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GAMMA ENERGY RELEASE FROM FISSION
PRODUCT DECAY FOLLOWING A SHORT
REACTOR TRANSIENT

MASTER

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

J. K. Warkentin

PHILLIPS
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ABSTRACT

This report presents the results of an investigation to determine the rate of gamma ray energy release from fission product decay following a short power transient. The investigation involved several experiments in which the energy release rate as a function of time from 1 to 10^4 seconds after fission was obtained by measuring the decay gamma dose rate near the essentially unshielded SNAPTRAN-1 reactor following a transient of less than 300 milliseconds duration. The results obtained are compared with both experimental and theoretically computed data found in the literature. For decay times less than 200 seconds, the results are in good agreement with the referenced experimental data but are considerably higher than the computed data. For longer decay times, agreement is good with all the referenced data.

SUMMARY

Following an instantaneous fission event such as a short power transient in a nuclear reactor, a considerable amount of energy continues to be released in the form of gamma rays emitted from the decay of radioactive fission products. A survey of the literature reveals uncertainty in the predicted rate of this energy release for short times after instantaneous operation involving the fission of U^{235} . Exact computations for decay times less than 100 seconds are precluded by the lack of information regarding the decay properties of some of the short-lived fission products. The amount of available experimental data is also limited, apparently because of the difficulties in obtaining accurate measurements during the first few seconds after fission.

The purpose of this report is to present the findings of an investigation of the total gamma energy release rate based on experimental gamma dose rate measurements taken near the essentially unshielded SNAP-TRAN-1 reactor following a short power transient. Recorded dose rates are presented for times between 1 and 10^4 seconds following a 1.5 MW-sec transient which lasted approximately 250 msec. To obtain the total gamma energy release rate per fission as a function of time after fission, calculations are made to determine the source strength versus time which would yield the measured dose rates thus permitting a direct conversion from dose rate (r/hr) to energy release rate (Mev/fiss-sec). These calculations can be done with reasonable accuracy since the reactor core, which is described in Section II, is relatively small and is separated from the dose rate detectors by less than one relaxation length of gamma shield material. A detailed discussion of the calculations is presented in Appendix A.

The derived energy release rates are compared with both experimental and theoretically computed data found in the literature. The results are from 10 to 20 percent higher than the referenced experimental data in the time interval, 1 to 10 seconds, and are considerably higher than the computed data for decay times less than about 200 seconds. Agreement is good with all the referenced data for times greater than about 500 seconds.

In addition to relating the measured gamma dose rate to the energy release rate, consideration is also given to the total gamma dose, prompt plus decay. Methods for calculating the prompt gamma dose are presented in Appendix B. A comparison of the sum of the predicted prompt dose and the integrated decay dose to a total dose measurement shows good agreement and tends to increase the confidence in the accuracy of the experimental measurements.

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I. INTRODUCTION

Knowledge of the rate of gamma energy release from fission product decay as a function of time after an instantaneous fission event is necessary to predict the heat generation rates in the fuel or the gamma radiation hazards following a fission burst in a uranium-fueled reactor. A search of the literature reveals that the numerous authors disagree on the rate of the gamma energy release per fission for the initial two or three hundred seconds following instantaneous operation, thus leaving some doubt as to which data should be employed in theoretical applications.

During the SNAPTRAN-1 transient testing program a study was undertaken to investigate the total gamma energy release rate from fission product decay for short times after instantaneous reactor operation. In each of several experiments, involving a reactor power transient lasting less than 300 msec, the decay gamma dose rate near the essentially unshielded reactor was recorded as a function of time after fission. From the recorded gamma dose rate the total gamma energy release rates (Mev/fiss-sec) starting at one second after fission have been derived based on theoretical dose rate computations. These computations, which are described in Appendix A, are considered to be reasonably accurate because the core is relatively small and is separated from the detectors with less than one relaxation length of gamma shield material.

The purpose of this report is to present typical results of the investigation and to compare the derived gamma energy release rates for times between 1 and 10^4 seconds after fission with the reported results of several pertinent studies which are reported in the literature.

The variation in the reported predictions of energy release rates for the first few hundred seconds following instantaneous fission appears to be primarily due to the uncertainty in the effects of the very short-lived fission products. To compute the total rate of energy release on a theoretical basis for short times after fission by summing the individual fission product contributions is essentially unfeasible because the half-lives, fission yields, and decay schemes of some of the short-lived fission products of U^{235} have not been determined. There-

fore, it is necessary to rely upon estimated data for the short-lived fission products or upon experimental measurements for short times after fission.

The available information with which the results of this investigation are compared include data obtained by experimental measurement and theoretical data resulting from computation. Prominent computed data are reported by Perkins and King ⁽¹⁾ who have summed the contributions from 123 fission products of U^{235} . These data cover decay times ranging from 10^2 to 10^8 seconds; shorter times are neglected because of insufficient input data for some short-lived fission products. In a more recent computation, Iyer and Ganguly ⁽²⁾ increased the total number of contributing fission products to 185 by estimating the energy spectra for some additional short-lived fission products thus extending the present results to times as short as 10^{-1} second. These results are, nevertheless, low for the first 200 seconds because of lack of data for about 50 isotopes, but are in excellent agreement with those computed by Perkins and King for times greater than 10^3 seconds.

Knabe and Putnam ⁽³⁾ present data for the time interval of 1 to 10^8 seconds which are based on a combination of ORNL experimental data, reported by Maienschein et al, ⁽⁴⁾ for 1 to 1.5×10^3 seconds and the computed results of Perkins and King ⁽¹⁾ for times greater than 10^4 seconds. For the time interval between 1.5×10^3 seconds and 10^4 seconds, they have extrapolated the experimental data so as to join smoothly with the computed results.

Comparison is also made with the gamma energy decay values obtained by an analytical representation presented by Shure ⁽⁵⁾. He has combined various author's results which he considers to be most reliable, both experimental and theoretical, and has presented these results in a practical form suited for calculation. The total gamma energy release rate in Mev/fiss-sec is given by $aAt_s^{-(a+1)}$, where t_s denotes cooling time and a and A are constants dependent upon various cooling time intervals.

The results obtained from this investigation are in good agreement with the data reported by Knabe and Putnam and that obtained by Shure's

analytical expression. The maximum difference is found to occur at 1 second after shutdown. At this time the magnitude of the energy release rate is approximately 20% higher than that presented by Knabe and Putnam and approximately 40% lower than Shure's analytical expression. The difference is less than 10% at 5×10^2 seconds.

II. EXPERIMENTAL FACILITY

The SNAPTRAN-1 reactor is a modified SNAP 2/10A flight machine which is designed to permit large reactivity insertions within a very short period of time resulting in a burst of fissions of considerable magnitude. The reactor package is shown in Figure 1.

The core is a right cylinder (8.875 inches in diameter and 12.25 inches long) containing 37 fuel rods and six beryllium filler pieces which act as neutron reflectors. A cross-sectional view is shown in Figure 2. The fuel-moderator for the reactor is an alloy of zirconium-hydride and 93% enriched uranium. The weight percentage composition of the fuel is 88.2% Zr, 1.8% H and 10% U. Its density is 6.08 gm/cm^3 . The fuel-moderator is clad with Hastelloy N having a density of 8.79 gm/cm^3 . The active core volume (total core minus Be filler pieces) is approximately $1.03 \times 10^4 \text{ cm}^3$ and contains the following volume fractions: 0.828 fuel-moderator, 0.051 cladding, and 0.121 void.

The core is housed in a 0.032 inch thick stainless steel vessel. Externally adjacent to the vessel is a beryllium reflector (Figure 2). The reflector contains four movable drums which are used to control the reactor. For the experiments used in this investigation, a door assembly (Figure 1) was removed from the thermal envelope so that the only materials lying directly between the detector position and the core were the beryllium reflector and the vessel.

A complete description of the SNAPTRAN-1 reactor facility and test program is presented in IDO-17076 (6).

Two types of instruments were used to measure gamma dose rates following the transient tests. These are: (1) a constant recording Tracerlab gamma dose rate detector which is sensitive in the range of 1 to approximately 10^3 r/hr and (2) a constant recording General Electric Type G-12 gamma ionization chamber which is sensitive in the range of approximately 5×10^2 to $5 \times 10^7 \text{ r/hr}$. The low level detector was calibrated in a known gamma radiation field using a standard cobalt source. Calibration of the high level chamber was obtained in the NRTS Test Reactor Area Gamma Facility. Both detectors are considered to have

Figure 1 SNAPTRAN-1 Reactor Assembly

Figure 2 Reactor Cross Section

a maximum potential error of $\pm 20\%$. However, the potential error is primarily one of constant magnitude due to uncertainty in the calibration. The maximum fluctuation due to recording instrumentation over the time interval considered has been determined to be less than $\pm 2\%$.

Gamma sensitive film badge dosimeters were also placed at the same location as the dose rate detectors to measure the total integrated gamma dose from prompt fission gammas during the power burst and decay gammas following the burst. The badges are similar to the ones normally worn by NRTS personnel and are capable of measuring an accumulated gamma dose in the range of 10^{-2} to 10^3 r. The accuracy of these film badges is considered to be within $\pm 10\%$. The badge measurements were made to provide an additional check on the decay gamma dose rate measurements by comparing the measured total dose to the sum of the predicted prompt gamma dose and the integrated experimental decay dose (see Appendix B).

The detectors were located adjacent to each other 7.5 feet from the reactor vessel with their centers on the horizontal axis of the cylindrical core. A top view of the experimental arrangement is shown in Figure 3.

Figure 3 Experimental Arrangement

III. EXPERIMENTAL RESULTS

1. GAMMA DOSE RATE MEASUREMENTS

Gamma dose rate measurements were made during several reactor transient experiments varying in magnitude from 1 to 5 MW-sec. The elapsed time of the power burst in each experiment was between 150 and 300 msec. A comparison of the dose rate recordings, corrected for variation in nuclear energy release, showed magnitude agreement well within detector accuracy. The time variation or decay rate was essentially identical for each experiment. The results of a typical experiment are presented in Figure 4. In this experiment, the transient energy release was 1.5 MW-sec and the total transient time was approximately 250 msec. The extrapolated portion of the curve is due to insufficient overlapping of the two detectors. The high level gamma chamber recording approached zero scale in the region of 7×10^1 seconds. The low level detector was saturated during the power transient and its recording did not return to scale until approximately 2×10^2 seconds after the transient.

2. TOTAL GAMMA DOSE MEASUREMENT

The total dose measured with the film badge for the 1.5 MW-sec transient was 121 r. This dose included the prompt gamma dose during the power transient and the accumulated dose from fission product decay gammas for 18 hours (6.48×10^4 sec) following the transient.

The total dose measurement serves as an additional check on the accuracy of the decay dose rate measurements when compared with the sum of the predicted prompt gamma dose and the integrated experimental decay dose. The prompt gamma dose was calculated to be 52 r. The total decay dose, obtained by numerical integration of the experimental decay curve (Figure 4) with minor corrections for the decay dose accumulated prior to 1 second and between 10^4 and 6.48×10^4 seconds, was determined to be between 61 and 65 r. When this integrated decay dose is added to the predicted prompt gamma dose of 52 r, the resulting total gamma dose of

Figure 4 Experimental Gamma Dose Rate after 1.5 MW-sec Transient

113 to 117 r is obtained. This compares well with the measured value of 121 r and tends to increase the confidence in the accuracy of the measurements.

The analysis to determine the prompt gamma dose and the total decay dose is discussed in Appendix B.

3. CONVERSION OF DOSE RATE TO TOTAL GAMMA ENERGY RELEASE RATE

To obtain the total gamma energy release rate $E_T(t)$ (Mev/fiss-sec) as a function of time after fission, calculations were performed for various times to determine the source strength in the reactor which would yield the measured dose rates (Figure 4) at the detector position. From the results of the calculations, the following relationships were obtained for the 1.5 MW-sec transient:

$$E_T(t) = \begin{cases} 3.20 \times 10^{-5} \times \text{dose rate,} & 10^0 \leq t \leq 10^2 \text{ sec} \\ 3.22 \times 10^{-5} \times \text{dose rate,} & t = 3 \times 10^2 \text{ sec} \\ 3.24 \times 10^{-5} \times \text{dose rate,} & t = 10^3 \text{ sec} \\ 3.31 \times 10^{-5} \times \text{dose rate,} & t = 3 \times 10^3 \text{ sec} \\ 3.33 \times 10^{-5} \times \text{dose rate,} & t = 10^4 \text{ sec} \end{cases}$$

The weak time dependence of the ratio of energy release rate to dose rate indicates that the changes in the energy spectrum of gamma rays passing through the small amounts of shielding are small and have a minor effect upon the calculated results. The ratio would vary significantly with time if there was a thick shield between the reactor and the detector position.

The calculational techniques and parameters used to obtain the above relationships are presented in Appendix A.

4. COMPARISON WITH REFERENCED DATA

The energy release rate curve obtained by multiplying the numbers presented in Section III-3 by the experimental dose rates in Figure 4 for corresponding times is compared in Figure 5 with data obtained from Perkins and King ⁽¹⁾, Iyer and Ganguly ⁽²⁾, Knabe and Putnam ⁽³⁾, and Shure ⁽⁵⁾. The referenced curves have been replotted directly from the

Figure 5 Total Gamma Energy Release Rate after Instantaneous Fission

reported results except for the data from Shure. The latter is obtained from the analytical representation, $aAt_s^{-(a+1)}$, using the numerical constants reported by Shure ⁽⁵⁾ which are as follows:

<u>Time Interval (sec)</u>	<u>a</u>	<u>A</u>
$1 \leq t_s < 1.5 \times 10^2$	0.1316	6.71
$1.5 \times 10^2 \leq t_s \leq 10^6$	0.2919	14.77

In plotting this curve in Figure 5, no attempt was made to eliminate the discontinuity at 1.5×10^2 seconds which arises from the change in constants. It should be noted that the analytical representation was presented by Shure to serve as a practical approximation suited for engineering calculations. The deviations from the actual release rate at points of discontinuity and the potential errors involved are discussed in Reference 5.

The referenced results from Iyer and Ganguly ⁽²⁾ are computed theoretically. In addition to these results, they also present experimental data based on spectrometer measurements of irradiated uranium samples. The experimental results are in excellent agreement with the referenced curve from Knabe and Putnam ⁽³⁾.

The time variation of the experimental curve in Figure 5 is essentially identical to that of the measured dose rate curve (Figure 4) from which it was derived. This is expected because of the slight effects upon the source gamma energy spectral distribution by the small amounts of shielding material surrounding the reactor core.

The uncertainties in the magnitude of the experimental curve which arise from the potential experimental error and the assumptions employed in the calculations (Appendix A) may be reduced considerably by comparison with the referenced data at times near 10^4 seconds. There is general agreement in the literature that the energy release rates for times near 10^4 seconds after fission are accurately known. This is indicated in Figure 5 where all of the referenced curves are shown to be in excellent agreement for decay times between 3×10^3 and 10^4 seconds. For this time interval, the experimental curve agrees within approximately 10% with all of the referenced data.

The comparison of results in Figure 5 shows good agreement between the experimental curve and the data reported by Knabe and Putnam ⁽³⁾ for decay times between 10^1 and 10^4 seconds. In the first decade, 1 to 10 seconds, the results show time variation similar to the Knabe and Putnam curve, which is based upon ORNL experimental data, but are higher in magnitude by approximately 20% at 1 second and 10% at 10 seconds. At 1 second, the release rate is about 40% lower than that obtained with the Shure representation ⁽⁵⁾, but the integrated results appear to be well approximated by this representation. The results are generally in good agreement with all the referenced data for times greater than 5×10^2 seconds after which the contribution from very short-lived fission products is no longer significant.

IV. CONCLUSIONS

The energy release rate results obtained in this investigation are generally in good agreement with data reported by Knabe and Putnam ⁽³⁾ and Shure ⁽⁵⁾ for 1 to 10^2 seconds after fission, during which time interval the decay of short-lived fission products is very significant. At 1 second the results are approximately 20% higher than the Knabe and Putnam data and 40% lower than the Shure representation. All three are within 12% of each other at 8 seconds.

During the short time interval, 1 to 10^2 seconds, the results are considerably higher than the referenced computed data from Iyer and Ganguly ⁽²⁾. The deviation at 10^2 seconds is approximately + 35%. The results are about 60% higher than the data computed by Perkins and King ⁽¹⁾ at 10^2 seconds, the shortest decay time they consider. There is generally good agreement with all the referenced data for times greater than about 5×10^2 seconds. At 10^4 seconds, the maximum decay time considered, agreement is within 10% which is within experimental error.

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APPENDIX A - GAMMA DOSE RATE COMPUTATIONS

The experimental gamma energy release rate curve presented in Figure 5 is derived from the measured dose rate curve (Figure 4) by performing dose rate computations for various decay times to determine the reactor source strength, in units of Mev/fiss-sec, necessary to yield the corresponding measured dose rates. The calculations are carried out so that the total gamma energy release rate, noted here by $E_T(t)$, is the only unknown. Thus, for each decay time, a direct ratio between dose rate (r/hr) and $E_T(t)$ (Mev/fiss-sec) is obtained.

The parameters and assumptions used in the calculations are discussed below. The spectrum of gamma rays reaching the detector position is divided into three energy groups, each represented by an assumed effective energy E_γ . The analytical approach is to calculate for each decay time the gamma flux (photons/cm²-sec at energy E_γ) for each group, convert the flux to dose rate, and sum the results. The resulting dose rate expressions contain only one unknown, $E_T(t)$.

The gamma flux for each energy group at the detector position on the horizontal axis of the cylindrical core is given by the following equation (7).

$$\phi = \frac{BS_V R_o^2}{2(a+z)} F(\theta, b_2) \quad \begin{array}{l} \text{gamma photons/cm}^2\text{-sec of} \\ \text{energy } E_\gamma \end{array}$$

where:

- B = symbolic dose buildup factor due to external shielding
- S_V = gamma source intensity of energy E_γ being emitted from the cylindrical core (γ 's/cm³-sec)
- R_o = radius of the cylindrical source (10.28 cm)
- a = distance from the side of the cylinder to the detector position (230 cm)
- z = effective self-attenuation distance of the cylindrical source (cm)
- θ = $\tan^{-1} (h/2(a+z))$ where h is the height of the cylindrical core (31.12 cm)

$$b_2 = \sum_i^n \mu_i t_i + \mu_s z$$

μ_i = macroscopic total cross section (linear absorption) of the i^{th} shield material (cm^{-1})

t_i = thickness of the i^{th} shield material (~ 6.35 cm Be, 0.081 cm steel)

μ_s = macroscopic cross section (energy absorption) of the source material (cm^{-1})

$$F(\theta, b_2) = \int_0^\theta e^{-b_2 \sec \theta'} d\theta'$$

The unknown $E_T(t)$ is contained in the source intensity term S_V .

Assuming 3.1×10^{10} fiss/W-sec, the source intensity for each energy group is given by the following equation:

$$S_V = 3.1 \times 10^{10} \frac{Pt_o f(t, E_\gamma) E_T(t)}{VE_\gamma} \quad \text{gamma photons/cm}^3\text{-sec of energy } E_\gamma$$

where:

Pt_o = the total integrated nuclear energy release during the reactor transient (1.5×10^6 W-sec)

V = the active volume of the reactor core (1.03×10^4 cm^3)

E_γ = the effective gamma energy for each energy group (Mev)

$E_T(t)$ = the total gamma energy release rate per fission as a function of time after fission (Mev/fiss-sec)

$f(t, E_\gamma)$ = the fraction of $E_T(t)$ in each energy group represented by E_γ .

As stated earlier, three energy groups are considered. The choice of values for effective energies E_γ representing these groups are based on the seven-group spectral distribution which is commonly used ⁽¹⁾⁽³⁾ as shown in Table I.

TABLE I
Decay Gamma Energy Groups

Group	Gamma Energy Range (Mev) ⁽³⁾	Effective E_γ (Mev)
I	0.1 - 0.4 } 0.4 - 0.9 }	0.9
II		
III	0.9 - 1.35 } 1.35 - 1.8 }	1.8
IV		
V	1.8 - 2.2 } 2.2 - 2.6 }	2.6
VI		
VII	2.6 - 5.5 }	

The values of $f(t, E_\gamma)$ used in the source intensity equation were obtained from the spectral curves computed by Perkins and King⁽¹⁾. The fractions and the effective energies they represent are presented for various times in Table II.

TABLE II
Effective Gamma Energy Distribution

<u>Time After Fission (sec)</u>	<u>Fraction $f(t, E_\gamma)$ for Each Effective Energy Group</u>		
	$E_\gamma = 0.9 \text{ Mev}$	$E_\gamma = 1.8 \text{ Mev}$	$E_\gamma = 2.6 \text{ Mev}$
10^2	0.12	0.60	0.28
3×10^2	0.11	0.58	0.31
10^3	0.19	0.53	0.28
3×10^3	0.30	0.46	0.24
10^4	0.43	0.34	0.23

Since Perkins and King do not present spectral data for times shorter than 100 seconds, it was assumed that the fractionation at 100 seconds is constant for shorter times. This is in agreement with the spectral data presented by Knabe and Putnam⁽³⁾. Although their fractional distribution is somewhat different than that of Perkins and King for times

less than 10^3 seconds, their results do indicate a nearly constant fractionation for the first 300 seconds.

The value of Pt_0 , 1.5 MW-sec, was obtained from the reactor power curves which were recorded on fast CEC oscillograph recorders and Ampex magnetic tape recorders.

For calculational purposes, the source is considered to be a right cylinder of the same cross-sectional area as that of the hexagonal portion of the core which is depicted in Figure 2. Thus, the cylindrical source volume is equivalent to the active volume (total core volume minus Be filler pieces). The power distribution in the source volume is assumed to be uniform.

The effective self-attenuation distance (z) of the cylindrical source for each effective energy E_γ is dependent upon the dimensions of the source, the distance to the detector position, and the macroscopic energy absorption cross section of the source material (μ_s) as a function of energy. To obtain the values of μ_s a homogeneous mixture of the uranium, zirconium, hydrogen, and Hastelloy N cladding over the cylindrical source volume is assumed. Using the fuel weight percentages and density, cladding density and volume fractions presented in Section II, the value of μ_s for each energy group is determined by:

$$\mu_s = 0.828 \left[0.10(\mu/\rho)_U + 0.882(\mu/\rho)_{Zr} + 0.018(\mu/\rho)_H \right] \times 6.08 \\ + 0.051(\mu/\rho)_{Ni} \times 8.79$$

where μ/ρ for each element, uranium, zirconium, hydrogen, and nickel (primary component of the cladding material), is the macroscopic cross section for energy absorption divided by density as a function of energy. The values of μ/ρ were obtained from Reference (8) for zirconium and from Reference (7) for the other elements.

The values of the energy dependent parameters used in obtaining the gamma flux ϕ for each effective energy are listed below:

	$E_\gamma = 0.9 \text{ Mev}$	$E_\gamma = 1.8 \text{ Mev}$	$E_\gamma = 2.6 \text{ Mev}$
$z \text{ (cm)}$	5.40	5.43	5.41
$\mu_{\text{steel}}(\text{cm}^{-1})$	0.482	0.327	0.288
$\mu_{\text{Be}}(\text{cm}^{-1})$	0.109	0.076	0.062
$\mu_s(\text{cm}^{-1})$	0.161	0.129	0.122
$F(\theta, b_2)$	0.0133	0.0195	0.0225

Values of z and μ_1 were obtained from Reference (7). Integrations of the functions $F(\theta, b_2)$ were performed on an IBM 7040 computer.

The relaxation lengths, $\mu_1 t_1$, for the steel vessel and beryllium reflector are much less than one mean-free-path. Therefore, the symbolic dose buildup factor B was assumed to be unity.

The gamma dose rate (r/hr) for each effective energy E_γ is obtained by multiplying the corresponding values of the flux ϕ (photons/cm²-sec of energy E_γ) by the following factors:

Effective Energy E_γ	γ Dose Rate per photon/cm ² -sec ⁽⁷⁾
0.9 Mev	$1.7 \times 10^{-6} \text{ r/hr}$
1.8 Mev	$2.9 \times 10^{-6} \text{ r/hr}$
2.6 Mev	$3.8 \times 10^{-6} \text{ r/hr}$

In the previous discussions all parameters needed to obtain the gamma flux ϕ , for each effective energy at time t , are defined except the total gamma energy release rate $E_T(t)$. By substituting the appropriate values for each effective energy E_γ in the flux equation, applying the above conversion factors, and summing the results for each time, the following relationships are obtained for the 1.5 MW-sec transient:

$$\text{Dose Rate} = \begin{cases} 3.12 \times 10^4 E_T(t), & 10^0 \leq t \leq 10^2 \text{ sec} \\ 3.10 \times 10^4 E_T(t), & t = 3 \times 10^2 \text{ sec} \\ 3.08 \times 10^4 E_T(t), & t = 10^3 \text{ sec} \\ 3.02 \times 10^4 E_T(t), & t = 3 \times 10^3 \text{ sec} \\ 3.00 \times 10^4 E_T(t), & t = 10^4 \text{ sec} \end{cases}$$

The close agreement between these relationships is indicative of the minor effects upon the gamma energy spectrum by the small amounts of shielding.

APPENDIX B - TOTAL GAMMA DOSE

The measured total gamma dose resulting from prompt and decay gammas for the 1.5 MW-sec transient was 121 r. The film badge exposure time was 6.48×10^4 seconds. To serve as an additional check upon the validity of the decay dose rate measurements (Figure 4), the following analysis is presented in which the prompt gamma dose is calculated and added to the integrated decay dose, based on Figure 4, for comparison with the film badge measurement. The determination of the prompt gamma dose is considered first.

1. PROMPT GAMMA DOSE

The dose resulting from prompt fission gammas emitted during the 1.5 MW-sec power burst is calculated by techniques quite similar to those used in Appendix A to obtain the decay dose rate. The only changes are that time is eliminated and a different effective energy spectrum is assumed.

The total energy released in the form of prompt gamma rays is approximately 7.2 Mev/fission ⁽⁴⁾⁽⁹⁾. To calculate the prompt gamma dose this total energy per fission is assumed to be released at three effective energies E_γ . The source intensity for each effective energy is determined by the following equation.

$$S_V = 3.1 \times 10^{10} \frac{Pt_o Y(E_\gamma)}{VE_\gamma} \quad \text{gamma photons/cm}^3 \text{ of energy } E_\gamma$$

where $Y(E_\gamma)$ is the effective gamma energy (Mev/fission) released at energy E_γ . Pt_o and V are as defined in Appendix A.

The values of $Y(E_\gamma)$ and the effective energies E_γ were obtained from Reference (9) and are as follows:

<u>$Y(E_\gamma)$ Mev/fission</u>	<u>E_γ Mev</u>
2.89	0.8
2.26	2.0
2.04	4.0

The integrated prompt gamma flux ϕ at the detector position, in γ 's/cm², for each effective energy E_γ is calculated using the same flux equation as given in Appendix A with the appropriate changes due to different values of E_γ . The values of the energy-dependent parameters used are listed below.

	$E_\gamma = 0.8 \text{ Mev}$	$E_\gamma = 2.0 \text{ Mev}$	$E_\gamma = 4.0 \text{ Mev}$
$z(\text{cm})$	5.45	5.43	5.41
$\mu_{\text{steel}}(\text{cm}^{-1})$	0.510	0.314	0.247
$\mu_{\text{Be}}(\text{cm}^{-1})$	0.114	0.071	0.048
$\mu_s(\text{cm}^{-1})$	0.167	0.127	0.146
$F(\theta, b_2)$	0.0120	0.0210	0.0219

All corresponding values are obtained in the same manner using the same references as in Appendix A.

The prompt gamma dose for each effective energy is obtained from the integrated prompt gamma flux, in γ 's/cm², by the following conversion factors:

<u>Effective Energy E_γ</u>	<u>Prompt γ-Dose per photon/cm²(7)</u>
0.8 Mev	$4.7 \times 10^{-10} \text{ r}$
2.0 Mev	$8.1 \times 10^{-10} \text{ r}$
4.0 Mev	$1.1 \times 10^{-9} \text{ r}$

Using the techniques discussed above to determine the prompt gamma dose for each effective energy E_γ and summing the results, the total dose from prompt gammas for the 1.5 MW-sec transient is calculated to be approximately 52 r.

2. INTEGRATED DECAY DOSE

Numerical integration of the experimental dose rate curve (Figure 4) from 10^0 to 6.48×10^4 seconds, assuming constant slope for times greater than 10^4 seconds, yields a total decay dose of approximately 54 r. However, it should be noted that the time interval, 0-1 second, after the power

burst has been neglected. The decay rate in this time region is uncertain; however, by extrapolating the dose rate curve (Figure 4) back to 10^{-1} second, the integrated decay dose from 0 and 1 second is estimated to be between 6 and 10 r.

In addition to the correction for 0 to 1 second, the dose accumulated after 10^4 seconds is slightly increased due to the contributions from fission products formed in transient tests prior to the 1.5 MW-sec test. This previous operating history consisted of 18 transients, ranging in nuclear energy release of 1-10 MW-sec, which were conducted over a time period of three months. The 18th transient was conducted approximately two weeks before the 1.5 MW-sec transient.

To account for these previously formed fission products, the operating history (magnitudes and burst times of transients and the cooling time intervals) was used as input data for computation of source energy decay using the IBM 7040 computer. The computer program used⁽¹⁰⁾ calculates the fission product activity after successive periods of reactor operation and shutdown based on the fission data reported by Perkins and King⁽¹⁾. From the computer results, it was determined that the previous operating history did not come into effect until approximately 2×10^4 seconds and that the total contribution of these long-lived fission products to the total decay dose was about 1 r.

The total integrated decay dose thus obtained from the extrapolated portion prior to 1 second, the integrated experimental curve (Figure 4) and the contribution from the previous operating history is approximately 61 to 65 r. When this is added to the calculated prompt gamma dose, 52 r, a total integrated dose of 113 to 117 r is obtained. This compares well within experimental accuracy to the film badge measurement of 121 r and tends to increase the confidence in the overall accuracy of the measurements.