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A FORTRAN PROGRAM FOR ESTIMATING RESIDUAL RADIATION LEVELS IN HIGH-ENERGY CHARGED-PARTICLE ACCELERATORS

J. B. Ball
C. B. Fulmer

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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MARCH 1964

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A FORTRAN PROGRAM FOR ESTIMATING RESIDUAL RADIATION LEVELS IN HIGH-ENERGY CHARGED-PARTICLE ACCELERATORS

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ABSTRACT

A FORTRAN II program is described for utilizing cross-section data for spallation products to obtain an estimate of the residual radiation from the bombardment of materials with high-energy particles.

INTRODUCTION

In the course of studying the feasibility of a high-intensity charged-particle accelerator, it is desirable to make a realistic appraisal of the radiation levels that will result from operation of the machine. Such an appraisal will help to ascertain the gamma shielding and remote handling facilities needed for safe operation and maintainance of the machine and associated experimental equipment. Expenditures for unnecessary facilities can thus be kept at a minimum without incurring unanticipated delays in maintainance operations due to high levels of residual radiation.

Calculation of residual radiation levels for a given spallation product as a function of incident beam intensity, bombardment time, and cooling time is straightforward. The total residual radiation level results, however, from the contributions of all the spallation products, and thus the amount of computation becomes prohibitively time consuming for hand calculation. This report describes a computer program that was prepared and used in residual radiation studies for the proposed ORNL Mc^2 Cyclotron, which is designed to accelerate 100 μa of protons to an energy of 810 Mev.

DESCRIPTION OF THE CALCULATION

It is assumed that a collimated beam of particles impinges normally on a slab of material. The incident beam intensity I_0 is attenuated in the material by the macroscopic geometric cross section Σ_t. Thus at a depth X in the slab,

$$I(X) = I_0 \exp(-\Sigma_t X) . \tag{1}$$

The production rate of spallation product j at position X is

$$R_j(X) = I(X)\Sigma_j , \tag{2}$$

where Σ_j is the macroscopic cross section for the reaction. After bombardment time t_B and cooling time t_c, the concentration of product j, as a function of X, is

$$N_j(X) = \left\{ R_j(X) \left[1 - \exp(-\lambda_j t_B)\right] \exp(-\lambda_j t_c) \right\} / \lambda_j \ , \tag{3}$$

where λ_j is the radioactive decay constant for product j. The activity A_j of j, as a function of X, is

$$A_j(X) = N_j(X)\lambda_j \ . \tag{4}$$

At a point p, a distance d outside the slab, the flux $\phi_j(X)$ of photons resulting from $A_j(X)$ is

$$\phi_j(X) = \left[A_j(X) \exp(-\mu_j X)\right] \ / \ 4\pi(X + d)^2 \ , \tag{5}$$

where μ_j is the absorption coefficient for the radiation. The radiation dose rate $D_j(X)$ due to $A_j(X)$ is[1]

$$D_j(X) = \text{const } \phi_j(X) E_j \ , \tag{6}$$

where E_j is the energy of the photons. The total dose rate at a point p due to all activity from product j distributed along the incident beam path is obtained by integration:

$$D_j = \left\{ \text{const } I_0 \Sigma_j E_j \left[1 - \exp(-\lambda_j t_B)\right] \exp(-\lambda_j t_c) \right\} \int_0^{X_{max}} \left\{ \left[\exp(-\Sigma_t + \mu_j)X\right] / (X + d)^2 \right\} dX \ , \tag{7}$$

where X_{max} is the smaller quantity of the slab thickness and the range of the incident protons in the slab material. In actual calculations, the integration does not need to extend to the range of several hundred Mev protons because of the exponential attentuation of the gamma radiation in the material. The analytical evaluation of the integral yields a slowly converging infinite series; therefore, numerical integration is used to evaluate D_j. For the total dose rate at a given point p, the D_j's for all the spallation products must be evaluated.

DESCRIPTION OF THE PROGRAM

The program determines the dose rate, for specified bombardment and cooling times, at the exposed surface of the irradiated material, at a distance of 10 cm from the surface, and at a distance of 100 cm.

Initially, the program reads and stores all the desired bombardment and decay times and the required information about each spallation product. The integral in Eq. (7) depends only on the formation cross section for a given species, the absorption coefficient for the radiation, and the distance from the surface. As the information about each spallation product is read and stored, the program evaluates this integral for the three distances and stores these in a two-dimensional array. For each bombardment and decay time the remainder of Eq. (7) is computed for each spallation product and is also stored in a two-dimensional array.

Finally, the total dose rate at each distance from the slab surface is calculated by taking the sum of the products of the appropriate elements from each array. In this manner the redundant parts of Eq. (7) are computed only once. The program prints out the total dose rates, as well as

[1] M. Honda and D. Lal, *Phys. Rev.* **118**, 1618 (1960).

the contribution of each spallation product to the total dose, for each set of bombardment and decay times. The FORTRAN listing for the main program is given in Appendix I.

The numerical evaluation of the integral in Eq. (7) is performed by a function subroutine AINT. The total range of the impinging particle in the slab material is divided into a specified number of layers. The contribution to the total dose is then calculated for each layer; the source is assumed to be concentrated at the midpoint of the layer. The total dose is then the sum of the individual layers. When the depth of the layer becomes great enough that the contribution is less than 0.1% of the contribution from the first layer, the sum is terminated and the value returned to the program. If very thin layers are chosen, the denominator of the integral is not well behaved for the case of the surface dose. To avoid this singularity in the function, the denominator is restricted to a lower limit of unity. This approximation leads to a consistent value of surface dose as a function of layer thickness. The FORTRAN listing for the AINT function is given in Appendix II.

USE OF THE PROGRAM

The first card of input data for each case contains four fields. The first three fields are eight columns each and are, in order, the total range of the incident particle in centimeters or the slab thickness (the smaller quantity is entered), the macroscopic total cross section for the particle in reciprocal centimeters, and the number of divisions of the range desired for the numerical integration. The decimal point is assumed to be at the right-hand edge of each field unless specifically entered. The final field is 60 columns and may contain any alphanumeric information to identify the calculation. This information will be printed at the top of the first output page for each case. In practice, it has been found convenient to make the number of range divisions about the same as the range so that each layer in the integration is about 1 cm thick.

The next card contains the desired bombardment and decay times. These times are entered in pairs with up to four pairs per card, making a total of eight fields per card. The fields are eight columns each and are successively bombardment time and decay time in hours. The program will accept up to 20 of these cards, or a total of 80 bombardment–decay-time pairs. The final card of this type must be followed by a card containing a -1 in the first eight columns.

The next cards contain the information about the individual spallation products. There is one card for each product. The data for these cards are summarized in Table 1 and discussed in more detail in the next section. The program will accept up to 89 of these cards. The last card must be followed by a card containing a -1 in the first eight columns.

The above cards constitute a complete case. As many complete cases as desired may be included in the input deck. A sample input sheet for a simple case is shown in Fig. 1, and the resulting output is shown in Fig. 2.

650 DATA SHEET

REQUEST _____ JOB TITLE _____ WRITTEN BY _____ DATE _____

1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	73-80
5.0	.0241	5.0	810 MEV	PRØTØNS	ØN	ALUMINUM	(5 CM	TARGET)	
100.0	1.0	100.0	10.0						
-1									
NE 24	.000097	.055	.47	.232					
NA 24	.000664	15.0	1.37	.142					
NA 24	.000664	15.0	2.75	.093					
NA 22	.00184	22776.	.5	.23					
NA 22	.00102	22776.	1.28	.144					
F 18	.000965	2.0	.5	.23					
Ø 15	.000735	.035	.5	.23					
N 13	.000122	.17	.5	.23					
C 11	.000361	.35	.5	.23					
BE 7	.00002171272.		.48	.231					
-1									

Fig. 1. Sample Input Data Sheet.

ACTIVATION DOSE RATE CALCULATION FOR 810 MEV PROTONS ON ALUMINUM (5 CM TARGET)

BOMBARDMENT TIME # 1.00E 02 ALL TIMES IN HOURS

COOLING TIME # 1.00E 00

SURFACE DOSE RATE # 3.86E 03 ALL DOSE RATES IN R/HR-MICROAMPERE OF INCIDENT BEAM

DOSE RATE AT 10 CM # 6.48E 01

DOSE RATE AT 1 METER # 8.92E-01

PRODUCT	MXS(1/CM)	HALFLIFE	EG(MEV)	MUABS	SURFACE DOSE	DOSE AT 10 CM	DOSE AT 1 M
NE 24	0.0000970	5.50E-02	0.470	0.232	1.79E-04	2.76E-06	3.68E-08
NA 24	0.0006640	1.50E 01	1.370	0.142	1.10E 03	1.81E 01	2.48E-01
NA 24	0.0006640	1.50E 01	2.750	0.093	2.32E 03	4.00E 01	5.53E-01
NA 22	0.0018400	2.28E 04	0.500	0.230	3.26E 00	5.03E-02	6.72E-04
NA 22	0.0010200	2.28E 04	1.280	0.144	5.05E 00	8.33E-02	1.14E-03
F 18	0.0009650	2.00E 00	0.500	0.230	3.99E 02	6.14E 00	8.21E-02
O 15	0.0007350	3.50E-02	0.500	0.230	1.08E-06	1.67E-08	2.23E-10
N 13	0.0001220	1.70E-01	0.500	0.230	1.21E 00	1.86E-02	2.49E-04
C 11	0.0003610	3.50E-01	0.500	0.230	2.91E 01	4.49E-01	5.99E-03
BE 7	0.0000217	1.27E 03	0.480	0.231	6.44E-01	9.92E-03	1.33E-04

Fig. 2. Sample Output Sheet. The output shown here resulted from the first case of the input data shown in Fig. 1.

Table 1. Summary of Data on Spallation-Product Cards

Field	Columns	Entry	Units
1	1–6	Alphanumeric identification of product	
2	9–16	Macroscopic production cross section	cm^{-1}
3	17–24	Half-life	hr
4	25–32	Energy of gamma ray	Mev
5	32–40	Absorption coefficient for gamma ray	cm^{-1}

PREPARATION OF INPUT DATA

The utility of the program is obviously dependent on a comprehensive set of spallation-product data. This entails a literature search from which a compilation of production cross sections for the spallation products is obtained. Extremely short and very long half-lives may be deleted. In the work for the ORNL Mc^2 Cyclotron, half-lives less than 1 min were not included; the input format of the program (in its present form) limits half-life values to 10^8 hr or about 11,500 yr. For products which decay to more than one final state, each branch is treated as a separate product with the production cross section prorated. Similarly, isomeric states are handled by treating each transition as a separate spallation product. Positron emitters are treated as 0.5-Mev gamma emitters with the production cross section doubled.

Examples of spallation-product data sets are illustrated in Tables 2 to 5 where data for the materials most extensively used in cyclotron construction are tabulated. The cross sections are for 800 Mev incident energy and in most cases can be used for 500 Mev to 1 Gev without incurring large errors. The cross-section data were obtained mainly from refs 1 to 5. The linear absorption coefficients were obtained by interpolating a table of linear absorption coefficients.[6]

The program can be used for high-energy neutrons as well as for charged particles. The main limitation is the availability of complete sets of spallation cross-section data. With appropriate assumptions the results of the computer calculation can be used to estimate residual radiation levels for oblique incidence and for distributed fluxes of incident particles. Examples of application of the program are presented in ref 7.

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[2]P. Benioff, *Phys. Rev.* **119**, 316 (1960).

[3]G. Rudstam, E. Bruninx, and A. C. Pappas, *Phys. Rev.* **126**, 1852 (1962).

[4]J. Hudis *et al.*, *Phys. Rev.* **129**, 434 (1963).

[5]E. Bruninx, *High-Energy Nuclear Reaction Cross-Sections.* I, CERN 61-1 (Jan. 16, 1961); *High-Energy Nuclear Reaction Cross-Sections.* II, CERN 62-9 (Feb. 15, 1962).

[6]Samuel Glasstone, *Principles of Nuclear Reactor Engineering*, p 78, D. Van Nostrand, 1955.

[7]C. B. Fulmer, K. S. Toth, and M. Barbier, "Residual Radiation Studies for Meson Factories," to be published in *Nuclear Instruments & Methods*.

ACKNOWLEDGMENT

The spallation-product cross-section data of Tables 2 to 5 were compiled from a literature search by K. S. Toth.

Table 2. Spallation-Product Data for 800-Mev Protons in Carbon

The data here and in Tables 3 to 5 are in the form of the computer output. MXS(1/CM) is the macroscopic production cross section in cm^{-1}; HALFLIFE is the half-life in hours; EG(MEV) is the energy in Mev of the emitted gamma; MUABS is the linear absorption coefficient in cm^{-1} of the slab material for the emitted gamma. In the column labeled HALFLIFE the number is listed as a coefficient times a decimal exponent.

PRODUCT	MXS(1/CM)	HALFLIFE	EG(MEV)	MUABS
C-11	0.0058200	3.30E-01	0.500	0.18
C-10	0.0006220	5.50E-03	0.500	0.18
C-10	0.0003110	5.50E-03	0.500	0.18
BE-7	0.0001300	1.27E 03	0.480	0.18

Table 3. Spallation-Product Data for 800-Mev Protons in Aluminum

PRODUCT	MXS(1/CM)	HALFLIFE	EG(MEV)	MUABS
NE 24	0.0000970	5.50E-02	0.470	0.232
NA 24	0.0006640	1.50E 01	1.370	0.142
NA 24	0.0006640	1.50E 01	2.750	0.093
NA 22	0.0018400	2.28E 04	0.500	0.230
NA 22	0.0010200	2.28E 04	1.280	0.144
F 18	0.0009650	2.00E 00	0.500	0.230
O 15	0.0007350	3.50E-02	0.500	0.230
N 13	0.0001220	1.70E-01	0.500	0.230
C 11	0.0003610	3.50E-01	0.500	0.230
BE 7	0.0000217	1.27E 03	0.480	0.231

Table 4. Spallation-Product Data for 800-Mev Protons in Iron

PRODUCT	MXS(1/CM)	HALFLIFE	EG(MEV)	MUABS
CO 55	0.0000424	1.80E 01	0.900	0.46
CO 55	0.0000085	1.80E 01	1.400	0.39
FE 59	0.0000340	1.08E 03	1.290	0.40
FE 59	0.0000509	1.08E 03	1.100	0.42
FE 52	0.0000594	8.00E 00	0.500	0.62
MN 56	0.0000509	2.60E 00	0.850	0.46
MN 56	0.0000169	2.60E 00	1.800	0.35
MN 56	0.0000085	2.60E 00	2.100	0.32
MN 54	0.0028017	7.20E 03	0.840	0.46
MN 52	0.0008490	1.37E 02	0.500	0.62
MN 52	0.0011037	1.37E 02	0.700	0.51
MN 52	0.0011037	1.37E 02	0.900	0.46
MN 52	0.0011037	1.37E 02	1.500	0.38
MN 51	0.0006792	7.00E-01	0.500	0.62
CR 51	0.0003056	6.72E 02	0.320	0.68
CR 49	0.0008490	7.00E-01	0.500	0.62
CR 49	0.0002122	7.00E-01	0.070	0.85
CR 48	0.0000849	2.30E 01	0.120	0.85
CR 48	0.0000849	2.30E 01	0.310	0.68
V 84	0.0002122	3.84E 02	0.500	0.62
V 48	0.0002122	3.84E 02	0.990	0.44
V 48	0.0002122	3.84E 02	1.300	0.40
V 47	0.0004245	5.00E-01	0.500	0.62
TI 45	0.0006368	3.00E 00	0.500	0.62
SC 48	0.0000424	4.40E 01	0.990	0.44
SC 48	0.0000424	4.40E 01	1.050	0.44
SC 48	0.0000424	4.40E 01	1.330	0.40
SC 47	0.0000552	8.20E 01	0.160	0.75
SC 46	0.0002717	2.02E 03	0.880	0.46
SC 46	0.0002717	2.02E 03	1.120	0.42
SC 44	0.0002207	4.00E 00	0.500	0.62
SC 44	0.0002207	4.00E 00	1.160	0.42
SC 43	0.0000085	4.00E 00	0.370	0.65
SC 43	0.0001019	4.00E 00	0.500	0.62
CA 47	0.0000009	1.08E 02	1.300	0.40
K 43	0.0001104	2.20E 01	0.370	0.65
K 43	0.0001019	2.20E 01	0.610	0.60
K 42	0.0000509	1.24E 01	1.530	0.38
CL 39	0.0000169	1.00E 00	0.250	0.72
CL 39	0.0000169	1.00E 00	1.270	0.39
CL 39	0.0000169	1.00E 00	1.500	0.38
CL 38	0.0000255	6.00E-01	1.600	0.37
CL 38	0.0000340	6.00E-01	2.200	0.32
CL 34M	0.0001019	5.00E-01	0.500	0.62
CL 34M	0.0000085	5.00E-01	1.200	0.41
CL 34M	0.0000085	5.00E-01	2.100	0.32
MG 28	0.0000255	2.10E 01	0.400	0.63

Table 4. (continued)

MG 28	0.0000255	2.10E 01	0.950	0.46
MG 28	0.0000594	2.10E 01	1.350	0.40
MG 28	0.0000849	2.10E 01	0.030	0.95
NA 24	0.0000297	1.50E 01	1.380	0.39
NA 24	0.0000297	1.50E 01	2.750	0.30
NA 22	0.0000297	2.28E 04	0.500	0.62
NA 22	0.0000297	2.28E 04	1.280	0.35
BE 7	0.0000297	1.27E 03	0.480	0.62

Table 5. Spallation-Product Data for 800-Mev Protons in Copper

PRODUCT	MXS(1/CM)	HALFLIFE	EG(MEV)	MUABS
CU 64	0.0018700	1.30E 01	0.500	0.72
CU 62	0.0037400	1.70E-01	0.500	0.72
CU 61	0.0011900	3.30E 00	0.500	0.72
CU 60	0.0002970	4.00E-01	0.500	0.72
CU 60	0.0001270	4.00E-01	1.300	0.46
CU 60	0.0000850	4.00E-01	1.760	0.40
NI 65	0.0000034	2.60E 00	1.110	0.50
NI 65	0.0000068	2.60E 00	1.480	0.44
NI 57	0.0000340	3.60E 01	0.500	0.72
NI 57	0.0000340	3.60E 01	1.370	0.46
NI 57	0.0000042	3.60E 01	1.900	0.39
CO 60	0.0000340	1.65E 00	0.070	1.06
CO 60M	0.0003400	1.80E-01	0.060	1.10
CO 60M	0.0003400	1.80E-01	1.170	0.48
CO 60M	0.0003400	1.80E-01	1.330	0.46
CO 60	0.0003400	4.65E 03	1.170	0.48
CO 60	0.0003400	4.65E 03	1.330	0.46
CO 58	0.0006800	1.70E 03	0.500	0.72
CO 58	0.0020400	1.70E 03	0.800	0.57
CO 56	0.0001700	1.85E 03	0.500	0.72
CO 56	0.0004200	1.85E 03	0.850	0.56
CO 56	0.0002970	1.85E 03	1.200	0.48
CO 56	0.0002120	1.85E 03	2.000	0.38
CO 55	0.0002100	1.80E 01	0.500	0.72
CO 55	0.0001700	1.80E 01	0.900	0.54
FE 59	0.0000250	1.08E 03	1.100	0.50
FE 59	0.0000255	1.08E 03	0.300	0.85
FE 52	0.0000170	8.00E 00	0.500	0.72
MN 56	0.0002550	2.60E 00	0.850	0.56
MN 56	0.0000850	2.60E 00	1.800	0.40
MN 56	0.0000510	2.60E 00	2.100	0.38
MN 54	0.0008490	7.20E 03	0.840	0.57
MN 52M	0.0003400	3.00E-01	0.500	0.72

Table 5. (continued)

MN 52M	0.0001700	3.00E-01	1.400	0.45
MN 52	0.0003400	1.37E 02	0.500	0.72
MN 52	0.0005100	1.37E 02	0.700	0.61
MN 52	0.0005100	1.37E 02	0.900	0.54
MN 52	0.0005100	1.37E 02	1.500	0.44
MN 51	0.0001360	7.50E-01	0.500	0.72
CR 51	0.0001700	6.72E 02	0.320	0.84
CR 49	0.0005100	7.00E-01	0.500	0.72
CR 49	0.0001300	7.00E-01	0.075	1.05
CR 48	0.0000420	2.30E 01	0.120	0.98
CR 48	0.0000510	2.30E 01	0.310	0.84
V 48	0.0001700	3.84E 02	0.500	0.72
V 48	0.0001700	3.84E 02	0.990	0.52
V 48	0.0001700	3.84E 02	1.300	0.46
V 47	0.0005100	5.00E-01	0.500	0.72
TI 45	0.0004200	3.00E 00	0.500	0.72
SC 48	0.0001700	4.40E 01	0.990	0.52
SC 48	0.0001700	4.40E 01	1.050	0.51
SC 48	0.0001700	4.40E 01	1.330	0.46
SC 47	0.0001700	8.20E 01	0.160	0.96
SC 46	0.0001700	2.02E 03	0.880	0.54
SC 46	0.0001700	2.02E 03	1.120	0.49
SC 44M	0.0002550	5.90E 01	0.270	0.87
SC 44M	0.0005100	5.90E 01	0.500	0.72
SC 44M	0.0002550	5.90E 01	1.160	0.48
SC 44	0.0005100	4.00E 00	0.500	0.72
SC 44	0.0002550	4.00E 00	1.160	0.48
SC 43	0.0005100	4.00E 00	0.500	0.72
SC 43	0.0000855	4.00E 00	0.370	0.82
CA 47	0.0000340	1.08E 02	0.040	1.15
CL 39	0.0000080	1.00E 00	0.250	0.89
CL 39	0.0000080	1.00E 00	1.270	0.47
CL 39	0.0000080	1.00E 00	1.500	0.44
CL 38	0.0000016	5.00E-01	1.600	0.43
CL 38	0.0000025	5.00E-01	2.200	0.37
CL 34M	0.0000051	5.00E-01	0.500	0.72
CL 34M	0.0000008	5.00E-01	2.100	0.42
K 43	0.0001110	2.20E 01	0.370	0.81
K 43	0.0001020	2.20E 01	0.610	0.65
K 42	0.0000420	1.20E 01	1.530	0.43
AR 41	0.0000590	1.80E 00	1.290	0.46
S 38	0.0000855	2.90E 00	1.880	0.41
MG 28	0.0001270	2.10E 01	0.400	0.75
MG 28	0.0001270	2.10E 01	0.950	0.52
MG 28	0.0002970	2.10E 01	1.350	0.46
NA 24	0.0000340	1.50E 01	1.380	0.45
NA 24	0.0000340	1.50E 01	2.750	0.34
NA 22	0.0000068	2.28E 04	0.500	0.72
NA 22	0.0000034	2.28E 04	1.280	0.47
F 18	0.0001700	2.00E 00	0.500	0.72
BE 7	0.0004240	1.27E 03	0.480	0.73

Appendix I

FORTRAN LISTING FOR MAIN PROGRAM

```
C       PROGRAM FOR COMPUTING ACTIVATION DOSE RATES
        DIMENSION TB(84),TD(84),PROD(90),SIGMAJ(90),HALFT(90),EGAMMA(90),
       1CABSJ(90),D(3),TITLE(10),SUMD(3),
       2F1(90,3),F2(90,84),DOSE(90,3)
   11 READINPUTTAPE10,41,RANGE,SIGTOT,RDIV,TITLE
        NI#-3
   12 NI#NI+4
        N2#NI+3
        READINPUTTAPE10,42,(TB(N),TD(N),N#NI,N2)
        IF(TB(NI))13,13,12
   13 D(1)#0.0
        D(2)#10.0
        D(3)#100.0
        DO191J#1,90
   14 READINPUTTAPE10,43,PROD(J),SIGMAJ(J),HALFT(J),EGAMMA(J),CABSJ(J)
        IF(SIGMAJ(J))20,20,15
   15 NJ#J
        DO16K#1,3
   16 F1(J,K)#AINT(SIGTOT,CABSJ(J),D(K),RANGE,RDIV)
   17 DO19I#1,NI
        IF(TB(I))191,191,18
   18 NI#I
        ARG1#EXPF(-0.693*TD(I)/HALFT(J))
        ARG2#1.0-EXPF(-0.693*TB(I)/HALFT(J))
   19 F2(J,I)#(8.86E5)*EGAMMA(J)*SIGMAJ(J)*ARG1*ARG2
  191 CONTINUE
   20 DO22I#1,NI
        DO21K#1,3
        SUMD(K)#0.0
        DO21J#1,NJ
        DOSE(J,K)#F2(J,I)*F1(J,K)
   21 SUMD(K)#SUMD(K)+DOSE(J,K)
        WRITEOUTPUTTAPE9,44,TITLE,TB(I),TD(I),(SUMD(L).L#1,3)
        WRITEOUTPUTTAPE9,45,(PROD(L),SIGMAJ(L),HALFT(L),EGAMMA(L),
       1CABSJ(L),(DOSE(L,LK),LK#1,3),L#1,NJ)
   22 CONTINUE
        GOTO11
   41 FORMAT(3F8.0,10A6)
   42 FORMAT(8F8.0)
   43 FORMAT(A6,2X,4F8.0)
   44 FORMAT(1H1,2X37HACTIVATION DOSE RATE CALCULATION FOR ,
       110A6/1H0/1H ,4X18HBOMBARDMENT TIME #1PE9.2,
       218X18HALL TIMES IN HOURS/1H0,4X14HCOOLING TIME #E9.2/
       31H0,4X19HSURFACE DOSE RATE #E9.2,17X51HALL DOSE RATES IN R/HR-MICR
       40AMPERE OF INCIDENT BEAM/1H0,4X20HDOSE RATE AT 10 CM #E9.2/
       51H0,4X22HDOSE RATE AT 1 METER #E9.2)
   45 FORMAT(1H0/1H0,4X7HPRODUCT,5X9HMXS(1/CM),5X8HHALFLIFE,5X7HEG(MEV),
       15X5HMUABS,5X12HSURFACE DOSE,5X13HDOSE AT 10 CM,5X11HDOSE AT 1 M//
       2(1H ,5XA6,0PF14.7,4X1PE9.2,0PF11.3,F11.3,7X1PE9.2,8XE9.2,8XE9.2))
        END(1,1,0,0,0,0,0,0,0,0,0,0,0,0)
```

Appendix II

FORTRAN LISTING FOR AINT FUNCTION

```
      FUNCTIONAINT(SIGTOT,CABSJ,D,R,RDIV)
      DIMENSIONG(500)
      XINC#R/RDIV
      PINT#0.0
      NDIV#RDIV
      ASSIGN20TOK
      DO32I#1,NDIV
      FLTGI#I
      X#(FLTGI-0.5)*XINC
      GOTOK,(20,30)
   20 IF(X+D-1.0)21,22,22
   21 DENOM#1.0
      GOTO31
   22 ASSIGN30TOK
   30 DENOM#(X+D)**2
   31 G(I)#EXPF(-X*(SIGTOT+CABSJ))/DENOM
      IF((G(I)/G(1))-0.001)33,32,32
   32 PINT#PINT+G(I)
   33 AINT#PINT*XINC
      RETURN
      END(1,1,0,0,0,0,0,0,0,0,0,0,0,0,0)
```

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