*Prepared by Doreen Bourne, Group X-10
Edited by Patricia W. Mendijs, Group IS-11*

An Affirmative Action/Equal Opportunity Employer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

*Predicted Bremsstrahlung Generation
by Energetic Electron Beams*

R. J. Faehl

C. M. Snell

R. K. Keinigs

CONTENTS

Abstract	1
Executive Summary	3
I. Introduction	5
II. Calculational Method	7
III. Intensity and Angular Distribution of the Forward-Directed Photon Beam	13
IV. Influence of Atmospheric Absorption	29
V. Influence of Electron Beam Divergence	31
VI. Total Bremsstrahlung Efficiencies	37
VII. Alternative Concepts and Future Work	43
Appendix - Calculated Bremsstrahlung Generation for Monoenergetic Electron Beams	45
References	58

PREDICTED BREMSSTRAHLUNG GENERATION BY ENERGETIC ELECTRON BEAMS

by

R. J. Faehl, C. M. Snell, and R. K. Keinigs

ABSTRACT

The CYLTRAN photon/electron Monte Carlo code has been employed to predict Bremsstrahlung generation by monoenergetic electron beams from 10 to 1000 MeV. The forward-directed Bremsstrahlung intensity is investigated as a function of beam energy, converter thickness, and material. At high energies, the forward extraction efficiency is maximized by using converters that are about 0.1-electron ranges thick. The largest intensities are attained with low-Z converter materials such as beryllium. Because the Bremsstrahlung radiation is strongly forward-directed, low divergence of the incident electron beam is crucial. Under ideal conditions, a 1000-MeV beam can produce intensities up to 10^8 MeV per steradian, per incident electron.

EXECUTIVE SUMMARY

Using a Monte Carlo transport model, we have carried out a systematic investigation of Bremsstrahlung generation by high-energy electron beams. An electron source energy range of $E = 10$ to 1000 MeV was considered, for converter thicknesses of $t_0 = 0.01$ -0.6 electron ranges. The following conclusions emerge from our study:

- (1) Electron beam energies of 500-1000 MeV exhibit Bremsstrahlung characteristics qualitatively different from lower energy beams, $E \leq 100$ MeV. The peak brightness is a very strong function of beam energy, scaling as $E^{4.2}$ for the higher energies.
- (2) Bremsstrahlung radiation at these energies is highly directional, with a cone half-angle of $10^{-1} - 10^{-2}$ degrees.
- (3) Very thin converters must be used to maximize the forward-directed Bremsstrahlung output. At an electron energy of 1000 MeV, a converter thickness of $t_0 \approx 0.1$ electron ranges gives the optimum beam brightness.
- (4) At high energies, low-Z materials such as beryllium provide slightly enhanced beam brightness as compared with high-Z materials. Also, the beam brightness is much less sensitive to variations in the target thickness " t_0 ." This surprising result is attributable to the less severe multiple scattering of electrons and the smaller cross-sections for scattering and reabsorption of Bremsstrahlung photons in the low-Z material.
- (5) Atmospheric absorption of Bremsstrahlung radiation has little effect on intensity within 25 meters of the converter plate. Such a range encompasses virtually all radiographic applications.
- (6) Quality of the electron beam exerts a crucial influence on the peak brightness and angular distribution of the Bremsstrahlung radiation. A uniform spread of one milliradian in the incident beam decreases the peak brightness on axis by about a factor of 4.
- (7) High electron beam energies and currents are needed to achieve extremely high on-axis peak brightnesses with a Bremsstrahlung conversion system. Perhaps the most difficult challenge is to obtain the small beam divergence that is also required. Future research must address the fundamental questions of a power source for the system and accelerator design to produce an intense beam of very high quality.

I. INTRODUCTION

Intense gamma ray bursts, due to the Bremsstrahlung radiation generated when a high-energy electron beam discharges into a converter plate, have a number of applications. These include flash radiography, x-ray cinematography, and pseudoholography. Any application of Bremsstrahlung radiation requires accurate knowledge of the radiation field produced by the converter. This radiation field is determined by transport of both the incident electrons and the generated photons through the converter plate. Although the single event-accumulated, scattering and absorption cross sections for the interaction of electrons with solids are well known, it is the effect of multiple events that determines the final spectrum and angular distribution of the extracted radiation. Extensive calculations have been performed to predict the radiation leaving the converter plate for electron beam energies of 1–20 MeV.^{1,2} These energies are appropriate to existing pulsed power electron beam machines. The corresponding data for higher energy beams do not exist. It is our purpose in this report to provide a comprehensive parameter study of the Bremsstrahlung intensity and angular distribution as functions of both the incident electron beam energy and converter thickness.

Previous studies for moderate electron beam energies have established a very strong dependence of dose rate on the electron energy, typically $\dot{D} \propto E^{2.65-2.8}$. The Bremsstrahlung cross section scales as $1 - (\hbar\omega/E) + 3(\hbar\omega/E)^2$. The single event spectrum extends up almost to the incident electron energy, and scales as $(\hbar\omega)^{-1}$ at lower photon energies.

Photon transport in the converter is dominated by Compton scattering and absorption at moderate energy. These cross sections decrease linearly with photon energy, however. There is an energy at which other processes become dominant. Depending on the material, this crossover point occurs between 1–10 MeV, at which energy pair-production becomes the dominant photon interaction mechanism. The overall photon loss rate increases slightly above this energy, but pair production does not scatter the photons so much as it annihilates them. It does not broaden the angular distribution. Moreover, the electrons and positrons can also contribute to the forward-scattered brightness. Given this competition between Compton scattering and pair-production, it is not obvious that the moderate energy brightness scaling laws should hold for the higher energy electron beams. One of the key results of this study is to show that the dependence of brightness on electron energy becomes even stronger at higher energies.

Another factor in Bremsstrahlung applications is the efficiency with which electron energy is converted into radiation. Single event interactions indicate that there

is a material-dependent electron energy at which Bremsstrahlung generation becomes equal to ionization losses. Above this energy, the Bremsstrahlung becomes progressively more dominant until 90–99% of the electron losses are due to it. Other physical mechanisms preclude achieving this high level of efficiency in the total conversion of electron beam energy to radiation. When elastic scattering of the electrons, reabsorption of the photons, and pair-production are taken into account, typical efficiencies are decreased below 50%. Halbleib and Sanford² find only a 20–25% extraction efficiency at 15 MeV. Their efficiency curve is still sharply increasing at 15 MeV, however. We have extended this extraction efficiency curve to 1000 MeV, and we find a saturation value of about 50% at higher energies. This value represents an integration over the total forward-scattered radiation field. We expect the forward-directed radiation cone to become concentrated into a smaller angle as the electron energy becomes greater. Quantifying the effective cone angle and determining the fraction of the radiated energy within this angle are objectives of this study.

This report is organized into seven sections. In Section II, we give a summary of the theoretical model and calculational method employed. Section III presents systematic predictions of the intensity and angular distribution of the forward-directed Bremsstrahlung. Also discussed are requirements for optimizing the converter, and a brief study of material dependence. The influence of atmospheric absorption is investigated in Section IV. Results of some preliminary calculations exploring electron beam divergence effects are summarized in Section V. Calculations of the total Bremsstrahlung conversion efficiency over 2π solid angle are given in Section VI. The extraction efficiency within the forward-directed radiation cone is also computed. Alternative concepts for directed photon generation and suggestions for future work are given in Section VII.

II. CALCULATIONAL METHOD

The calculations discussed in this report were performed with the two-dimensional coupled electron/photon Monte Carlo transport code, CYLTRAN.^{3,4} This code accurately simulates the physics of the entire electron/photon cascade, including Bremsstrahlung production, positron annihilation, knock-on electrons, and K-shell electron impact ionization. Photon interactions include pair production, Compton scattering, and photoionization. Ionization is followed by the generation of fluorescence photons or Auger electrons. Provision is made to treat *L* and *M* shell interactions at lower energies if required. All primary and secondary particles are tracked until they either escape from the system, undergo absorption, or have their energies reduced below a specified cut-off level. Photonuclear interactions are not included in these calculations. These may be a significant source of photon attenuation in the narrow bands between 15–25 MeV and between 250–350 MeV for high-*Z* converter materials. An effort is in progress to implement appropriate physical models for these effects. Extensive diagnostics in the code provide information on all aspects of the particle interaction. Of greatest interest are tallies that give the transmitted photon flux, angular distribution, and energy spectrum.

For most of the calculations in this parameter study, we have restricted our attention to monoenergetic electron beams normally incident on Bremsstrahlung converter slabs. Since CYLTRAN is a 2D axisymmetric code, the radial outer boundary was set to a sufficiently large value so that lateral escape of the photons never occurred. Transverse scatter and diffusion were still permitted. Suppression of lateral escape produced a transport geometry very similar to the 1D geometry employed in previous studies.² The number of Bremsstrahlung photons generated for very thin converter plates was sometimes inadequate to give satisfactory statistics. In these cases, the photon output was artificially increased by scaling up the cross sections for Bremsstrahlung production, allowing statistically meaningful photon output to be obtained without following an excessive number of electrons. The weights of the Bremsstrahlung photons were then readjusted downward by the same factor to obtain unbiased predictions. To save computing time, secondary electron production was turned off in some of the very high-energy calculations (≥ 250 MeV). This omission had little or no effect on the high-energy forward-directed Bremsstrahlung photons, which are generated mainly by primary beam electrons; several test runs were made to verify that this was indeed the case. An energy cutoff of approximately 0.005 times the electron beam energy was employed. All calculations were run long enough to achieve a statistical standard deviation of 1–4% in the calculated photon angular distributions and energy spectra.

The beam profile employed was a uniform density disk, with a radius much smaller (2.5%) than that of the converter plate. Realistic accelerator beam profiles are not uniform, and will depend upon the beam parameters and type of accelerator employed. Detailed quantification of beam profile effects was beyond the scope of this study.

As a further check on the accuracy of the calculations, we have compared our results with the earlier paper of Halbleib and Sanford.² The present study overlaps with previous work only at the low-energy end. Accordingly, we chose to examine the results for an electron beam energy $E = 10$ MeV. Figure 1 displays the Bremsstrahlung conversion efficiency as a function of scaled tantalum converter thickness " t_0 ." Figure 2 shows the Bremsstrahlung energy spectrum for an optimum thickness converter. Finally, Fig. 3 compares the angular distributions of Bremsstrahlung photons. In all cases, the CYLTRAN calculations agree closely with the 1-D results of Halbleib and Sanford. The distribution functions differ very slightly at certain points because different bin sizes were used to accumulate the tallies; these differences are not physically significant.

Fig. 1. Total Bremsstrahlung conversion efficiency into 2π as a function of tantalum converter thickness: comparison of 10 MeV CYL-TRAN calculations with results of Halbleib and Sanford.²

Fig. 2. Bremsstrahlung photon number spectrum for a 10-MeV incident electron beam: comparison of CYLTRAN calculation with results of Halbleib and Sanford.²

Fig. 3. Normalized angular distribution of Bremsstrahlung photons for a 10-MeV incident electron beam: comparison of CYLTRAN calculation with results of Halbleib and Sanford.² (Vertical scale has been arbitrarily normalized, but is identical for both calculations.)

III. INTENSITY AND ANGULAR DISTRIBUTION OF THE FORWARD-DIRECTED PHOTON BEAM

In this section, we discuss model predictions of the radiation field and its angular and energy dependence. Our goal is to optimize the Bremsstrahlung intensity emitted over a narrow cone angle in the forward direction. The forward-directed radiation intensity per unit angle, or brightness, is the figure of merit that will be emphasized here. We have performed CYLTRAN calculations to explore the effects of converter thickness, material, and incident beam energy. Table I summarizes the parameter space encompassed by the study. The first parameter varied was the scaled converter thickness, t_0 . This quantity is always expressed in terms of the continuous-slowing-down approximation or CSDA electron range at a given energy in the converter material. The CSDA ranges used to select the converter thicknesses for the calculations were obtained from the standard NBS tables,⁵ and were cross-checked against other references⁶ to assure accuracy. There were no significant discrepancies among the tabulated CSDA ranges for the cases investigated here. For each set of calculations, the scaled thickness " t_0 " was varied by small increments over the range from 0.01 to 0.3 or 0.6. Most of the tantalum calculations were terminated at a thickness $t_0 = 0.3$. In the energy range above 300 MeV, the brightness had already dropped off dramatically at this thickness; at moderate energies (10–70 MeV), the variation in brightness was a weak function of thickness, but was monotonically decreasing by $t_0 = 0.3$ –0.4. The second parameter varied was the incident electron beam energy. For tantalum converters, beam energies covered the range from 10 to 1000 MeV in 10 steps with approximately logarithmic spacing. Finally, three different materials were compared at an energy of 1000 MeV: beryllium ($Z = 4$), iron ($Z = 26$), and tantalum ($Z = 73$). In this section, we will present results for all of these comparisons.

The key parameter for optimizing Bremsstrahlung output at a given beam energy is the converter plate thickness t_0 . Figure 4 compares the peak Bremsstrahlung brightness as a function of t_0 , for three different converter materials. These calculations are for an electron beam energy $E = 1000$ MeV. Surprisingly, the highest intensity is achieved with very thin converters, $t_0 \approx 0.1$. More precisely, the optimum occurs near $t_0 \approx 0.08$ for tantalum, $t_0 \approx 0.1$ for iron, and $t_0 \approx 0.12$ –0.16 for beryllium. It is likewise noteworthy that the range in which high output is achieved is quite narrow for tantalum ($t_0 \approx 0.04$ –0.12), but is considerably broader for iron ($t_0 \approx 0.04$ –0.22) and especially for beryllium ($t_0 \approx 0.06$ –0.40). The peak intensity at optimum thickness is highest for beryllium, and lowest for tantalum. The full-width at half maximum angle for these distributions scaled roughly as $Z^{-0.23}$. For this limited sample of materials, it is evident that the low- Z material has an

TABLE I
MATERIALS AND PARAMETERS EMPLOYED IN THE
BREMSSTRAHLUNG GENERATION STUDY

Material and Symbol	Atomic Number "Z"	Density " ρ " (gm/cm ³)	Scaled Thicknesses " t_0 " (electron ranges)	Incident Electron Energies (MeV)
Tantalum, Ta	73	16.6	0.01-0.3	10-1000 MeV
Iron, Fe	26	7.86	0.01-0.6	1000 MeV
Beryllium, Be	4	1.85	0.01-0.6	1000 MeV

Energies selected for the tantalum calculations:

E(MeV) | 10 25 50 70 100 150 250 500 700 1000

Fig. 4 Bremsstrahlung intensities as a function of converter plate thickness, for 1000-MeV electrons incident on tantalum (solid curve), iron (dashed), and beryllium (dotted).

advantage in terms of both peak brightness and insensitivity to converter thickness. All of these results are diametrically opposite to expectations based on lower-energy Bremsstrahlung studies.

In Fig. 5, we have plotted the brightness, I , as a function of t_0 , for the highest electron beam energies of 1000 and 700 MeV. These data are also summarized in Table II. The brightness drops off rapidly with decreasing beam energy. However, the optimum converter thickness remains in the range $t_0 \approx 0.04$ – 0.12 for both of these very high energies.

It is of interest to determine whether the steep decline in brightness with decreasing beam energy noted in Fig. 5 continues to lower beam energies. Utilizing all of the tantalum calculations, we have determined the peak brightness at optimum converter thickness. The results are plotted versus beam energy in Fig. 6. The brightness varies approximately as $I \sim E^{4.2}$ for $E > 100$ MeV, but only as $I \sim E^3$ for $E \lesssim 50$ MeV. Earlier studies at moderate energies had determined that the dose (and dose rate) scale roughly as $D \sim E^{2.65-2.8}$ for $E < 50$ MeV. Our calculations are consistent with those results.

For all Bremsstrahlung sources, the photon spectrum is quite broad, with $f(w) \propto (\hbar\omega)^{-1}$. When $E \lesssim 50$ MeV, a significant fraction of the photons are subject to strong Compton effects in the converter. Elastic Compton scattering in particular will tend to decrease forward-directed brightness, if not the overall extraction efficiency. As the electron energy is increased, fewer of the Bremsstrahlung photons will experience Compton effects. Pair production is the dominant interaction when $\hbar\omega > 10$ MeV. This process removes photons from the flux, but it does not scatter them into greater angles. The electrons and positrons produced by high energy gammas are very forward directed. As a result, when they generate Bremsstrahlung, it will add to the brightness in the forward cone. This may be the reason for the enhanced brightness scaling when $E > 250$ MeV. Although such arguments are not quantitative, they suggest a physical basis for the enhanced brightness scaling.

The peak intensities displayed in Fig. 6 refer to the on-axis location, at the center of the beam. The angular distribution of intensity is also a matter of considerable interest. Figure 7 shows the angular intensity distribution for 1000-MeV electrons incident on tantalum, iron, and beryllium. The cone angle of the radiation is quite narrow: the intensity has decreased by a factor of two at an angle $\theta \approx 0.03^\circ$. In fact, the intensity is down by five orders of magnitude at $\theta = 3^\circ$! It is obvious that the high-energy Bremsstrahlung converter is a very narrow-angle generator rather than a shotgun. As noted previously, the radiation intensities on axis are highest for beryllium and lowest for tantalum. However, the beryllium curve drops off more rapidly with increasing angle, and it is lower than the other curves for $\theta > 0.1^\circ$.

The angular distributions for the highest electron beam energies of 1000 and 700 MeV are compared in Fig. 8. The angular spread is slightly broader and less sharply peaked near $\theta = 0^\circ$ for the lower beam energy, as expected.

The angular intensity distributions for all beam energies from 1000 to 50 MeV are summarized in Tables II (high energies) and III (low energies). Coarser angular binning is employed for the low energies because the beam is less forward directed.

Fig. 5. Comparison of Bremsstrahlung intensities for two beam energies (tantalum converter).

Fig. 6. Peak forward-directed intensity as a function of energy, for optimum-thickness tantalum converters.

TABLE II

SUMMARY OF NORMALIZED ANGULAR INTENSITY DISTRIBUTIONS AS A FUNCTION OF ENERGY, FOR MONOENERGETIC ELECTRON BEAMS INCIDENT ON TANTALUM PLATES OF OPTIMUM THICKNESS. ALL INTENSITIES ARE EXPRESSED IN UNITS OF MeV/SR-ELECTRON-MeV.

Angle "θ" (°)	E (MeV)			
	1000	700	500	250
0.00 -0.01	8.56e4	2.83e4	5.58e3	8.36e2
0.01 -0.02	5.57e4	2.23e4	4.74e3	8.08e2
0.02 -0.03	3.71e4	1.53e4	4.46e3	7.72e2
0.03 -0.04	1.80e4	1.02e4	3.32e3	7.04e2
0.04 -0.05	1.13e4	6.67e3	2.45e3	6.28e2
0.05 -0.075	5.28e3	3.70e3	8.18e2	5.12e2
0.075-0.10	2.10e3	1.76e3	8.18e2	3.51e2
0.10 -0.20	5.68e2	4.39e2	2.16e2	1.72e2
0.20 -0.30	7.05e2	1.40e2	5.24e1	8.16e1
0.30 -0.40	1.56e2	9.47e1	2.40e1	5.68e1
0.40 -0.60	1.39e2	8.11e1	1.75e1	4.44e1
0.60 -0.80	1.27e2	6.91e1	1.25e1	3.76e1
0.80 -1.0	1.08e2	5.96e1	1.03e1	3.04e1
1.0 -1.5	2.71e1	1.39e1	1.47e0	1.48e1
1.5 -2.0	8.88e0	3.76e0	1.88e-1	6.72e0
2.0 -2.5	7.17e0	7.70e-1	2.18e-2	3.41e0
2.5 -3.0	5.99e-1	2.19e-1	3.96e-2	1.95e0

TABLE III
SUMMARY OF NORMALIZED ANGULAR INTEN-
SITY DISTRIBUTIONS FOR LOWER BEAM ENERGIES

Angle "θ" (°)	E (MeV)			
	150	100	70	50
0-0.1	1.31e2	5.07e1	2.41e1	1.28e1
0.1-0.2	7.67e1	4.00e1	2.26e1	1.24e1
0.2-0.3	4.91e1	2.73e1	1.79e1	1.08e1
0.3-0.4	3.88e1	2.30e1	1.51e1	9.70e0
0.4-0.5	3.35e1	2.00e1	1.36e1	8.36e0
0.5-0.6	3.15e1	1.73e1	1.23e1	7.70e0
0.6-0.8	2.74e1	1.53e1	1.09e1	6.86e0
0.8-1.0	6.20e1	1.34e1	9.46e0	6.08e0
1.0-1.5	1.46e1	9.88e0	8.07e0	5.16e0
1.5-2.0	1.15e1	7.03e0	6.48e0	4.36e0
2.0-2.5	7.93e0	5.01e0	5.07e0	3.62e0
2.5-3.0	5.70e0	3.48e0	4.16e0	3.08e0
3.0-4.0	3.35e0	2.06e0	3.01e0	2.42e0
4.0-5.0	8.07e-1	5.21e-1	1.38e0	1.36e0
5.0-10.0	6.93e-2	5.85e-2	4.31e-1	5.88e-1
10.0-20.0	2.07e-3	3.01e-3	4.77e-2	1.15e-1
20.0-30.0	1.68e-4	1.28e-4	2.73e-3	9.94e-3

Fig. 7. (a) Comparison of angular intensity distributions for 1000 MeV electrons incident on Be (dotted), Fe (dashed), and Ta (solid) (optimum-thickness converter plates); (b) close-up of small angle region.

Fig. 8. Comparison of angular intensity distributions, for 1000 MeV (solid curve) and 700 MeV (dashed curve) electrons incident on tantalum.

Fig. 9. Angular intensity distributions for 1000 MeV electrons, incident on tantalum. The curves represent an optimum thickness plate ($t_0 = 0.08$, solid curve), a thin plate, ($t_0 = 0.01$, dashed), and a thick plate ($t_0 = 0.3$, dotted).

Angular distributions for different converter plate thicknesses at 1000 MeV are compared in Fig. 9. The solid curve is for optimum plate thickness, the dotted curve for a thick plate, and the dashed curve for a thin plate. The optimum thickness curve is, of course, highest at small angles. However, the "thick plate" curve declines less steeply with angle, and crosses above the optimum curve at $\theta = 0.4^\circ$. This trend is indicative of more severe multiple-scattering effects and consequent higher fluxes at large angles for the thick plate. The intensity for the thin plate lies below the other two curves at all angles due to the much less efficient Bremsstrahlung conversion.

At lower energies we find a significantly different trend with converter thickness. Figure 10 shows the same three thicknesses, expressed in terms of electron range for 25-MeV electrons. In this case, the intensity at the smallest angles exhibits little variation between "thick" and "intermediate" converters. The brightness at large angles is now a strong function of thickness, and scales at least as the square of " t_0 ." The intensity for the thin plate again lies below the other two curves at all angles.

We note from Fig. 6 that 100 MeV is the transitional energy for brightness scaling. Figure 11 shows the same thickness comparison as was given in Figs. 9 and 10. Again, we find that the "thin" converter gives lower brightness at all angles. The intermediate thickness is again brightest at small angles, but it is less bright than the "thick converter" at angles greater than 2° .

It is apparent that the angular distribution shows qualitative changes as a function of electron energy. Single event theory yields a fairly simple scaling for an effective cone angle, $\langle\theta\rangle \sim \gamma^{-1}$, where γ is the Lorentz factor of the electron. To make quantitative comparisons between the angular distributions, we define a cone angle, $\theta_{0.1}$, as that angle for which the brightness will be 10% of the on-axis, peak brightness. The variation of this parameter with electron energy is shown in Fig. 12. This measure always yields a larger angle than γ^{-1} . Moreover, cone angles at the lower energies $E \lesssim 100$ MeV dramatically exceed γ^{-1} .

At energies $E \gtrsim 300$ MeV, the cone angle is virtually independent of t_0 , at least for $t_0 \leq 0.3$. This is shown in Fig. 13, for $E = 1000$ MeV, for which the cone angle is $\theta_{0.10} \simeq 0.06^\circ$. The variation with thickness is barely 5%. The amount of energy within the cone angle is maximized near the converter thickness which yields peak brightness. In the low energy regime, the cone angle increases continuously with converter thickness. Figure 14 gives the variation of "10% brightness" cone angle with converter thickness for 25-MeV electrons. This variation extends from $\theta_{0.10} = 4^\circ$ at $t_0 = 0.01$, to $\theta_{0.10} = 17^\circ$ at $t_0 = 0.30$. The total energy within this angle increases with the cone angle. Finally, we show transitional energies in Figs. 15 and 16 at 100 MeV and 250 MeV, respectively. The variation with thickness is still a factor of 4 at 100 MeV, but less than a factor of 2.5 at 250 MeV.

Fig. 10. Angular intensity distributions for 25-MeV electrons incident on tantalum. The curves represent an intermediate thickness plate ($t_0 = 0.08$, solid curve), a thin plate ($t_0 = 0.01$, dashed), and a thick plate ($t_0 = 0.30$, dotted).

Fig. 11. Angular intensity distributions for 100-MeV electrons incident on tantalum. The curves represent an intermediate thickness plate ($t_0 = 0.08$, solid curve), a thin plate ($t_0 = 0.01$, dashed), and a thick plate ($t_0 = 0.30$, dotted).

Fig. 12. Variation of the "10% brightness" cone angle with electron energy. The converter thickness which gave optimum peak intensity was used for these measurements. The solid curve represents the single event cone angle, $\langle \theta \rangle \sim 57.1/\gamma$ (degrees).

Fig. 13. Angle for which the intensity has dropped to 10% of its peak value as a function of tantalum converter thickness; 1000-MeV electrons.

Fig. 14. Angle for which the intensity has dropped to 10% of its peak value as a function of tantalum converter thickness; 25-MeV electrons.

Fig. 15. Angle for which the intensity has dropped to 10% of its peak value as a function of tantalum converter thickness; 100-MeV electrons.

Fig. 16. Angle for which the intensity has dropped to 10% of its peak value as a function of tantalum converter thickness; 250-MeV electrons.

Also of interest for certain applications is the spectrum of the forward-directed photons. In Fig. 17, we compare the spectra tallied over an angle interval of 0–0.01°, for 1000-MeV electrons incident on tantalum (solid curve), iron (dashed), and beryllium (dotted). The optimum-thickness converters were chosen for this comparison. At most energies, the photon number fluxes are highest for beryllium and lowest for tantalum. Above 100 MeV, beryllium produces the hottest spectrum by a small margin. A hot output spectrum could be advantageous for some target interactions. The number spectra for all three materials can be approximately fitted by the equation

$$n(\text{MeV}^{-1}\text{sr}^{-1}) = 1.696 \times 10^5 E_{\omega}^{-1.0765}, \quad (1)$$

where n = number of photons per MeV per sr, for 1000-MeV electrons; E_{ω} the photon energy.

This fit is accurate to $\pm 20\%$ over the photon energy range from 5 to 700 MeV.

The photon number spectra for different incident electron beam energies are plotted in Fig. 18. Again, we note the rapid decline in flux with decreasing beam

Fig. 17. Forward-directed energy spectra, for 1000-MeV electrons incident on beryllium, iron, and tantalum converters of optimum thickness. The number spectrum can be approximately described by a fit of the form $n(\text{MeV}^{-1} \text{SR}^{-1}) = 1.696 \times 10^5 E^{-1.0765}$.

Fig. 18. Comparison of forward-directed energy spectra, for 1000-MeV and 700-MeV electrons on tantalum.

energy. The spectra roughly conform to the characteristic E^{-1} dependence on photon energy for both cases.

Output intensities from Monte Carlo calculations are conventionally expressed in terms of MeV per steradian, per incident electron. These units are quite convenient for comparing different calculations, but are physically somewhat unfamiliar. To provide a more comfortable frame of reference, we have replotted the calculated Bremsstrahlung intensities in terms of the fluence in Joules per cm^2 per Coulomb of beam charge. Since there are 1.6×10^{-13} MeV per Joule and 6.24×10^{18} electrons per Coulomb, the conversion factor from MeV/Sr-e to J/ cm^2 -Coul is just $10^6/r^2$, where r is the distance from the converter, in centimeters. We have chosen one meter as a convenient distance, but the numbers are readily rescaled for other distances. For one meter, the conversion factor from MeV per steradian per electron to Joules per cm^2 per Coulomb is exactly 100.

Results are displayed in Fig. 19. At optimum converter plate thickness, the peak value is 8.56×10^9 Joules/ cm^2 /Coul (for tantalum), 9.87×10^9 Joules/ cm^2 /Coul (for iron), and 1.04×10^{10} Joules/ cm^2 /Coul (for beryllium).

Fig. 19. Peak Bremsstrahlung flux at a range of 1 meter as a function of converter plate thickness, for 1000-MeV electrons incident on tantalum (solid curve), iron (dashed), and beryllium (dotted).

IV. INFLUENCE OF ATMOSPHERIC ABSORPTION

In many radiography applications, the Bremsstrahlung distribution must propagate through the air, both between the converter and the radiography object and between the object and the detector. The Bremsstrahlung will undergo scattering and pair production losses as it propagates. To quantitatively explore these effects, we have performed several calculations. An air layer was inserted immediately after the Bremsstrahlung converter, and was modeled as a gas mixture of 21% O₂ and 79% N₂ by weight. We used the 1000-MeV electron beam incident on tantalum, because the peak brightness is a sensitive function of scatter for these parameters. Our calculations indicate that the peak brightness is reduced by about 2% after propagating through 10 meters of air. Even 25 meters of air leads to less than 6% reduction in peak brightness, compared with propagation through 25 meters of vacuum. To assess the sensitivity of these results with regard to numerical effects, and also to examine the influence of trace gases in the air, a number of different models for the air region were studied computationally. In all cases, results differed from the standard calculation by less than $\pm 3\%$. We conclude that atmospheric propagation will have little effect on most radiographic applications.

V. INFLUENCE OF ELECTRON BEAM DIVERGENCE

The Bremsstrahlung radiation generated by a high-energy electron beam is strongly forward-directed. For a 1000-MeV beam, the angle at half intensity is only about 0.03° or 0.5 milliradians (see, for example, Fig. 7 of Section III). This fact leads us to expect that the radiation pattern will be extremely sensitive to the quality of the incident electron beam, at least for high beam energies. To test this hypothesis, we have performed a number of calculations with electron beams that are not perfectly unidirectional. A representative result is displayed in Fig. 20 for beam divergences $\theta_0 = 0, 1, 2, 3, 5$, and 10 milliradians. Here, the number distribution function of the incident beam versus angle was assumed to be uniform out to angle θ_0 , and zero for angles beyond θ_0 . This distribution function is somewhat unrealistic. Nonetheless, it provides an estimate of the effect of milliradian beam scatter. We see that the Bremsstrahlung intensity for small angles is significantly reduced. Brightness is reduced by a factor of 240 for 10 milliradians divergence. The central part of the angular distribution is almost flat, due to the angular spread of the incident electrons. At larger angles $\theta \gtrsim 0.04^\circ$ to 0.1° , the scattered beams give slightly higher intensities than the unidirectional beam. In Fig. 21, we have plotted the peak brightness on axis for the six calculations discussed above. The dramatic decrease in brightness with increasing divergence angle is overwhelmingly evident.

The results obtained for other polar angle distribution functions are quite similar. For example, a calculation has been done with a cosine-law distribution truncated at an angle θ_{max} . The distribution function has the following form:

$$P(\cos(\theta)) = \left[\cos^2(\theta_{max}) + R_n (1 - \cos^2(\theta_{max})) \right]^{1/2} \quad (2)$$

P = probability that an incident electron has initial direction "θ" to the Z-axis, where $0 < \theta < \theta_{max}$;

θ_{max} = maximum angle at which the distribution is truncated;

R_n = random number on the interval $0 \rightarrow 1$.

The results, displayed in Fig. 22, are virtually identical to the uniform distribution.

Fig. 20. Angular distribution of intensity for isotropic scattered beams with $\theta_0 = 0, 1, 2, 3, 5,$ and 10 milliradians.

Fig. 21. Peak on-axis intensities for a unidirectional beam and for isotropic scattered beams with $\theta_0 = 1, 2, 3, 5,$ and 10 milliradians. (1000-MeV electrons incident on optimum thickness tantalum plate.)

Fig. 22. Angular distribution of intensity, for cosine-law scattered beams with $\theta_0 = 0, 1, 2, 3, 5$, and 10 milliradians. (1000 -MeV electrons, incident on optimum thickness tantalum plate.)

The lack of difference between the truncated section of an isotropic angular distribution and a cosine-law distribution is not surprising for angles less than 10 milliradians (0.57°). To better understand the effect of beam divergence on brightness, we chose a completely different distribution, Gaussian scatter. Such a distribution may accurately characterize beams which have undergone many small angle deflection events in the accelerator. We constructed the Gaussian distribution for the incident electrons from a standard algorithm. The probability distribution over unequal angular increments and the corresponding probability density are displayed in Fig. 23(a) and 23(b). Figure 23(b) shows the Gaussian nature of the scatter.

A series of calculations was performed with this distribution for mean scatter angles of $\bar{\theta} = 0, 1, 2, 3, 5$, and 10 milliradians. A systematic decrease in peak brightness with divergence angle was again found. The quantitative details of the brightness were considerably different, however. The angular distributions of intensity displayed in Fig. 24 exhibit a much slower decrease with scatter angle than was seen with the isotropic and cosine-law distributions. Figure 25, which should be compared with Fig. 21, shows that the on-axis peak brightness is down by a factor of about 25 for Gaussian scatter of 10 milliradian, and as opposed to 240 for $\theta_0 = 10$ milliradian. Qualitatively, the angular variation is not nearly so flat at small angles. It even

Fig. 23. (a) Gaussian probability distribution over unequal $\Delta\theta$ increments, sampled for 100,000 points; (b) probability density distribution corresponding to the above test case.

Fig. 24. Angular distribution of intensity for a unidirectional beam, and for Gaussian scattered beam distributions with $\bar{\theta} = 1, 2, 3, 5, \text{ and } 10$ milliradians. (1000-MeV electrons incident on optimum thickness tantalum plate.)

Fig. 25. Peak intensity versus $\bar{\theta}$ for Gaussian distribution scattered beams.

remains approximately Gaussian. Figure 26 provides a direct comparison between unidirectional, isotropic, cosine-law, and Gaussian-scattered beams. Though these results indicate that the details of the scattered distribution can strongly influence peak brightness, all of the distributions show a large decrease in brightness with small (1 milliradian) scatter.

We conclude that the electron beam quality is critical for high-energy Bremsstrahlung converters that depend on the narrow cone angle to produce very high intensities. Divergences of 1 milliradian or less are essential for achieving optimum performance at high energies.

Generation of an electron beam with the requisite low divergence may be the most difficult task in design of a Bremsstrahlung system. Milliradian divergences are routinely achieved in conventional low-current accelerators. However, space charge and self-field effects inevitably increase the beam emittance at very high currents. The only fundamental constraints on the Bremsstrahlung accelerator are that the required beam energy and total charge be delivered within an acceptable time interval ($\sim$ several μ s). Thus, design difficulties can be mitigated by using multiple beams of lower current, a larger physical system with lower space charge density, or a longer beam pulse duration. These approaches have not yet been explored, but such techniques are essential to the development of a suitable high-current accelerator. A substantial research effort must be pursued to address the key questions of accelerator design and beam quality.

Fig. 26. Comparison of angular intensity profiles for unidirectional beam, and scattered beams with cosine law, isotropic ($\theta_0 = 1.0$ mrad); and Gaussian distributions ($\bar{\theta} = 1.0$ mrad). (1000-MeV electrons, incident on optimum thickness tantalum plate.)

VI. TOTAL BREMSSTRAHLUNG CONVERSION EFFICIENCIES

The radiation field from a high-energy Bremsstrahlung converter is intensely concentrated in the forward direction. Applications of the device depend upon this directionality to achieve high fluxes. Thus, the quantity of interest is the forward-directed or on-axis intensity of the Bremsstrahlung radiation. This is the quantity that we have discussed in the preceding sections.

In laboratory and simulation applications, the target to be irradiated may be adjacent to the Bremsstrahlung converter. It then becomes possible to utilize a large fraction of the 2π radiation output, rather than just the forward-directed cone of radiation. In this case, the total efficiency for converting electron energy to Bremsstrahlung becomes an important parameter. This quantity is sometimes called the total conversion efficiency or the 2π extraction efficiency. Extensive studies have been published of the extraction efficiencies for moderate electron beam energies.² However, corresponding information is not available for the higher energies investigated here. Although it is not the primary purpose of this paper, we have computed the total Bremsstrahlung extraction efficiencies for all of the CYLTRAN calculations. These results are tabulated in the Appendix, and plotted in Figs. 27 and 28. Figure 27 displays the total efficiency as a function of scaled converter thickness " t_0 ," for 1000-MeV electrons incident on tantalum, iron, and beryllium. The maximum efficiency is approximately 43% for tantalum and iron, and 39% for beryllium. Converter thicknesses required to optimize total efficiency are $t_0 = 0.2 - 0.3$ for tantalum and iron, and $t_0 = 0.5$ for beryllium. These thicknesses are obviously much greater than the values which yield optimum brightness (Section III, above). This difference arises because the forward-directed radiation is strongly influenced by photon scattering inside the converter plate, which can smear out the narrow radiation cone and reduce the intensity. A thin converter is required to suppress the self-scattering effect. Total conversion efficiency over 2π is not sensitive to this small-angle photon scattering, and it is therefore possible to use a much thicker plate and convert more of the electron beam energy into Bremsstrahlung.

The total efficiencies for other electron beam energies are plotted in Fig. 28. The thickness at which peak efficiency occurs moves to larger thickness as the energy is decreased. The maximum efficiencies are comparable for beam energies in the 50-1000-MeV range, then gradually decline at lower energies. This trend is more clearly displayed in Fig. 29, which shows the efficiency at thickness $t_0 = 0.3$ versus beam energy. Excessively thick converter plates drop the efficiency down to a few percent, as Fig. 30 shows.

We have also computed the average energy of all photons emitted over a solid angle of 2π . This information is of potential interest for effects simulation. The results are not plotted here, but are listed in full in the Appendix.

Gamma-ray brightness varies by many orders of magnitude as a function of angle. In many applications, only a limited range of brightness can be tolerated. The cone of greatest brightness centered on the forward direction then becomes the only region of practical interest. In Section III, we defined a cone angle, inside of which the brightness was no less than 10% of its peak, on-axis value. Because of different photon transport processes at low and high energies, we found a qualitative difference in the scaling of this angle with thickness. It is of practical interest to determine how much energy is contained within this cone angle. In Fig. 31, we display the efficiency of conversion of electron energy into radiation within this cone angle, as a function of Ta thickness, for 1000-MeV electrons. While Fig. 13 in Section III shows almost total independence of this angle on thickness, Fig. 31 shows that the efficiency peaks at a thickness $t_0 = 0.07$ (cf. Fig. 4), at a value of about 7%. Figure 31 is typical for high energy electrons, although the conversion efficiency decreases with decreasing electron energy.

Between 150 and 250 MeV, the shape of the conversion efficiency curve, as a function of plate thickness, changes completely. We found that the "10% brightness" cone angle increased monotonically with plate thickness for lower-energy electrons (c.f. Figs. 14 and 15). Since the peak brightness showed little variation with plate thickness, we might expect that larger angles would correspond to more of the energy within the cone angle. As Fig. 32 shows, this is what actually occurs. For low energies $E < 100$ MeV, the conversion efficiency is still increasing at a thickness $t_0 = 0.3$. This trend is due to increase in the cone angle, however, and does not correspond to enhanced brightness. The net result is that conversion efficiencies peak at about 7% at high energies (Fig. 31), but can be in the range of 12–20% for low energies (Fig. 32).

Fig. 27. Total Bremsstrahlung conversion efficiencies in 2π solid angle, for 1000-MeV monenergetic electrons incident on Ta (solid curve), Fe (dashed), and Be (dotted) converter plates of various thicknesses.

Fig. 28. Total Bremsstrahlung conversion efficiencies in 2π solid angle, for monenergetic electrons incident on Ta converter plates of various thicknesses. The energies plotted are 1000-MeV (solid), 250-MeV (dashed), and 50-MeV (dotted).

Fig. 29. Variation of total Bremsstrahlung conversion efficiency for a "fixed" thickness, $0.3 t_0$, of Ta as a function of incident electron energy.

Fig. 30. Variation of total Bremsstrahlung conversion efficiency for very thick, $4 t_0$, Ta plates as a function of incident electron energy.

Fig. 31. Variation of the conversion efficiency within the "10% cone angle" for 1000-MeV monoenergetic electrons incident on various thicknesses of Ta.

Fig. 32. Variation of the conversion efficiency within the "10% cone angle" for 25-MeV monoenergetic electrons incident on various thicknesses of Ta.

VII. ALTERNATIVE CONCEPTS AND FUTURE WORK

Bremsstrahlung is not the only process for converting electron beam energy into collimated gamma radiation. Two interesting alternatives have been discussed by Arutyunyan and Tumanian,^{7,8} channeling radiation and inverse Compton-scattering. In the former, the radiation is modified by interference effects which arise between the electrons and a crystal lattice. Coherent emission should lead to a qualitatively different spectrum from that observed in the usual Bremsstrahlung interaction. Inverse Compton scattering can be regarded as scattering of a photon gas by the electron beam. Energy is transferred to the photons, which are characteristically emitted in the forward direction. H. Leber has analyzed this process and found that the gamma brightness can exceed that from optimized Bremsstrahlung sources in the relativistic regime.

As a practical matter, the use of crystals with intense electron beams presents severe difficulties, with regard to both radiation damage and collisional (electron/lattice) interactions. These difficulties are not so serious when the interaction is with a photon gas. Inverse Compton-scattering cross sections are sufficiently small, however, that the interaction length can be quite long for physically realizable photon distributions. The cross section is about 300 mb for 1000 MeV electrons interacting with optical photons ($\epsilon_\nu = 1.5\text{--}5$ eV). Significant progress has been made in generating very bright photon sources, so this problem may be resolvable. We are continuing to study inverse Compton-scattering to determine if practical gamma sources can be derived from it.

Synchrotron sources are another alternative for converting electron beam energy into high energy photons. Devices to produce intense collimated x-ray sources ($E_\nu < 100$ keV) using synchrotron radiation exist today. A synchrotron source with an appreciable intensity and with photon energies $E_\nu \gtrsim 10$ MeV would require extremely large magnetic fields, on the order of tens of megagauss. Unless this limitation can be circumvented, synchrotron radiation does not seem promising as a gamma radiation source.

The calculational study of Bremsstrahlung converters is quite comprehensive and has accurately defined the optimum source parameters. The only outstanding question in this area concerns the influence of strange particle cascade during atmospheric propagation. Such effects are probably small at GeV energy levels. However, it would be worthwhile to perform a calculation of the full electron-gamma shower for a typical case to verify this contention.

This report has not examined the related issues of:

- (1) Power source for the Bremsstrahlung system;
- (2) Design of an accelerator for intense electron beams with extremely low divergence; and,
- (3) Signal-to-noise ratios for radiographic imaging.

These topics must be investigated both theoretically and experimentally to develop a viable system design.

APPENDIX
CALCULATED BREMSSTRAHLUNG GENERATION
FOR MONOENERGETIC ELECTRON BEAMS
WITH ENERGIES $E = 1000$ TO 10 MeV

This Appendix lists the principal results of CYLTRAN Monte Carlo calculations for Bremsstrahlung generation by monoenergetic electron beams. Each table gives data for a single beam energy and material, as a function of converter thickness. Successive columns in the table are: (1) arbitrary two-character run identifier; (2) scaled converter thickness " t_0 " (expressed in electron ranges); (3) physical converter thickness " t " (in centimeters); (4) total Bremsstrahlung conversion efficiency " ϵ " over a solid angle of 2π ; (5) average Bremsstrahlung photon energy " ω_{avg} ," for all photons emitted over a solid angle of 2π (in MeV); and (6) peak Bremsstrahlung brightness in the forward direction " I " (in MeV/sr-electron). The first three tables are for beryllium, iron, and tantalum at an energy of 1000 MeV. The remaining tables give tantalum results for energies of 700 MeV to 10 MeV, in descending order.

TABLE A.I
BREMSSTRAHLUNG GENERATION FOR 1000-MeV
ELECTRONS INCIDENT ON BERYLLIUM (Z=4)

Run	Scaled Thickness " t_0 " (Electron Ranges)	Thickness " t " (cm)	Total 2π Efficiency " ϵ " (%)	Average 2π Photon Energy " $\omega_{avg.}$ " (MeV)	Forward- Directed Peak Intensity " I " (MeV/Sr-elec.)
EA	0.01	0.8523	2.72	153.9	2.10+7
EB	0.02	1.7046	4.42	154.8	3.87+7
EC	0.03	2.5569	6.46	151.1	5.31+7
ED	0.04	3.4092	8.41	150.4	6.42+7
EE	0.06	5.114	12.16	147.9	8.43+7
EF	0.08	6.818	15.48	145.0	8.98+7
EG	0.10	8.523	18.58	142.8	9.69+7
EH	0.12	10.228	21.45	140.7	1.04+8
EI	0.14	11.932	23.80	137.5	9.90+7
EJ	0.16	13.637	26.10	135.4	1.01+8
EK	0.18	15.341	28.13	133.1	9.93+7
EL	0.20	17.046	29.92	130.5	9.98+7
EM	0.22	18.751	31.43	128.2	9.43+7
EN	0.24	20.455	32.95	126.4	9.31+7
EO	0.26	22.160	34.14	123.9	8.59+7
EP	0.28	23.864	35.04	121.8	0.09+7
EQ	0.30	25.569	36.14	120.3	8.92+7
ER	0.40	34.092	38.75	111.9	7.62+7
ES	0.50	42.615	38.86	103.9	6.21+7
ET	0.60	51.138	37.34	97.51	4.96+7

TABLE A.II
BREMSSTRAHLUNG GENERATION FOR 1000-MeV
ELECTRONS INCIDENT ON IRON (Z=26)

Run	Scaled Thickness " t_0 " (Electron Ran _e s)	Thickness " t " (cm)	Total 2π Efficiency " ϵ " (%)	Average 2π Photon Energy " $\omega_{avg.}$ " (MeV)	Forward- Directed Peak Intensity " I " (MeV/Sr-elec.)
DA	0.01	0.07211	3.83	152.1	3.35+7
DB	0.02	0.14422	7.47	150.0	5.65+7
DC	0.03	0.21633	10.82	147.8	7.24+7
DD	0.04	0.28844	13.88	144.5	8.26+7
DE	0.06	0.43266	19.58	140.4	9.47+7
DF	0.08	0.57688	24.15	135.0	9.63+7
DG	0.10	0.7211	28.33	130.8	9.87+7
DH	0.12	0.8653	31.74	126.4	9.65+7
DI	0.14	1.0095	34.57	122.8	8.97+7
DJ	0.16	1.1538	36.89	118.6	8.51+7
DK	0.18	1.2980	38.98	115.1	8.39+7
DL	0.20	1.4422	40.46	111.8	7.53+7
DM	0.22	1.5864	41.57	107.6	7.35+7
DN	0.24	1.7306	42.49	105.0	6.95+7
DO	0.26	1.8749	42.87	101.5	6.51+7
DP	0.28	2.0191	43.22	98.53	6.28+7
DQ	0.30	2.1633	43.55	96.21	5.47+7
DR	0.40	2.8844	41.41	82.71	4.44+7
DS	0.50	3.6055	37.11	72.89	3.45+7
DT	0.60	4.3260	32.18	64.69	2.50+7

TABLE A.III
BREMSSTRAHLUNG GENERATION FOR 1000-MeV
ELECTRONS INCIDENT ON TANTALUM (Z=73)

Run	Scaled Thickness " t_0 " (Electron Ranges)	Thickness " t " (cm)	Total 2π Efficiency " ϵ " (%)	Average 2π Photon Energy " $\omega_{avg.}$ " (MeV)	Forward- Directed Peak Intensity " I " (MeV/Sr-elec.)
GA	0.01	0.0212	4.64	144.3	3.36+7
GB	0.02	0.0425	8.87	142.3	5.41+7
GC	0.03	0.0637	12.77	139.4	6.61+7
GD	0.04	0.0849	16.35	136.1	7.33+7
GE	0.06	0.1274	22.70	131.9	8.27+7
GF	0.08	0.170	27.84	126.5	8.56+7
GG	0.10	0.212	31.98	121.2	8.04+7
GH	0.12	0.255	35.28	115.9	7.07+7
GI	0.14	0.297	38.10	112.0	6.78+7
GJ	0.16	0.340	39.96	107.1	6.39+7
GK	0.18	0.382	41.35	102.4	6.04+7
GL	0.20	0.425	42.40	98.86	5.61+7
GM	0.22	0.467	43.15	95.14	5.34+7
GN	0.24	0.510	43.26	91.25	4.95+7
GO	0.26	0.552	43.38	88.28	4.62+7
GP	0.28	0.595	42.96	84.75	4.53+7
GQ	0.30	0.637	42.65	81.53	4.15+7

TABLE A.IV
BREMSSTRAHLUNG GENERATION FOR 700-MeV
ELECTRONS INCIDENT ON TANTALUM

<u>Run</u>	<u>Scaled Thickness "t₀" (Electron Ranges)</u>	<u>Thickness "t" (cm)</u>	<u>Total 2π Efficiency "ε" (%)</u>	<u>Average 2π Photon Energy "ω_{avg.}" (MeV)</u>	<u>Forward- Directed Peak Intensity "I" (MeV/Sr-elec.)</u>
HA	0.01	0.01977	4.24	100.0	1.03+7
HB	0.02	0.03954	8.29	100.4	1.64+7
HC	0.03	0.05931	12.00	97.40	1.86+7
HD	0.04	0.07908	15.52	96.71	1.98+7
HE	0.06	0.1186	21.49	92.54	1.95+7
HF	0.08	0.1582	26.66	89.42	1.93+7
HG	0.10	0.1977	30.87	85.82	1.84+7
HH	0.12	0.2372	34.15	82.36	1.61+7
HI	0.14	0.2768	37.09	79.15	1.66+7
HJ	0.16	0.3163	39.32	76.27	1.48+7
HK	0.18	0.3559	41.06	73.36	1.33+7
HL	0.20	0.3954	42.47	70.82	1.28+7
HM	0.22	0.4349	43.33	68.20	1.28+7
HN	0.24	0.4745	43.95	65.65	1.04+7
HO	0.26	0.5140	44.12	63.50	1.02+7
HP	0.28	0.5536	44.10	61.08	1.02+7
HQ	0.30	0.5931	44.08	59.07	9.73+6

TABLE A.V
BREMSSTRAHLUNG GENERATION FOR 500-MeV
ELECTRONS INCIDENT ON TANTALUM

<u>Run</u>	<u>Scaled Thickness "t₀" (Electron Ranges)</u>	<u>Thickness "t" (cm)</u>	<u>Total 2π Efficiency "ε" (%)</u>	<u>Average 2π Photon Energy "ω_{avg.}" (MeV)</u>	<u>Forward- Directed Peak Intensity "I" (MeV/Sr-elec.)</u>
IA	0.01	0.01839	3.90	71.11	2.79+6
IB	0.02	0.03678	7.48	69.93	3.70+6
IC	0.03	0.05517	11.14	69.91	4.97+6
ID	0.04	0.07356	14.16	68.74	4.44+6
IE	0.06	0.11034	20.00	66.52	3.88+6
IF	0.08	0.14712	24.94	64.41	4.30+6
IG	0.10	0.18390	29.03	61.72	3.91+6
IH	0.12	0.22068	32.38	59.40	3.71+6
II	0.14	0.25746	35.36	57.45	3.31+6
IJ	0.16	0.29424	37.66	55.31	3.65+6
IK	0.18	0.33102	39.68	53.59	3.19+6
IL	0.20	0.36780	41.35	51.81	2.65+6
IM	0.22	0.40458	42.31	49.91	2.95+6
IN	0.24	0.44136	43.07	48.15	2.62+6
IO	0.26	0.47814	43.59	46.53	2.50+6
IP	0.28	0.51492	43.89	43.81	2.54+6
IQ	0.30	0.55170	43.90	43.60	2.65+6

TABLE A.VI
BREMSSTRAHLUNG GENERATION FOR 250-MeV
ELECTRONS INCIDENT ON TANTALUM

Run	Scaled Thickness " t_0 " (Electron Ranges)	Thickness " t " (cm)	Total 2π Efficiency " ϵ " (%)	Average 2π Photon Energy " $\omega_{avg.}$ " (MeV)	Forward- Directed Peak Intensity " I " (MeV/Sr-elec.)
JA	0.01	0.01554	3.35	36.67	1.85+5
JB	0.02	0.03108	6.53	36.05	2.07+5
JC	0.03	0.04662	9.54	35.66	1.96+5
JD	0.04	0.06216	12.34	34.98	1.92+5
JE	0.06	0.09324	17.45	33.83	1.91+5
JF	0.08	0.12432	21.99	32.72	1.81+5
JG	0.10	0.15540	25.96	31.73	1.73+5
JH	0.12	0.18648	29.44	30.77	1.71+5
JI	0.14	0.21756	32.44	29.83	1.76+5
JJ	0.16	0.24864	35.10	28.93	1.51+5
JK	0.18	0.27972	37.30	28.08	1.54+5
JL	0.20	0.31080	39.18	27.25	1.47+5
JM	0.22	0.34188	40.81	26.47	1.39+5
JN	0.24	0.37296	42.06	25.70	1.30+5
JO	0.26	0.40404	42.99	24.94	1.28+5
JP	0.28	0.43512	43.94	24.34	1.26+5
JQ	0.30	0.46620	44.50	23.59	1.16+5
JR	0.40	0.62160	45.04	20.76	9.80+4
JS	0.50	0.77700	42.90	18.49	7.79+4

TABLE A.VII
BREMSSTRAHLUNG GENERATION FOR 150-MeV
ELECTRONS INCIDENT ON TANTALUM

Run	Scaled Thickness " t_0 " (Electron Ranges)	Thickness " t " (cm)	Total 2π Efficiency " ϵ " (%)	Average 2π Photon Energy " $\omega_{avg.}$ " (MeV)	Forward- Directed Peak Intensity " I " (MeV/Sr-elec.)
KA	0.01	0.01345	2.86	21.81	2.39+4
KB	0.02	0.02690	5.63	21.60	2.25+4
KC	0.03	0.04035	8.21	21.23	2.37+4
KD	0.04	0.05380	10.65	20.93	2.20+4
KE	0.06	0.08070	15.33	20.56	2.49+4
KF	0.08	0.10760	19.38	19.75	2.07+4
KG	0.10	0.13450	23.19	19.24	2.55+4
KH	0.12	0.16140	26.49	18.73	2.13+4
KI	0.14	0.18830	29.45	18.19	2.24+4
KJ	0.16	0.21520	32.20	17.72	2.08+4
KK	0.18	0.24210	34.59	17.26	2.03+4
KL	0.20	0.26900	36.49	16.85	1.83+4
KM	0.22	0.29590	38.28	16.38	1.76+4
KN	0.24	0.32280	39.86	15.96	1.87+4
KO	0.26	0.34970	41.21	15.59	1.80+4
KP	0.28	0.37660	42.42	15.21	1.76+4
KQ	0.30	0.40350	43.22	14.86	1.54+4

TABLE A.VIII
BREMSSTRAHLUNG GENERATION FOR 100-MeV
ELECTRONS INCIDENT ON TANTALUM

Run	Scaled Thickness "t ₀ " (Electron Ranges)	Thickness "t" (cm)	Total 2π Efficiency "ε" (%)	Average 2π Photon Energy "ω _{avg.} " (MeV)	Forward- Directed Peak Intensity "I" (MeV/Sr-elec.)
LA	0.01	0.01181	2.51	14.50	4.44+3
LB	0.02	0.02362	4.92	14.12	4.86+3
LC	0.03	0.03430	7.19	13.86	4.94+3
LD	0.04	0.04724	9.43	13.73	5.07+3
LE	0.06	0.07086	13.62	13.35	4.96+3
LF	0.08	0.09448	17.45	12.97	4.96+3
LG	0.10	0.11810	20.93	12.56	4.91+3
LH	0.12	0.14172	24.16	12.20	4.91+3
LI	0.14	0.16534	27.18	11.84	4.77+3
LJ	0.16	0.18896	29.87	11.48	4.64+3
LK	0.18	0.21258	32.37	11.16	4.59+3
LL	0.20	0.23620	34.57	10.79	4.75+3
LM	0.22	0.25981	36.66	10.50	4.28+3
LN	0.24	0.28344	38.69	10.19	4.54+3
LO	0.26	0.30706	40.25	9.89	4.10+3
LP	0.28	0.33068	42.01	9.64	4.11+3
LQ	0.30	0.35430	43.32	9.36	3.92+3

TABLE A.IX
BREMSSTRAHLUNG GENERATION FOR 70-MeV
ELECTRONS INCIDENT ON TANTALUM

Run	Scaled Thickness " t_0 " (Electron Ranges)	Thickness " t " (cm)	Total 2 π Efficiency " ϵ " (%)	Average 2 π Photon Energy " $\omega_{avg.}$ " (MeV)	Forward- Directed Peak Intensity " I " (MeV/Sr-elec.)
MA	0.01	0.01039	2.16	12.87	1.37+3
MB	0.02	0.02078	4.24	12.74	1.19+3
MC	0.03	0.03117	6.22	12.54	1.39+3
MD	0.04	0.04156	8.18	12.47	1.38+3
ME	0.06	0.06234	11.97	12.26	1.50+3
MF	0.08	0.08312	15.41	12.00	1.61+3
MG	0.10	0.10390	18.47	11.70	1.59+3
MH	0.12	0.12468	21.56	11.46	1.59+3
MI	0.14	0.14546	24.28	11.28	1.51+3
MJ	0.16	0.16624	26.95	11.00	1.44+3
MK	0.18	0.18702	29.45	10.83	1.50+3
ML	0.20	0.20780	31.60	10.58	1.48+3
MM	0.22	0.22858	33.64	10.41	1.49+3
MN	0.24	0.24936	35.49	10.19	1.37+3
MO	0.26	0.27014	37.23	9.99	1.40+3
MP	0.28	0.29092	38.91	9.78	1.29+3
MQ	0.30	0.31170	40.32	9.11	1.37+3

TABLE A.X
BREMSSTRAHLUNG GENERATION FOR 50-MeV
ELECTRONS INCIDENT ON TANTALUM

Run	Scaled Thickness " t_0 " (Electron Ranges)	Thickness " t " (cm)	Total 2π Efficiency " ϵ " (%)	Average 2π Photon Energy " $\omega_{avg.}$ " (MeV)	Forward- Directed Peak Intensity " I " (MeV/Sr-elec.)
NA	0.01	0.00907	1.87	7.30	4.87+2
NB	0.02	0.01814	3.67	7.18	5.43+2
NC	0.03	0.02721	5.42	7.12	5.34+2
ND	0.04	0.03628	7.13	7.04	5.72+2
NE	0.06	0.05442	10.43	6.93	5.98+2
NF	0.08	0.07256	13.51	6.81	5.94+2
NG	0.10	0.09070	16.40	6.67	6.43+2
NH	0.12	0.10884	19.11	6.55	6.00+2
NI	0.14	0.12698	21.74	6.43	6.21+2
NJ	0.16	0.14512	24.13	6.31	6.16+2
NK	0.18	0.16326	26.39	6.19	6.19+2
NL	0.20	0.18140	28.47	6.07	5.87+2
NM	0.22	0.19954	30.57	5.98	6.13+2
NN	0.24	0.21768	32.28	5.85	5.86+2
NO	0.26	0.23582	34.02	5.76	5.74+2
NP	0.28	0.25396	35.67	5.67	5.60+2
NQ	0.30	0.27210	37.28	5.58	5.65+2

TABLE A.XI
BREMSSTRAHLUNG GENERATION FOR 25-MeV
ELECTRONS INCIDENT ON TANTALUM

Run	Scaled Thickness "t ₀ " (Electron Ranges)	Thickness "t" (cm)	Total 2π Efficiency "ε" (%)	Average 2π Photon Energy "ω _{avg.} " (MeV)	Forward- Directed Peak Intensity "I" (MeV/Sr-elec.)
OA	0.01	0.00653	1.29	3.47	5.35+1
OB	0.02	0.01306	2.52	3.43	6.12+1
OC	0.03	0.01959	3.79	3.45	6.36+1
OD	0.04	0.02612	4.98	3.43	6.37+1
OE	0.06	0.03918	7.36	3.42	6.46+1
OF	0.08	0.05224	9.68	3.40	6.85+1
OG	0.10	0.06530	11.90	3.37	7.13+1
OH	0.12	0.07836	14.01	3.34	7.38+1
OI	0.14	0.09142	16.11	3.31	7.15+1
OJ	0.16	0.10448	18.15	3.28	7.17+1
OK	0.18	0.11754	20.06	3.24	7.13+1
OL	0.20	0.13060	21.19	3.21	7.08+1
OM	0.22	0.14366	23.72	3.17	7.19+1
ON	0.24	0.15672	25.37	3.14	7.20+1
OO	0.26	0.16978	26.94	3.10	7.14+1
OP	0.28	0.18284	28.39	3.08	7.07+1
OQ	0.30	0.19590	29.76	3.04	7.12+1

TABLE A.XII

**BREMSSTRAHLUNG GENERATION FOR 10-MeV
ELECTRONS INCIDENT ON TANTALUM**

Run	Scaled Thickness " t_0 " (Electron Ranges)	Thickness " t " (cm)	Total 2π Efficiency " ϵ " (%)	Average 2π Photon Energy " $\omega_{avg.}$ " (MeV)	Forward- Directed Peak Intensity " I " (MeV/Sr-elec.)
PA	0.01	0.00374	0.7	1.28	2.57
PB	0.02	0.00748	1.4	1.30	3.16
PC	0.03	0.01122	2.0	1.31	3.33
PD	0.04	0.01496	2.7	1.32	3.53
PE	0.06	0.02244	4.2	1.34	3.64
PF	0.08	0.02992	5.6	1.36	3.70
PG	0.10	0.03740	7.1	1.37	3.84
PH	0.12	0.04488	8.6	1.37	4.06
PI	0.14	0.05236	10.1	1.37	3.91
PJ	0.16	0.05984	11.5	1.38	4.36
PK	0.18	0.06732	13.1	1.37	3.55
PL	0.20	0.07480	14.4	1.37	4.62
PM	0.22	0.08228	15.5	1.37	3.26
PN	0.24	0.08976	16.8	1.37	4.04
PO	0.26	0.09724	17.7	1.37	4.34
PP	0.28	0.10472	19.4	1.37	4.15
PQ	0.30	0.11220	21.6	1.36	3.77

Acknowledgments

Appreciation is expressed to Jack Brownell and John Halbleib for encouragement, discussions, and a plethora of useful information.

References

1. R. L. Weitz, K. J. Adams, and H. Schreiber, SAIC report 88/6512 (August 1988); also R. L. Weitz, et al., SAIC report (September 1986).
2. J. A. Halbleib and T. W. L. Sanford, "Predicted Flash X-Ray Environments Using Standard Converter Configurations," Sandia National Laboratories report SAND83-2572 (September 1985).
3. J. A. Halbleib and T. A. Mehlhorn, "ITS: The Integrated TIGER Series of Coupled Electron/Photon Monte Carlo Transport Codes," Sandia National Laboratories report SAND84-0573 (November 1984).
4. J. A. Halbleib and W. H. Vandevender, Nucl. Sci. Eng. **57**, 94 (1975).
5. "Stopping Powers and Ranges of Electrons and Positrons," National Bureau of Standards, NBSIR-82-2550 (August 1982).
6. Lucien Pages, Evelyne Bertel, Henri Joffre, and Laodamos Sklavenitis, Atomic Data **4**, 1-127 (1972).
7. F. R. Arutyunyan and V. A. Tumanian, "The Compton Effect on Relativistic Electrons and the Possibility of Obtaining High Energy Beams," Phys. Lett. **4**, 176 (1963).
8. F. R. Arutyunyan and V. A. Tumanian, "Quasi-Monochromatic and Polarized High-Energy Gamma Rays," Sov. Phys. Uspekhi **83**, 339 (1964).
9. H. Lee, Report in preparation.

END

DATE FILMED

02 / 21 / 91