UNCLASSIFIED

AD NUMBER
ADB023353
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; JUL 1977. Other requests shall be referred to Rome Air Development Center, Griffiss AFB, NY.**
AUTHORITY
RADC ltr 14 Apr 1980

THIS PAGE IS UNCLASSIFIED

THIS REPORT HAS BEEN DELIMITED
AND CLEARED FOR PUBLIC RELEASE
UNDER DOD DIRECTIVE 5200.20 AND
NO RESTRICTIONS ARE IMPOSED UPON
ITS USE AND DISCLOSURE.

DISTRIBUTION STATEMENT A

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED.

RADC-TR-77-252
Scientific Report
July 1977

SOFT X-RAY PHOTOEMISSION

D. J. Strickland
SCIENCE APPLICATIONS, INC.
8400 Westpark Drive
McLean, Virginia 22101

This research was sponsored by the DEFENSE NUCLEAR AGENCY
under Subtask Z99QAXTA040, Work Unit Code 01, entitled
"Electron Interaction Calculations".

ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

This technical report has been reviewed and approved for publication.

APPROVED:

John C. Garth
JOHN C. GARTH
Project Engineer

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19 REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER 18 RADC-TR-77-252	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 SOFT X-RAY PHOTOEMISSION.		5. ~~TYPE OF REPORT & PERIOD~~ COVERED 9 Final Report. 1 Oct 1976 - 15 Apr 1977 6. ~~PERFORMING ORG. REPORT NUMBER~~
7. AUTHOR(s) 10 D. J./Strickland		8. CONTRACT OR GRANT NUMBER(s) 15 F19628-76-C-0308 new
9. PERFORMING ORGANIZATION NAME AND ADDRESS Science Applications, Inc. 8400 Westpark Drive McLean, Virginia 22101 12 56p.		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62704H CDNA11AI
11. CONTROLLING OFFICE NAME AND ADDRESS HQ Defense Nuclear Agency Washington, D. C. 20305		12. REPORT DATE 11 July 1977 13. NUMBER OF PAGES 68
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Deputy for Electron Technology (RADC/ESR) Hanscom AFB MA 01731 Contract Monitor: Dr. John C. Garth/ESR		15. SECURITY CLASS. (of this report) Unclasssified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

1 JULY 1977

Distribution Limited to U.S. Government Agencies Only: Test and Evaluation of Military Hardware. Other requests for this document must be referred to RADC/ESR, Hanscom AFB, Massachusetts 01731.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

16 CDNA, Z99QAXT 17 11, A040

18. SUPPLEMENTARY NOTES

This research was sponsored by the Defense Nuclear Agency under Subtask Z99QAXTA040, Work Unit Code 01, entitled "Electron Interaction Calculations".

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Soft X-Ray Photoemission Yields

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This work was undertaken to develop a capability to predict photoemission from materials for soft x-ray sources. By soft, ~~we mean~~ x-rays ~~with~~ have energies of a few keV or less. The Boltzmann equation was solved for the electron flux - from this flux, other quantities of interest may be obtained, e.g., the photo-emission yields. Three materials have been examined: aluminum, aluminum oxide, and silicon dioxide. Back photoemission yields are presented in this report for these materials. For aluminum, an extensive series of runs was made. In particular, results were obtained for a series of narrow Gaussian

next page

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

408 404

LB

ITEM 20: ABSTRACT (Continued)

photon distributions from 0.5 to 10 keV and for blackbody spectra over a temperature range from 1 to 10 keV.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

Section 1

INTRODUCTION AND SUMMARY

This work was undertaken to develop a capability to predict photoemission from materials for soft x-ray sources. By soft, we mean x-rays with energies of a few keV or less. The electron transport description required for soft x-ray sources is significantly different than the standard multiple scattering - continuous slowing down approach used at higher photon energies.[1-5] At low energies, the standard approach must be abandoned in favor of the more exact single scattering approach which requires detailed scattering energy loss information for each important electron interaction. Said another way, the two parameter description, the parameters being the stopping power and

---

[1] W. L. Chadsey, "POEM," AFCRL Report TR-75-0327 (1975).

[2] H. M. Colbert, "SANDYL," Sandia Laboratories, SLL-74-0012 (1974).

[3] M. J. Berger and S. M. Seltzer, "Electron and Photon Transport Programs," (I) NBS Report 9836, (II) NBS Report 9837.

[4] T. A. Dellin and C. J. MacCallum, IEEE Trans. Nuc. Sci., NS-20, No. 6, 91 (1973).

[5] J. C. Garth and J. V. O'Brien, IEEE Trans. Nuc. Sci., NS-20, No. 6, 82 (1973).

multiple scattering formula, must be replaced by a multi-parameter description where the parameters are the differential inverse mean free paths for the various electron interactions. In terms of transport equations, a Fokker-Planck type equation is replaced by a Boltzmann type integro-differential equation.

We have chosen to solve the Boltzmann equation for the electron flux - from this flux, other quantities of interest may be obtained, e.g., the photoemission yields. In the brief time allotted, this work was made possible by the extensive amount of work previously carried out by Strickland on electron transport in gases.[6] We have borrowed coding from that work wherever possible. Nevertheless, extensive code development was required. Coding, together with acquisition of needed atomic data, consumed the major portion of time available. In spite of this, a considerable number of results will be presented in this report. A word of caution must be given. The results are the first of their kind and have not been critically tested against measurements nor can they be critically tested against results of other existing methods. Furthermore, at this time, we do not know how sensitive the results are to gridding, uncertainties in cross section, etc. Fortunately, a sensitivity study is now underway as well as a comparison with available data under Defense Nuclear Agency (DNA) sponsorship.

---

[6] D. J. Strickland, D. L. Book, T. P. Coffey, and J. A. Fedder, J. Geophys. Res., 81, 2755 (1976).

We have examined three materials — aluminum, aluminum oxide, and silicon dioxide, all of which were mutually agreed upon by SAI, RADC, and DNA. Back photoemission yields are presented in this report for these materials. For aluminum, an extensive series of runs was made. In particular, results were obtained for a series of narrow Gaussian photon distributions from 0.5 to 10 keV and for blackbody spectra over a temperature range from 1 to 10 keV. Where comparisons could be made with POEM, the results of this work were found to be higher, but within reasonable agreement.

An exploding wire spectrum from a recent Physics International report was considered for obtaining results for all three materials. The total back yield was found to be sensitive to the material with aluminum providing the highest value and silicon dioxide the lowest.

Section 2

METHOD OF SOLUTION

To properly model the transport of electrons over an energy range which extends below $\sim$1 keV, a single scattering description is required. This entails consideration of all important scattering and loss mechanisms on an individual basis. One can choose to either use a single scattering Monte Carlo approach or solve a Boltzmann equation in its integro-differential form. The latter approach has been chosen here and is based on the earlier work by Strickland, et al.,[6] for electron transport in gases. In this section, we present the transport equation, list the important photon and electron processes, give the matrix representation to the transport equation, and mention how the equation is solved. The discussion will be brief with emphasis placed on publications and reports where more details may be found.

The Boltzmann equation in its integro-differential form is:

$$\mu \frac{d\phi}{dx}(x,E,\mu) = -K_T(E)\phi(x,E,\mu) + \int_{4\pi} d\Omega' \int_{E'>E} dE' \sum_{\ell} K_{\ell}(E,E',\Theta)\phi(x,E',\mu') + P(x,E,\mu) \qquad (1)$$

---

[6] D. J. Strickland, D. L. Book, T. P. Coffey, and J. A. Fedder, J. Geophys. Res., 81, 2755, 1976.

The terms are:

- x - depth in cm,
- E - energy in eV,
- μ - cosine of pitch angle with respect to back surface normal,
- Θ - scattering angle,
- K_T - total inverse mean free path (IMFP) in cm^{-1},
- K_ℓ - differential inverse mean free path (DIMFP) for ℓth process in $cm^{-1}ev^{-1}sr^{-1}$,
- ϕ - electron flux in electrons/cm^2-sec-ev-sr,
- P - electron volume production rate in electrons/cm^3-sec-ev-sr.

One spatial (x) and two velocity (represented by E and μ) variables are considered of the six possible phase space variables. The equation is thus one-dimensional with azimuthal symmetry about the surface normal and is appropriate to broad uniform photon sources normally incident on a material. No restrictions are placed on the description of scattering and energy loss in equation (1). In particular, scattering through any angle, discrete energy loss, and production of secondary electrons are permitted.

The electron volume production rate P contains electrons for the following photon processes:

(1) The photoelectric effect,

(2) Compton scattering, and

(3) Auger emission.

The incident photon spectrum is allowed to be attenuated in the calculations and thus leads to the depth dependence in P expressed in equation (1). An angular dependence given by $1-aP_2(\cos\theta)$ is assigned to the photoelectrons[7] where P_2 is the second Legendre polynomial and θ is the emission angle with respect to the incident photon direction. In this work, the parameter <u>a</u> was set to unity. Isotropic angular dependence is assumed for Auger emission. The dependence for Compton electrons comes from the standard Compton expression — the Klein-Nishina formula (see Evans[8]). For soft x-ray sources, the electron density inserted into this formula is for the electrons in the conduction and/or valence bands of the material. The particular value used is not important since Compton scattering provides relatively few electrons for soft photon sources. Each Auger feature is given a narrow triangular distribution over five equally spaced grid points in energy.

Electron processes modeled in the DIMFP's are:

(1) Elastic scattering,
(2) Plasmon excitation,
(3) Conduction/valence band ionization,
(4) Inner shell ionization, and
(5) Auger emission.

---

[7] J. W. Cooper and S. T. Manson, Phys. Rev. <u>177</u>, 157 (1969).

[8] R. D. Evans, <u>The Atomic Nucleus</u>, McGraw-Hill Book Co., New York, New York (1955).

Assumptions concerning each process and the corresponding form of the DIMFP may be found in the 1977 RADC final report on x-ray photoemission.[9] Briefly, elastic scattering is permitted through an angle of 180°, plasmon excitation is assumed to be a discrete energy loss process with no change in direction of the incident electron, the ionization processes describe both energy loss of the incident electron and secondary electron production, and, finally, Auger emission is assumed isotropic and triangular in energy as in the case of shell vacancy creation by photons. Angular dependences assigned to degraded primaries and secondaries in the ionization process are based on the laws of energy and momentum conservation.

Choosing a discrete set of energy and angular points, the Boltzmann equation may be transformed into the following matrix equation:

$$\mu_i \frac{d\phi_{ni}(x)}{dx} = \sum_{m \le n} \sum_j R_{nmij}\, \phi_{mj}(x) + P_{ni}(x) \qquad (2)$$

where indices n and m refer to energy and i and j refer to pitch angle. The index m does not exceed n in value since electrons cannot gain energy in our formulation. For details on the form of the matrix elements, see Strickland,

[9] W. L. Chadsey, B. L. Beers, V. W. Pine, D. J. Strickland, and C. W. Wilson, "X-Ray Photoemission; X-Ray Dose Enhancement," RADC Final Report (January 1977).

et al.,[6] and the RADC x-ray photoemission final report.[9] It is convenient to define a new source term given by

$$S_{ni}(x) = \sum_{m<n} \sum_{j} R_{nmij}\, \phi_{mj} + P_{ni}(x) \quad . \qquad (3)$$

Equation (2) is now

$$\mu_i \frac{d\phi_{ni}(x)}{dx} = \sum_{j} R_{nnij}\, \phi_{nj}(x) + S_{ni}(x) \qquad (4)$$

or without the explicit appearance of subscript n,

$$\mu_i \frac{d\phi_i(x)}{dx} = \sum_{j} R_{ij}\, \phi_j(x) + S_i(x) \quad . \qquad (5)$$

This equation is solved by an eigenvalue method, one energy at a time, beginning with the highest energy.[6]

---

[6] D. J. Strickland, D. L. Book, T. P. Coffey, and J. A. Fedder, J. Geophy. Res., 81, 2755 (1976).

[9] W. L. Chadsey, B. L. Beers, V. W. Pine, D. J. Strickland, and C. W. Wilson, "X-Ray Photoemission; X-Ray Dose Enhancement," RADC Final Report (January 1977).

Section 3

CODE DEVELOPMENT

The following codes are required in this work for obtaining photoemission characteristics of materials:

(1) a source code,

(2) a matrix code, and

(3) a Boltzmann matrix equation solving code.

The source code generates the production rate $P(x,E,\mu)$ for a given normally incident photon source. The matrix code generates the matrix elements R_{nmij} by carrying out detailed integrations of DIMFP's over energy and angle. Finally, the Boltzmann matrix equation solving code obtains the electron flux $\phi(x,E,\mu)$ for the given outputs of the first two codes. Given the solution ϕ, this code further performs various integrations over x, E, and μ to obtain such quantities as differential and total yields, currents, and dose profiles.

The major part of the work performed was directed to developing the above codes. The source code is totally new whereas the matrix and Boltzmann codes are modified versions of codes used for electron transport in gases. Only minor modifications were needed on the Boltzmann code whereas an essentially new code was developed for obtaining the required matrix.

Following the basic development of these codes, further changes have recently been made so that the three codes may be run as multisteps in a single job. This has significantly increased efficiency in making production runs. A control statement program is now being used which does file manipulation and allows for new multistep runs by merely changing a few selected control and data statements.

Section 4

ATOMIC DATA

The three materials which were investigated are aluminum (Aℓ), aluminum oxide ($A\ell_2O_3$), and silicon dioxide (SiO_2). In this section, the photoabsorption cross sections, Auger yields, and IMFP's used in the calculations are presented for these materials.

The energy levels considered for each material are designated in Tables 1-3. The energies assigned to the valance bands in $A\ell_2O_3$ and SiO_2 were taken from ORNL tabulations.[10,11] Minor shifts that occur in inner shell binding energies in going from the atomic species (Aℓ, Si, O) to the molecular species ($A\ell_2O_3$, SiO_2) have been ignored.

Information pertaining to Auger emission is given in Table 4. The description is simple, but adequate to account for conversion of potential energy of inner shell vacancies to kinetic energy of the emitted Auger electrons. For Aℓ and Si, every K shell vacancy is

---

[10] J. C. Ashley, C. J. Tung, V. E. Anderson, and R. H. Ritchie, "Inverse Mean Free Path, Stopping Power, CSCA Range, and Straggling in Aluminum and Aluminum Oxide for Electrons of Energy ≤10 keV," AFCRL-TR-75-0583 (December 1975).

[11] C. J. Tung, J. C. Ashley, V. E. Anderson, and R. H. Ritchie, "Inverse Mean Free Path, Stopping Power, CSDA Range, and Straggling in Silicon and Silicon Dioxide for Electrons of Energy ≤10 keV," Report No. RADC-TR-76-125 (1976).

TABLE 1. ENERGY LEVELS FOR ALUMINUM

LEVEL DESIGNATION	ENERGY (keV)
Conduction Band	0 - 0.011
L_{23}	0.073
L_1	0.114
K	1.56

TABLE 2. ENERGY LEVELS FOR ALUMINUM OXIDE

LEVEL DESIGNATION	ENERGY (keV)
Valance Bands	$\begin{Bmatrix} 0.009 \\ 0.029 \end{Bmatrix}$
$A\ell(L_{23})$	0.073
$A\ell(L_1)$	0.114
O(K)	0.533
$A\ell(K)$	1.56

TABLE 3. ENERGY LEVELS FOR SILICON DIOXIDE

LEVEL DESIGNATION	ENERGY (keV)
Valance Bands	$\left\{\begin{matrix} 0.0094 \\ 0.024 \end{matrix}\right\}$
$Si(L_{23})$	0.10
$Si(L_1)$	0.151
O(K)	0.533
Si(K)	1.84

TABLE 4. AUGER ENERGIES AND YIELDS FOR Aℓ, Si, AND O

VACANCY	AUGER ENERGY (keV)	YIELD
Aℓ(K)	1.4	0.95
Aℓ(L)	0.07	1.0
Si(K)	1.6	0.94
Si(L)	0.08	1.0
O(K)	0.50	1.0

assumed to first lead to a KLL Auger electron with probability given by the Auger yield. This leads to two L shell vacancies and, in turn, to two further Auger electrons with assumed probability of unity. For oxygen, only KLL Auger electrons are treated. Intra L-shell emission occurs at $\lesssim 20$ ev, below the region of interest in this work. Useful references to the Auger process for low-Z atoms are, e.g., McGuire,[12] Yasko and Whitmoyer,[13] and Walters and Bhalla.[14]

The photoabsorption cross sections appear in Figures 1-3 and were taken from Biggs and Lighthill.[15] No attempt was made to separate the L shell cross section into its L_1 and L_{23} components. The L shell binding energy was taken to be that for the L_{23} shell.

The IMFP's for electron processes listed in the previous section are shown in Figures 4-6. All inelastic IMFP's come from the work of the Health Physics Group at

---

[12] E. J. McGuire, Phys. Rev. 185, 1 (1969).

[13] R. N. Yasko and R. D. Whitmoyer, J. Vac. Sci. Tech. 8, 733 (1972).

[14] D. L. Walters and C. P. Bhalla, Phys. Rev. A, 4, 2164 (1971).

[15] F. Biggs and R. Lighthill, Report #SC-RR-71-0507, Sandi Laboratories (1971).

ORNL.[10,11,16] The elastic IMFP's are based on the screened Rutherford cross section with the screening parameter of Molieré.[17] Below 0.1 keV, the elastic IMFP is allowed to become constant in a manner similar to that observed for N_2, O_2, and O.[18,19]

---

[10] J. C. Ashley, C. J. Tung, V. E. Anderson, and R. H. Ritchie, "Inverse Mean Free Path, Stopping Power, CSDA Range, and Straggling in Aluminum and Aluminum Oxide for Electrons of Energy ≤10 keV," AFCRL-TR-75-0583 (December 1975).

[11] C. J. Tung, J. C. Ashley, V. E. Anderson, and R. H. Ritchie, "Inverse Mean Free Path, Stopping Power, CSDA Range, and Straggling in Silicon and Silicon Dioxide for Electrons of Energy ≤10 keV," Report No. RADC-TR-76-125 (1976).

[16] C. J. Tung, R. H. Ritchie, J. C. Ashley, and V. E. Anderson, "Inelastic Interacations of Swift Electrons in Solids," Report No. ORNL-TM-5188 (1976).

[17] G. Molieré, Z. Naturforsch, A3, 78 (1948).

[18] J. B. Fisk, Phys. Rev. 49, 167 (1936).

[19] G. Sunshine, B. B. Aubrey, and B. Bederson, Phys. Rev. 154, 1 (1967).

Section 5

RESULTS

The basic quantity calculated in this work is the electron flux $\phi(x,E,\mu)$. This gives the energy and angular dependence of photoelectrons throughout the slab of material being considered. The quantity of primary interest here is the cumulative back yield which is related to ϕ by

$$Y_B(E) = 2\pi \int_E^{E_{max}} dE' \int_{-1}^{0} d\mu\mu\phi(x=0,E',\mu)\Big/F \qquad (6)$$

(electrons/photon above electron energy E)

where F is the total number of incident photons. The differential yield in energy $\frac{dY_B}{dE}$ is also of interest:

$$\frac{dY_B(E)}{dE} = 2\pi \int_{-1}^{0} d\mu\mu\phi(x=0,E,\mu)\Big/F \qquad (7)$$

(electrons/photon-keV).

The emphasis in this section will be on these two quantities.

5.1 PHOTOEMISSION FROM Aℓ FOR GAUSSIAN SOURCES

The purpose in considering photon distributions which are Gaussian in energy is for the simulation of line sources. The simulation is effective provided the distribution is limited to an energy range over which the yield varies by only a few percent. This was achieved by using the Gaussian formula

$$F(E) = \exp[(E-E_o)/aE_o]^2$$

with a $\lesssim$ 0.1. For most cases, an a-value of 0.05 was used. Smaller values were also considered, specifically, for energies close to the K-edge energy in aluminum.

Figure 7 gives the calculated back emission yield for Aℓ versus Gaussian photon energy E_o over a range from 0.5 to 10 keV. Electron emission was calculated down to ∿0.1 keV. Several other results are shown in the figure for comparison. Measurements are provided by Eliseenko, et al.[20] and Savinov, et al.[21] Transport results are shown from the codes POEM[22] and QUICKE2[4] and were obtained by running these codes specifically for this comparison.

---

[4] T. A. Dellin and C. J. MacCallum, IEEE Trans. Nuc. Sci., NS-20, No. 6, 91 (1973).

[20] L. G. Eliseenko, V. N. Shehemelev, and M. A. Runsh, Sov. Phys. - Tech. Phys. 13, 122 (1968).

[21] E. P. Savinov, A. P. Lukirskii, and Yu. F. Shepelev, Sov. Phys. - Sov. State 6, 2624 (1965).

[22] W. L. Chadsey and C. W. Wilson, "X-Ray Photoemission," Report No. HDL-CR-75-138-1 (1975).

Finally, the empirical result of Schaefer[23] is shown which is based on the sum of products of the photon absorption coefficient at E_o and the penetration depths of the various types of electrons produced.

The agreement with the other available yields above the aluminum K-edge is encouraging considering the limited testing so far performed on the newly developed codes. The difference between our results and the measurements by Savinov, et al.[21] below the K-edge remains to be determined. Based on the recent range calculations by Ashley, et al.,[10] Schaefer's result at low energies will significantly increase using this new information in place of his low energy extrapolated range.

The next several figures serve to provide more detailed information on our results for Gaussian photon sources. Differential back yields [$dY_B(E)/dE$] and cumulative back yields [$Y_B(E)$] are shown in Figures 8-14 for E_o = 0.5, 1.0, 1.4, 1.7, 2.0, 4.0, and 10.0 keV. Table 5 gives the value of $Y_B(E)$ for these E_o values for the lowest electron energy E treated in the calculations (either 0.1 or 0.05 keV). For E_o < 1.56 keV (K-edge energy), the highest energy peak in dY_B/dE is due to L

---

[10] J. C. Ashley, C. J. Tung, V. E. Anderson, and R. H. Ritchie, "Inverse Mean Free Path, Stopping Power, CSDA Range, and Straggling in Aluminum and Aluminum Oxide for Electrons of Energy ≤10 keV," Report No. AFCRL-TR-75-0583 (December 1975).

[21] E. P. Savinov, A. P. Lukirskii, and Yu. F. Shepelev, Sov. Phys. - Sov. State 6, 2624 (1965).

[23] R. R. Schaefer, J. Appl. Phys. 44, 152 (1973).

TABLE 5. CUMULATIVE YIELD Y_B FOR SEVERAL GAUSSIAN SOURCES

GAUSSIAN PEAK ENERGY E_o	Y_B (e/phot)
0.5	2.5×10^{-3}
1.0	9.9×10^{-4}
1.4	8.6×10^{-4}
1.7	7.8×10^{-3}
2.0	5.7×10^{-3}
4.0	2.7×10^{-3}
10.0	1.2×10^{-3}

photoelectrons. The 0.07 keV feature is due to LMM Auger electrons. Starting with Figure 11, E_o is greater than the K-edge energy and results in significant changes in both types of yields. In Figure 11, for example, the peaks in dY_B/dE in order of decreasing energy are due to L-photo-, KLL Auger, K-photo-, and finally, LMM Auger electrons. For photon energies just above the K-edge, the spectra are seen to be dominated by KLL Auger electrons. At E_o = 10 keV, however, Auger electrons provide only a minor contribution with the dominant source coming from K-photoelectrons.

5.2 PHOTOEMISSION FROM Aℓ FOR BLACKBODY SOURCES

We next present results for a series of blackbody spectra incident on Aℓ. Five spectra with temperatures of 1.0, 2.0, 5.0, 7.5, and 10 keV were considered. The yield Y_B is shown in Figure 15, and is tabulated in Table 6, versus temperature in keV. For comparison, available POEM[9] results are also shown and, as with the previous comparison, are found to be below the results of this work. The difference increases with decreasing source temperature, as expected, since sub-kilovolt electrons are becoming increasingly important.

Figures 16-19 provide further information for the results in Figure 15. Shown in each of these figures are $dY_B(E)/dE$ and $Y_B(E)$ versus electron energy E for a different blackbody temperature. The temperatures selected for these results are 1.0, 2.0, 4.0, and 10.0 keV. The differential

---

[9] W. L. Chadsey, B. L. Beers, V. W. Pine, D. J. Strickland, and C. W. Wilson, "X-Ray Photoemission; X-Ray Dose Enhancement," RADC Final Report (January 1977).

TABLE 6. CUMULATIVE YIELD Y_B FOR SEVERAL BLACKBODY SOURCES

TEMPERATURE (keV)	Y_B (e/phot) (This work)	Y_B (e/phot) (POEM)
1	2.6×10^{-3}	--
2	2.1×10^{-3}	1.3×10^{-3}
5	1.1×10^{-3}	8.8×10^{-4}
7.5	8.8×10^{-4}	6.4×10^{-4}
10	6.3×10^{-4}	5.0×10^{-4}

yields shown have some noticeable differences compared with those shown in Figures 8-14 for narrow Gaussian photon sources. Here, a broad K-photoelectron continuum typically dominates the spectrum. As before, we observe the KLL and LMM Auger features starting at ∿1.4 and 0.07 keV. With the exception of T=1 keV, photoelectrons, rather than Auger electrons, dominate the photoemission spectrum.

5.3 PHOTOEMISSION FROM Aℓ, $A\ell_2O_3$, and SiO_2 FOR AN EXPLODING WIRE SPECTRUM

The primary goal of work begun under the given DNA/RADC contract is to develop a predictive capability in soft x-ray photoemission for making comparisons with photoemission data and providing physical insight into the photoemission process itself in the DNA sponsored exploding wire radiation program (EWR). As a beginning in the study of photoemission for EWR sources, we have run our transport codes for the photon spectrum shown in Figure 20, which is based on information appearing in a January 1977 Physics International report.[24] The spectra in this report show that ∿50% of the energy resides in the line features occurring at 1.6 and 1.7 keV. The Gaussian feature peaking at 1.65 keV in Figure 20 has been substituted for these lines and itself contains ∿50% of the total energy. One should not necessarily interpret this figure to mean that no photons are present at lower energies for actual wires spectra in the test chamber. We are using data available

---

[24] K. Nielson, "Exploding Wire Radiation Source Support for Skynet Phenomenology Experiments," Physics International (January 1977).

to us at this time which covers the range from 1.3 to 3.4 keV. Over this range beginning at 3.4 keV, reported cumulative energy distributions reach 100% at 1.6 keV.

The yields dY_B/dE and Y_B for $A\ell$ and $A\ell_2O_3$ are shown in Figure 21 for the source spectrum in Figure 20. The results for SiO_2 appear in Figure 22. The dominant feature starting at $\sim$1.4 keV and continuing to lower energies in both spectra in Figure 21 is Auger electron emission arising from $A\ell$ K-shell vacancies. The dominance by Auger electrons is due to the abundance of photons lying just above the 1.56 keV K-edge of aluminum. The minor contribution above 1.5 keV in both spectra is due to L photoelectrons which weakly reflect the source spectrum. Below 0.2 keV, the spectra rise and peak at 0.07 keV as a result of both K-photoelectron and Auger electron emission. Here the Auger electrons arise from L-shell vacancies in aluminum. The additional feature in the $A\ell_2O_3$ spectrum at 0.5 keV is due to Auger emission arising from K-shell vacancies in oxygen.

Significant differences are seen between photoemission from $A\ell$ and $A\ell_2O_3$. The most striking difference is in Auger photoemission for the $A\ell$ KLL transition. We expect the decrease shown in $A\ell_2O_3$ since over the same mean free path distance in either material, the available number of aluminum atoms has decreased by more than a factor of two in $A\ell_2O_3$. We see that the cumulative yield at 0.05 keV is about twice as large for $A\ell$.

The photoemission spectrum for SiO_2 in Figure 22 is noticeably different compared to Aℓ and $A\ell_2O_3$, due primarily to the K-edge of silicon being situated above the 1.65 keV Gaussian feature in the source spectrum. The Si K-edge occurs at 1.84 keV. The primary contribution to the 1.55 keV feature is Si KLL Auger electrons although Si L-photoelectrons arising from the 1.65 keV Gaussian photon feature also contribute. The peak at 1.1 keV is due to O K-photoelectrons, that at 0.5 keV comes from O KLL Auger electrons, and, finally, the low energy feature results from Si K-photoelectrons and Si LMM Auger electrons. Unlike Aℓ or $A\ell_2O_3$, KLL Auger electrons do not dominate the emission spectrum which is a result of the Si K-edge lying above an important energy region of the source spectrum. For this same reason, SiO_2 has the smallest total yield of the three materials. Its value is 2.1×10^{-3} electrons/photon compared with 7.1×10^{-3} and 3.8×10^{-3} for Aℓ and $A\ell_2O_3$.

REFERENCES

1. W. L. Chadsey, "POEM," AFCRL Report TR-75-0327 (1975).

2. H. M. Colbert, "SANDYL," Sandia Laboratories, SLL-74-0012 (1974).

3. M. J. Berger and S. M. Seltzer, "Electron and Photon Transport Programs," (I) NBS Report 9836, (II) NBS Report 9837.

4. T. A. Dellin and C. J. MacCallum, IEEE Trans. Nuc. Sci., NS-20, No. 6, 91 (1973).

5. J. C. Garth and J. V. O'Brien, IEEE Trans. Nuc. Sci., NS-20, No. 6, 82 (1973).

6. D. J. Strickland, D. L. Book, T. P. Coffey, and J. A. Fedder, J. Geophys. Res., 81, 2755 (1976).

7. J. W. Cooper and S. T. Manson, Phys. Rev. 177, 157 (1969).

8. R. D. Evans, The Atomic Nucleus, McGraw-Hill Book Co., New York, New York (1955).

9. W. L. Chadsey, B. L. Beers, V. W. Pine, D. J. Strickland, and C. W. Wilson, "X-Ray Photoemission; X-Ray Dose Enhancement," RADC Final Report (January 1977).

10. J. C. Ashley, C. J. Tung, V. E. Anderson, and R. H. Ritchie, "Inverse Mean Free Path, Stopping Power, CSDA Range, and Straggling in Aluminum and Aluminum Oxide for Electrons of Energy ≤10 keV," Report No. AFCRL-TR-75-0583 (December 1975).

11. C. J. Tung, J. C. Ashley, V. E. Anderson, and R. H. Ritchie, "Inverse Mean Free Path, Stopping Power, CSDA Range, and Straggling in Silicon and Silicon Dioxide for Electrons of Energy ≤10 keV," Report No. RADC-TR-76-125 (1976).

12. E. J. McGuire, Phys. Rev. 185, 1 (1969).

13. R. N. Yasko and R. D. Whitmoyer, J. Vac. Sci. Tech. 8, 733 (1972).

REFERENCES (Continued)

14. D. L. Walters and C. P. Bhalla, Phys. Rev. A, 4, 2164 (1971).

15. F. Biggs and R. Lighthill, Report No. SC-RR-71-0507, Sandia Laboratories (1971).

16. C. J. Tung, R. H. Ritchie, J. C. Ashley, and V. E. Anderson, "Inelastic Interactions of Swift Electrons in Solids," Report No. ORNL-TM-5188 (1976).

17. G. Moliere, Z. Naturforsch. A3, 78 (1948).

18. J. B. Fisk, Phys. Rev. 49, 167 (1936).

19. G. Sunshine, B. B. Aubrey, and B. Bederson, Phys. Rev. 154, 1 (1967).

20. L. G. Eliseenko, V. N. Shehemelev, and M. A. Runsh, Sov. Phys. - Tech. Phys. 13, 122 (1968).

21. E. P. Savinov, A. P. Lukirskii, and Yu. F. Shepelev, Sov. Phys. - Sov. State 6, 2624 (1965).

22. W. L. Chadsey and C. W. Wilson, "X-Ray Photoemission," Report No. HDL-CR-75-138-1 (1975).

23. R. R. Schaefer, J. Appl. Phys. 44, 152 (1973).

24. K. Nielson, "Exploding Wire Radiation Source Support for Skynet Phenomenology Experiments," Physics International (January 1977).

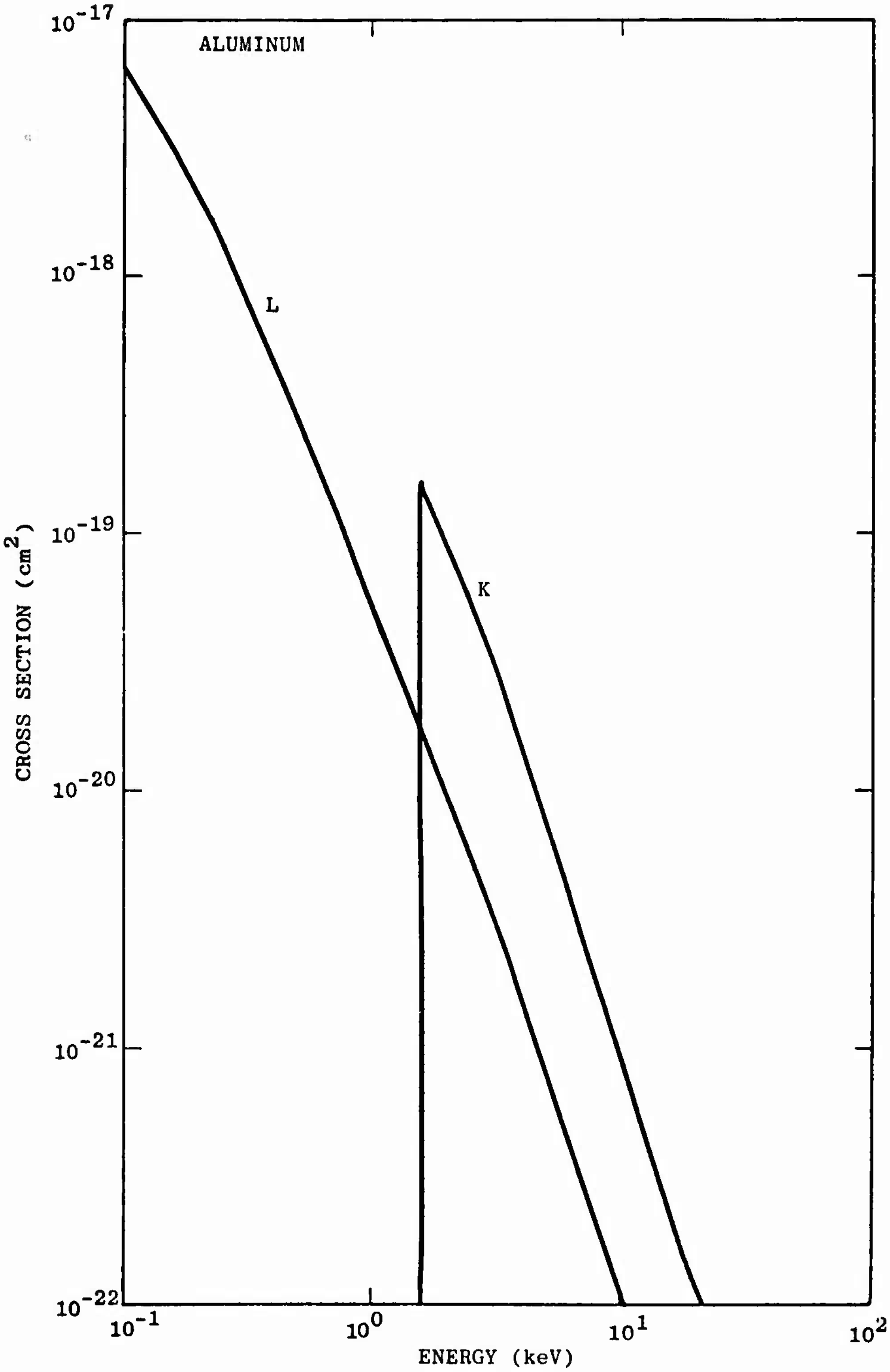

FIGURE 1. Photoabsorption Cross Section for Aℓ Taken from Biggs and Lighthill[15]

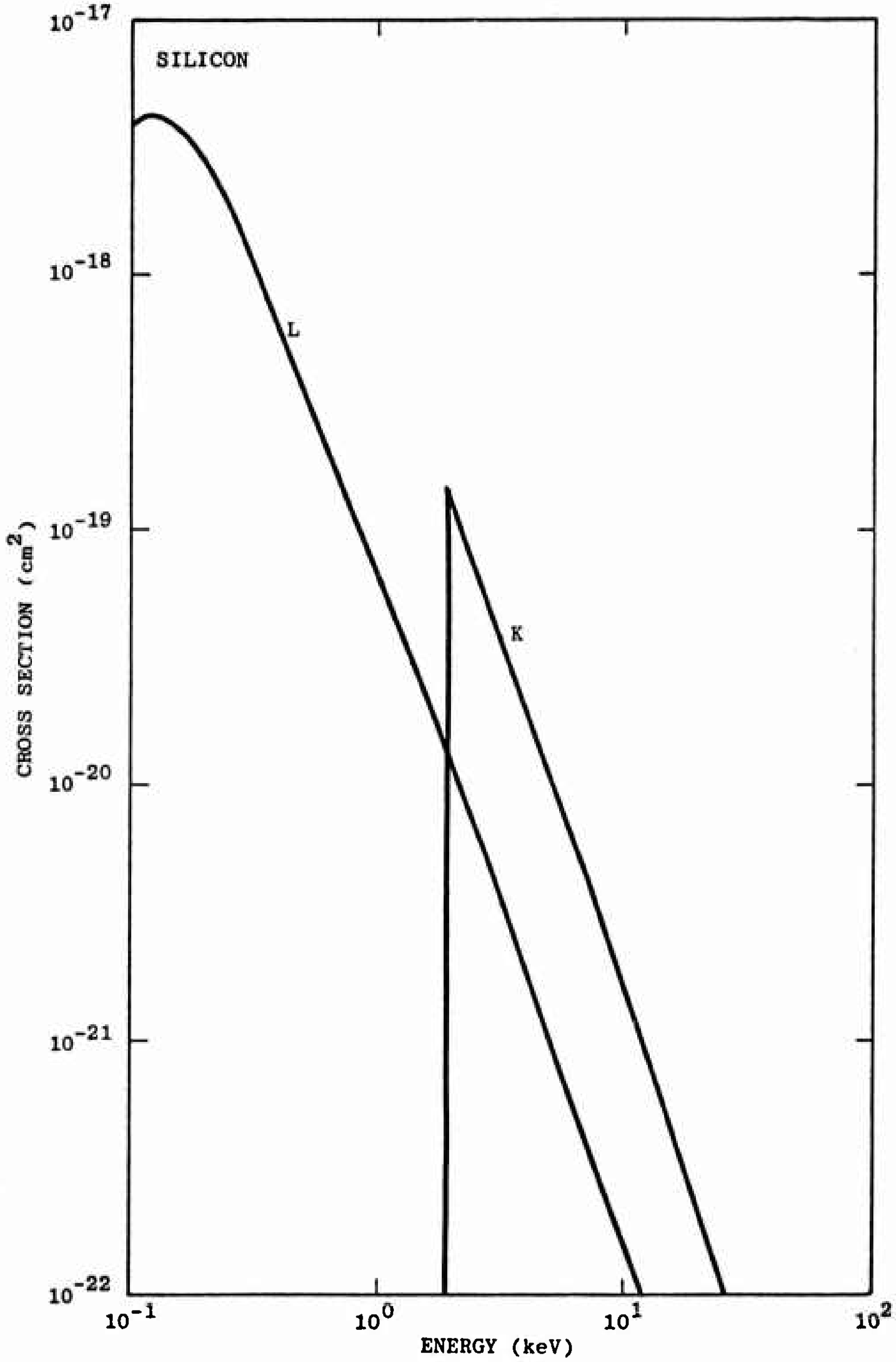

FIGURE 2. Photoabsorption Cross Section for Si Taken from Biggs and Lighthill[15]

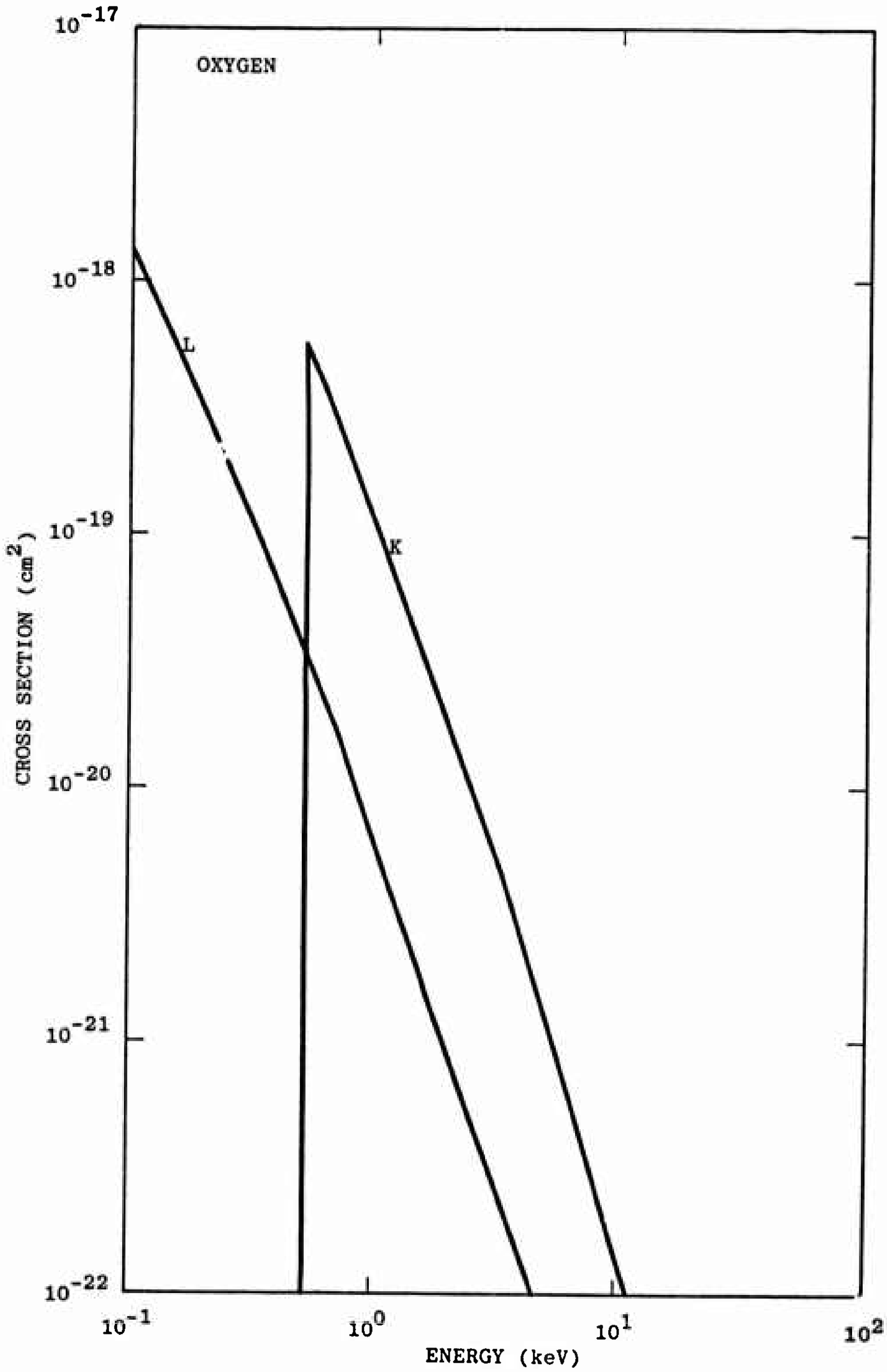

FIGURE 3. Photoabsorption Cross Section for O Taken from Biggs and Lighthill[15]

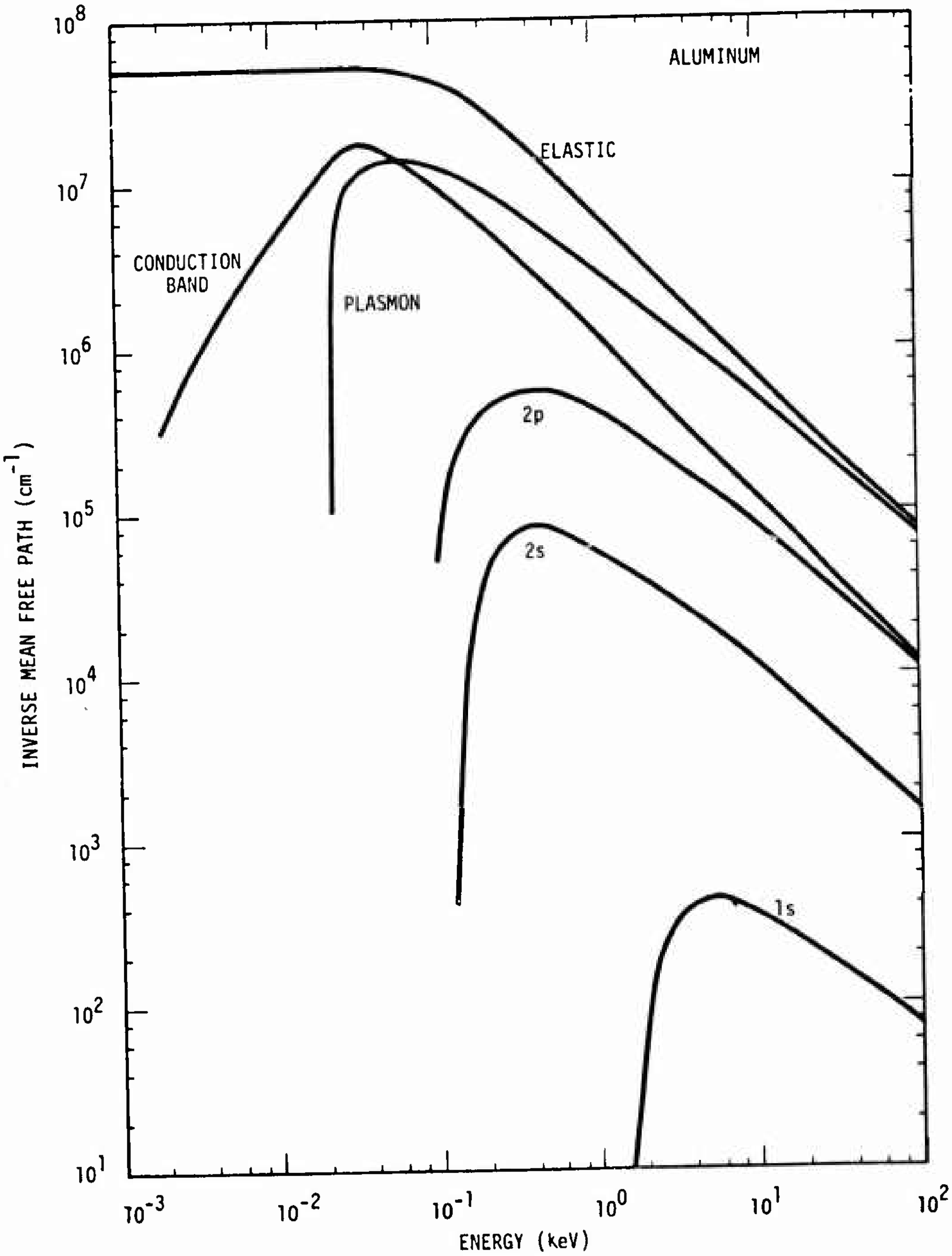

FIGURE 4. IMFP's for Aℓ. Inelastic IMFP's Were Taken from Tung, et al.[16]

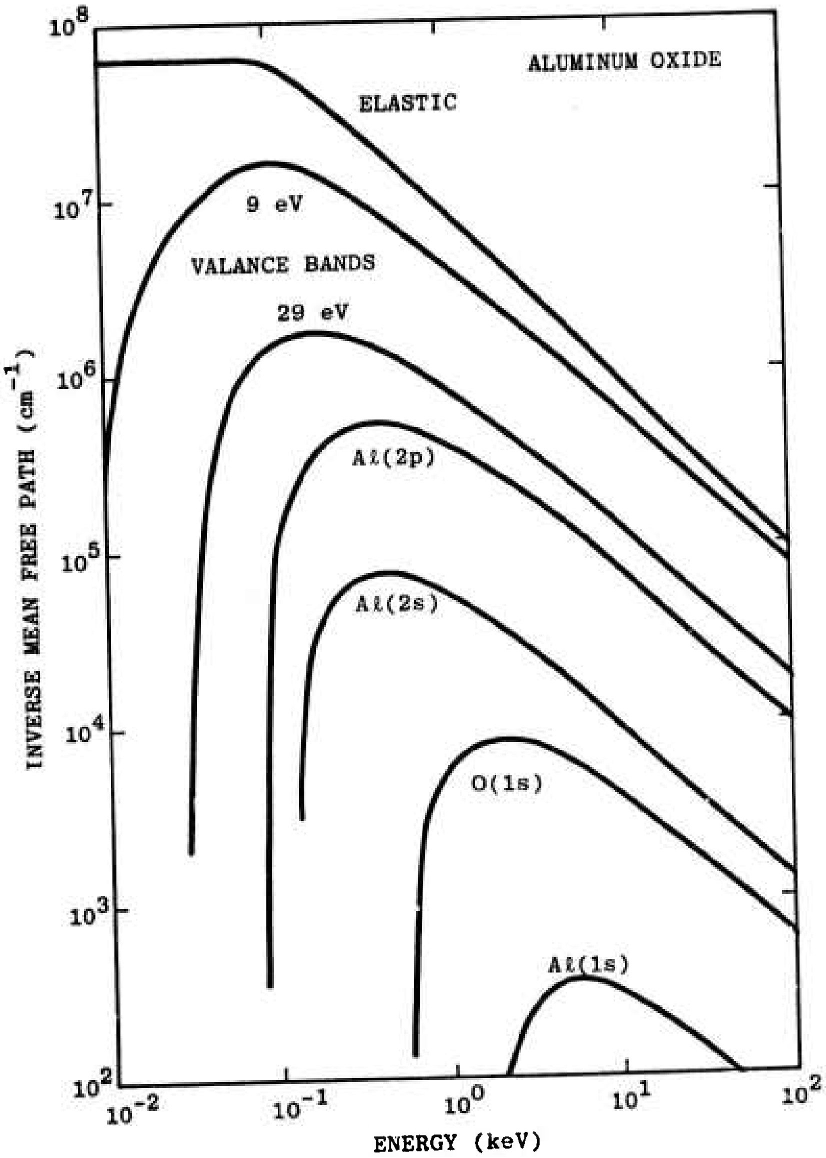

FIGURE 5. IMFP's for $A\ell_2O_3$. Inelastic IMFP's Were Taken from Ashley, et al.[10]

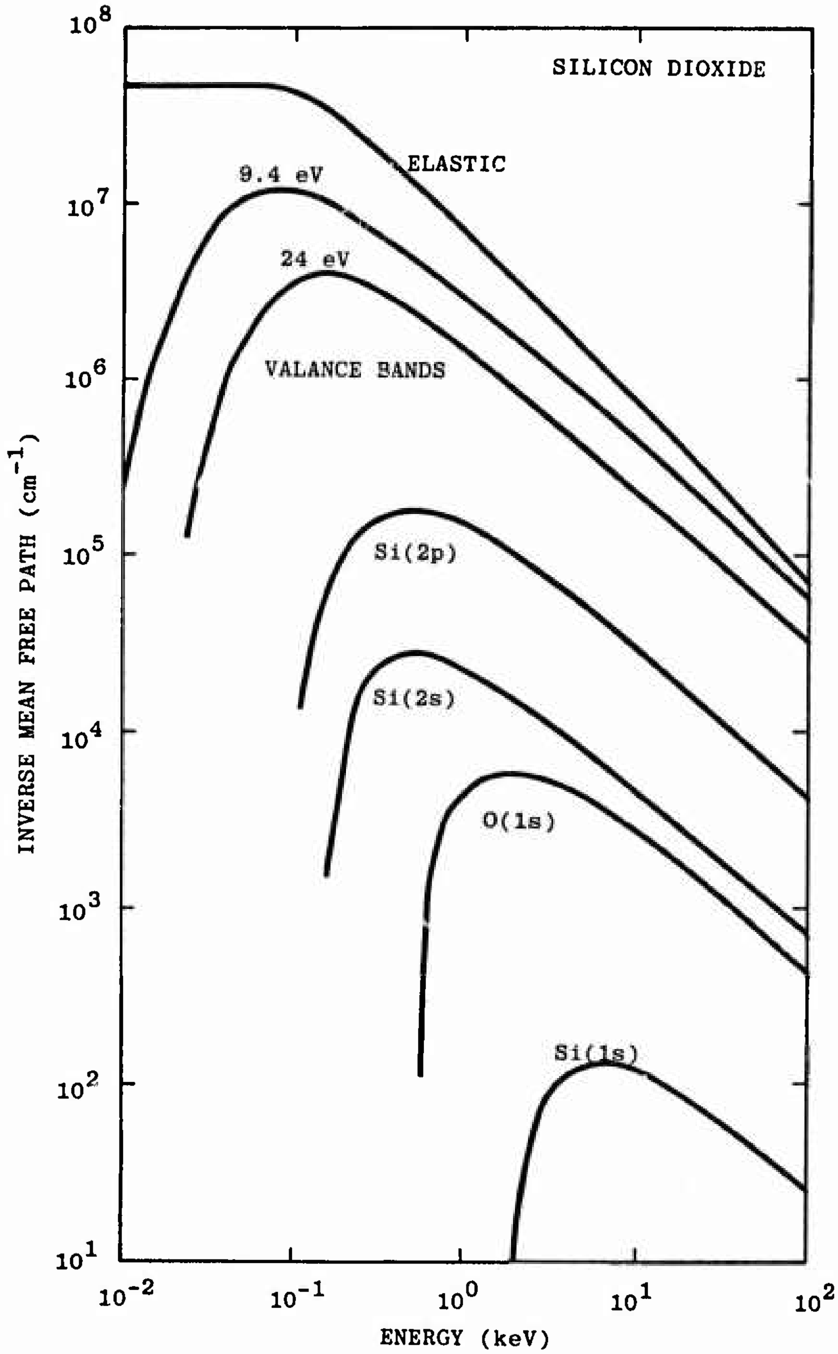

FIGURE 6. IMFP's for SiO_2. Inelastic IMFP's Were Taken from Tung, et al.[11]

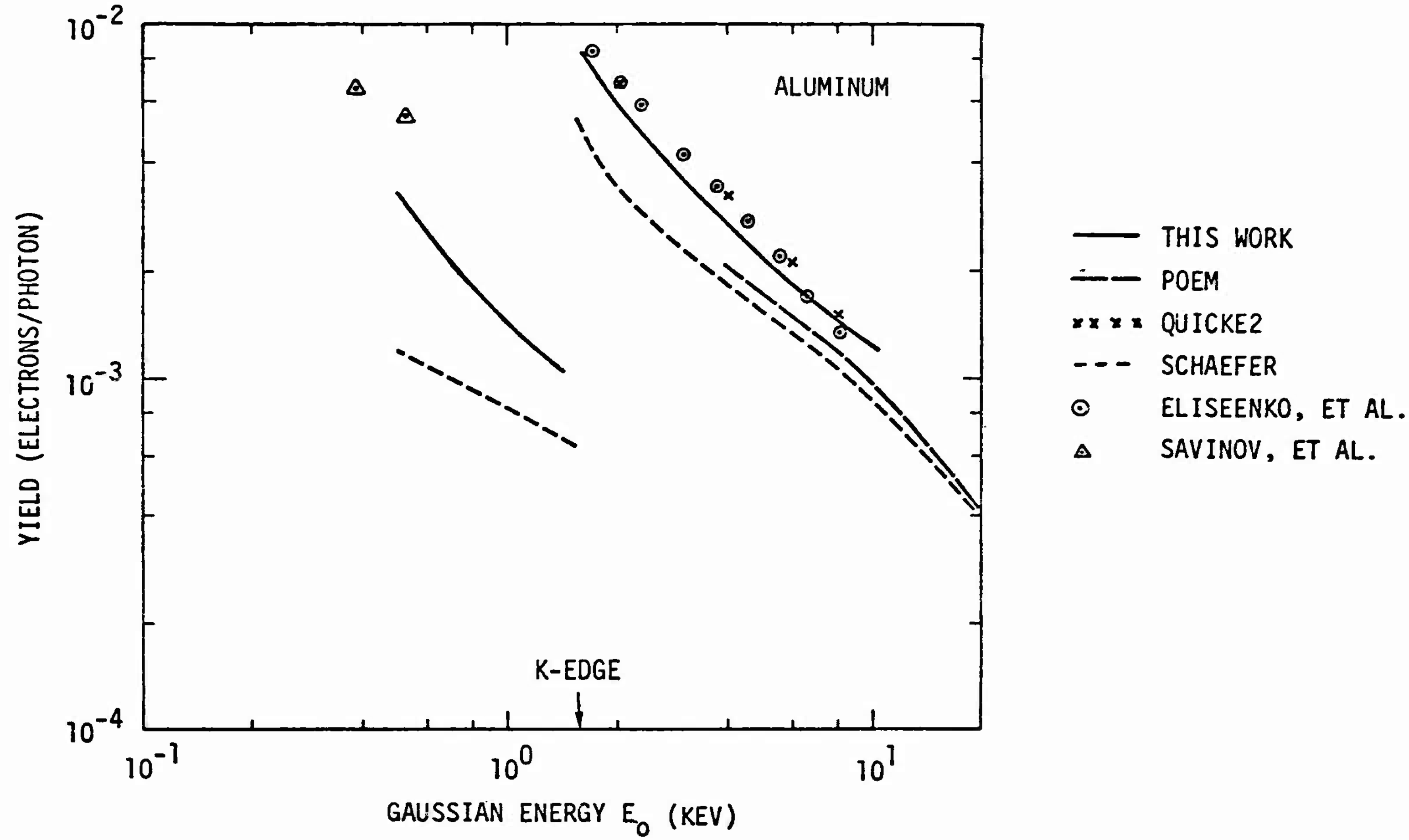

FIGURE 7. Back Yields versus Photon Energy

The Yields from this Work Were Obtained for Narrow Gaussian Photon Distribution

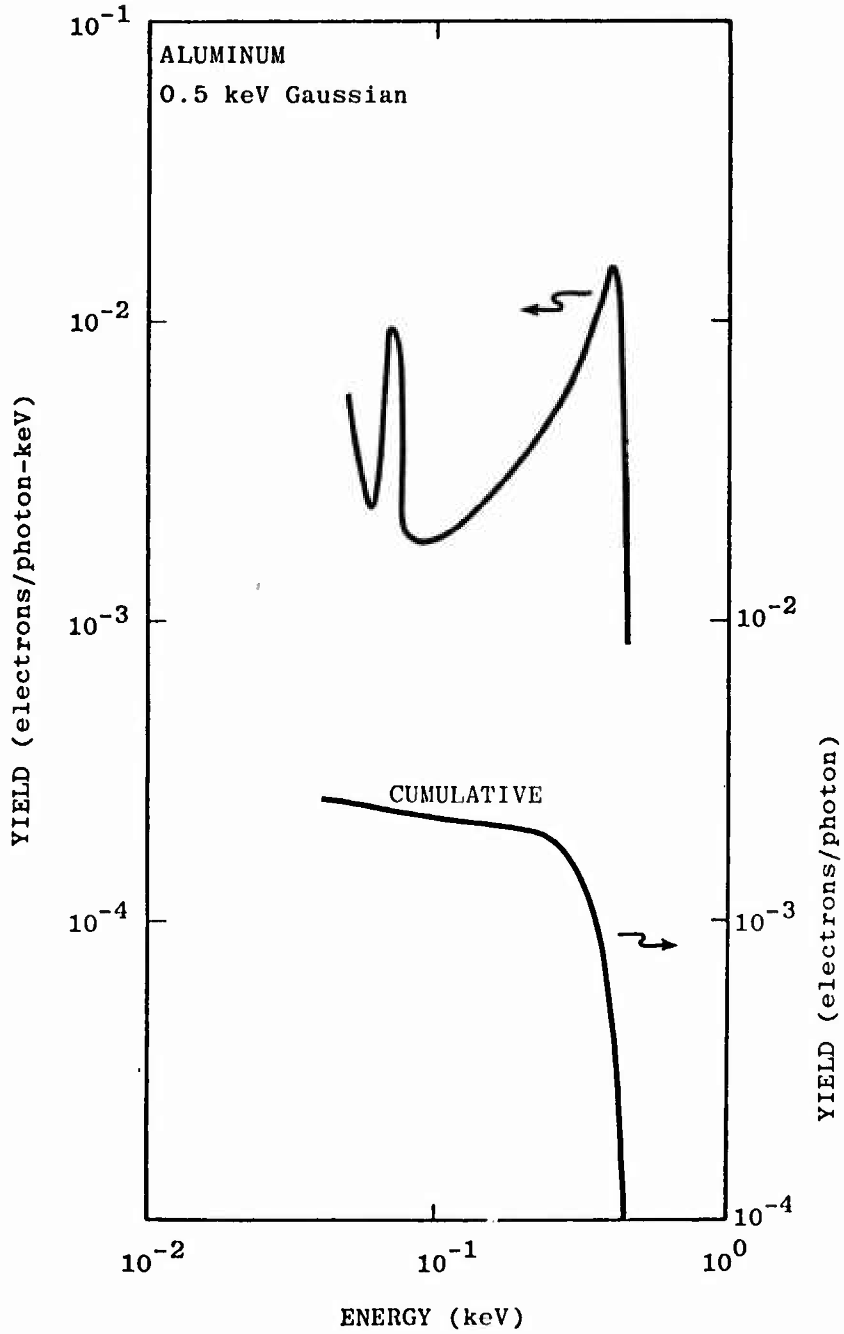

FIGURE 8. Differential and Cumulative Back Yields for Aℓ for a 0.5 keV Gaussian Photon Distribution

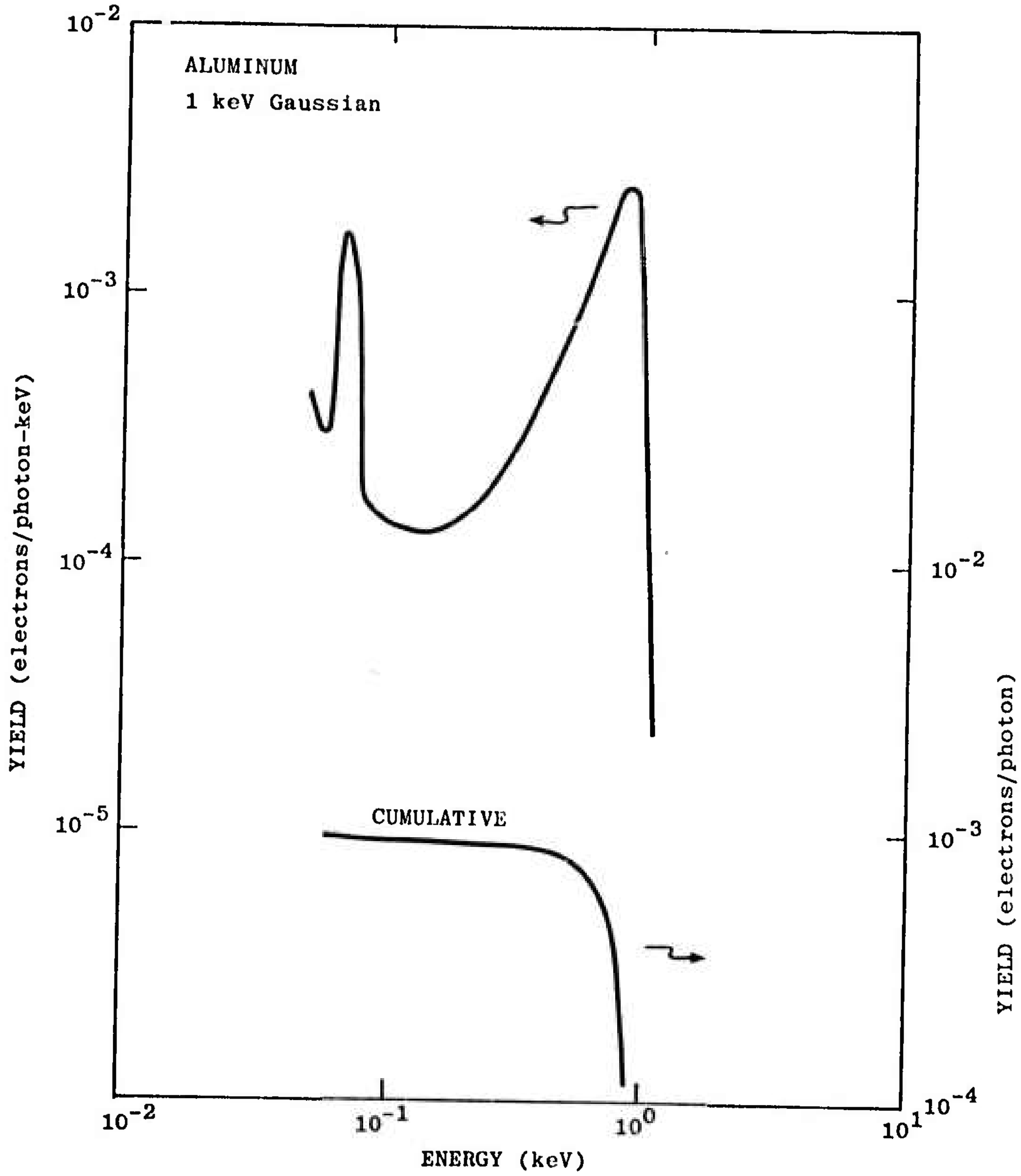

FIGURE 9. Back Yields for a 1.0 keV Gaussian Photon Distribution

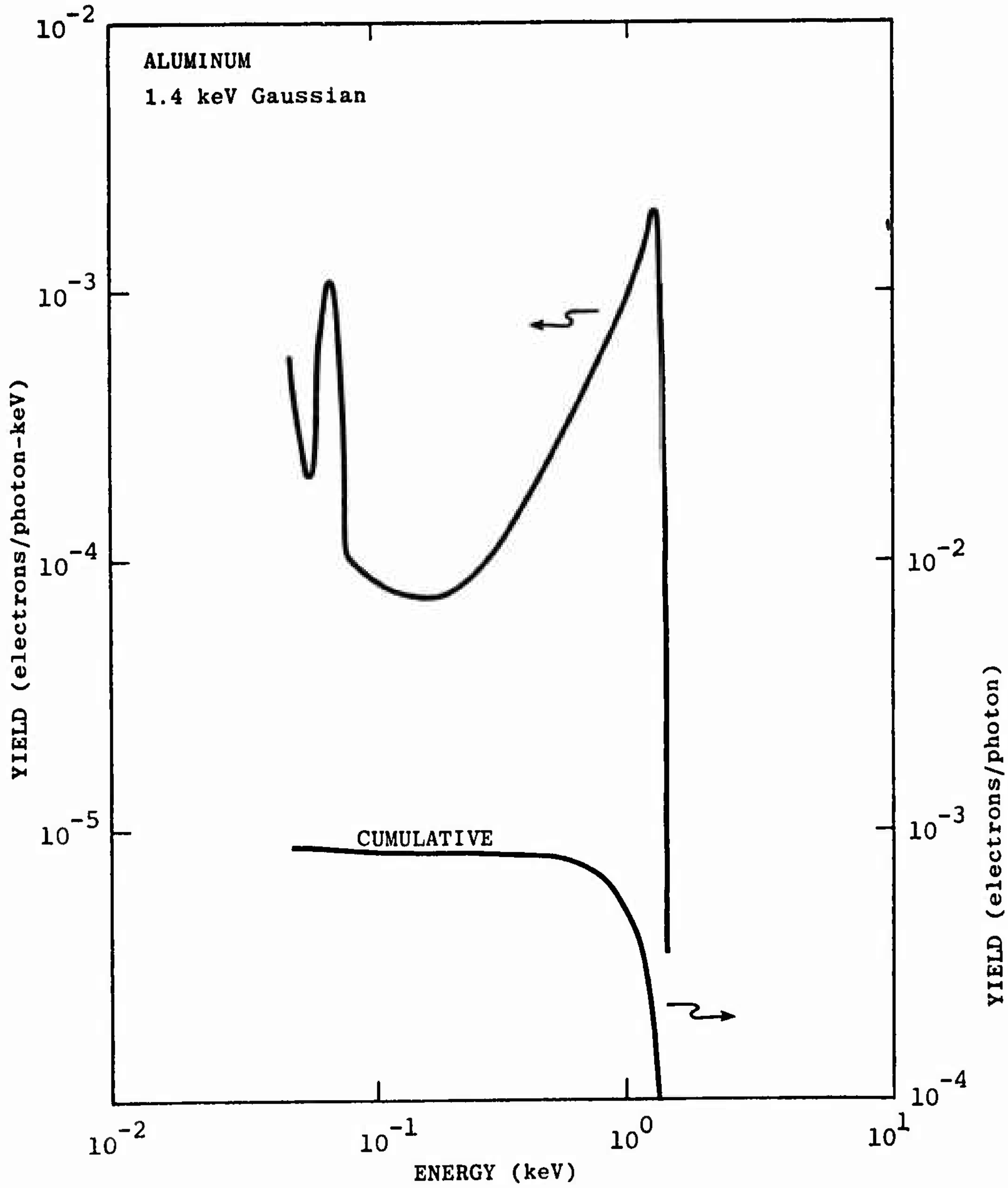

FIGURE 10. Back Yields for a 1.4 keV Gaussian Photon Distribution.

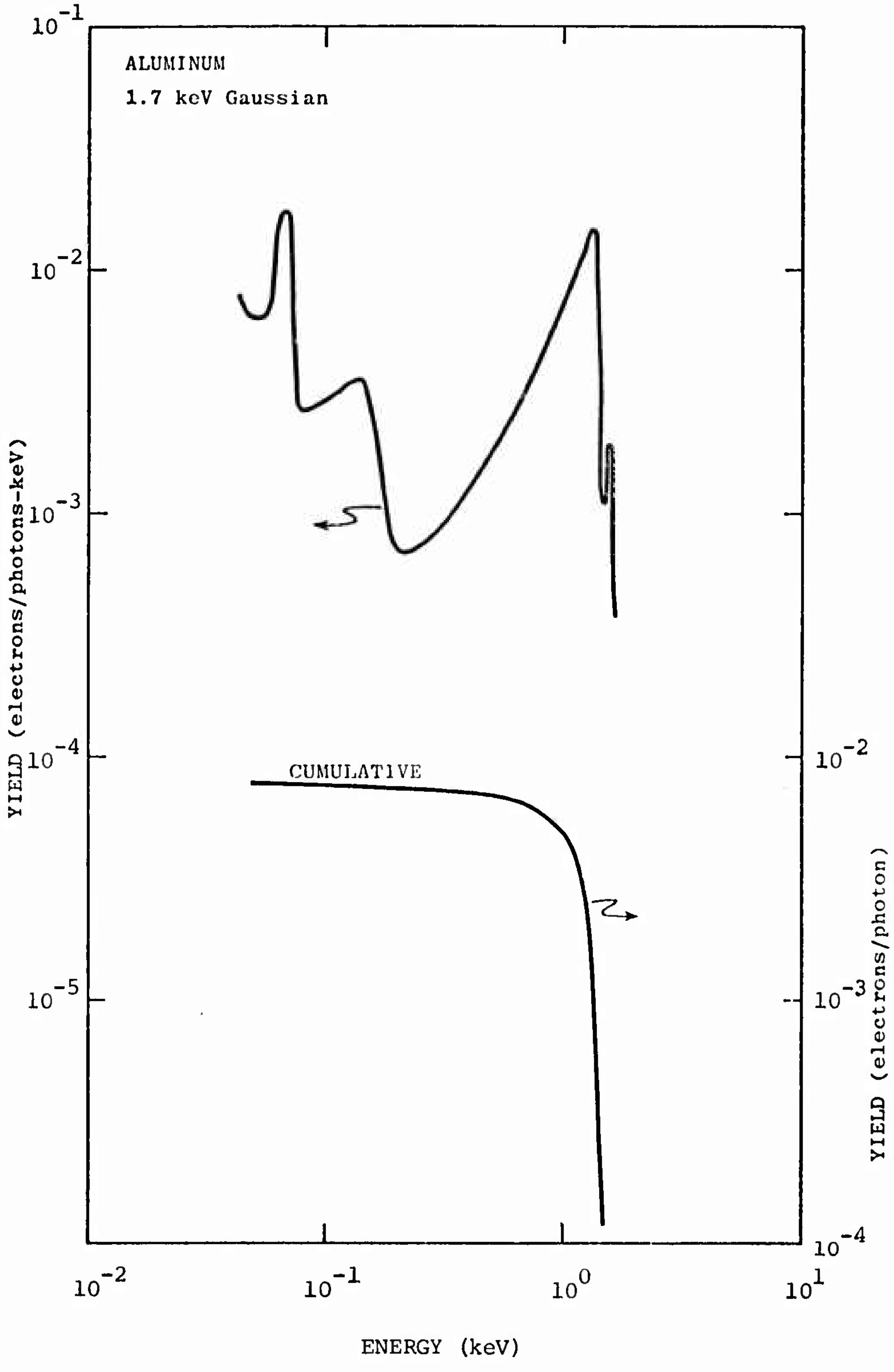

FIGURE 11. Back Yields for a 1.7 keV Gaussian Photon Distribution

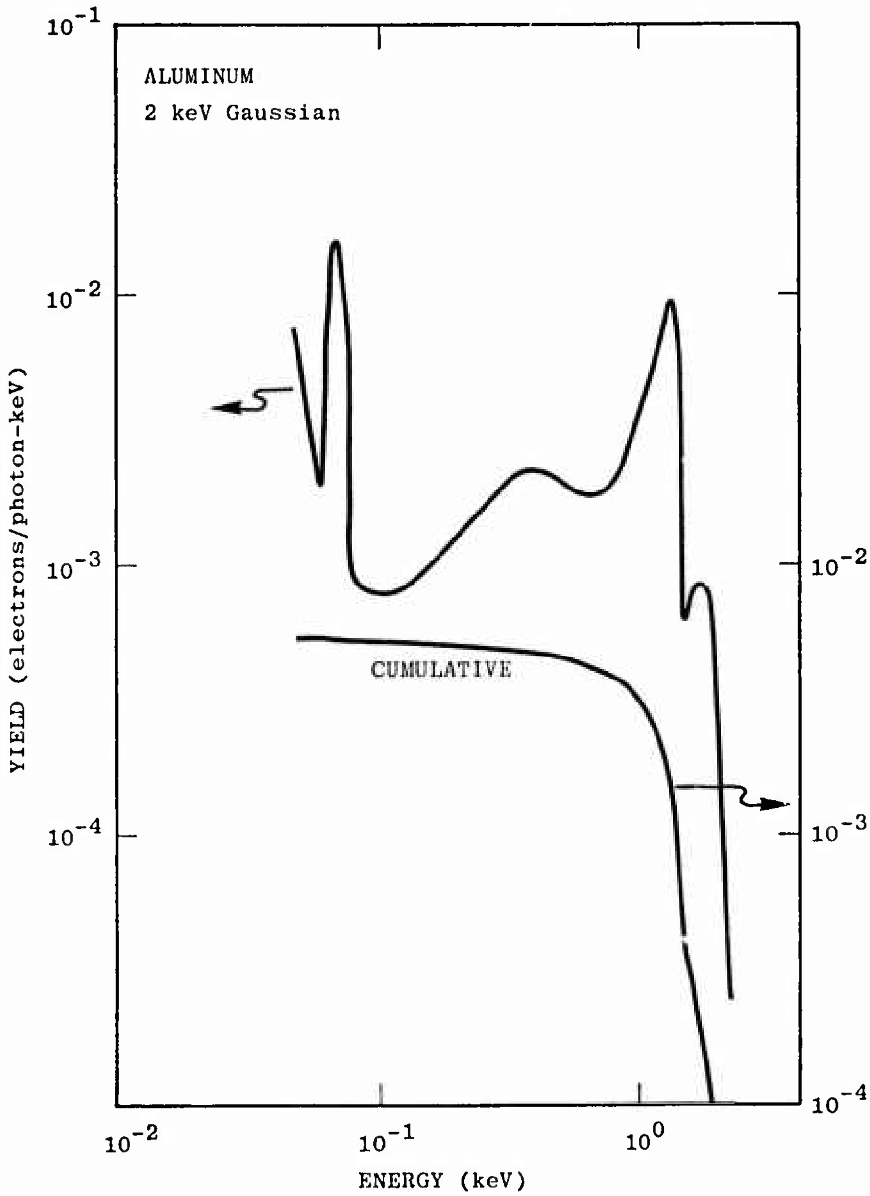

FIGURE 12. Back Yields for a 2 keV Gaussian Photon Distribution

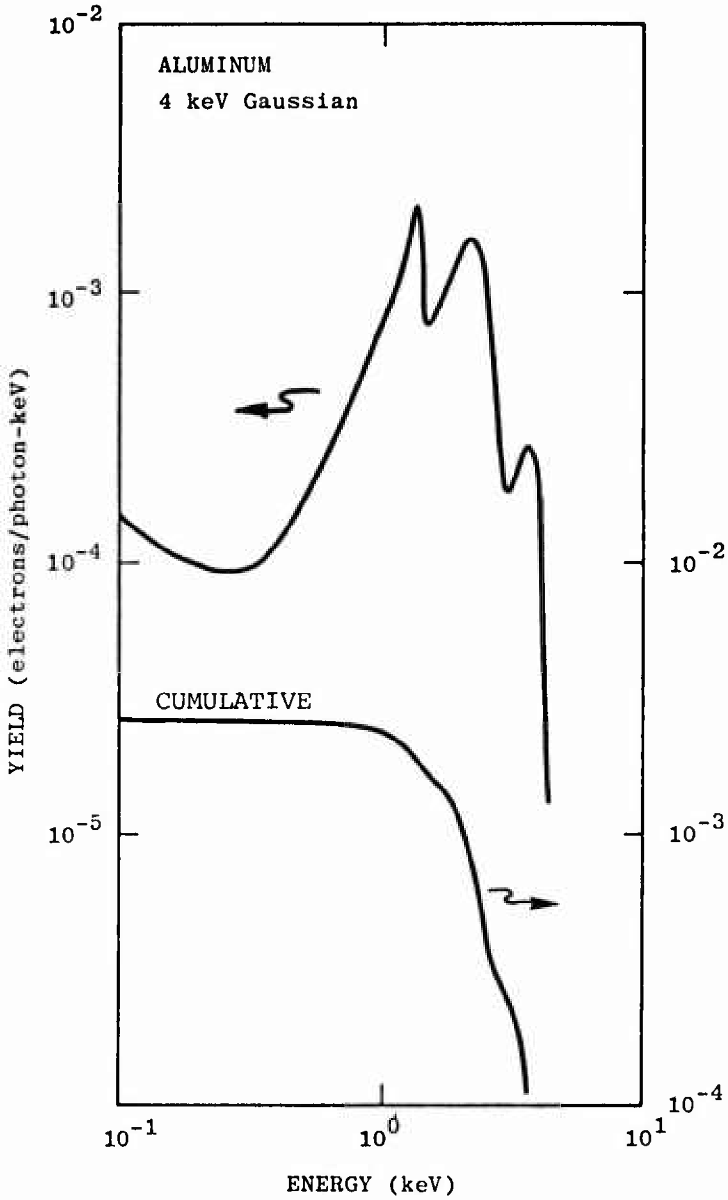

FIGURE 13. Back Yields for a 4 keV Gaussian Photon Distribution

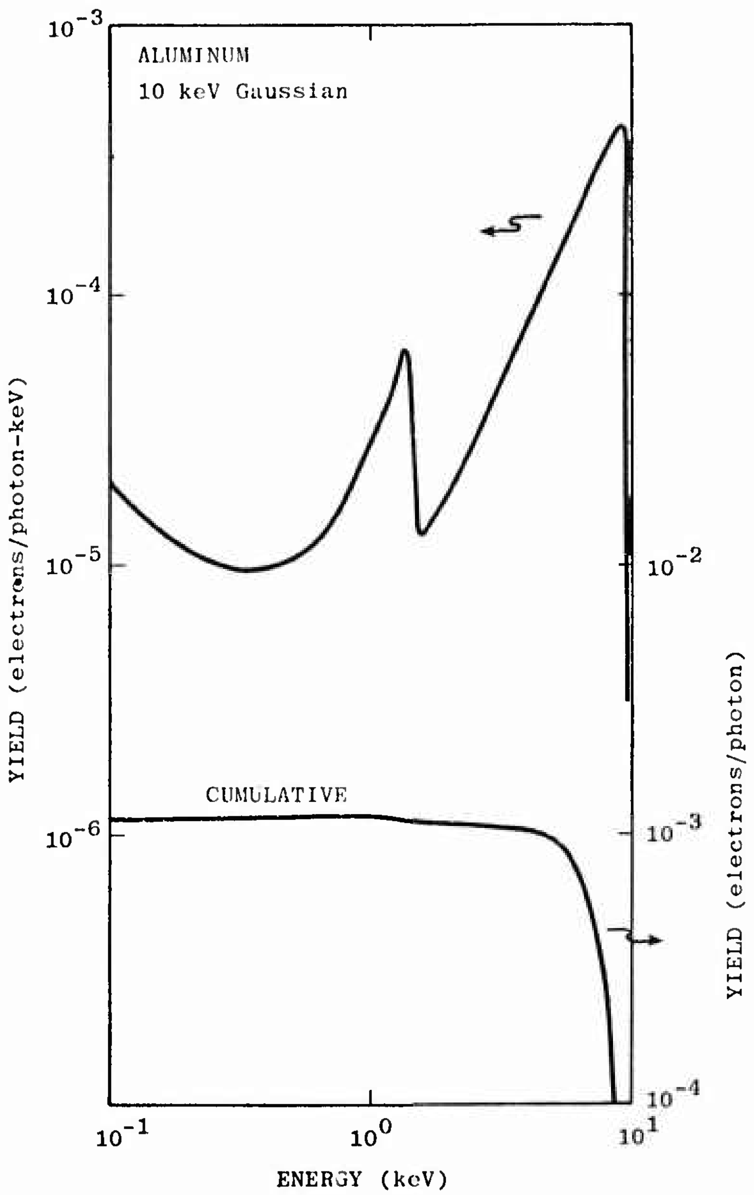

FIGURE 14. Back Yields for a 10 keV Gaussian Photon Distribution

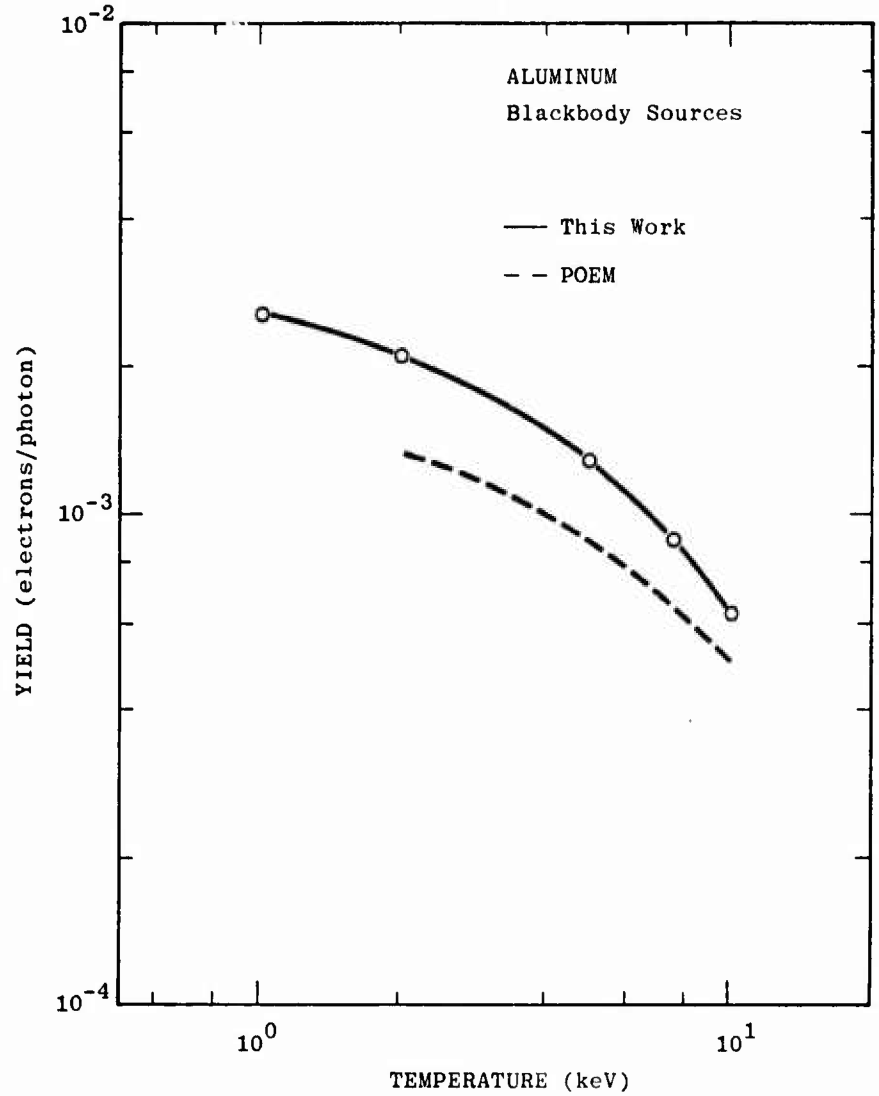

FIGURE 15. Back Yields for Aℓ for Blackbody Spectra.

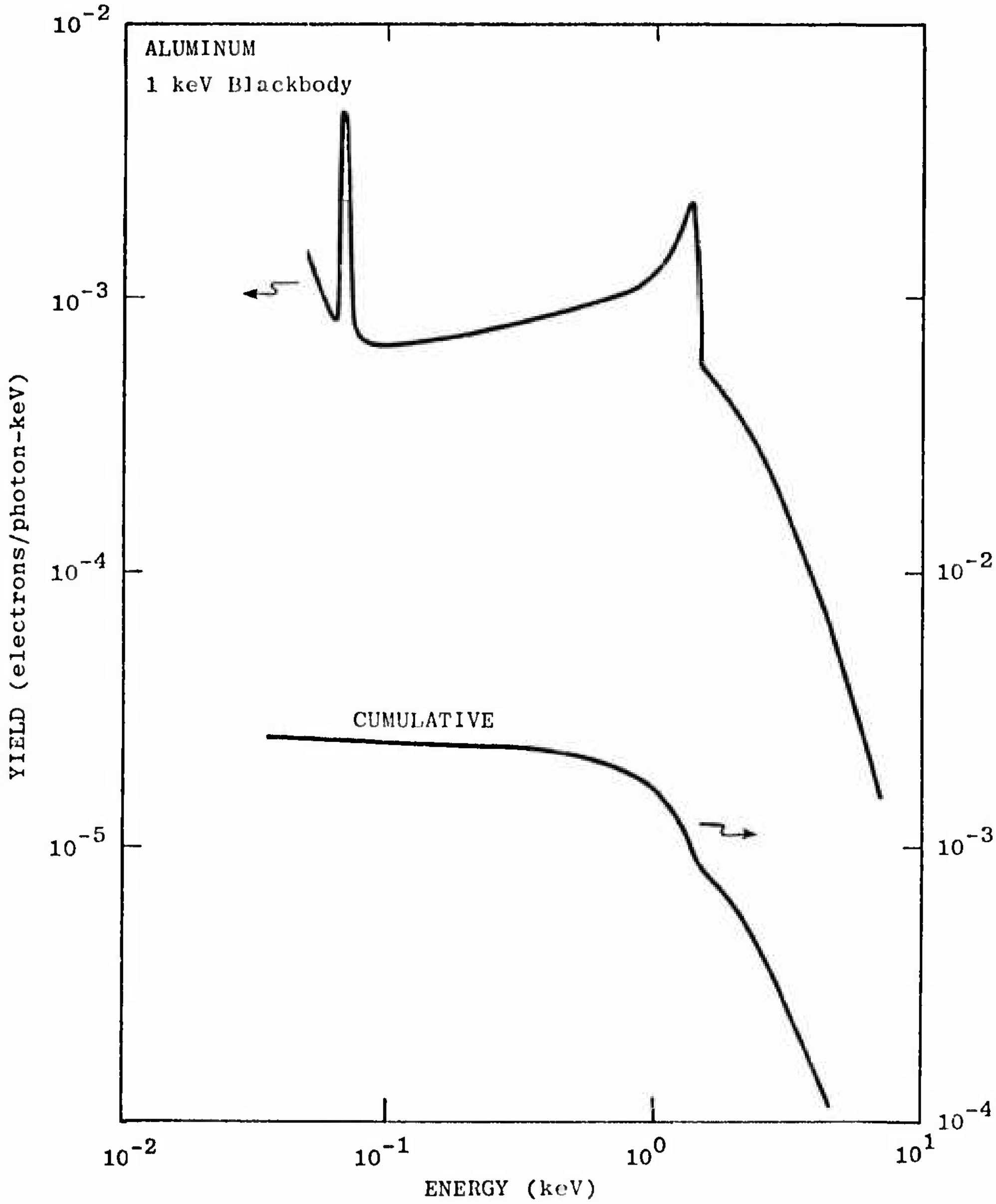

FIGURE 16. Differential and Cumulative Back Yields for Aℓ for a 1 keV Blackbody Spectrum

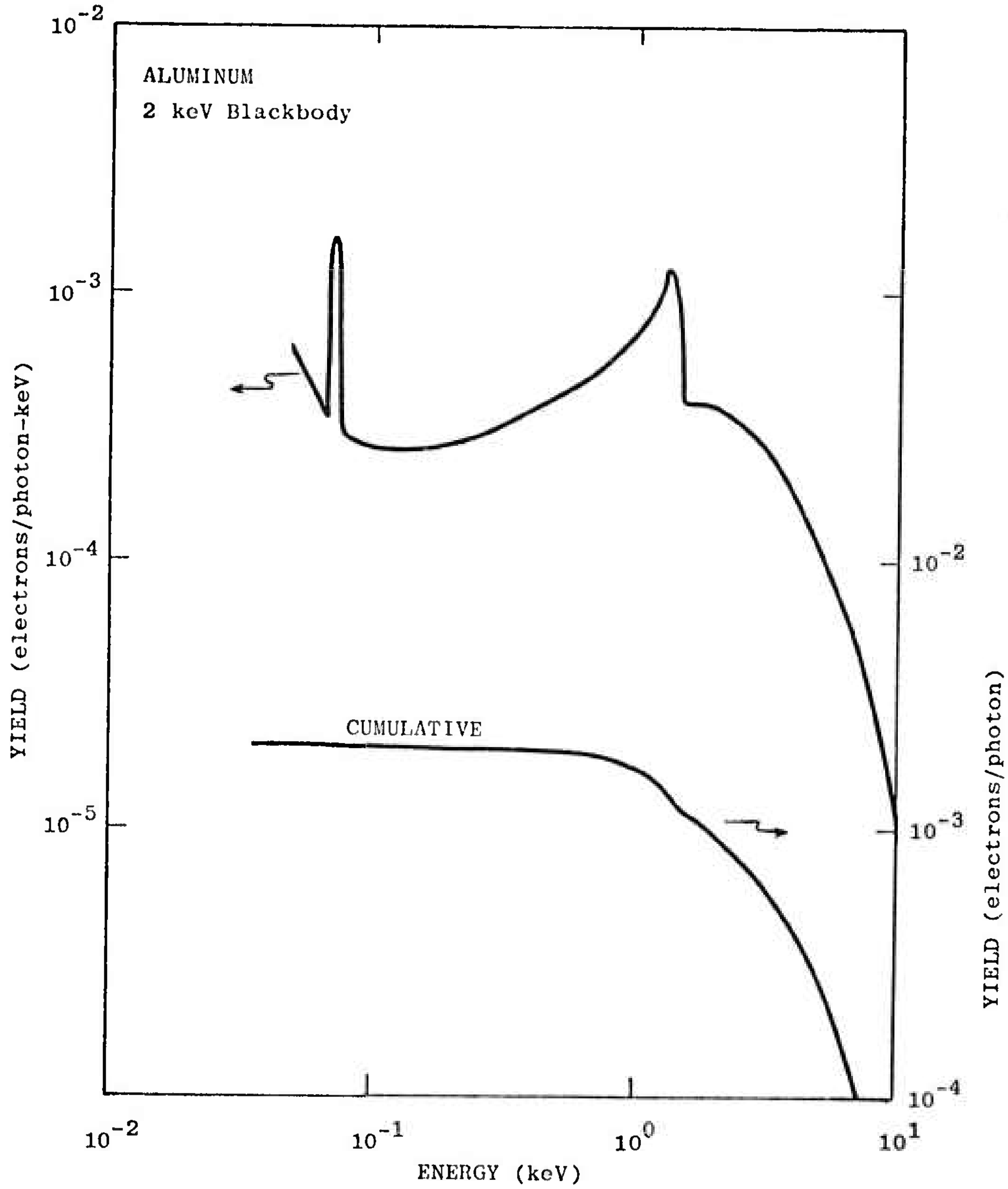

FIGURE 17. Back Yields for a 2 keV Blackbody Spectrum

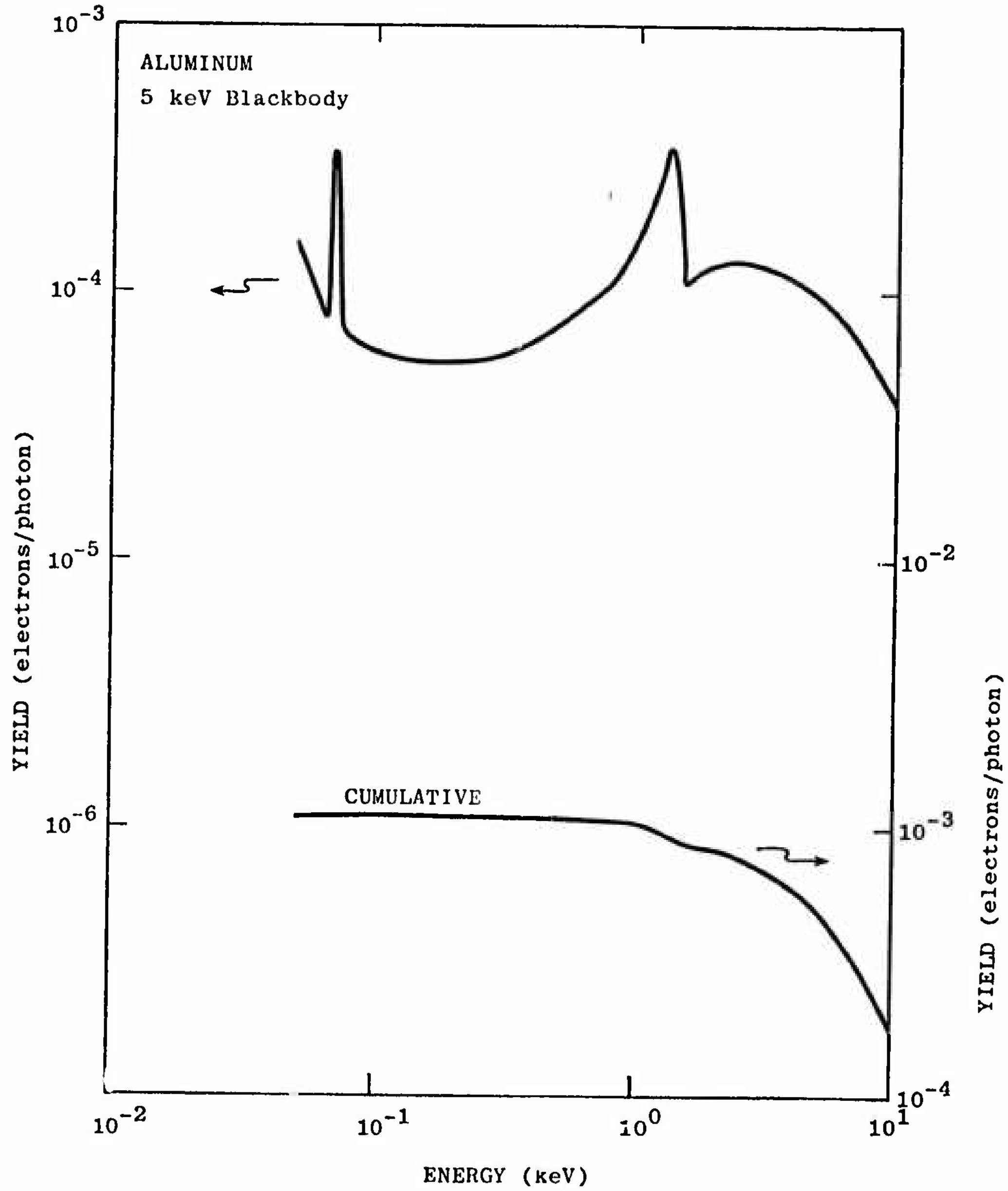

FIGURE 18. Back Yields for a 5 keV Blackbody Spectrum

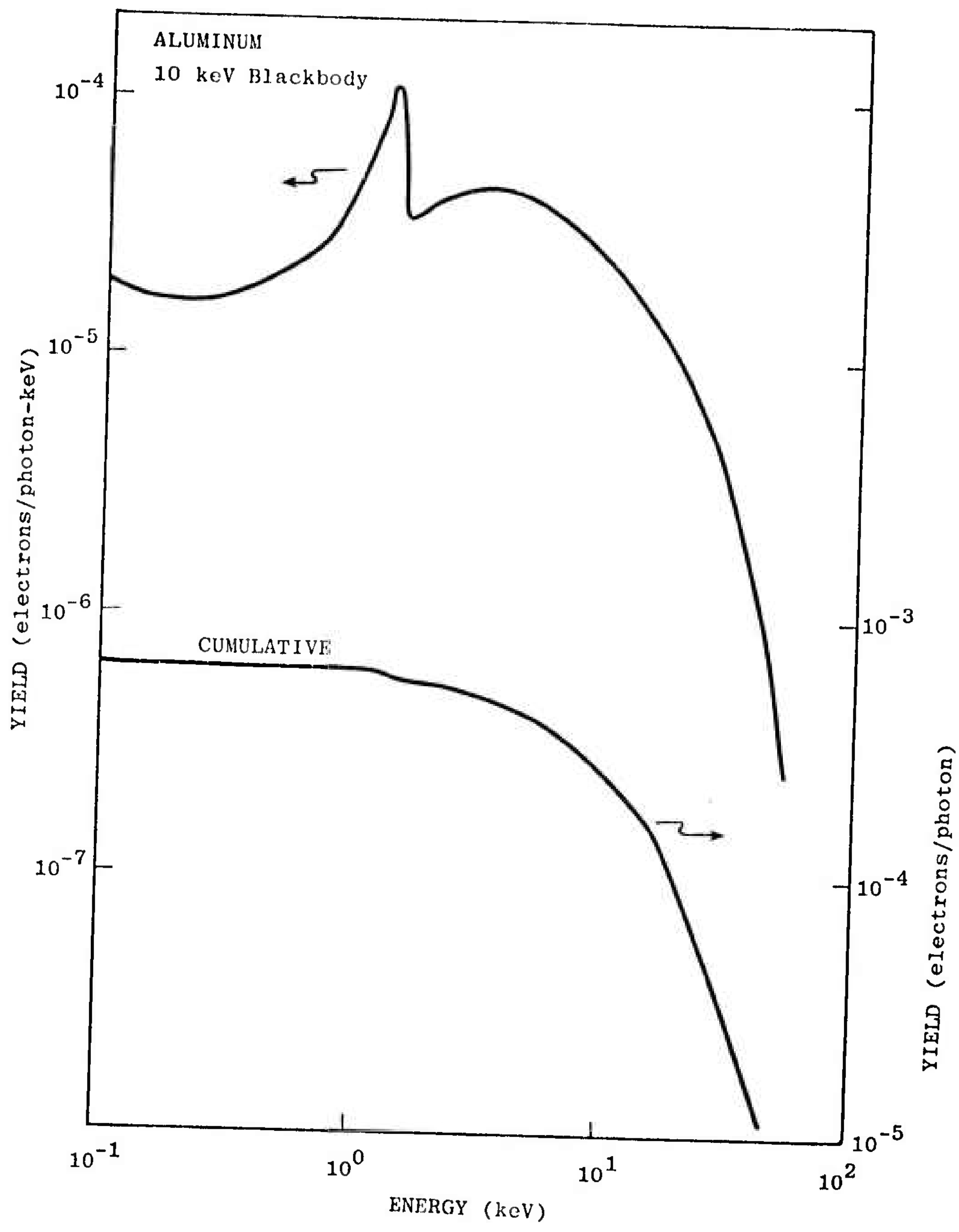

FIGURE 19. Back Yields for a 10 keV Blackbody Spectrum

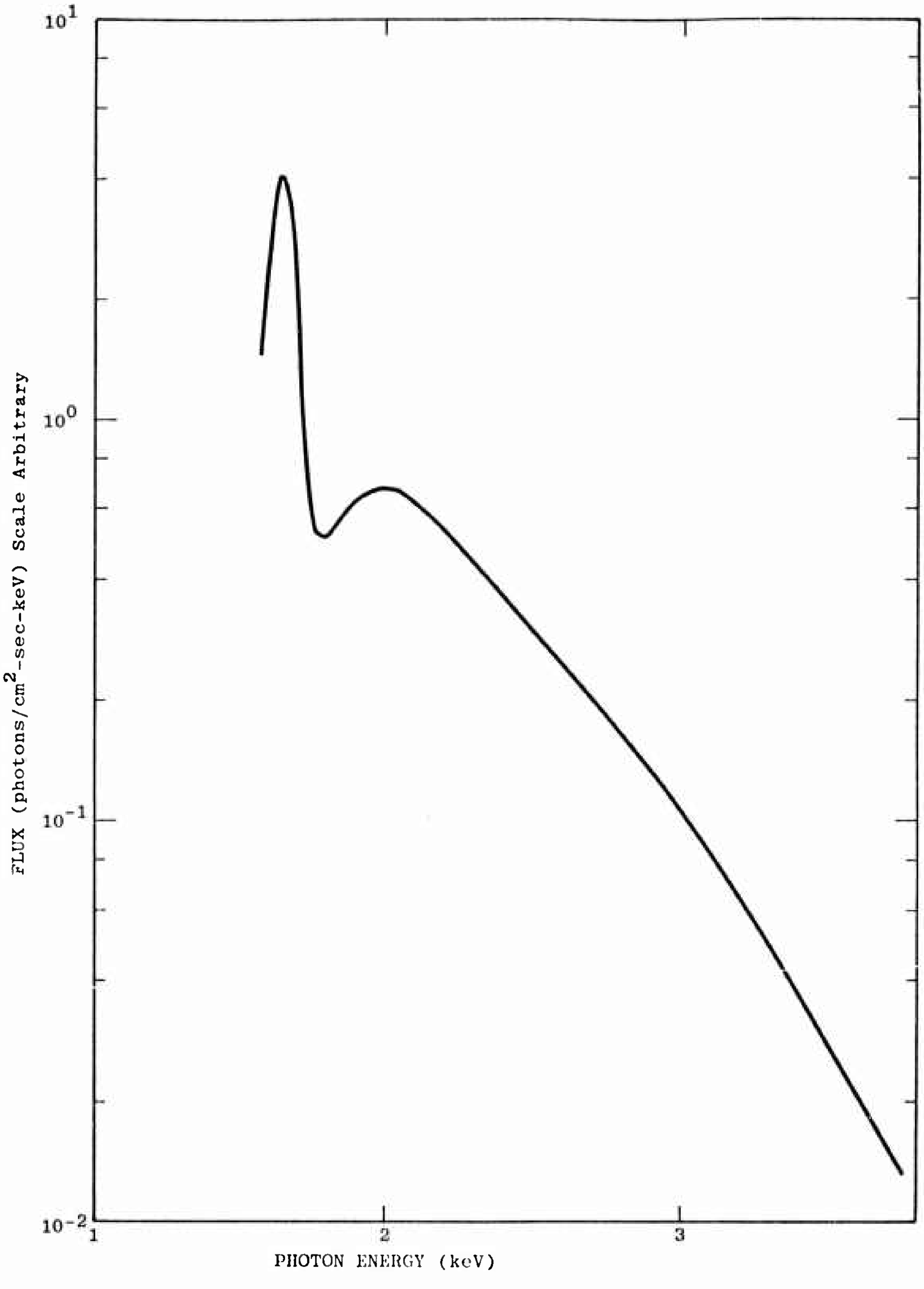

FIGURE 20. Representation of an Exploding Wire Radiation Source

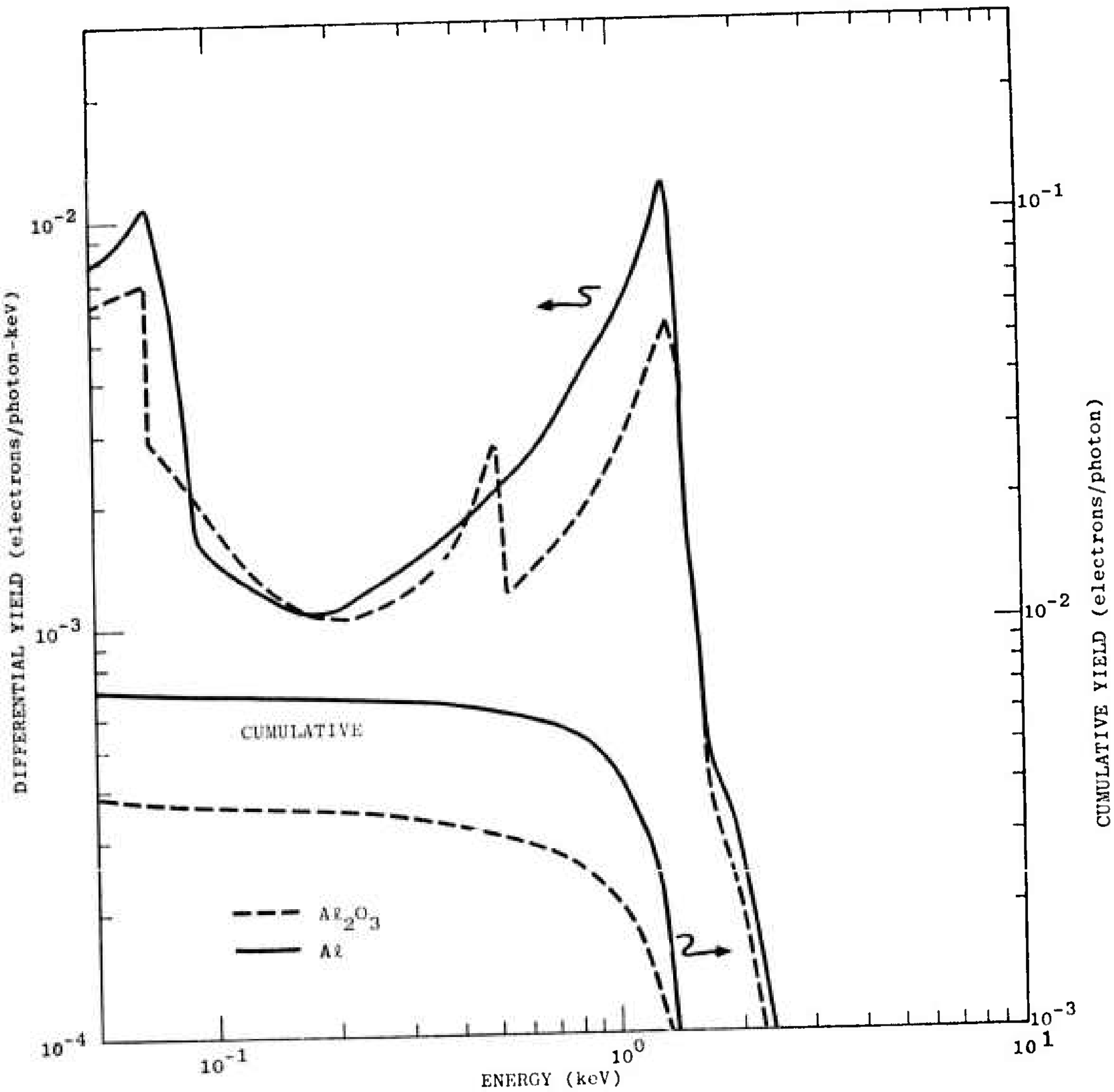

FIGURE 21. Exploding Wire Radiation Back Yields for $A\ell$ and $A\ell_2O_3$

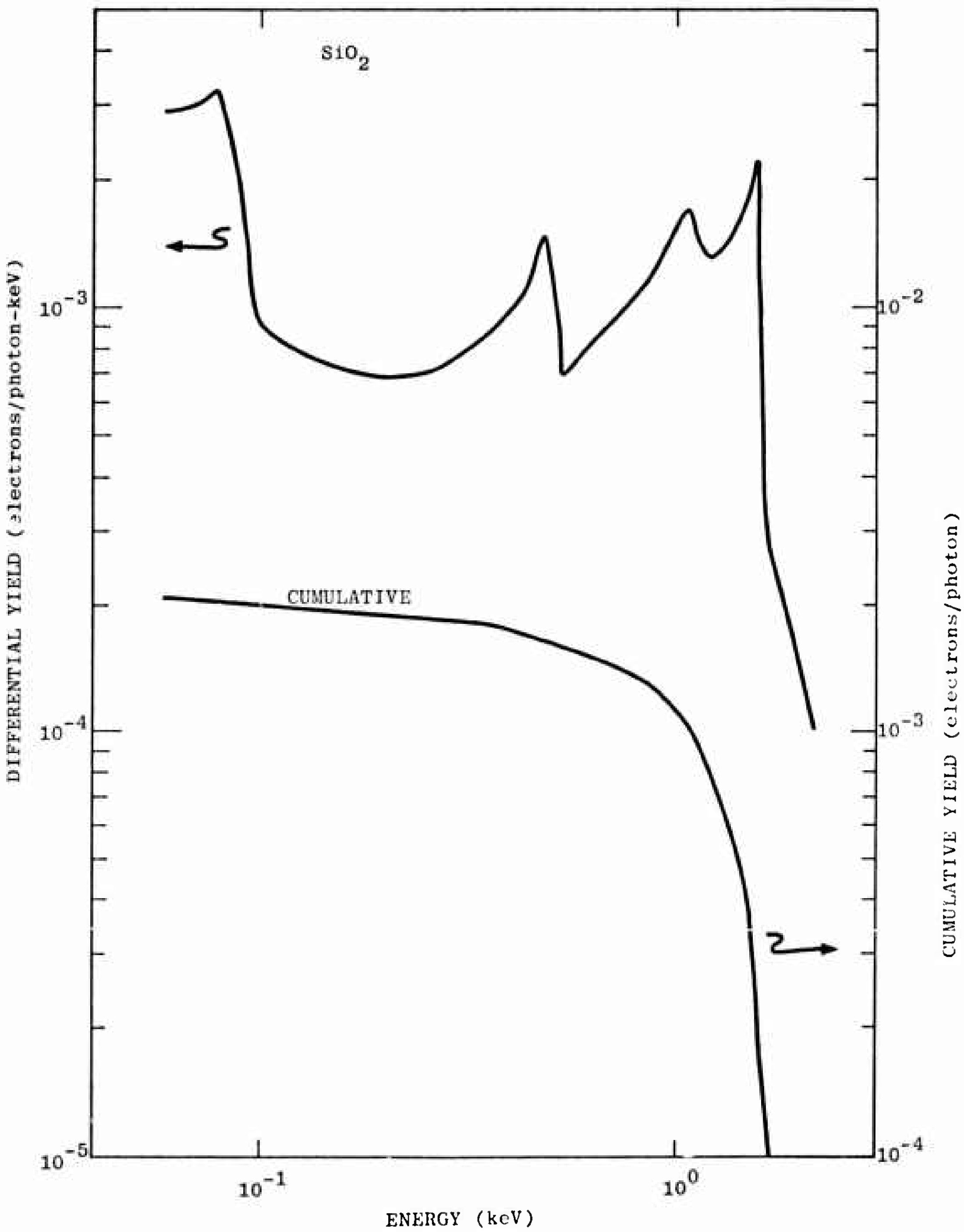

FIGURE 22. Exploding Wire Radiation Back Yields for SiO_2

DISTRIBUTION LIST

DEPARTMENT OF DEFENSE

Defense Communication Engineer Center
1860 Wiehle Ave
Reston, VA 22090
Attn: Code R320 C W Bergman
Attn: Code R410 J W McClean

Director
Defense Communications Agency
Washington DC 20305
Attn: Code 540.5
Attn: Code 930 M I Burgett Jr

Defense Documentation Center
Cameron Station
Alexandria VA 22314
Attn: TC

Director
Defense Intelligence Agency
Washington DC 20301
Attn: DS-4A2

Director
Defense Nuclear Agency
Washington DC 20305
Attn: TITL Tech Library
Attn: DDST
Attn: RAEV
Attn: STVL

Dir of Defense Rsch & Engineering
Department of Defense
Washington DC 20301
Attn: S&SS (OS)

Commander
Field Command
Defense Nuclear Agency
Kirtland AFB NM 87115
Attn: FCPR

Director
Interservice Nuclear Weapons School
Kirtland AFB NM 97115
Attn: Document Control

Director
Joint Strat Tgt Planning Staff JCS
Offutt AFB Omaha NB 68113
Attn: JLTW-2

Chief
Livermore Division Fld Command DNA
Lawrence Livermore Laboratory
P.O. Box 808
Livermore CA 94550
ATTN: FCPRL

Director
National Security Agency
Ft. George G. Meade MD 20755
Attn: O O Van Gunten R-425
Attn: TDL

DEPARTMENT OF ARMY

Project Manager
Army Tactical Data Systems
US Army Electronics Command
Fort Monmouth NJ 07703
Attn: DRCPN-TDS-SD
Attn: DWAINE B. Huewe

Commander
BMD System Command
P.O. Box 1500
Huntsville AL 35807
Attn: BDMSC-TEN Noah J. Hurst

Commander
Frankford Arsenal
Bridge and Tacony Sts
Philadelphia PA 19137
Attn: SARFA FCD/M. Elnick

Commander
Harry Diamond Laboratories
2800 Powder Mill Road
Adelphi MD 20783
Attn: J. Halpin
Attn: DRXDO-RB/J. R. Miletta
Attn: DRXDO-RCC/J. E. Thompkins
Attn: DRXDO-NP/F. N. Wimenitz
Attn: DRXDO-EM/R. Bostak
Attn: DRXDO-RC/R. B. Oswald Jr.
Attn: DRXDO-EM/R. E. McCoskey
Attn: DRXDO-TI/Tech Library
Attn: J. McGarrity

Commanding Officer
Night Vision Laboratory
U S Army Electronics Command
Fort Belvoir VA 22060
Attn: Capt. Allan S. Parker

Commander
Picatinny Arsenal
Dover NJ 07801
Attn: SMUPA-ND-D-B/E. J. Arber
Attn: SARPA-FR-F/L. Avrami
Attn: SMUPA-ND-N-E
Attn: SMUPA-FR-S-P
Attn: SARPA-ND-C-E/A. Nordio
Attn: SMUPA-ND-W

Commander
Redstone Scientific Information Center
US Army Missile Command
Redstone Arsenal AL 35809
Attn: Chief, Documents

Secretary of the Army
Washington DC 20310
Attn: ODUSA or D. Willard

Director
Trasana
White Sands Missile Range NM 88002
Attn: ATAA-EAC/F. N. Winans

Director
US Army Ballistic Research Labs
Aberdeen Proving Ground, MD 21005
Attn: DRXBR-VI/J. W. Kinch
Attn: DRXBR-VL/R. L. Harrison
Attn: DRXBR-AM/W. R. Vanantwerp
Attn: DRXRD-BVL/D. L. Riggoti

Chief
US Army Communications Systems Agency
Fort Monmouth NJ 07703
Attn: SCCM-AD-SV/Library

Commander
US Army Electronics Command
Fort Monmouth NJ 07703
Attn: DRSEL-TL-MD/G. K. Gaule
Attn: DRSEL-TL-IR/E. T. Hunter
Attn: DRSEL-CE/T. Preiffer
Attn: DRSEL-GG-TD/W. R. Werk
Attn: DRSEL-TL-ND/S. Kronenbey
Attn: DRSEL-PL-ENV/H. A. Bomke

Commandant
US Army Engineer School
Ft. Belvoir VA 22060
Attn: ATSE-CTD-CS/C. S. Grazier

Commander-in-Chief
US Army Europe & Seventh Army
APO New York 09403
(Heidelberg)
Attn: ODCSE-E AEAGE-PI

Commandant
US Army Field Artillery School
Fort Sill OK 73503
Attn: ATSFA-CTD-ME/H. Moberg

Commander
US Army Material Dev & Readiness CMD
5001 Eisenhower Ave
Alexandria VA 22333
Attn: DRCDE-d/L. Flynn

Commander
US Army Missile Command
Redstone Arsenal AL 35809
Attn: DRSMI-RGD/V. Ruwe
Attn: DRSMI-RRR/F. P. Gibson
Attn: DRCPM-PE-EA/W. O. Wagner

Chief
US Army Nuc & Chemical Surety GP
Bldg 2073, North Area
Ft Belvoir VA 22060
Attn: MOSG-ND/Maj. S. W. Winslow

Commander
US Army Nuclear Agency
7500 Backlick Road
Building 2073
Springfield VA 22150
Attn: ATCN-W/Ltc. L. A. Sluga

Commander
US Army Tank Automotive Command
Warren MI 48090
Attn: DRCPM-GCM-SW/L. A. Wolcott

Commander
White Sands Missile Range
White Sands Missile Range NM 88002
Attn: STEWS-TE-NT/M. P. Squires

DEPARTMENT OF NAVY

Chief of Naval Research
Navy Department
Arlington VA 22217
Attn: Code 427

Commander Officer
Naval Avionics Facility
21st & Arlington Ave
Indianapolis IN 46218
Attn: Branch 942/D. J. Repass

Commander
Naval Electronic Systems Command Hqs
Washington DC 20360
Attn: Code 5032/C. W. Neill
Attn: Code 504511/C. R. Suman
Attn: Code 50451
Attn: PME 117-21
Attn: ELEX 05323/C. F. Watkins

Commanding Officer
Naval Intelligence Support Ctr
4301 Suitland Road, Bldg. 5
Washington DC 20390
Attn: NISC-45

Director
Naval Research Laboratory
Washington, DC 20375
Attn: Code 4004/E. L. Brancato
Attn: Code 2627/D. R. Folen
Attn: Code 5210/J. E. Davey
Attn: Code 6440/G. Sigel
Attn: Code 601/E. Wolicki
Attn: Code 6631/J. C. Ritter
Attn: Code 5216/H. L. Hughes
Attn: Code 7701/J. D. Brown

Commander
Naval Sea Systems Command
Navy Department
Washington DC 20362
Attn: SEA-9931/R. B. Lane
Attn: SEA-9931/S. A. Barham

Officer-in-Charge
Naval Surface Weapons Center
White Oak, Silver Spring, MD 20910
Attn: Code WA52/R. A. Smith
Attn: Code WA501/Navy Nuc Prgms Off
Attn: Code WA50

Commander
Naval Weapons Center
China Lake CA 93555
Attn: Code 533 Tech Library

Commanding Officer
Naval Weapons Evaluation Facility
Kirtland AFB Albuquerque NM 87117
Attn: Code ATG/Mr. Stanley

Commanding Officer
Naval Weapons Support Center
Crane, IN 47522
Attn: Code 7024/J. Ramsey
Attn: Code 70242/J. A. Munarin

Commanding Officer
Nuclear Weapons TNG Center Pacific
Naval Air Station, North Island
San Diego CA 92135
Attn: Code 50

Director
Strategic Systems Project Office
Navy Department
Washington DC 20376
Attn: SP 2701/J. W. Pitsenberger
Attn: NSP-2342/R. L. Coleman
Attn: NSP-27331/P. Spector

DEPARTMENT OF THE AIR FORCE

RADC/Deputy for Electronic Technology
Hanscom AFB MA 01731
Attn: ET/Stop 30/E. Cormier
Attn: ES/Stop 30/F. Shepherd
Attn: ES/Stop 30/E. A. Burke

AF Institute of Technology, AU
Wright-Patterson AFB OH 45433
Attn: ENP/C. J. Bridgman

AF Materials Laboratory, AFSC
Wright-Patterson AFB OH 45433
Attn: LTE

AF Weapons Laboratory, AFSC
Kirtland AFB NM 87117
Attn: ELS
Attn: ELA
Attn: ELP Tree Section
Attn: ELP/J. Nichols
Attn: NTS
Attn: ELXT
Attn: DEX

AFTAC
Patrick AFB FL 32925
Attn: TFS/Maj. M. F. Schneider

AF Avionics Laboratory, AFSC
Wright-Patterson AFB OH 45433
Attn: DHE/H. J. Hennecke
Attn: DHM/C. Friend
Attn: DH/Ltc. McKenzie
Attn: AAT/M. Friar

Commander
ASD
Wright-Patterson AFB OH 45433
Attn: ASD/ENESS/P. T. Marth
Attn: ASD-YH-EX/Ltc. R. Leverette
Attn: ENACC/R. L. Fish

Hq ESD
Hanscom AFB MA 01731
Attn: YSEV

Hq ESD
Hanscom AFB MA 01731
Attn: YWET

Commander
Foreign Technology Division, AFSC
Wright-Patterson AFB OH 45433
Attn: FTDP

Commander
Rome Air Development Center, AFSC
Griffiss AFB NY 13440
Attn: RBRP/C. Lane
Attn: RBRAC/T. L. Krulac

Commander
RADC/Deputy for Electronic Technology
Hanscom AFB MA 01731
Attn: ES/A. Kahan
Attn: ES/B. Buchanan
Attn: ES/R. Dolan

SAMSO/DY
Post Office Box 92960
Worldway Postal Center
Los Angeles CA 90009
Attn: DYS/Capt. E. Merz

SAMSO/IN
Post Office Box 92960
Worldway Postal Center
Los Angeles CA 90009
Attn: IND/I. J. Judy

SAMSO/MN
Norton AFB CA 92409
Attn: MNNH

SAMSO/RS
Post Office BOX 92960
Worldway Postal Center
Los Angeles CA 90009
Attn: RSMG/Capt. Collier
Attn: RSSE/Ltc. K. L. Gilbert

SAMSO/SK
Post Office Box 92960
Worldway Postal Center
Los Angeles CA 90009
Attn: SKF/P. H. Stadler

SAMSO/SZ
Post Office Box 92960
Worldway Postal Center
Los Angeles CA 90009
Attn: SZJ/Capt. J. H. Salch

Commander in Chief
Strategic Air Command
Offutt AFB NB 68113
Attn: XPFS/Maj. B. G. Stephan
Attn: NRI-STINFO Library

US ENERGY RSCH & DEV ADMIN

University of California
Lawrence Livermore Laboratory
P.O. Box 808
Livermore CA 94550
Attn: L. Cleland/L-156
Attn: R. L. Ott/L-531
Attn: Tech Info Dept/L-3
Attn: H. Kruger/L-96
Attn: J. E. Keller Jr./L-125

Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos NM 87545
Attn: Doc Con for B. W. Noel
Attn: Doc Con for J. A. Freed

SANDIA Laboratories
P.O. Box 5800
Albuquerque NM 87115
Attn: Doc Con for Org 2110/J A Hood
Attn: Doc Con for 3141 Sandia Rpt Coll
Attn: Doc Con for Org 2140/R. Gregory

US Energy Research & Dev Admin
Albuquerque Operations Office
P. O. Box 5400
Albuquerque NM 87115
Attn: Doc Con for WSSB

OTHER GOVERNMENT

Department of Commerce
National Bureau of Standards
Washington, DC 20234
Attn: Judson C. French

DEPARTMENT OF DEFENSE
CONTRACTORS

Aerojet Electro-Systems Co.
Div of Aerojet-General Corp.
P. O. Box 296, 1100 W. Hollyvale Dr
Azusa, CA 91702
Attn: T. D. Hanscome

Aerospace Corp.
P. O. Box 92957
Los Angeles CA 90009
Attn: John Ditre
Attn: Irving M. Garfunkel
Attn: S. P. Bower
Attn: Julian Reinheimer
Attn: L. W. Aukerman
Attn: Library
Attn: William W. Willis

Analog Technology Corp.
3410 East Foothill Boulevard
Pasadena CA 91107
Attn: J. J. Baum

AVCO Research & Systems Group
201 Lowell St
Wilmington MA 01887
Attn: Research Lib/A830 Rm 7201

BDM Corp.
7915 Jones Branch Drive
McClean VA 22101
Attn: T. H. Neighbors

BDM Corporation
P O Box 9274
Albuquerque International
Albuquerque NM 87119
Attn: D. R. Alexander

Bendix Corp.
Communication Division
Fast Joppa Road
Baltimore MD 21204
Attn: Document Control

Bendix Corp.
Research Laboratories Division
Bendix Center
Southfield MI 48075
Attn: Mgr Prgm Dev/D. J. Niehaus
Attn: Max Frank

Boeing Company
P. O. Box 3707
Seattle, WA 98124
Attn: H. W. Wicklein/MS 17-11
Attn: Itsu Amura/2R-00
Attn: Aerospace Library
Attn: R. S. Caldwell/2R-00
Attn: Carl Rosenberg/2R-00

Booz-Allen and Hamilton, Inc.
106 Apple Street
Tinton Falls NJ 07724
Attn: Raymond J. Chrisner

California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena CA 91103
Attn: J. Bryden
Attn: A. G. Stanley

Charles Stark Draper Laboratory Inc.
555 Technology Square
Cambridge MA 02139
Attn: Kenneth Fertig
Attn: Paul R. Kelly

Cincinnati Electronics Corp.
2630 Glendale - Milford Road
Cincinnati OH 45241
Attn: Lois Hammond
Attn: C. R. Stump

Control Data Corporation
P. O. Box 0
Minneapolis, MN 55440
Attn: Jack Meehan

Cutler-Hammer, Inc.
AIL Division
Comac Road
Deer Park NY 11729
Attn: Central Tech Files/A. Anthony

Dikewood Industries, Inc.
1009 Bradbury Drive, S. E.
Albuquerque, NM 87106
Attn: L. Wayne Davis

E-Systems, Inc.
Greenville Division
P.O. Box 1056
Greenville TX 75401
Attn: Library 8-50100

Effects Technology, Inc.
5383 Hollister Avenue
Santa Barbara CA 93111
Attn: Edward J. Steele

Exp & Math Physics Consultants
P.O. Box 66331
Los Angeles CA 90066
Attn: Thomas M. Jordan

Fairchild Camera & Instrument Corp.
464 Ellis St
Mountain View CA 94040
Attn: Sec Dept for 2-233 D. K. Myers

Fairchild Industries, Inc.
Sherman Fairchild Technology Center
20301 Century Boulevard
Germantown, MD 20767
Attn: Mgr Config Data & Standards

Florida, University of
P.O. Box 284
Gainesville FL 32601
Attn: Patricia B. Rambo
Attn: D. P. Kennedy

Ford Aerospace & Communications Corp.
3939 Fabian Way
Palo Alto, CA 94303
Attn: Edward R. Hahn/MS-X22
Attn: Donald R. McMorrow/MS-G30
Attn: Samuel R. Crawford/MS-531

Ford Aerospace & Comm Operations
Ford & Jamboree Roads
Newport Beach CA 92663
Attn: F. R. Poncelet Jr.
Attn: Ken C. Attinger
Attn: Tech Info Section

Franklin Institute, The
20th St and Parkway
Philadelphia PA 19103
Attn: Ramie H. Thompson

Garrett Corporation
P.O. Box 92248, 9851 Sepulveda Blvd
Los Angeles CA 90009
Attn: Robert E. Weir/Dept 93-9

General Dynamics Corp.
Electronics Div Orlando Operations
P.O. Box 2566
Orlando, FL 32802
Attn: D. W. Coleman

General Electric Company
Space Division
Valley Forge Space Center
Goddard Blvd King of Prussia
P.O. Box 8555
Philadelphia PA 19101
Attn: Larry I. Chasen
Attn: John L. Andrews
Attn: Joseph C. Peden/VFSC, Rm. 4230M

General Electric Company
Re-Entry & Environmental Systems Div
P.O. Box 7722
3198 Chestnut St
Philadelphia, PA 19101
Attn: Robert V. Benedict
Attn: John W. Palchefsky Jr.
Attn: Ray E. Anderson

General Electric Company
Ordnance Systems
100 Plastics Ave.
Pittsfield MA 01201
Attn: Joseph J. Reidl

General Electric Company
Tempo-Center for Advanced Studies
816 State St (P O Drawer QQ)
Santa Barbara CA 93102
Attn: Royden R. Rutherford
Attn: DASIAC
Attn: M. Espig

General Electric Company
Aircraft Engine Business Group
Evendale Plant Int Hwy 75 S
Cincinnati OH 45215
Attn: John A. Ellerhorst E2

General Electric Company
Aerospace Electronics Systems
French Road
Utica NY 13503
Attn: Charles M. Hewison/Drop 624
Attn: W. J. Patterson/Drop 233

General Electric Company
P.O. Box 5000
Binghamton NY 13902
Attn: David W. Pepin/Drop 160

General Electric Company-Tempo
c/o Defense Nuclear Agency
Washington DC 20305
Attn: DASIAC
Attn: William Alfonte

General Research Corporation
P.O. Box 3587
Santa Barbara CA 93105
Attn: Robert D. Hill

Georgia Institute of Technology
Georgia Tech Research Institute
Atlanta GA 30332
Attn: R. Curry

Grumman Aerospace Corporation
South Oyster Bay Road
Bethpage NY 11714
Attn: Jerry Rogers/Dept 533

GTE Sylvania, Inc.
Electronics Systems GRP-Eastern Div
77 A St
Needham MA 02194
Attn: Charles A. Thornhill, Librarian
Attn: James A. Waldon
Attn: Leonard L. Blaisdell

GTE Sylvania, Inc.
189 B St
Needham Heights MA 02194
Attn: Paul B. Fredrickson
Attn: Herbert A. Ullman
Attn: H & V Group
Attn: Charles H. Ramsbottom

Gulton Industries, Inc.
Engineered Magnetics Division
13041 Cerise Ave
Hawthorne CA 90250
Attn: Engnmagnetics Div

Harris Corp.
Harris Semiconductor Division
P. O. Box 883
Melbourne, FL 32901
Attn: Wayne E. Abare/MS 16-111
Attn: Carl F. Davis/MS 17-220
Attn: T. L. Clark/MS 4040

Hazeltine Corp.
Pulaski Rd
Greenlawn, NY 11740
Attn: Tech Info Ctr/M. Waite

Honeywell Inc.
Avionics Division
2600 Ridgeway Parkway
Minneapolis, MN 55413
Attn: Ronald R. Johnson/A1622
Attn: R. J. Kell/MS S2572

Honeywell Inc.
Avionics Division
13350 U.S. Highway 19 North
St. Petersburg, FL 33733
Attn: H. H. Noble/MS 725-5A
Attn: S. H. Graaff/MS 725-J

Honeywell Inc.
Radiation Center
2 Forbes Road
Lexington, MA 02173
Attn: Technical Library

Hughes Aircraft Company
Centinela and Teale
Culver City CA 90230
Attn: Dan Binder/MS 6-D147
Attn: Billy W. Campbell/MS 6-E-110
Attn: Kenneth R. Walker/MS D157
Attn: John B. Singletary/MS 6-D133

Hughes Aircraft Co, El Segundo Site
P.O. Box 92919
Los Angeles CA 90009
Attn: William W. Scott/MS A1080
Attn: Edward C. Smith/MS A620

IBM Corporation
Route 17C
Owego, NY 13827
Attn: Frank Frankovsky
Attn: Harry W. Mathers/Dept M41

Intl Tel & Telegraph Corp
500 Washington Ave
Nutley NJ 07110
Attn: Alexander T. Richardson

Ion Physics Corp.
South Bedford St
Burlington, MA 01803
Attn: Robert D. Evans

IRT Corp.
P. O. Box 81087
San Diego, CA 92138
Attn: MDC
Attn: Leo D. Cotter
Attn: R. L. Mertz

JAYCOR
205 S. Whitting St, Suite 500
Alexandria, VA 22304
Attn: Catherine Turesko
Attn: Robert Sullivan

Johns Hopkins University
Applied Physics Laboratory
Johns Hopkins Road
Laurel MD 20810
Attn: Peter E. Partridge

Kaman Sciences Corp.
P.O. Box 7463
Colorado Springs, CO 80933
Attn: Jerry I. Lubell
Attn: Walter E. Ware
Attn: John R. Hoffman
Attn: Donald H. Bryce
Attn: Albert P. Bridges

Litton Systems, Inc.
Guidance & Control Systems Division
5500 Canoga Ave
Woodland Hills, CA 91364
Attn: John P. Retzler
Attn: Val J. Ashby/MS 67

Litton Systems, Inc.
Electron Tube Division
1035 Westminster Drive
Williamsport, PA 17701
Attn: Frank J. McCarthy

Lockheed Missiles & Space Co. Inc.
P. O. Box 504
Sunnyvale, CA 94088
Attn: B. T. Kimura/Dept 81-14
Attn: E. A. Smith/Dept 85-85
Attn: George F. Heath/Dept 81-14
Attn: Samuel I. Taimuty/Dept 85-85
Attn: L. Rossi/Dept 81-64

Lockheed Missiles and Space Co. Inc.
3251 Hanover St
Palo Alto, CA 94304
Attn: Tech Info Ctr D/Coll

M. I. T. Lincoln Laboratory
P. O. Box 73
Lexington MA 02173
Attn: Leona Loughlin, Librarian A-082

Martin Marietta Aerospace
Orlando Division
P. O. Box 5837
Orlando, FL 32805
Attn: Jack M. Ashford/MP 537
Attn: William W. Mras/MP 413
Attn: Mona C. Griffith/Lib MP-30

Martin Marietta Corp.
Denver Division
P. O. Box 179
Denver, CO 80201
Attn: Paul G. Kase/Mail 8203
Attn: Research Lib 6617 J. R. McKee
Attn: J. E. Goodwin/Mail 0452
Attn: B. T. Graham/MS PO-454

McDonnell Douglas Corp.
P O Box 516
St Louis, Missouri 63166
Attn: Tom Ender
Attn: Technical Library

McDonnell Douglas Corp.
5301 Bolsa Ave
Huntington Beach, CA 92647
Attn: Stanley Schneider

McDonnell Douglas Corp.
3855 Lakewood Boulevard
Long Beach, CA 90846
Attn: Technical Library, C1-290/36-84

Mission Research Corp.
735 State St
Santa Barbara, CA 93101
Attn: William C. Hart

Mission Research Corp. -San Diego
P. O. Box 1209
La Jolla, CA 92038
Attn: V. A. J. Van Lint
Attn: J. P. Raymond

The MITRE Corp.
P. O. Box 208
Bedford, MA 01730
Attn: M. E. Fitzgerald
Attn: Library

National Academy of Sciences
2101 Constitution Ave, NW
Washington DC 20418
Attn: National Materials Advisory Board
Attn: R. S. Shane, Nat Materials Advsy

University of New Mexico
Electrical Engineering & Computer
Science Dept
Albuquerque, NM 87131
Attn: Harold Southward

Northrop Corp.
Electronic Division
1 Research Park
Palos Verdes Peninsula, CA 90274
Attn: George H. Towner
Attn: Boyce T. Ahlport

Northrop Corp.
Northrop Research & Technology Ctr
3401 West Broadway
Hawthorne, CA 90250
Attn: Orlie L. Curtis, Jr.
Attn: David N. Pocock
Attn:. J. R. Srour

Northrop Corp.
Electronic Division
2301 West 120th St
Hawthorne, CA 90250
Attn: Vincent R. DeMartino
Attn: Joseph D. Russo
Attn: John M. Reynolds

Palisades Inst for Rsch Services Inc
201 Varick St
New York, NY 10014
Attn: Records Supervisor

Physics International Co.
2700 Merced St
San Leandro, CA 94577
Attn: Doc Con for C. H. Stallings

R&D Associates
P. O. Box 9695
Marina Del Rey CA 90291
Attn: S. Clay Rogers

Raytheon Company
Hartwell Road
Bedford, MA 01730
Attn: Gajanan H. Joshi, Radar Sys Lab

Raytheon Company
528 Boston Post Road
Sudbury, MA 01776
Attn: Harold L. Flescher

RCA Corp.
Government Systems Division
Astro Electronics
P. O. Box 800, Locust Corner
Fast Windsor Township
Princeton, NJ 08540
Attn: George J. Brucker

RCA Corporation
Camden Complex
Front & Cooper Sts
Camden, NJ 08012
Attn: E. Van Keuren 13-5-2

Rensselaer Polytechnic Institute
P. O. Box 965
Troy, NY 12181
Attn: Ronald J. Gutmann

Research Triangle Institute
P. O. Box 12194
Research Triangle Park, NC 27709
Attn: Eng Div Mayrant Simons Jr.

Rockwell International Corp.
P. O. Box 3105
Anaheim, CA 92803
Attn: George C. Messenger FB61
Attn: Donald J. Stevens FA70
Attn: K. F. Hull
Attn: N. J. Rudie FA53

Rockwell International Corporation
5701 West Imperial Highway
Los Angeles, CA 90009
Attn: T. B. Yates

Rockwell International Corporation
Collins Divisions
400 Collins Road NE
Cedar Rapids, IA 52406
Attn: Dennis Sutherland
Attn: Alan A. Langenfeld
Attn: Mildred A. Blair

Sanders Associates, Inc.
95 Canal St
Nashua, NH 03060
Attn: Moe L. Aitel NCA 1 3236

Science Applications, Inc.
P.O. Box 2351
La Jolla, CA 92038
Attn: J. Robert Beyster
Attn: Larry Scott

Science Applications, Inc.
Huntsville Division
2109 W. Clinton Ave
Suite 700
Huntsville, AL 35805
Attn: Noel R. Byrn

Singer Company (Data Systems)
150 Totowa Road
Wayne, NJ 07470
Attn: Tech Info Center

Sperry Flight Systems Division
Sperry Rand Corp.
P. O. Box 21111
Phoenix, AZ 85036
Attn: Charles L. Craig EV
Attn: Paul Maraffino

Sperry Univac
Univac Park, P.O. Box 3535
St. Paul, MN 55165
Attn: James A. Inda/MS 41T25

Stanford Research Institute
333 Ravenswood Ave
Menlo Park, CA 94025
Attn: Philip J. Dolan

Stanford Research Institute
306 Wynn Drive, N.W.
Huntsville, AL 35805
Attn: MacPherson Morgan

Sundstrand Corp.
4751 Harrison Ave.
Rockford, IL 61101
Attn: Curtis B. White

Systron-Donner Corp.
1090 San Miguel Road
Concord, CA 94518
Attn: Gordon B. Dean
Attn: Harold D. Morris

Texas Instruments, Inc.
P. O. Box 5474
Dallas, TX 75222
Attn: Donald J. Manus/MS 72

Texas Tech University
P.O. Box 5404 North College Station
Lubbock, TX 79417
Attn: Travis L. Simpson

TRW Defense & Space Sys Group
One Space Park
Redondo Beach CA 90278
Attn: Robert M. Webb R1 2410
Attn: Tech Info Center/S1930
Attn: O. E. Adams R1-2036
Attn: R. K. Plebuch R1-2078

TRW Defense & Space Sys Group
San Bernardino Operations
P.O. Box 1310
San Bernardino, CA 92402
Attn: F. B. Fay
Attn: R. Kitter

United Technologies Corp.
Hamilton Standard Division
Bradley International Airport
Windsor Locks, CT 06069
Attn: Raymond G. Gibuere

Vought Corp.
P.O. Box 5907
Dallas, TX 75222
Attn: Technical Data Ctr

ADDITIONAL DISTRIBUTION LIST

Hanscom AFB MA 01731
Attn: AFGL/SUSRP/Stop 30
Attn: AFGL/CC/Stop 30
Attn: AFGL/SUOL/Stop 20
Attn: ESD/XR/Stop 30
Attn: ESD/XR/Stop 30/D. Brick
Attn: DCD/SATIN IV
Attn: MCAE/Lt. Col. D. Sparks
Attn: ES/Stop 30
Attn: EE/Stop 30

Griffiss AFB NY 13441
Attn: RADC/OC
Attn: RADC/IS
Attn: RADC/DC
Attn: RADC/RB
Attn: RADC/IR
Attn: RADC/CA
Attn: RADC/TIR
Attn: RADC/DAP
Attn: RADC/TILD

Maxwell AFB AL 36112
Attn: AUL/LSE-67-342

US Army Missile Command Labs
Redstone Scientific Information Ctr.
Redstone Arsenal, AL 35809
Attn: Chief, Documents

SAMSO (YA/AT)
P. O. Box 92960
Worldway Postal Center
Los Angeles, CA 90009
Attn: Mr. Hess

Naval Postgraduate School
Superintendent
Monterey, CA 93940
Attn: Library (Code 2124)

U. S. Dept. of Commerce
Boulder Laboratories
Boulder CO 80302
Attn: Library/NOAA/ERL

USAF Academy
Library
Colorado 80840
Attn: 80840

Eglin AFB FL 32542
Attn: ADTC/DLOSL

Scott AFB IL 62225
Attn: AWS/DNTI/Stop 400

NASA Scientific & Technical
Information Facility
P. O. Box 33
College Park, MD 20740

NASA Goddard Space Flight Center
Goddard Space Flight Center
Greenbelt, MD 20771
Attn: Technical Library, Code 252,
Bldg. 21

Naval Surface Weapons Center
White Oak Lab.
Silver Spring, MD 20910
Attn: Library Code 730, RM 1-321

US Naval Missile Center
Point Mugu, CA 93041
Attn: Tech. Library - Code NO322

NASA Johnson Space Center
Attn: JM6, Technical Library
Houston, TX 77058

NASA
Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135
Attn: Technical Library

Wright-Patterson AFB OH 45433
Attn: AFAL/CA
Attn: AFIT/LD, Bldg. 640, Area B
Attn: ASD/ASFR
Attn: ASD/FTD/ETID

Defense Communications Engineering
Center
1860 Wiehls Ave
Reston, VA 22090
Attn: Code R103R

Director, Technical Information
DARPA
1400 Wilson Blvd.
Arlington, VA 22209

Department of the Navy
800 North Quincy St
Arlington VA 22217
Attn: ONRL Documents, Code 102IP

SAMSO
P. O. Box 92960
Worldway Postal Center
Los Angeles, CA 9000[illegible]
Attn. Lt. Col. Staubs

US Army Electronics Command
Fort Monmouth, NJ 07703
Attn: AMSEL-GG-TD

Kirtland AFB NM 87117
Attn: AFWL/SUL Technical Library

US Naval Weapons Center
China Lake, CA 93555
Attn: Technical Library

Los Alamos Scientific Lab.
P. O. Box 1663
Los Alamos, NM 87544
Attn: Report Library

Hq DNA
Washington DC 20305
Attn: Technical Library

Secretary of the Air Force
Washington DC 20330
Attn: SAFRD

Scott AFB IL 62225
Attn: ETAC/CB/Stop 825

Andrews AFB
Washington DC 20334
Attn: AFSC/DLC

Army Material Command
Washington DC 20315
Attn: AMCRD

NASA Langley Research Center
Langley Station
Hampton, VA 23365
Attn: Technical Library/MS 185

NASA
Washington DC 20546
Attn: Library (KSA -10)

Andrews AFB
Washington, D.C. 20334
Attn: AFSC/DLS

AFOSR, Bldg. 410
Bolling AFB Washington DC 20332
Attn: CC

AFML
Wright Patterson AFB OH 45433

The Pentagon
Room 3-D-139
Washington, D.C. 20301
Attn: ODDR&E - OSD (Library)

ONR (Library)
Washington, D.C. 20360

Defense Intelligence Agency
Washington, D.C. 20301
Attn: SO-3A

AFAL
Wright-Patterson AFB OH 45433
Attn: WRA 1/Library
Attn: TSR-5/Technical Library

Advisory Group on Electron Devices
201 Varick St, 9th Floor
New York, NY 10014

White Sands Missile Range, NM 88002
Attn: STEWS-AD-L/Technical Library

University of New Mexico
Dept of Campus Security & Police
1821 Roma, NE
Albuquerque, NM 87106
Attn: D. Neaman

METRIC SYSTEM

BASE UNITS:

Quantity	Unit	SI Symbol	Formula
length	metre	m	...
mass	kilogram	kg	...
time	second	s	...
electric current	ampere	A	...
thermodynamic temperature	kelvin	K	...
amount of substance	mole	mol	...
luminous intensity	candela	cd	...

SUPPLEMENTARY UNITS:

Quantity	Unit	SI Symbol	Formula
plane angle	radian	rad	...
solid angle	steradian	sr	...

DERIVED UNITS:

Quantity	Unit	SI Symbol	Formula
Acceleration	metre per second squared	...	m/s
activity (of a radioactive source)	disintegration per second	...	(disintegration)/s
angular acceleration	radian per second squared	...	rad/s
angular velocity	radian per second	...	rad/s
area	square metre	...	m
density	kilogram per cubic metre	...	kg/m
electric capacitance	farad	F	A·s/V
electrical conductance	siemens	S	A/V
electric field strength	volt per metre	...	V/m
electric inductance	henry	H	V·s/A
electric potential difference	volt	V	W/A
electric resistance	ohm		V/A
electromotive force	volt	V	W/A
energy	joule	J	N·m
entropy	joule per kelvin	...	J/K
force	newton	N	kg·m/s
frequency	hertz	Hz	(cycle)/s
illuminance	lux	lx	lm/m
luminance	candele per square metre	...	cd/m
luminous flux	lumen	lm	cd·sr
magnetic field strength	ampere per metre	...	A/m
magnetic flux	weber	Wb	V·s
magnetic flux density	tesla	T	Wb/m
magnetomotive force	ampere	A	...
power	watt	W	J/s
pressure	pascal	Pa	N/m
quantity of electricity	coulomb	C	A·s
quantity of heat	joule	J	N·m
radiant intensity	watt per steradian	...	W/sr
specific heat	joule per kilogram-kelvin	...	J/kg·K
stress	pascal	Pa	N/m
thermal conductivity	watt per metre-kelvin	...	W/m·K
velocity	metre per second	...	m/s
viscosity, dynamic	pascal-second	...	Pa·s
viscosity, kinematic	square metre per second	...	m/s
voltage	volt	V	W/A
volume	cubic metre	...	m
wavenumber	reciprocal metre	...	(wave)/m
work	joule	J	N·m

SI PREFIXES:

Multiplication Factors	Prefix	SI Symbol
$1\ 000\ 000\ 000\ 000 = 10^{12}$	tera	T
$1\ 000\ 000\ 000 = 10^{9}$	giga	G
$1\ 000\ 000 = 10^{6}$	mega	M
$1\ 000 = 10^{3}$	kilo	k
$100 = 10^{2}$	hecto*	h
$10 = 10^{1}$	deka*	da
$0.1 = 10^{-1}$	deci*	d
$0.01 = 10^{-2}$	centi*	c
$0.001 = 10^{-3}$	milli	m
$0.000\ 001 = 10^{-6}$	micro	µ
$0.000\ 000\ 001 = 10^{-9}$	nano	n
$0.000\ 000\ 000\ 001 = 10^{-12}$	pico	p
$0.000\ 000\ 000\ 000\ 001 = 10^{-15}$	femto	f
$0.000\ 000\ 000\ 000\ 000\ 001 = 10^{-18}$	atto	a

* To be avoided where possible.

MISSION
of
Rome Air Development Center

RADC plans and conducts research, exploratory and advanced development programs in command, control, and communications (C^3) activities, and in the C^3 areas of information sciences and intelligence. The principal technical mission areas are communications, electromagnetic guidance and control, surveillance of ground and aerospace objects, intelligence data collection and handling, information system technology, ionospheric propagation, solid state sciences, microwave physics and electronic reliability, maintainability and compatibility.

Printed by
United States Air Force
Hanscom AFB, Mass. 01731