_a \frac{\mu a}{\rho}]_g \quad (1)$$

where

$$I_o^0 = \bar{E}_g N_g^0 = \text{uncollided energy flux (MeV/cm}^2\text{-sec)}$$

$$N_g^0 = \text{uncollided photon flux (photons/cm}^2\text{-sec)}$$

$$\bar{E}_g = \text{average photon group energy}$$

$$B_a = \text{average energy absorption buildup factor for iron accounting for Compton-scattered photons over paths from source volumes to detector point (dimensionless)}$$

$$\frac{\mu a}{\rho} = \text{mass energy absorption cross section for iron (cm}^2\text{/gm)}$$

$$K = \text{conversion from MeV to joules}$$

$$= 1.6021 \times 10^{-13} \text{ joules/MeV.}$$

$[B_a I_o^0]_g$ results from integrating the point-kernel Green's function over the distributed-source differential volumes for source group g .

$$[B_a I_o^0]_g = \int_V \frac{B_a(|\vec{r} - \vec{r}'|, \bar{E}_g) \bar{E}_g S_o(r, \bar{E}_g) e^{-\sum_k \mu_k R_k}}{4\pi |\vec{r} - \vec{r}'|^2} dV \quad (2)$$

where

$$S_o = \text{source density (photons/sec)}$$

$$\mu_k = \text{linear attenuation coefficient for material in } k^{\text{th}} \text{ region between } dV \text{ and detector}$$

$$R_k = \text{path length in } k^{\text{th}} \text{ region}$$

$$[B_a I_o^0]_g = \text{total energy flux at detector resulting from distributed source in group } g, \text{ is sum of uncollided flux } I_{og}^0 \text{ plus Compton-scattered flux } I_{og}^S$$

$$[B_a I_o^0]_g = [I_o^0 + I_o^S]_g \quad (3)$$

$$\text{where } I_{og}^S = (B_a - 1)_g I_{og}^0 \quad (4)$$

The uncollided flux I_{og}^0 is obviously present in each source group. The

Compton-scattered flux is distributed in some fashion below the source group. The distribution is unknown from the point-kernel equation. Only the integral of the detector response is given by point-kernel integrations.

$$R(\text{response})_{\text{watts/gm}} = \sum_g R_g \quad (5)$$

where R_g is given by Equation (1).

A photon spectrum from each source group can be derived from Equations (3), and (4) under some reasonable assumption relative to Compton-scattered energy flux. A $1/E$ scattered photon flux (photons/cm²-sec-MeV) in groups below each source group results from assuming that the energy flux I_0^S given by Equation (4) is uniformly distributed below the source group. The ordinate for the uniformly-distributed energy flux I'_{og} is then given by

$$I'_{og} = I_{og}^S \frac{\Delta E_g}{\delta E} = (B_a - 1) I_{og}^O \frac{\Delta E_g}{\delta E} \quad (6)$$

δE

ΔE_g = group width of source group (MeV)

δE = width in MeV from lower energy bound of source group to lower energy bound of group 15 (0.21 MeV)

$\delta E = (E_g - 0.21) \text{ MeV.}$

The photon flux resulting from any given I'_{og} is then given by

$$N'_{og}(E) = \frac{I'_{og}}{\bar{E}\delta(\text{MeV})} \quad (7)$$

where I'_{og} is given by Equation (6).

The resultant total energy flux I_{ok} in any group k is then the sum of the uncollided flux from group k plus the sum of scattered energy fluxes (uniformly distributed) from all source groups g above group k .

$$I_{ok} = I_{ok}^0 + \sum_{g=1}^{k-1} I'_{og} \quad (8)$$

The photon flux in group k is then given by

$$N_{ok} = \frac{I_{ok}}{\bar{E}_k} \quad (9)$$

where $\bar{E}_k$ is the mean energy of group k . The graph of $\frac{N_{ok}}{\Delta E_k}$ is plotted in Figure 3, for detector point 5 on the cold leg.

The total number of photons/cm²-sec is then the integral of the differential photon spectra Equation (9) over all energy.

$$N_0 = \sum_{k=1}^G N_{ok} \frac{\text{Photons}}{\text{cm}^2\text{-sec}} \quad (10)$$

Table IX gives each quantity in Equations (1) - (10) for detector point 5 on the cold leg. N_0 for detector point 5 is 2.858×10^6 photons/cm²-sec from reactor internal sources (Figure 3).

This value is to be compared with 1×10^7 (photons/cm²-sec) assumed in UCID-17365 in both the skew and flat reactor background spectrum.

Detector point 5 on the cold leg for the internal-reactor γ sources corresponds to detector point 4 for the N_{16} data lists.

The corresponding spectrum at detector point 9 located at the bottom of the cold-leg pipe would be identical to detector point 5 spectrum outside

Figure 3. Detector Point 5 Spectrum Flux Density Function.

of normalization to the heating rate ratio.

$$\begin{array}{l} \text{Normalization at} \\ \text{Detector point 9} \end{array} = \frac{10}{8.5} = 1.1765$$

The integral photon spectrum incident at detector point 9 is then

$$1.1765 \times 2.858 \times 10^6 = 3.362 \times 10^6 \frac{\text{photons}}{\text{cm}^2\text{-sec}}$$

In Figure 3, the low-energy portion of the photon flux curve has been modified to take account of the increasing low energy photoelectric absorption of the scattered photons. This modification is a guess but is felt to be realistic. The resultant curve should be renormalized if this alternate low energy tail is adopted.

2.4 Additional Sources

One additional photon source for the densitometer background requires mention. A large high-energy photon flux due to secondary-capture gammas in the PV and STIW streams up the PV annulus to detector point 8, in Figure 2 just above the titanium-hydride annular plug. The dose at this point is 66 rem/hr at steady-state operation. These photons will scatter off the primary piping and the PV flange to the densitometer. The calculation of this scattered flux is very difficult due to the complicated geometry involved, but the scattered flux could be substantial. The simple expedient of covering the top of the PV annulus with steel plates at the location of the densitometer piping will eliminate this source of radiation.

3.0 REFERENCES

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TABLE IX
PARAMETERS FOR EQUATIONS 1 THROUGH 10

Group	Energy Limits (MeV)	$\bar{E}_g$ (MeV)	ΔE_g (MeV)	δE (MeV)	$\Delta E_g / \delta E$
1	10 - 8	9	2	7.8	0.2564
2	8 - 7	7.5	1	6.8	0.14706
3	7 - 6	6.5	1	5.8	0.1724
4	6 - 5	5.5	1	4.8	0.2083
5	5 - 4	4.5	1	3.8	0.2632
6	4 - 3.5	3.75	0.5	3.3	0.1515
7	3.5 - 3	3.25	0.5	2.8	0.1786
8	3 - 2.5	2.75	0.5	2.3	0.2174
9	2.5 - 2	2.25	0.5	1.8	0.2778
10	2 - 1.6	1.80	0.4	1.4	0.2857
11	1.6 - 1.2	1.40	0.4	1.0	0.40
12	1.2 - 0.9	1.05	0.3	0.7	0.4286
13	0.9 - 0.6	0.75	0.3	0.4	0.75
14	0.6 - 0.4	0.50	0.2	0.2	1.0
15	0.4 - 0.21	0.305	0.2	0.2	1.0

TABLE IX

(Continued)

Group	Source PV + STIW			Source ST H ₂ O			Energy Flux		Total Iok	Photons cm ² -sec Nok
	I _o ⁰	Ba	I _o ^S	I _o ⁰	Ba	I _o ^S	Scattered Io'g	ΣI'og		
1.	4.95+4	3.31	1.143+5				2.93+4	0	4.95+4	5.5+3
2	3.59+5	3.94	1.055+6				1.55+5	2.93+4	3.883+5	5.177+4
3	3.68+4	4.55	1.306+5				2.25+4	1.843+5	2.211+5	3.40+4
4	2.094+4	5.405	9.224+4				1.92+4	2.068+5	2.277+5	4.14+4
5	1.045+4	6.74	6.0+4				1.58+4	2.26+5	2.365+5	5.254+4
6	9.09+2	8.31	6.645+3	2.78+1	7.09	1.693+2	1.032+3	2.418+5	2.427+5	6.472+4
7	1.37+3	9.83	1.21+4	1.21+1	8.43	9.0+1	2.177+3	2.428+5	2.566+5	7.895+4
8	3.55+2	12.01	3.94+3	5.82+3	10.4	5.47+4	1.275+4	2.45+5	2.512+5	9.13+4
9	4.63+1	15.62	6.77+2	1.45+3	13.5	1.813+4	5.225+3	2.577+5	2.592+5	1.152+5
10	10.6	21.05	2.125+2	0.091	13.2	1.56	61.2	2.63+5	2.63+5	1.46+5
11	1.38	30.8	41.12	0.014	25.6	0.358	16.6	2.63+5	2.63+5	1.878+5
12	0.085	50.4	4.20				1.8	2.63+5	2.63+5	2.505+5
13								2.63+5	2.63+5	3.507+5
14								2.63+5	2.63+5	5.26+5
15								2.63+5	2.63+5	8.62+5

Heating

8.223 x 10⁻⁹ watts/gm Fe

Heating

2.66 x 10⁻¹⁰ watts/gm Fe

Total Heating Detector Point 5

8.5 x 10⁻⁹ watts/gm FeHeating filler source 7.174 x 10⁻¹² watts/gm Fe

APPENDIX A

NOTES ON POINT KERNEL CODES

The Boltzman equation is:

$$\vec{\Omega} \cdot \vec{\nabla} F(r, E, \vec{\Omega}) + \Sigma_T F(r, E, \vec{\Omega}) = \iint \Sigma_S(E' \rightarrow E, \vec{\Omega} \cdot \vec{\Omega}') F(r, E, \vec{\Omega}') dE' d\Omega' + S(r, E, \vec{\Omega}). \quad (A1)$$

Outside of geometry, the scattering energy transfer integral introduces most of the complications in the energy dependent Boltzman equation. The scattering integral is eliminated if one considers the monoenergetic equivalent of Equation (A1).

The monoenergetic solution for a point source is then.

$$N_0^0(r', E) = \frac{S_0(r, E) e^{-\Sigma_k \mu_k R_k}}{4\pi |\vec{r} - \vec{r}'|^2} \quad (A2)$$

$$N_0^0 = \frac{\text{Photons}}{\text{cm}^2\text{-sec}},$$

$$S_0 = \frac{\text{Photons}}{\text{sec}}$$

o lower subscript implies scalar (isotropic) quantities.

o superscript implies uncollided (monoenergetic) quantities.

μ_k = total photon interaction cross section for the kth material along the path to detector points.

Define uncollided energy flux

$$\begin{aligned} I_0^0(r', E) &= E N_0^0(r', E) \\ &= \frac{E S_0(r, E) e^{-\Sigma_k \mu_k R_k}}{4\pi |\vec{r} - \vec{r}'|^2} \end{aligned} \quad (A3)$$

= point source Green's function.

For an energy-dependent source, the total uncollided energy flux is

$$I_0^0(r') = \int I_0^0(r', E) dE \quad (A4)$$

The energy flux is of interest because heating rates and ionization at the detector points is a function of energy deposited. The uncollided energy absorption rate at the detector is,

$$R(r') = \int \frac{\mu_a(E)}{\rho} I_0^0(r', E) dE. \quad (A5)$$

where $\frac{\mu_a}{\rho}$ = mass energy absorption coefficient.

Equation (A5) will underestimate the energy deposition at the detector because only the uncollided flux is contributing. In Equation (A3), μ_k is the sum of the Compton scattering cross section and absorption processes. Compton scattering in Equation (A3) is treated as absorption. An experimental measurement would yield a spectrum of Compton scattered photons $I_0^S(r', E)$ in addition to the uncollided flux.

The energy buildup factor is the ratio of the total true flux integral to the uncollided flux integral.

$$B_E(\vec{r}-\vec{r}', E) = \frac{\int I_0(r', E) dE}{\int I_0^0(r', E) dE} = 1 + \frac{\int I_0^S(r', E) dE}{\int I_0^0(r', E) dE} \quad (A6)$$

where $I_0^S(r', E)$ = scattered flux spectrum at the detector.

$B_E(\vec{r}-\vec{r}', E)$ is a function of mfp to the detector and the energy of source photons.

It is easier to measure ionization or heat deposition. Two additional buildup factors result.

$$B_D = \frac{\int \mu_a^{\text{air}}(E) I_0(r', E) dE}{\int \mu_a^{\text{air}}(E) I_0^0(r', E) dE} \quad (A7)$$

$$B_a^Z = \frac{\int \mu_a^Z(E) I_0(r', E) dE}{\int \mu_a^Z(E) I_0^0(r', E) dE} \quad (A7)$$

Equation (A7) defines the dose buildup factor and Equation (A8) defines the energy absorption buildup factor for an element of atomic number Z . In both cases B depends on the total number of mfp between the source and the detector points and upon the energy of the source photons.

Given a point-kernel solution for the uncollided flux. The true response at the detector by a monoenergetic source is then

$$R(r') = B(\vec{r}-\vec{r}', E_0) \frac{\mu_a}{\rho}(E_0) I_0^0(r', E_0) \quad (A8)$$

where I_0^0 is given by Equation (A3).

For a multigroup source spectrum the total response is Equation (A8) summed over all source groups.

Buildup factors have been calculated for a wide variety of materials and source energies over a large range of mfp between simple source geometries and detector points.

The method is useful in practical calculations because.

1. Buildup factors have been found to vary slowly with mfp and source energy and therefore may be fit to simple functions.
2. I_0^0 is relatively easy to calculate even for complicated source geometries and heterogeneous arrangements of shielding materials.

The QAD point kernel codes use a moments fit to infinite-medium buildup-factor data.

For low Z materials:

$$B(\mu|\vec{r}-\vec{r}'|, E) = \sum_{j=0}^4 \sum_{i=0}^3 C_{ij}(\mu|\vec{r}-\vec{r}'|)^i (E)^j, \quad (A9)$$

for high Z materials

$$= \sum_{j=0}^4 \sum_{i=0}^3 C_{ij}(\mu|\vec{r}-\vec{r}'|)^i \left(\frac{1}{E}\right)^j \quad (A10)$$

The coefficients C_{ij} are tabulated for dose and energy-absorption buildup-factors for H_2O , Al , Fe and Pb .

The total response at the detector is then obtained by numerically integrating Equation (A8) over the distributed-source volume elements dV and summing over the multigroup source spectrum. Each multigroup is handled as if it were a monoenergetic source.

$$\begin{aligned}
 R(r') &= K \sum_g \int_V B(\mu|\vec{r}-\vec{r}'|, \bar{E}) \frac{\mu_a(\bar{E})}{\rho} I_0^o(r', \bar{E}) dV \\
 &= K \sum_g \int_V B(\mu|\vec{r}-\vec{r}'|, \bar{E}) \frac{\mu_a(\bar{E})}{\rho} \frac{\bar{E} S_o(r, \bar{E})}{4\pi|\vec{r}-\vec{r}'|^2} e^{-\sum_k \mu_k R_k} dV
 \end{aligned} \tag{A11}$$

where $\bar{E}$ is the average group g energy.

K = normalization factor for detector response units e.g., watts/gm.

The graphical interpretation for a single group is given below.