

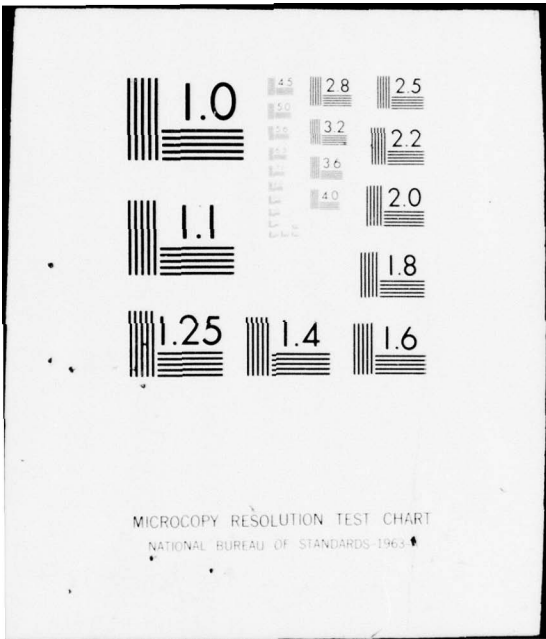
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GENERAL RESEARCH CORP SANTA BARBARA CALIF  
THE ROSCOE MANUAL, VOLUME 17. HIGH-ALTITUDE DEBRIS-ENERGY DEPOS--ETC(U)  
SEP 75 D A HAMLIN, J Y WANG, M R SCHOONOVER DNA001-74-C-0182  
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# THE ROSCOE MANUAL

## Volume 17 - High Altitude Debris-Energy Deposition

Science Applications, Inc.  
P. O. Box 2351  
La Jolla, California 92038

22 September 1975

Final Report for Period 1 March 1974-31 January 1975

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19 REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1 REPORT NUMBER DNA 3964F-17	2 GOVT ACCESSION NO.	3 RECIPIENT'S CATALOG NUMBER
4 TITLE (and Subtitle) THE ROSCOE MANUAL Volume 17—High-Altitude Debris-Energy Deposition	5 TYPE OF REPORT & PERIOD COVERED Final Report for Period 1 Mar 74—31 Jan 75	6 PERFORMING ORG. REPORT NUMBER SAI-75-609-LJ, Vol. 5
7 AUTHOR(s) Daniel A. Hamlin, Jon Y. Wang, Melvin R. Schoonover John I. Valerio	8 CONTRACT OR GRANT NUMBER(s) DNA 001-74-C-0182	
9 PERFORMING ORGANIZATION NAME AND ADDRESS Science Applications, Inc. P.O. Box 2351 La Jolla, California 92038	10 PROGRAM ELEMENT PROJECT, TASK AREA & WORK UNIT NUMBERS NWED Subtasks S99QAXHC064-28/32	
11 CONTROLLING OFFICE NAME AND ADDRESS Director Defense Nuclear Agency Washington, D.C. 20305	12 REPORT DATE 22 September 1975	13 NUMBER OF PAGES 126
14 MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15 SECURITY CLASS. (of this report) UNCLASSIFIED	15a. DECLASSIFICATION DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18 SUPPLEMENTARY NOTES This work sponsored by the Defense Nuclear Agency under RDT&E RMSS Codes B322074464 S99QAXHC06428 and B322075464 S99QAXHC06432 H2590D.		
19 KEY WORDS (Continue on reverse side if necessary and identify by block number) ROSCOE Energy Deposition by Debris Particles Radar Blackout Code (Loss-Cone, Ion-Leak, and Charge Energy Deposition by X-Rays Exchange) Energy Depositions by Ultraviolet Radiation		
20 ABSTRACT (Continue on reverse side if necessary and identify by block number) Models of the high-altitude debris-energy partition and deposition have been adopted for use in ROSCOE. The models for the debris-energy partition and heavy-particle source spectra incorporate the work of Crevier and Kilb for the loss-cone and ion-leak particles. The determi- nation of the total (and spectrum of the) UV portion of the kinetic yield remaining after that assigned to all the heavy-particle motion is based on the work of Fajen and Sappenfield. Representative points in the spatial		

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18. SUPPLEMENTARY NOTES (Continued)

EDITORS NOTE

Volumes 13 to 17 were originally published by SAI to describe the atmospheric, geomagnetic, and high-altitude energy deposition and neutral heave models for ROSCOE. This whole section of code, when associated with an appropriate DRIVER subroutine, operated as a package that ran independently of the rest of the ROSCOE structure. Provision was also made, within this high-altitude package, for two completely independent descriptions of atmospheric heave, each with its own description of atmospheric chemistry.

When GRC incorporated this section of code within the ROSCOE framework, some modifications were necessary, which means that some of the descriptions in Volumes 13 to 17 are inappropriate to ROSCOE as it now exists. In particular, the NRL heave routines (deck NRLHYD) and associated chemistry (deck NRLCHM) are not presently used in ROSCOE. Three other subroutines are different: subroutines ATMOSU, EIF, and XTCOEF correspond to the ROSCOE subroutines ATMOS, EXPINT, and WDXP respectively. With these exceptions, the subroutines described in Volumes 13 to 17 correspond exactly to those currently in ROSCOE.

20. ABSTRACT (Continued)

distribution function specified for the loss-cone and ion-leak particles are used as effective source points through which magnetic field lines are traced in the downward direction through the intercepted grid cells in the geocentric quadrupole coordinate system. Conventional heavy-particle range-energy theory is employed along these paths, without regard to spiralling effects, to deposit the energy of these heavy particles in the traversed cells. Charge-exchange particles are deposited without regard to the magnetic field. The total heavy-particle energies deposited by inelastic and by elastic collisions in each cell are partitioned into various modes and species which are ultimately made compatible with the late-time grid chemistry. The UV energy groups, as well as the x-ray energy, are deposited by tracing ray paths (and constructing line integrals of relevant species) from the event point to each cell in the high-altitude grid treated as a target cell. The portion of all the deposited energy available for hydro is computed as well as the instantaneously-produced species to be used as starting conditions for the subsequent hydrodynamics and chemistry. Herein are presented details of the models for the debris-energy partition and deposition, including detailed flow charts for the more complicated routines.

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## 1. CONTROL ROUTINE FOR DEPOSITION OF THE ENERGY IN THE HIGH-ALTITUDE GRID (SUBROUTINE PROMPG)

Subroutine PROMPG, called by DRIVER, controls the deposition of the energy in the high-altitude grid (HAG). The overall procedure is complicated, as Subroutine PROMPG directly calls 12 subroutines which in turn call an additional 26 subroutines. The tasks performed by Subroutine PROMPG include the following:

a. Tests whether or not the event point is above the bottom of the grid. If it is, the program proceeds to the next task; if not, the program returns to DRIVER after printing an appropriate message. It may be desirable to deposit at least the Group- $\gamma$  and possibly the Group-X energy for certain events below the bottom of the grid, but this feature has not been implemented yet.

b. Calls Subroutine BOUNDY to set up the array GR(NCEL) for the geocentric radius to the top boundary of each cell NCEL in the HAG. Subroutine BOUNDY is different in SAIHYD than in NRLHYD because the definitions of a cell boundary are different in the two versions of the hydrodynamics.

c. Sets up the array RHOKK(NCEL) for the mass density of each cell in the HAG by appropriately calling Subroutine ECRD to get successive columns.

d. Changes the geographic location of the event point by a small amount so that if the event point is inputted on a cell boundary, as it would be if it were placed, e. g., at the origin of the quadrupole coordinate system, the event point would be moved off the boundary to facilitate the code's assigning the event point to the proper cell in the

grid. This movement of the event point is made by (1) converting the geographic coordinates of the event point to quadrupole coordinates by calling Subroutine GEOQUA, (2) multiplying the quadrupole coordinates by the fraction 0.999997 to obtain the new quadrupole coordinates, and (3) converting the new quadrupole coordinates to geographic coordinates by calling Subroutine QUAGEO.

e. Calls Subroutine INDEX to obtain the indices (IEC, JEC, KEC) of the event cell and the vertical fractional-position parameter (FRACB) for the event point within the event cell. Again, Subroutine INDEX is different in SAIHYD than in NRLHYD. The event-point indices are printed and stored in EVENTX Common as members of arrays.

f. Calls Subroutine PROPTY to obtain, print, and store in array PP(7) the following event-point properties: mass density, mass-density scale height, heavy-particle temperature, and magnetic-field strength, dip angle, declination angle, and dipole colatitude.

g. Moves the event point slightly away from the center or boundary of a cell if either of the quadrupole coordinates or the geocentric radius of the event point differs from that of the cell center or boundary by less than the fraction  $10^{-5}$ . The new coordinate is made to differ from the cell-center or boundary coordinate by the fraction  $3 \times 10^{-5}$ .

h. Computes the geocentric cartesian coordinates (X1, Y1, Z1) of the event point, given the quadrupole coordinates and the geocentric radius of the event point. The Z-axis is through the quadrupole north pole; the X-axis is through the quadrupole west pole.

i. Calls Subroutine DEBRIS which serves as the principal control routine for computing the partitioning and deposition of the Group-D (debris) energy. Subroutine DEBRIS controls 16 subroutines, including direct calls to Subroutines HDPART, CONSPC, LEKSPC, CHXSPC, and BLINE.

j. Sets up the Group-U (ultraviolet) properties by (1) calling Subroutine EUXFIT to get the energy in each of the five Subgroups L, (2) establishing pressure efficiencies PREFF(L,I) for Subgroup-L photons incident on Species I, and (3) establishing absorption coefficients XMU1 of O<sub>2</sub> for Subgroup 1 of Group U. (These latter two functions should probably be done elsewhere.) The calculated pressure efficiencies follow the somewhat arbitrary assumption in FS-73 that all photoelectron kinetic energies below 10 eV, and 0.80 of the kinetic energy of photoelectrons more energetic than 10 eV, are thermalized; the remaining energy is discarded, as having been lost in radiative processes.

k. Computes the deposition of the Group-X (x ray), Group-U, and Group-CHEX (charge exchange) energies by making a triple DO-loop over all the cells in the HAG, during which calls are made to the following subroutines:

- PLINE - Computes line integrals, with aid of Subroutines PINT and BEDGE.
- CHXDEP - Computes deposition of CHEX energy.
- HPCHEM - Computes prompt chemistry due to Group-D energy deposition.
- PHEAT - Computes heating due to Group-D, -X, and -U energies.
- PCHEM - Combines results of Subroutines HPCHEM with prompt chemistry due to Groups X and U.

l. Stores in array BUF those cell quantities updated in Subroutine PCHEM and stored in the temporary scratch area.

Figure 1 is a simplified flow chart that summarizes the functions performed by Subroutine PROMPG. Figure 2 is a simplified flow chart of the triple DO-loop within Subroutine PROMPG that loops over all cells in the HAG.



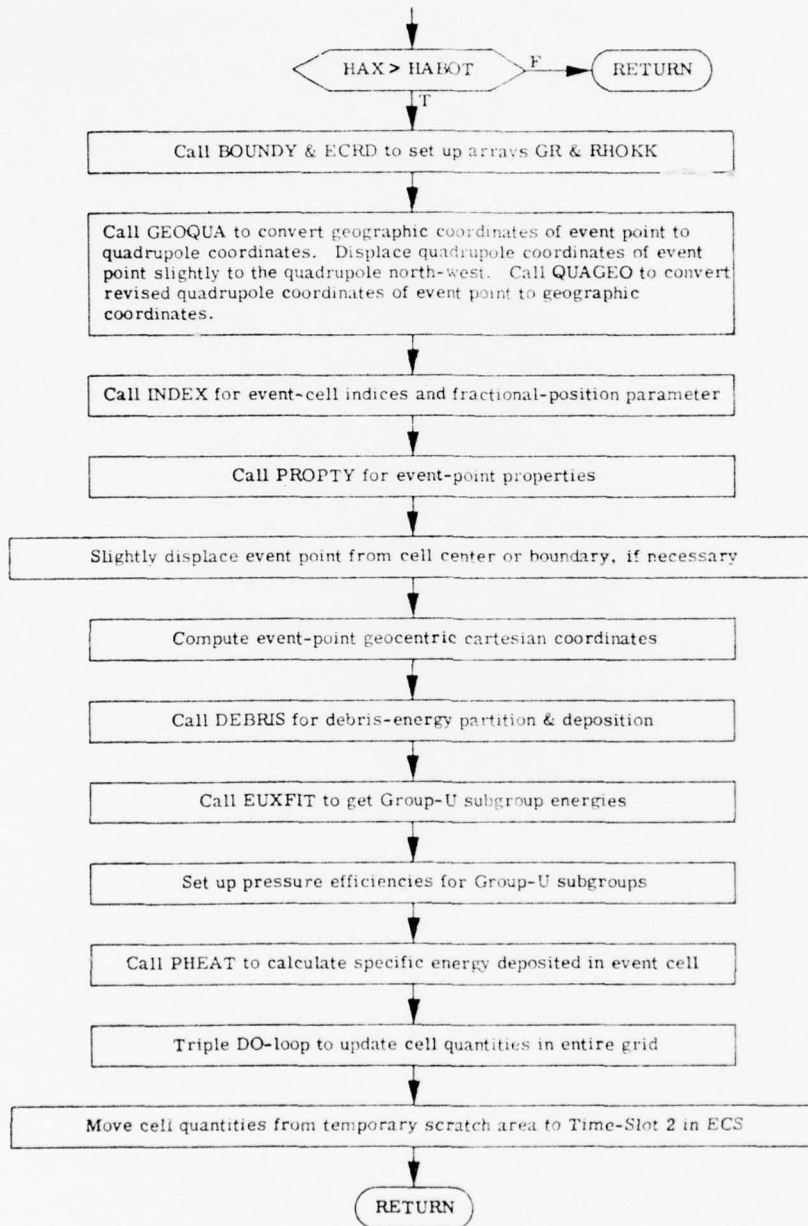


Fig. 1. Simplified Flow Chart for Subroutine PROMPG Which Controls the Energy-Deposition Routines.

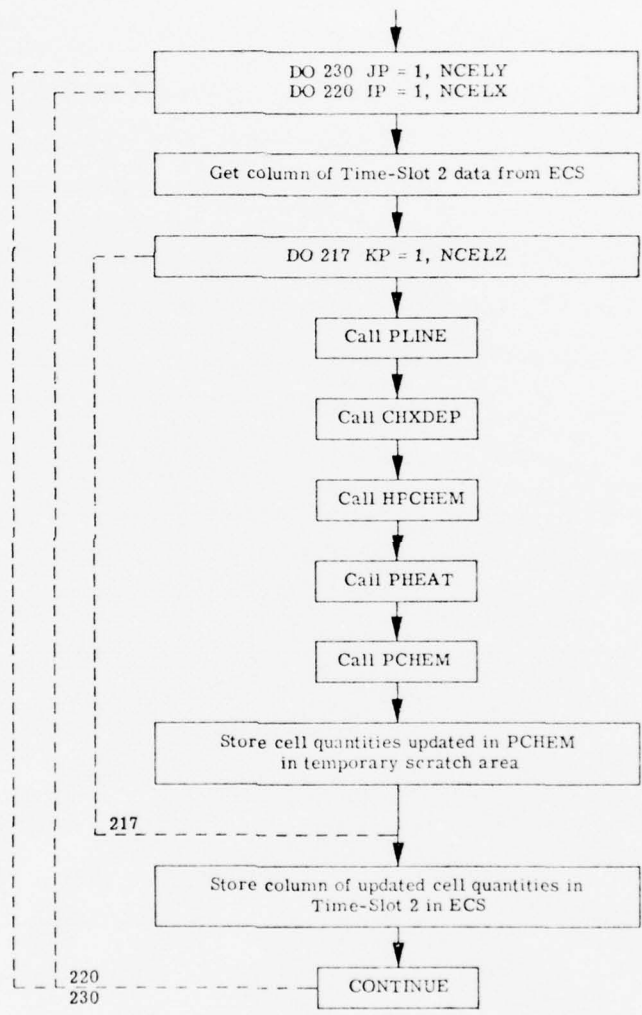


Fig. 2. Simplified Flow Chart for the Subroutine PROMPG Triple DO-Loop Over All Cells in the High-Altitude Grid.

## 2. SOME AUXILIARY ROUTINES

### 2.1 SUBROUTINE BOUNDY

Subroutine BOUNDY establishes a one-dimensional array GR(NCEL) of the geocentric radii to all the cell top-boundaries in the HAG. This information is developed by using the cell-center heights stored as cell properties and obtained by calling Subroutine ECRD.

Subroutine BOUNDY is different in SAIHYD and NRLHYD. As discussed in Volume 16, the differential-quadrature formulation of the Lagrangian hydrodynamics (NRLHYD) does not employ the concept of a cell in computing the hydrodynamic motion, as is done in the difference-equation formulation of the Lagrangian hydrodynamics (SAIHYD). However, the deposition of energy (in SAIROS) has been formulated in terms of a cellular grid for use with SAIHYD. To make use of this energy deposition procedure with NRLHYD, it is necessary to establish cells and cell boundaries in NRLHYD to correspond to the same quantities in SAIHYD. Subroutine BOUNDY in NRLHYD establishes such cell boundaries.

For N Lagrangian points (initially specified in Subroutine ATMOSG to be at the N-1 SAIHYD cell centers plus one more point at the SAIHYD grid bottom), the N-1 interior boundaries are defined to be midway between the adjacent Lagrangian points. For the top cell, the outer boundary is placed so that the top Lagrangian point is at the center of the top cell. The parameter HABOT, originally read in by DRIVER in SETUP1 as the bottom of the grid for SAIHYD, is reset in ATMOSG to be the bottom boundary of the lowest NRLHYD cell. Since the value of HABOT is not allowed to change with time, the bottom Lagrangian point does not remain at the center of the bottom cell despite its not moving.



## 2.2 SUBROUTINE INDEX

For a given Point X in geographic coordinates (GCX, GLX), Subroutine INDEX calls Subroutine GEOQUA to compute the quadrupole coordinates (QCX, QLX) of the point. Subroutine INDEX then finds the indices IX, JX, and KX of the Point X. If the Point X is to the quadrupole-north of, quadrupole-west of, or below the grid boundary, index IX, JX, or KX is set equal to zero. If the Point X is to the quadrupole-south of, quadrupole-east of, or above the grid boundaries, the index IX, JX, or KX is set equal to (NCELX+1), (NCELY+1), or (NCELZ+1), respectively, and an appropriate warning message is printed. Subroutine INDEX also computes the fractional-height position of the Point X within the cell at the time the subroutine is called.

If the Point X is on a quadrupole colatitude or east longitude boundary, Subroutine INDEX identifies Point X as being in the cell for which the boundary is the south or east boundary of the cell.

The version of Subroutine INDEX used with NRLHYD differs from that used with SAIHYD mainly in that (1) the vertical-direction index (KX) has a plus or minus sign associated with it to denote whether the Point X is above or below the Lagrangian Point KX, respectively, and (2) the fractional-height parameter refers to the fractional distance between the two adjacent Lagrangian points instead of the fractional distance within the cell (with both fractional distances being measured upward from the bottom).

## 2.3 SUBROUTINE PROPTY

Subroutine PROPTY computes the mass density [PP(1)], the density scale height [PP(2)], and the heavy-particle temperature [PP(3)] of a given Point X inside the HAG. By calling Subroutine BFIELD,

Subroutine PROPTY also obtains the local dip angle [PP(4)], declination angle [PP(5)], strength [PP(6)], and cosine of the dipole colatitude [PP(7)] of the dipole magnetic field line passing through the point.

### 3. DEBRIS ENERGY PARTITION AND PARTICLE-SOURCE SPECTRA

#### 3.1 INTRODUCTION

Certain overall partitioning of the total yield for three selected devices is given by Knapp et al. [in Volume 12] as part of the GET ROSCOE Model 3. This partitioning includes statements for the fractional yields of x rays and hydrodynamics. The additional partitioning of the hydrodynamics yield into several types of heavy-particle emissions and UV emission, needed for computing the energy deposition in the HAG, is not completely understood. We have, of necessity, adopted a specific procedure, but it certainly deserves review and improvement.

It is convenient to classify the heavy-particle emission from the expanding weapon debris-air mixture into loss-cone, ion-leak, and charge-exchange (CHEX) particles even though the division among these three groups is not unique. For our purposes, we consider loss-cone particles to be debris ions that escape the burst region along the magnetic field direction. Ion-leak particles are also emitted along magnetic field lines but they are composed mainly of air ions heated by the weapon debris expansion. CHEX particles are mainly fast neutral air atoms born through ion-to-neutral charge-exchange reactions within the debris-air mixture.

Partitioning of the weapon kinetic yield into loss-cone and ion-leak energies follows the prescription given by Crevier and Kilb [in Volume 10] as part of the MRC ROSCOE Model 12a. The fraction of the remaining kinetic yield emitted as CHEX particles is computed from the RANC-IV formulation [GE-70]. Thus, the sum of the loss-cone, ion-leak, and charge-exchange yields is subtracted from the total

hydrodynamic yield before the UV yield is determined by the prescription of Fajen and Sappenfield [FS-71a, FS-73]. We do not discuss the physical validity of our modeling of the hydro-yield partitioning; we do discuss and provide Fortran energy-deposition routines. Hopefully, future modifications of the hydro-yield partitioning will require only minor modifications of these routines.

### 3.2 HYDRO-ENERGY PARTITIONING

Partitioning of the weapon kinetic yield is summarized in Fig. 3; the directed dashed line shows the computational order. The energy indicated in each energy block is successively subtracted from the remaining energy until the residual UV-plus-thermal energy is obtained. The partitioning into the three heavy-particle modes is performed by calls from Subroutine HDPART to Subroutines LOSCON, IONLEK, and CHXLOS. The final division into UV and thermal energies is performed in Subroutine EUXFIT.

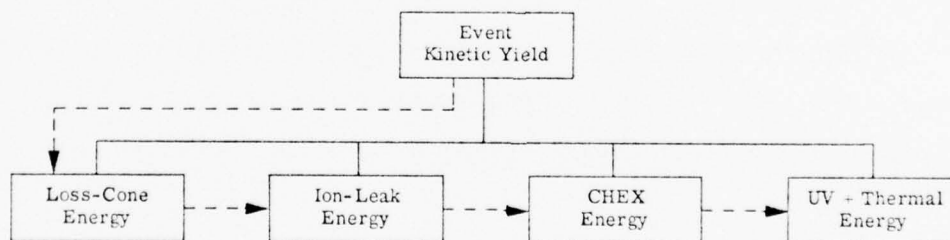


Fig. 3. Illustration of the Order of Partitioning of the Total Kinetic Yield into Loss-Cone, Ion-Leak, CHEX, and UV-plus-Thermal Energies.

### 3.2.1 Loss-Cone Energy

The energy fraction in the loss cones, with neglect of collisions, is [Vol. 10, Eq. (2-23)]

$$F_{\ell c} = 1 - (1 - \epsilon_1)^{\frac{3}{2}} - \left[ 2 - (1 - \epsilon_1)^{\frac{3}{2}} (2 + \epsilon_1 - 3\epsilon_1^2) \right] / 5\epsilon \quad (1)$$

where

$$\epsilon = \frac{1.40 \times 10^{-20}}{B^2} \left[ \frac{v_d^5 n_a}{W_K Z_d^{5/2} Z_a^{1/2}} \right]^{(10)}, \quad [\text{Vol. 10, Eq. (2-26)}] \quad (2)$$

and

$$\epsilon_1 = \min(\epsilon, 1) . \quad [\text{Vol. 10, Eq. (2-22)}] \quad (3)$$

Here,  $W_K$  is the weapon kinetic energy in MT,  $B$  is the burst-point magnetic field in gauss,  $v_d$  is the debris velocity in cm/sec,  $n_a$  is the air-ion density in  $\text{cm}^{-3}$ ,  $Z_d$  is the debris-ion charge state, and  $Z_a$  is the air-ion charge state. However, with collisions included, the energy in MT leaving the burst region in the downward direction is given by [Vol. 10, p. 14]

$$W_{\ell cd} = \frac{1}{2} W_K F_{\ell c} \left[ \max \left\{ 0, \left[ 1 - (\rho_a / 2 \times 10^{-12})^2 \right] \right\} \right], \quad (4)$$

where  $\rho_a$  is the burst-point mass density, and the energy leaving in the upward direction is given by [Vol. 10, p. 14]

$$W_{\ell cu} = \frac{1}{2} W_K F_{\ell c} \left[ \max \left\{ 0, \left[ 1 - (\rho_a / 2 \times 10^{-11})^2 \right] \right\} \right]. \quad (5)$$

The total energy in MT leaving the burst region through the loss cones is [Vol. 10, Subroutine LOSCON]

$$W_{\ell c} = W_{\ell cd} + W_{\ell cu} . \quad (6)$$

For more information about this formulation the reader is referred to ,  
Volume 10.

The total fraction of the weapon kinetic energy (with collisions included) leaving the burst region in the loss cones is

$$f_{\ell c} = W_{\ell c} / W_K \quad (7a)$$

which, for burst-point densities less than  $\rho_a \approx 2 \times 10^{-12} \text{ g/cm}^3$ , is very nearly equal to the fraction  $F_{\ell c}$  for neglect of collisions. For the downward direction the fraction corresponding to  $f_{\ell c}$  is

$$f_{\ell cd} = W_{\ell cd} / W_K \quad (7b)$$

For  $\rho_a < 2 \times 10^{-12} \text{ g/cm}^3$ ,

$$f_{\ell cd} \approx 0.5 f_{\ell c} \quad (8)$$

In Fig. 4 we have plotted  $f_{\ell c}$  as a function of the kinetic yield  $W_K$ . The curves have been drawn through points computed from the Subroutine LOSCON given in Vol. 10 and used in SAIROS. The altitudes correspond to densities from the CIRA-1965 Model-5 8-hr atmosphere [CI-65]; we used  $B = 0.5$  gauss. For the 150-km curve,  $f_{\ell cd} = 0$ .

### 3.2.2 Ion-Leak Energy

The energy in MT moving downward from the burst region due to the ion-leak mechanism is [Vol. 10, Eq. (3-1)]

$$W_{i\ell d} = 0.45 W_1 \left[ 1 - \left( \rho_a / 2 \times 10^{-12} W_1^{\frac{1}{3}} \right)^{0.04 / (W_1^{0.4})} \right] \quad (9)$$

where  $W_1$ , given by

$$W_1 = W_K - W_{\ell c} \quad (10)$$



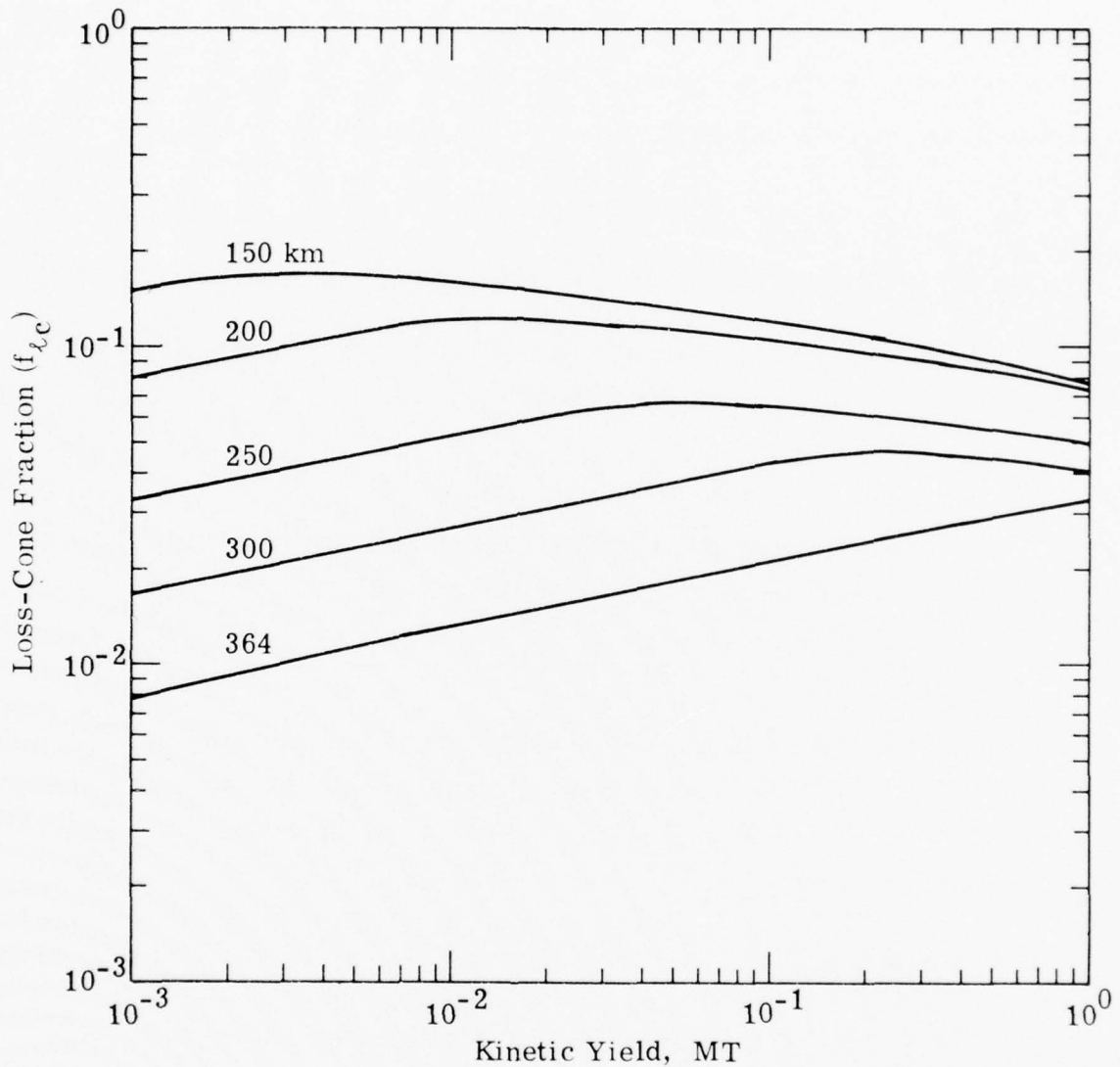


Fig. 4. Fraction of the Total Kinetic Yield Escaping the Event-Point Region by the Loss-Cone Mechanism, for Several Event Altitudes. Curves are drawn for  $B = 0.5$  gauss and the CIRA-65 mean atmosphere. At 150-km, the downward fraction  $f_{tcd}$  is zero.

is the kinetic yield left after the loss-cone energy is removed. No statement is made in Vol. 10 about the magnitude of the upward-moving ion-leak energy. Since we must know the amount lost by this mechanism in all directions to estimate the kinetic yield left for subsequent yield partitioning, we arbitrarily set the total ion-leak energy loss as

$$W_{i\ell} = 2 W_{i\ell d} . \quad (11)$$

Final determination of  $W_{i\ell}$  must be deferred to some future date.

The total fraction of the weapon kinetic energy leaving the burst region by the ion-leak mechanism is

$$f_{i\ell} = W_{i\ell}/W_K . \quad (12)$$

By our simplifying assumption in Eq. (11), we see that the fraction for the downward direction is

$$f_{i\ell d} = 0.5 f_{i\ell} . \quad (13)$$

In Fig. 5 we have plotted  $f_{i\ell}$  as a function of the kinetic yield  $W_K$ . The curves have been drawn through points computed from the Subroutine IONLEK given in Vol. 10 and used in SAIROS. We used the same input conditions as for Fig. 4.

### 3.2.3 CHEX Energy

Time constraints did not allow us to develop a new model for the energy leaving the burst region via fast neutrals produced through charge exchange. As an interim procedure we have just applied the RANC IV model [GE-70] to the remaining kinetic yield so that a place for CHEX particles might be formally introduced in the code.



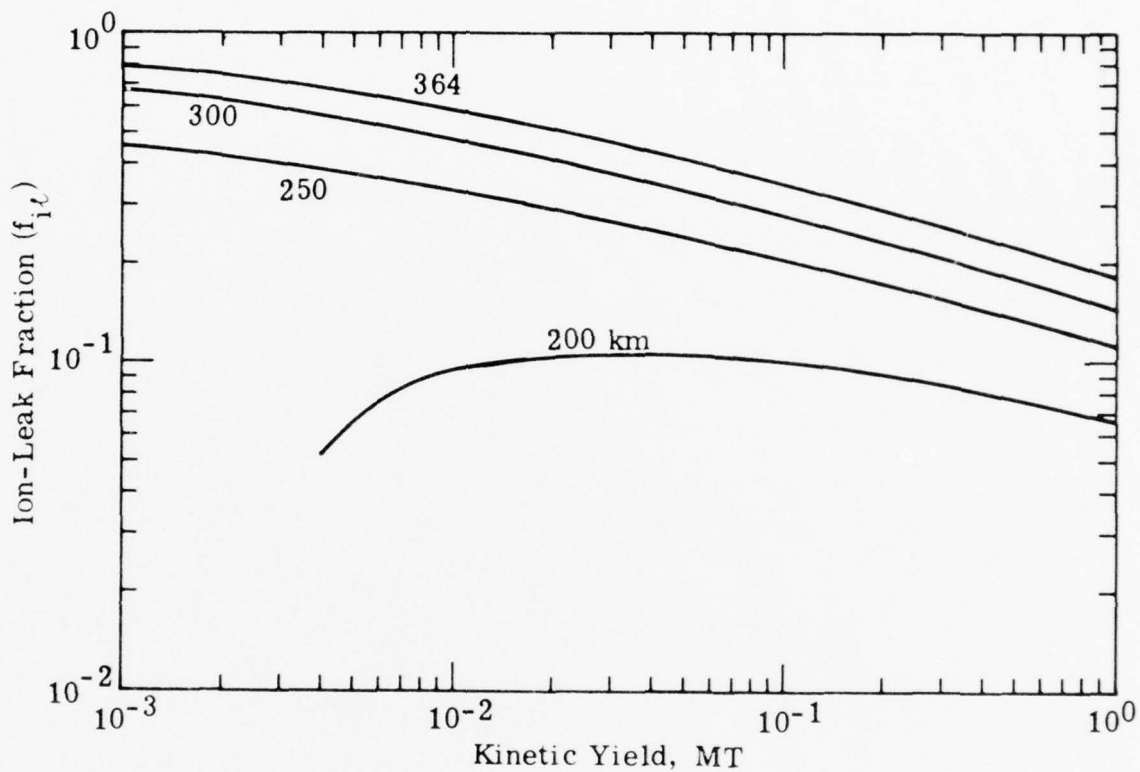


Fig. 5. Fraction of the Total Kinetic Yield Escaping the Event-Point Region by the Ion-Leak Mechanism, for Several Event Altitudes. Curves are drawn for  $B = 0.5$  gauss and the CIRA-65 mean atmosphere. By our assumption the downward fraction  $f_{i\ell d}$  equals  $0.5 f_{i\ell}$ .

The RANC IV prescription for CHEX-particle energy emission (in MT), adapted to our needs, is

$$W_{\text{chex}} = \frac{1}{6} (F_{\text{CED}} + F_{\text{CEU}} + 4 F_{\text{CE}}) W_2 \quad (14a)$$

$$W_2 = W_K - W_{\ell c} - W_{i\ell} , \quad (14b)$$

where  $F_{\text{CED}}$ ,  $F_{\text{CEU}}$ , and  $F_{\text{CE}}$  are coefficients associated with the downward, upward, and horizontal directions, respectively. In terms of the burst-point mass density  $\rho_a$ , their values are

$$F_{\text{CED}} = \begin{cases} 0.0 & \rho_a \geq 3 \times 10^{-13} \\ 10^{-15}/\rho_a & 3 \times 10^{-15} \leq \rho_a < 3 \times 10^{-13} \\ -0.27 \ln(10^{14} \rho_a) & 2.6 \times 10^{-16} < \rho_a < 3 \times 10^{-15} \\ 0.98 & \rho_a \leq 2.6 \times 10^{-16} \end{cases} \quad (15a)$$

$$F_{\text{CEU}} = \begin{cases} 0.25 \times 10^{-13}/\rho_a & \rho_a > 4.65 \times 10^{-14} \\ 0.25 \times 10^{14} \rho_a & \rho_a \leq 4.65 \times 10^{-14} \end{cases} \quad (15b)$$

$$F_{\text{CE}} = \begin{cases} 3 \times 10^{-15}/\rho_a & \rho_a \geq 3.16 \times 10^{-15} \\ 0.95 & 1.15 \times 10^{-15} \leq \rho_a < 3.16 \times 10^{-15} \\ 0.2 \ln(10^{17} \rho_a) & 10^{-17} < \rho_a < 1.15 \times 10^{-15} \\ 0.0 & \rho_a \leq 10^{-17} \end{cases} \quad (15c)$$

The fraction of the weapon kinetic energy leaving the burst region by the charge-exchange mechanism is

$$f_{\text{chex}} = W_{\text{chex}}/W_K . \quad (16)$$

In Fig. 6 we have plotted  $f_{\text{chex}}$  as a function of the kinetic yield  $W_K$ . We question the validity of the predicted CHEX emission for events below 150 km. Some modification of the model at low altitudes is clearly required.

### 3.2.4 Residual Energy for UV and Thermal Modes

After subtraction of the energies in the loss-cone, ion-leak, and CHEX particles, we obtain the energy left for the production of UV-photon and thermal energies. If the residual energy is given (in MT) by

$$W_R = W_K - W_{lc} - W_{il} - W_{\text{chex}} , \quad (17)$$

then the fraction of the kinetic yield available is

$$f_R = W_R / W_K . \quad (18)$$

The fraction of the weapon kinetic energy available for the UV and thermal modes is plotted in Fig. 7 as a function of the kinetic yield  $W_K$ .

## 3.3 PARTICLE ENERGY DISTRIBUTION

Each source of fast heavy-particles has a different energy distribution. We record the distributions presently used.

### 3.3.1 Loss-Cone Spectrum

The velocity distribution of downward-going loss-cone particles is assumed to be [ Vol. 10, Eq. (4-4) ]

$$\frac{dW}{dv} = \frac{5 W_{lcd} v^4}{v_2 - v_1} \text{ (MT sec cm}^{-1}\text{)} . \quad (19a)$$

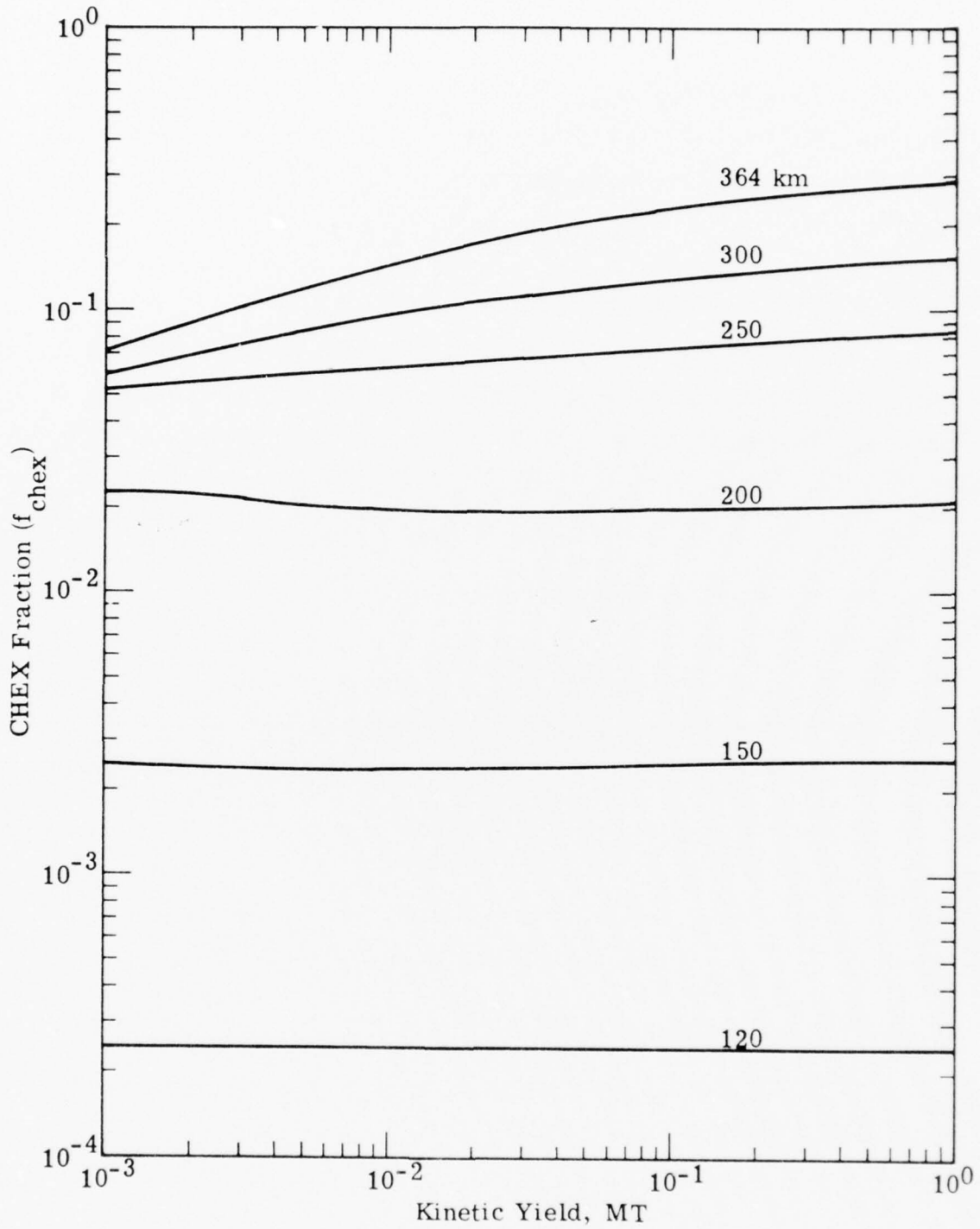


Fig. 6. Fraction of Total Kinetic Yield Escaping the Event-Point Region by the Charge-Exchange Mechanism, for Several Event Altitudes. Curves are drawn for the same conditions as in Figs. 4 and 5.

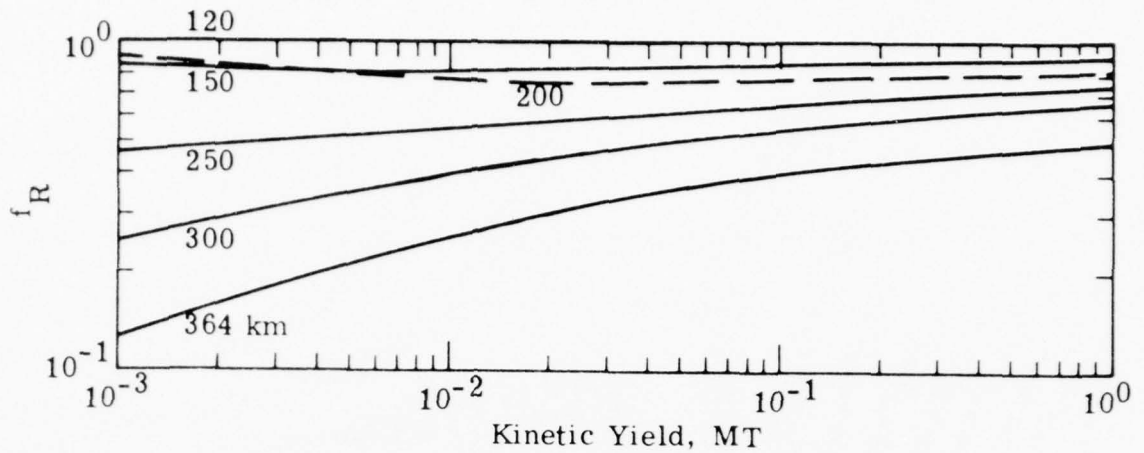


Fig. 7. Fraction of the Total Kinetic Yield Remaining for the UV and Thermal Modes ( $f_R$ ) After the Subtraction of the Loss-Cone, Ion-Leak, and Charge-Exchange Fractions. Curves are drawn for the same conditions as in Figs. 4, 5, and 6.

Equation (19a) is readily integrated to give an integral velocity distribution which may be transformed to an integral energy distribution,

$$\frac{W_{tcd}(\leq E)}{W_{tcd}} = \frac{E^{5/2} - E_{\min}^{5/2}}{E_{\max}^{5/2} - E_{\min}^{5/2}}, \quad (19b)$$

where

$$E_{\min} = \frac{1}{2} m_d v_1^2 \text{ (erg)} \quad (20a)$$

$$E = \frac{1}{2} m_d v^2 \text{ (erg)} \quad (20b)$$

$$E_{\max} = \frac{1}{2} m_d v_2^2 \text{ (erg)} \quad (20c)$$

$$v_1 = \max\{0, v_2 - 4 \times 10^7\} \text{ (cm/sec)} \text{ [Vol. 10, Eq. (4-3)]} \quad (20d)$$

$$v_2 = v_d + 2 \times 10^7 \text{ (cm/sec)} \quad [\text{Vol. 10, Eq. (4-3)}] \quad (20e)$$

$$v_d = 2.7 \times 10^8 W_K^{0.27} \text{ (cm/sec)}, \quad [\text{Vol. 10, Eq. (4-1)}] \quad (20f)$$

with  $m_d$  the debris-ion mass in grams and  $W_K$  the burst kinetic energy in MT.

### 3.3.2 Ion-Leak Spectrum

The velocity distribution of downward-going ion-leak particles is assumed to be [Vol. 10, Eq. (4-11)]

$$\frac{dW}{dv} = \frac{W_{i\ell d}}{v_2 - v_3} \text{ (MT sec cm}^{-1}\text{)}. \quad (21)$$

Equation (21) is readily integrated to give an integral velocity distribution which may be transformed to an integral energy distribution,

$$\frac{W_{i\ell d}(\leq E)}{W_{i\ell d}} = \frac{E^{1/2} - E_{\min}^{1/2}}{E_{\max}^{1/2} - E_{\min}^{1/2}} \quad (22)$$

where

$$E_{\min} = \frac{1}{2} m v_3^2 \quad (23a)$$

$$E = \frac{1}{2} m v^2 \quad (23b)$$

$$E_{\max} = \frac{1}{2} m v_2^2 \quad (23c)$$

with  $m$  the ion-leak particle mass,  $v_2$  given by Eq. (20e), and

$$v_3 = 1.5 \times 10^7 \text{ (cm/sec)}. \quad [\text{Vol. 10, Eq. (4-11)}] \quad (24)$$

### 3.3.3 CHEX Spectrum

The charge-exchange particle spectrum tends to vary widely with burst altitude, direction of emission, and the weapon expansion velocity. To satisfy our immediate needs we have assumed an exponential energy distribution. Examination of earlier work [HL-71, HM-72b] tends to lend support for this functional form. Explicitly, the integral energy spectrum is

$$\frac{W_{\text{chex}}(E)}{W_{\text{chex}}} = \frac{e^{-aE_{\text{min}}} - e^{-aE}}{e^{-aE_{\text{min}}} - e^{-aE_{\text{max}}}} \quad (25a)$$

with

$$a = 10^{-4} \text{ (eV)}^{-1} \quad (25b)$$

$$E_{\text{min}}(\text{eV}) = \frac{m (10^7)^2}{2 \times 1.6 \times 10^{-12}} \quad (25c)$$

$$E_{\text{max}}(\text{eV}) = \frac{m v_2^2}{2 \times 1.6 \times 10^{-12}} \quad (25d)$$

$m$  corresponding to a mass-15 particle, and  $v_2$  given by Eq. (20e).



#### 4. UV SOURCE CHARACTERISTICS

We have adopted the HARC-code prescription, given in our Subroutine EUXFIT, for the UV spectrum as a function of the event-point density and kinetic energy. This prescription, based on calculations by Fajen and Sappenfield [FS-71a, Table IV; FS-73], gives the fraction  $f_i$  ( $i = 1, 5$ ) of the kinetic energy converted to UV in each of five spectral energy groups (with energy-bin edges at 0, 13.6, 15.6, 17, and 30 eV), according to the expression

$$f_i = (a_i x^2 + b_i x + c_i) y^2 + (d_i x^2 + e_i x + f_i) y + g_i x^2 + h_i x + p_i, \quad (26)$$

where

$$x = \ln K$$

$$y = \ln \rho$$

$K$  (KT) = available kinetic energy

$\rho$  ( $\text{g}/\text{cm}^3$ ) = event-point density .

Because of the approximate nature of the equations, the total fraction (FRU) is given [FS-71a] by Eq. (26) with another set of coefficients ( $i = 7$  in the code). However, the code limits FRU to a maximum value of 0.98. If either  $f_i$  or FRU is negative for certain conditions, it is set equal to zero. The intended [FS-71a] range of validity of Eq. (26) is given by the expressions

$$8 \times 10^{-10} \leq \rho \leq 6 \times 10^{-14}$$

$$5 \leq K \leq 10^4 .$$



In the HARC Subroutine DSFIT, which we renamed EUXFIT after making minor changes, D. H. Sowle introduced a sixth energy group due to effective, low-energy x rays. The fraction  $f_6''$  is given by

$$f_6'' = f_6' + \frac{\text{FRX} \times \text{EX}}{\text{EUX}}$$

where

$$f_6' = \frac{0.01}{0.01 + \sum_{i=1}^5 f_i} \frac{\text{FRU} \times \text{EH}}{\text{EUX}},$$

EH = K, EX is the x-ray energy, and EUX is the sum of the Group-U and an effective low-energy portion of Group X, given by

$$\text{EUX} = \text{FRU} \times \text{EH} + \text{FRX} \times \text{EX}.$$

Here, FRX is given by

$$\text{FRX} = \text{Max}[0.08(1 - \text{TBAREX}), 10^{-6}].$$

TBAREX = fraction of x-ray energy escaping a 10-km radius, obtained by calling Subroutine XTCOEF.

The fractions  $f_i$  in Eq. (26) are normalized by the expression

$$f_i' = \frac{f_i}{0.01 + \sum_{i=1}^5 f_i} \frac{\text{FRU} \times \text{EH}}{\text{EUX}}, \quad i = 1, 5.$$

One can verify that

$$\sum_{i=1}^5 f_i' + f_6'' = 1.$$

The Fortran variables for  $f_i'$  ( $i = 1, 5$ ) and  $f_6''$  are FR(I),  $I = 1, 6$ . FR(6) is not used in the HAG module.

## 5. X-RAY SOURCE CHARACTERISTICS AND ENERGY DEPOSITION

To facilitate development of the HAG module, we used the HARC Subroutine XTCOEF instead of the corresponding GET routines for the x-ray source and deposition characteristics. By improving the HARC procedure for x-ray energy deposition, we also eliminated use of the HARC Subroutine XDCOEF, used for x-ray energy deposition. Our calculation of the x-ray energy deposition is done in Subroutine PHEAT.

The HARC Subroutine XTCOEF(EM, TBARX) provides the effective energy transport coefficient for six spectral types, each characterized by the value of an index ( $1 \leq \text{IDSX} \leq 6$ ). The argument EM ( $\text{g/cm}^2$ ) is the intervening air mass and TBARX is the fraction of the energy reaching the depth EM. To prevent Subroutine XTCOEF from returning a physically impossible value in excess of 1.0 (due to using the same formula for extrapolation as interpolation), we revised the routine by using the formula

$$\text{TBARX} = 1 - \frac{\text{EM}}{10^{-7}} [1 - \text{COEF}(1, \text{IDSX})]$$

for values of EM less than  $10^{-7} \text{ g/cm}^2$ , where COEF(1, IDSX) is the coefficient for the spectral index IDSX.

To deposit x-ray energy, we use the formula

$$\text{DAIXX}(\text{erg/g}) = \frac{\text{EX}}{4\pi} \frac{\text{TBXIN} - \text{TBXOUT}}{(\rho/3)(R_{\text{out}}^3 - R_{\text{in}}^3)},$$

where EX is the total x-ray energy, TBXIN and TBXOUT are obtained by calls to Subroutine XTCOEF(EMIN, TBXIN) and XTCOEF(EMOUT, TBXOUT), and the input arguments EMIN and EMOUT are given by

$$\text{EMIN}(\text{g/cm}^2) = \int_0^{R_{\text{in}}} \rho \, dR$$

$$\text{EMOUT}(\text{g/cm}^2) = \int_0^{R_{\text{out}}} \rho \, dR \ ,$$

with  $\rho(\text{g/cm}^3)$  being the total mass density.  $R_{\text{in}}$  and  $R_{\text{out}}$  are the distances from the event point to the points of entry and exit of a cell, measured along the ray path from the event point through the cell center.

For permanent use one needs to replace the HARC Subroutine XTCOEF with the GET [ Vol. 12] equivalent Subroutines WOX1(I) and WOXC(I, PMASS, FCONT) and Function EXPINTP(X1, Y1, X2, Y2, X). Our DRIVER should call WOX1(I) to read (a) the fractional x-ray energy in each of 18 energy groups (SPECX), and (b) the yield fraction in x rays (FEDX), and fill WOX Common. One needs to change the current calls to Subroutine XTCOEF in Subroutines EUXFIT and PHEAT by calls to Subroutine WOXC, and take account of the fact that FCONT returned by Subroutine WOXC is the fraction of x-ray energy contained within PMASS ( $\text{g/cm}^2$ ) rather than being the fraction transmitted beyond EM ( $\text{g/cm}^2$ ) as in Subroutine XTCOEF. One also needs to get the total energy WB (MT) into DEVICE Common, as well as convert from MT to ergs.

## 6. DEPOSITION OF DEBRIS PARTICLES

### 6.1 INTRODUCTION

Before we proceed with the detailed physical and geometric considerations necessary for deposition, we will outline the overall procedure. The total weapon kinetic yield is divided into loss-cone, ion-leak, CHEX, UV, and thermal energies. Each of these energy components, except the last, is deposited separately in the HAG. First, the loss-cone particles are deposited in a field-aligned tube centered about the burst-point field line. Next, the ion-leak particles are also deposited within a field-aligned tube but of size different from the loss-cone tube. Then we deposit the CHEX particles as neutral particles without any consideration of subsequent ionization and magnetic field focusing. Deposition of UV energy is discussed in Section 9.

Changes of chemical species produced in each cell by the sum of the heavy-particle energy depositions modify the species composition that would normally be seen by the UV photon flux. Although the final species complement may differ in a heavily-dosed cell if the UV were deposited first, the differences are not expected to be large. In lightly-dosed cells, the order of irradiation is probably of minor consequence. At any rate, we found it convenient to deposit the heavy-particle energy first in our implementation.

### 6.2 HEAVY-PARTICLE ENERGY LOSS

According to heavy-particle stopping theory [LS-63], the differential energy loss rate of a particle traversing matter is

$$\frac{dE}{dx} = - n S(E) \quad (\text{eV/cm}) \quad (27)$$

where  $E$  is the particle energy,  $x$  the distance, and  $n$  the number density of target atoms. The stopping cross-section  $S(E)$  has an elastic contribution  $\alpha$  and an inelastic portion  $\beta\sqrt{E}$ ; viz,

$$S(E) = \alpha + \beta\sqrt{E} \quad (\text{eV cm}^2) . \quad (28)$$

Values for oxygen and aluminum atoms slowing down in nitrogen are found by direct substitution into Eqs. (2.5) and (2.7') in LS-63. If the particle energy  $E$  is measured in eV, the values of  $\alpha$  and  $\beta$  are, for oxygen,

$$\alpha_{\text{O}} = 2.98 \times 10^{-14} \quad [\text{eV cm}^2 (\text{target atom})^{-1}]$$

$$\beta_{\text{O}} = 1.13 \times 10^{-16} \quad [\text{eV}^{\frac{1}{2}} \text{ cm}^2 (\text{target atom})^{-1}]$$

and, for aluminum,

$$\alpha_{\text{Al}} = 5.47 \times 10^{-14} \quad [\text{eV cm}^2 (\text{target atom})^{-1}]$$

$$\beta_{\text{Al}} = 1.52 \times 10^{-16} \quad [\text{eV}^{\frac{1}{2}} \text{ cm}^2 (\text{target atom})^{-1}] .$$

Note that the value of  $\alpha_{\text{O}}$  is much larger than that propagated into the work of HM-72b from Appendix 4A of HL-71.

In Eq. (27) it is often convenient to introduce the areal mass density ( $\text{g/cm}^2$ )

$$d\xi = mn \, dx \quad (29)$$

traversed by a particle in lieu of the rectilinear distance; i. e.,

$$m \frac{dE}{d\xi} = -S(E) . \quad (30)$$

Here,  $m$  is the mass of a target atom. From Eq. (30) we can compute by straightforward integration the areal mass density required to slow a particle from energy  $E_1$  to  $E_2$ ,

$$\xi(E_1 \rightarrow E_2) = -m \int_{E_1}^{E_2} \frac{dE}{S(E)} \quad (31a)$$

After inserting Eq. (28) in Eq. (31a) and integrating, we obtain the result

$$\xi(E_1 \rightarrow E_2) = \frac{2m\alpha}{\beta^2} \left\{ \frac{\beta}{\alpha} (\sqrt{E_1} - \sqrt{E_2}) - \ln \frac{1 + \frac{\beta}{\alpha} \sqrt{E_1}}{1 + \frac{\beta}{\alpha} \sqrt{E_2}} \right\} \quad (31b)$$

which is required for the calculation of energy deposition in a cell.

In our application of Eq. (31b) we will normally know  $\xi$  along the particle path in a cell and the cell-entrance energy  $E_1$  of the particle; we will then calculate the particle cell-exit energy  $E_2$  by use of the Function Routine FZET which, given the range, iteratively solves for the energy in the range-energy equation. The difference  $E_1 - E_2$  is then the total energy deposited by the particle in the cell, of which a fraction  $f_\alpha$  is due to elastic collisions and a fraction  $f_\beta$  is due to inelastic collisions, where

$$f_\alpha = \delta E_\alpha / (E_1 - E_2) \quad (32a)$$

$$\delta E_\alpha = \alpha \xi(E_1 \rightarrow E_2) / m \quad (32b)$$

$$f_\beta = 1 - f_\alpha \quad (32c)$$

If the error in using the first-order Taylor expansion of Eq. (29) is less than the corresponding tolerance accepted in using the Function Routine FZET, as is the case if the traversed areal density is very small, we compute the cell-exit energy by using the (second-order) Taylor expansion of Eq. (30).



### 6.3 ENERGY DEPOSITION OVER A DISTRIBUTION FUNCTION

Although Eq. (28) gives the stopping cross-section for a monoenergetic particle of energy  $E$ , the particle emissions span a distribution of energies. The sum of the elastic ( $\epsilon_e$ ) and inelastic ( $\epsilon_i$ ) energy contributions per target atom ( $\text{eV atom}^{-1}$ ) is

$$\epsilon_t = \frac{1}{A} \int_0^\infty dE (\alpha + \beta\sqrt{E}) \left( -\frac{dN}{dE_0} \frac{dE_0}{dE} \right)_{E_0=E_\xi+E} \quad (33a)$$

$$= \epsilon_e + \epsilon_i \quad (33b)$$

with  $A$  the cross-sectional area of the particle beam at the deposition location,  $E_0$  the particle energy at the source prior to penetration of any matter,  $E$  the particle energy at the deposition location after traversal of  $\xi$  ( $\text{g/cm}^2$ ) of material, and  $E_\xi$  the energy lost by the particle to reach the deposition location. The energy transformation function is just

$$\frac{dE_0}{dE} = \frac{S(E_0)}{S(E)} \quad (34)$$

and the number-vs-energy distribution is related to the integral number spectrum by

$$N(>E) = - \int_E^\infty dE_0 \frac{dN}{dE_0} \quad (35)$$

### 6.4 PRACTICAL IMPLEMENTATION

In the practical situation where deposition must be done in hundreds of cells, it is desirable to have analytical expressions for the two integrals in Eq. (33a). Number-distribution functions for the particle sources outlined in Section 3.3 do not lead to expressions analytically integrable.

To circumvent this difficulty we have represented each continuous energy distribution by a number-vs-energy histogram of equal energy intervals. Each bar of the histogram represents a fixed number of particles at a single energy midway between the edge values. Each monoenergetic beam is then deposited as a separate source. An attractive feature of this approach is its adaptability to any distribution that may arise in the future.

#### 6.4.1 Histogram Representation

If the number-vs-energy distribution of the source function is represented by  $p$  monoenergetic beams,

$$\frac{dN}{dE} = \sum_{k=1}^p N_k \delta(E - E_k) , \quad (36)$$

then the elastic and inelastic energies ( $\text{eV atom}^{-1}$ ) deposited at a depth  $\xi (\text{g/cm}^2)$  from the source location are, from Eq. (33b),

$$\epsilon_e = \frac{\alpha}{A} \int_0^{\infty} dE \sum_{k=1}^p N_k \delta(E - \overline{E_k - E_{\xi}}) \quad (37a)$$

$$= \frac{\alpha}{A} \sum_{k=1}^p N_k ; \quad E_k \geq E_{\xi} \quad (37b)$$

and

$$\epsilon_i = \frac{\beta}{A} \int_0^{\infty} dE \sqrt{E} \sum_{k=1}^p N_k \delta(E - \overline{E_k - E_{\xi}}) \quad (38a)$$

$$= \frac{\beta}{A} \sum_{k=1}^p N_k \sqrt{E_k - E_{\xi}} ; \quad E_k \geq E_{\xi} . \quad (38b)$$

The number of particles at energy  $E_k$  for each particle source function is found from

$$N_k = \frac{1}{p} \frac{W}{E_k} \quad (39)$$

where  $W$  assumes, in turn, each of the values (expressed in eV) of  $W_{lcd}$ ,  $W_{ild}$ , and  $W_{chex}$ . Beam energies  $E_k$  are determined from the  $p+1$  histogram-bar edges by

$$E_k = \frac{1}{2} (E_i + E_{i+1}) ; \quad \begin{cases} i = 1, \dots, p \\ k = i \end{cases} \quad (40)$$

#### 6.4.2 Loss-Cone Histogram

Histogram-bar energy edges for the downward-going loss-cone yield is found by equating the right-hand side of Eq. (19b) to the fraction of the energy below  $E_{i+1}$ . Explicitly we have

$$\frac{E_{i+1}^{5/2} - E_{\min}^{5/2}}{E_{\max}^{5/2} - E_{\min}^{5/2}} = \frac{i}{p} ; \quad i = 1, \dots, p \quad (41)$$

or

$$E_{i+1} = \left[ E_{\min}^{5/2} + \frac{i}{p} (E_{\max}^{5/2} - E_{\min}^{5/2}) \right]^{2/5} ; \quad i = 1, \dots, p \quad (42)$$

with

$$E_1 = E_{\min} , \quad E_{p+1} = E_{\max} .$$

#### 6.4.3 Ion-Leak Histogram

For the ion-leak source we use Eq. (22) to find the energy edges,

$$\frac{E_{i+1}^{\frac{1}{2}} - E_{\min}^{\frac{1}{2}}}{E_{\max}^{\frac{1}{2}} - E_{\min}^{\frac{1}{2}}} = \frac{i}{p} ; \quad i = 1, \dots, p \quad (43)$$

or

$$E_i = \left[ E_{\min}^{\frac{1}{2}} + \frac{i}{p} \left( E_{\max}^{\frac{1}{2}} - E_{\min}^{\frac{1}{2}} \right) \right]^2 ; \quad i = 1, \dots, p \quad (44)$$

with

$$E_1 = E_{\min} , \quad E_{p+1} = E_{\max} .$$

#### 6.4.4 CHEX Histogram

In a similar manner we use Eq. (25a) to find the energy histogram-bar edges for the CHEX-particle source:

$$\frac{e^{-aE_{\min}} - e^{-aE_{i+1}}}{e^{-aE_{\min}} - e^{-aE_{\max}}} = \frac{i}{p} ; \quad i = 1, \dots, p \quad (45)$$

or

$$E_{i+1} = -\frac{1}{a} \ln \left[ e^{-aE_{\min}} - \frac{i}{p} \left( e^{-aE_{\min}} - e^{-aE_{\max}} \right) \right] ; \quad i = 1, \dots, p \quad (46)$$

with

$$E_1 = E_{\min} , \quad E_{p+1} = E_{\max} .$$

### 6.5 PARTICLE SPATIAL DISTRIBUTIONS

In addition to an energy distribution, each of the three heavy-particle sources has its own spatial distribution. Since we did not have time to introduce the re-direction effects of the geomagnetic field in the

deposition of CHEX particles, we assumed the particles to be emitted with spherical symmetry. However, the loss-cone and ion-leak particles are guided by the geomagnetic field in the deposition processes within tubes about the burst-point field line. In this section we discuss the deposition and the particle spatial distribution within these tubes; we ignore spiralling effects.

Before presenting the formulas, we describe the overall procedure. The differential form for the radial distribution of the downward-moving loss-cone and ion-leak energies has been specified at 100-km altitude by Crevier and Kilb [Vol. 10]. We consider the corresponding integral distribution function and form  $q$  concentric rings in the tangent plane so that each ring contains  $1/q$  of the total energy for either the loss-cone or ion-leak particles. We compute the location (geographic colatitude and east longitude) of the center of the distribution function, i. e., the origin of the tangent-plane coordinate system at 100-km altitude, by tracing the event-point field line. The source points (in the vicinity of the event point) corresponding to representative points in the concentric rings are determined by tracing the field lines passing through the representative points to their intersections with the equipotential surface through the event point.

#### 6.5.1 Representation of the Spatial Distribution at 100-km Altitude

The spatial distribution suggested by Vol. 10 for the downward-going particle-energy in the loss-cone and ion-leak tubes is of the form

$$dW_d = \frac{W_d}{\pi R_o^2} \frac{r}{[1 + (r/R_o)^2]^2} dr d\phi , \quad (47)$$

such that the integration over the cross-sectional area of the tube,

$$\frac{W_d}{\pi R_0^2} \int_0^{2\pi} d\varphi \int_0^\infty dr \frac{r}{[1 + (r/R_0)^2]^2} = W_d, \quad (48)$$

is just the downward-going energy. In these expressions  $r$  and  $\varphi$  are the coordinates in the tube's cross-sectional area,  $W_d$  acquires the value  $W_{\ell cd}$  or  $W_{i\ell d}$ , and  $R_0$  acquires the characteristic tube radius  $R_{\ell c}$  or  $R_{i\ell}$  for the loss-cone and ion-leak particles, respectively. The variable  $r$  is ultimately defined in Vol. 10 as the horizontal distance, at 100-km altitude, from the burst-point field line to the field line through a representative point.

The integral distribution function for the particle energy passing within a distance  $r$  of the event-point field line is found from Eq. (48) by integrating from 0 to radius  $r$ , i. e.,

$$\frac{W_d(0, r)}{W_d} = 1 - \frac{1}{1 + r^2/R_0^2}. \quad (49)$$

To avoid the concept of a tube with infinite radius, we limit the radius of the tube to  $3R_0$ . According to Eq. (49),  $W_d(0, 3R_0)/W_d = 0.90$ , i. e., 0.90 of the energy lies within the radius  $3R_0$ . However, we will re-normalize the distribution function so that the entire energy  $W_d$  is within the radius  $3R_0$ . Our new integral distribution function for the radial distribution of the particle energy is

$$f = \frac{1}{0.9} \frac{\rho^2}{1 + \rho^2} \quad (50a)$$

where

$$\rho \equiv r/R_0. \quad (50b)$$



If we solve Eq. (50a) for  $\rho$ ,

$$\rho = \left[ \frac{0.9f}{1 - 0.9f} \right]^{\frac{1}{2}} \quad (51a)$$

or

$$r = R_0 \left[ \frac{0.9f}{1 - 0.9f} \right]^{\frac{1}{2}}, \quad (51b)$$

we then can compute the radius for a given value of  $f$ . For the present we are using four annular rings, with outer radii corresponding to values of  $f$  equal to  $1/4$ ,  $1/2$ ,  $3/4$ , and  $1$ , and characteristic circles within these annular rings with radii corresponding to values of  $f$  equal to  $1/8$ ,  $3/8$ ,  $5/8$ , and  $7/8$ . These radii are tabulated in Table 1. On each characteristic circle we place four representative points at 90-deg intervals except that we also place a representative point at the center and on the fourth characteristic circle we double the number of points. To the set of  $s$  equally-spaced representative points on alternate characteristic circles, we apply a rotation about the event-point field line equal to  $\pi/s$ . The weight assigned to each of the  $s$  representative points within one of the  $q$  annular rings is  $1/(qs)$ . The annular rings, characteristic circles, and representative points currently used are shown in Fig. 8.

#### 6.5.2 Particle Allocations

The spatial allocation of the source particles  $N_k$  (cf. Eq. (39)) at energy  $E_k$  is simply  $N_k/(qs)$  for every field line traced.

Table 1. Radii of Annular Rings and Characteristic Circles Used to Approximate the Radial Distribution Function of Downward-Moving Loss-Cone and Ion-Leak Energies.

Integral Fraction of Energy, $f$	Outer Radius of Annular Ring <sup>a</sup>	Radius of Characteristic Circle <sup>a</sup>
0	0	
0.125		0.356
0.250	0.539	
0.375		0.713
0.500	0.904	
0.625		1.134
0.750	1.441	
0.875		1.925
1.000	3.000	

<sup>a</sup>In units of the characteristic tube radius  $R_0$ .

## 6.6 STARTING COORDINATES OF THE FIELD LINES

It remains to establish the geocentric coordinates (longitude, colatitude, and geocentric-radius) of each of the particle source points in the vicinity of the event point. As mentioned above, these source points, corresponding to the representative points in the tangent plane at 100-km altitude, are determined by tracing the field lines passing through the representative points to their intersection with the equipotential surface through the event point. We now derive the equations to determine these intersections.

The equation for a dipole field line is

$$r = r_0 \sin^2 \chi \quad (52)$$

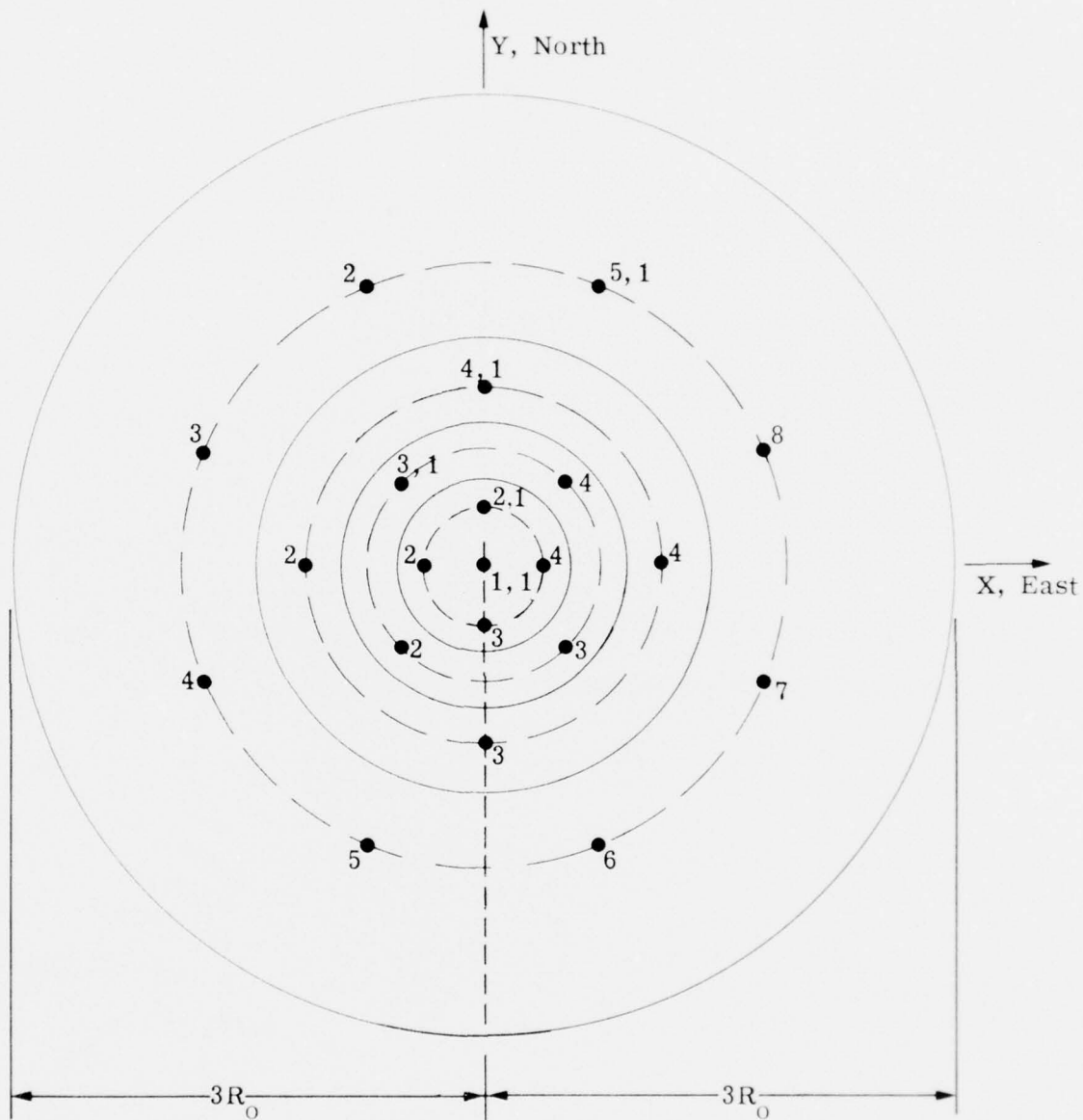


Fig. 8. Four Annular Rings, Four Characteristic Circles, and 21 Representative Points Used to Approximate the Radial Distribution of Downward-Moving Loss-Cone and Ion-Leak Energies. The plane of the paper represents a tangent plane at 100-km altitude with origin at the event-point field line. East on the diagram corresponds to the tangent-plane X axis.

where  $r_0$  is the equatorial radius and  $\chi$  is the dipole colatitude. (The  $r$  in Eq. (52) should not be confused with the  $r$  in Section 6.5.1.) The potential function for a magnetic dipole is

$$V = |M| r^{-2} \cos \chi \quad (53)$$

where  $|M|$  is the magnitude of the magnetic dipole moment. For a constant value of  $V$ ,

$$|M| r^{-2} \cos \chi = |M| r_1^{-2} \cos \chi_1, \quad (54)$$

where the subscript 1 denotes the event point, so that the equation for the equipotential curve is

$$r = r_1 \left[ \frac{\cos \chi}{\cos \chi_1} \right]^{\frac{1}{2}}. \quad (55)$$

The equation for the field line through a source point is given by Eq. (52) which we rewrite as

$$\cos^2 \chi = 1 - r/r_0. \quad (56)$$

By eliminating  $\cos^2 \chi$  between Eqs. (55) and (56), we get

$$r_s^4 = \frac{r_1^4}{\cos^2 \chi_1} \left[ 1 - \frac{r_s}{r_0} \right] \quad (57)$$

or

$$x^4 + AB^{-1}x - A = 0 \quad (58)$$

where

$$x = 1 + h_s/R_e \quad (59a)$$

$$A = \frac{(1 + h_1/R_e)^4}{\cos^2 \chi_1} \quad (59b)$$

$$B = 1 + h_o/R_e \quad (59c)$$

We use Newton's method of iteration to solve the quartic, Eq. (58), for the (reduced) geocentric radius at which the source-point field line intersects the event-point equipotential surface. Given the geographic coordinates of a representative point in the tangent plane at 100-km altitude, Subroutine CONJUG will trace the field line through the point to an altitude  $h_s$  and return the desired geocentric coordinates (latitude and longitude) of the intersection of the source-point field line and the event-point equipotential surface.

#### 6.7 FIELD-LINE TRACING

We need to know the heavy-particle energy deposited in each cell, which can be found if we know the areal mass density along the path within a cell (the product of the field-line path length within the cell and the mass density in the cell). Thus, we must trace a field line from the source point through each cell until the boundary of the HAG is reached.

To trace the field lines we start at a given source point at altitude  $h_s$ . Given the geographic coordinates of the source point and a new altitude  $h_v$  and altitude step  $\Delta h$ , where

$$h_v = h_s - \Delta h \quad , \quad (60)$$

$$\Delta h = \Delta \ell \sin I \quad , \quad (61)$$

and  $I$  is the local dip angle, Subroutine CONJUG will return the geographic coordinates of the new altitude point and Subroutine INDEX will

return the indices of the cell containing the new point. If the new point is in the same cell as the source point, a second new altitude point, lower by an amount  $\Delta h$ , is selected. Again, Subroutine CONJUG, given the geographic coordinates of the source point and the altitude ( $h_s - 2\Delta h$ ) of the second point, will return the geographic coordinates of the second point on the field line and Subroutine INDEX returns the indices of the cell containing the second point. This procedure is continued until the cell indices indicate the field line has exited from the cell. An iterative backup-and-boundary-crossing procedure is then followed in which  $\Delta l$ , initially set to 8 km, is repeatedly halved and the boundary crossing is finally accepted when  $\Delta l = 1$  km. The field-line path length from the starting point to the (approximate) exit point is also returned by Subroutine CONJUG. This exit point is then used as a new starting point with  $\Delta l = 8$  km and the field line is further traced until it exits the cell from which it last started. This procedure is continued until the field line leaves the HAG or until the most energetic particle being followed has stopped. This procedure is then repeated for every source point corresponding to the set of representative points in the tangent plane at 100-km altitude.

#### 6.8 LOSS-CONE AND ION-LEAK PARTICLE DEPOSITION

Energy deposition for loss-cone and ion-leak particles, while based on Eqs. (37b) and (38b), must be done differently to conserve energy explicitly. In particular, the specific energies (erg/g) deposited in a cell by loss-cone and ion-leak heavy-particle elastic collisions and inelastic collisions, are, respectively,

$$\epsilon'_e = \frac{\epsilon_0}{M} \sum_{k=1}^p N_k (E_{in} - E_{out})_k f_{\alpha k} \quad (62)$$



and

$$\epsilon'_i = \frac{\epsilon_0}{M} \sum_{k=1}^p N_k (E_{in} - E_{out})_k (1 - f_{\alpha k}) \quad (63)$$

where  $E_{in}$  and  $E_{out}$  are the entrance and exit energies (eV) of the particle in the  $k$ th energy group,  $M$  is the cell mass in grams,  $\epsilon_0 = 1.6 \times 10^{-12}$  erg/eV, and  $f_{\alpha k}$  is given by Eq. (32a) with an additional subscript  $k$ .

### 6.9 CHEX-PARTICLE DEPOSITION

As mentioned in Section 6.5, the CHEX-particles are considered emitted with spherical symmetry, or the energy emitted per steradian is given by  $W_{chex}/4\pi$ . Particle paths through each cell are straight and have a direction determined by the line that connects the event point and the center of the cell. Path lengths within each cell, from entrance to exit, are found by the Subroutine PLINE and the intercepted steradianal mass is given by

$$M_{\Omega} = \frac{1}{3} \rho (R_{out}^3 - R_{in}^3) \quad (64)$$

Here,  $\rho$  is the cell mass density;  $R_{in}$  and  $R_{out}$  are slant distances from the event point to the cell entrance and exit, respectively.

The specific energies deposited in a cell by CHEX heavy-particle elastic and inelastic collisions, are, respectively,

$$\epsilon'_e = \frac{\epsilon_0}{M_{\Omega}} \sum_{k=1}^p \frac{N_k}{4\pi} (E_{in} - E_{out})_k f_{\alpha k} \quad (65)$$

and

$$\epsilon'_i = \frac{\epsilon_0}{M_{\Omega}} \sum_{k=1}^p \frac{N_k}{4\pi} (E_{in} - E_{out})_k (1 - f_{\alpha k}) \quad (66)$$

where, again,  $E_{in}$  and  $E_{out}$  are the entrance and exit energies (eV) of the particle in the  $k$ th energy group.

## 7. PARTITIONING OF THE DEPOSITED DEBRIS ENERGY AND CONSEQUENT SPECIES (SUBROUTINE HPCHEM)

Subroutine HPCHEM partitions the total energy lost in each cell by loss-cone, ion-leak, and CHEX particles undergoing inelastic and elastic collisions. The energy is partitioned into heavy-particle thermal, electron thermal, dissociation, ionization, excitation, and radiation. A model of heavy-particle prompt chemistry is also used to compute the changes in number densities of N<sub>2</sub>, O<sub>2</sub>, N(4S), N(2D), O, N<sub>2</sub><sup>+</sup>, O<sub>2</sub><sup>+</sup>, N<sup>+</sup>, O<sup>+</sup>, and electrons.

One of the simplifications made in depositing the heavy-particle energies is that the range-energy relation used in Subroutines DEPO and CHXDEP is based on the total mass density of a cell whereas in Subroutine HPCHEM only the species N<sub>2</sub>, O<sub>2</sub>, and O are considered as targets. The modeling of the associated heavy-particle prompt chemistry is based on a speculative treatment [HM-72b, Section 6; HL-73b, Section 5], modified by the need to interface with the late-time grid chemistry. (The rationale for the heavy-particle prompt-chemistry modeling, to the extent it exists, will not be repeated here.) In this late-time chemistry, for atomic nitrogen only N(<sup>2</sup>D) is carried as an excited term and for atomic oxygen only O(<sup>1</sup>D) is accounted for (implicitly) as an excited term. Thus, N(<sup>2</sup>P) and O(<sup>1</sup>S) are purposely excluded as possible reaction products of the heavy-particle prompt chemistry. Conversion of N<sub>2</sub><sup>+</sup> and O<sub>2</sub><sup>+</sup> into NO<sup>+</sup> (the only molecular ion in the grid chemistry) is performed at the beginning of Subroutine PCHEM.

In Table 2 we summarize the reactions from inelastic and elastic collisions that are modeled in the prompt chemistry from heavy-particle energy deposition.

Table 2. Heavy-Particle Prompt-Chemistry Reactions from Inelastic and Elastic Collisions.

	Reaction	Branching Ratio	Number of Reactions, <sup>a</sup> cm <sup>-3</sup>
INELASTIC	N <sub>2</sub> →	N <sub>2</sub> <sup>+</sup> + e	1/1.35
		N( <sup>4</sup> S) + N <sup>+</sup> + e	0.35/1.35
	O <sub>2</sub> →	O <sub>2</sub> <sup>+</sup> + e	1/1.35
		O( <sup>3</sup> P) + O <sup>+</sup> + e	0.35/1.35
	O →	O <sup>+</sup> + e	$\frac{[O]}{n}$ [e]
ELASTIC	N <sub>2</sub> →	N( <sup>4</sup> S)	4/14
		N( <sup>2</sup> D)	10/14
	O <sub>2</sub> →	O( <sup>3</sup> P)	9/14
		O( <sup>1</sup> D)	5/14
	O →	O( <sup>3</sup> P)	9/14
		O( <sup>1</sup> D)	5/14

<sup>a</sup> n = 2{[N<sub>2</sub>] + [O<sub>2</sub>]} + [O] = number density of nuclei.  
n<sub>c</sub> = number density of particles in cascade of elastic-collision energy.

In Subroutine HPCHEM, before dealing explicitly with the partitioning of the species and energies from the inelastic and elastic collisions, we must make a number of preliminary steps and establish several parameters used in the modeling.

1. From the extended core storage for the cell of interest, obtain the total mass density  $\rho(\text{g/cm}^3)$  and the number densities ( $\text{cm}^{-3}$ ) of  $\text{N}_2$ ,  $\text{O}_2$ , and  $\text{O}$ .

2. For both the inelastic and elastic-collision contributions, sum the specific energies deposited by the loss-cone (PEI and PEE), ion-leak (QEI and QEE), and CHEX (CEI and CEE) particles.

$$\epsilon_i(\text{erg/g}) = \text{PEI} + \text{QEI} + \text{CEI}$$

$$\epsilon_e(\text{erg/g}) = \text{PEE} + \text{QEE} + \text{CEE} .$$

3. Compute the number density of nuclei in  $\text{N}_2$ ,  $\text{O}_2$ , and  $\text{O}$ .

$$n(\text{nuclei/cm}^3) = 2 \{ [\text{N}_2] + [\text{O}_2] \} + [\text{O}] .$$

4. Compute the threshold-energy parameter used in modeling the cascade of elastic energy.

$$E_t = \{ 39.04[\text{N}_2] + 20.48[\text{O}_2] + 25.40[\text{O}] \} / n .$$

In this equation the coefficient of  $[\text{O}]$  includes the replacement of  $\epsilon_m(\text{O})$  by  $\epsilon_m(\text{O}) + \epsilon_r(\text{O})$  in Eq. (68) of HM-72b (or Eq. (40) of HL-73b).

5. Compute the weighted value of the energy removed per collision in the cascade of elastic energy.

$$\epsilon(\text{eV}) = \{ C_1[\text{N}_2] + C_2[\text{O}_2] + C_3[\text{O}] \} / n$$

where

$$C_1 = 2[9.76 + 2.37(1 - F_9) + 12.0]$$

$$C_2 = 2[5.12 + 1.96 F_{10} + 12.0]$$

$$C_3 = 1.96 F_{10} + 12.0$$

$$F_9 = 4/14$$

$$F_{10} = 5/14 .$$

6. Limit the specific energies to values less than those required, according to the model, for complete ionization and (effective) dissociation of the  $N_2$ ,  $O_2$ , and O densities in excess of 1.0. Define

$$N_{HP}(\text{cm}^{-3}) = [N_2] + [O_2] + [O] - 3.0$$

$$\epsilon_{imax} = 28.5 \epsilon_1 N_{HP}$$

$$\epsilon_{emax} = \epsilon \epsilon_1 N_{HP}$$

where the conversion factor  $\epsilon_1$  is

$$\epsilon_1(\text{erg eV}^{-1} \text{ cm}^3 \text{ g}^{-1}) = \epsilon_0 / \rho$$

$$\epsilon_0 = 1.60 \times 10^{-12} \text{ erg/eV} .$$

The fractions of  $N_{HP}$  destroyed by inelastic and by elastic processes are, respectively,

$$g_i = \epsilon_i / \epsilon_{imax}$$

and

$$g_e = \epsilon_e / \epsilon_{emax} .$$



If  $g_i + g_e > 1.0$ , one must reduce  $\epsilon_i$  and  $\epsilon_e$  by the ratio  $1/(g_i + g_e)$ .

We are now ready to deal explicitly with the inelastic collisions.

1. Compute the electron density:

$$[e] = \epsilon_i / (28.5 \epsilon_1) .$$

2. Partition the charged species from inelastic collisions.

$$[N_2^+] = \frac{1}{1.35} \frac{2[N_2]}{n} [e]$$

$$[O_2^+] = \frac{1}{1.35} \frac{2[O_2]}{n} [e]$$

$$[N^+] = \frac{0.35}{1.35} \frac{2[N_2]}{n} [e]$$

$$[O^+]_2 = \frac{0.35}{1.35} \frac{2[O_2]}{n} [e]$$

$$[O^+]_1 = \frac{[O]}{n} [e]$$

$$[O^+] = [O^+]_2 + [O^+]_1 .$$

3. Record the corresponding neutral-atom densities produced in dissociative ionization in inelastic collisions:

$$[N(^4S)] = [N^+]$$

$$[O(^3P)] = [O^+]_2 .$$

4. Partition the energy from inelastic collisions into four modes and the fraction of energy in each mode.

Electron Thermal Energy:

$$E(\text{eV}/\text{cm}^3) = 1.5 [e]$$

$$f'_{\text{KE}} = \epsilon_1 E / \epsilon_i$$

Dissociation Energy:

$$D_i(\text{eV}/\text{cm}^3) = 9.76 [\text{N}^+] + 5.12 [\text{O}^+]_2$$

$$f'_D = \epsilon_1 D_i / \epsilon_i$$

Ionization Energy:

$$I(\text{eV}/\text{cm}^3) = 15.58 [\text{N}_2^+] + 12.06 [\text{O}_2^+] + 14.53 [\text{N}^+] + 13.62 [\text{O}^+]$$

$$f_I = \epsilon_1 I / \epsilon_i$$

$$I_1(\text{erg/g}) = \epsilon_1 I$$

Radiation Energy:

$$f'_R = 1 - (f'_{\text{KE}} + f'_D + f_I)$$

$$R_1(\text{eV}/\text{cm}^3) = f'_R \epsilon_i / \epsilon_1 \cdot$$

We now deal explicitly with the elastic collisions:

1. Compute the total number density of particles from the cascade of elastic energy:

$$n_c(\text{cm}^{-3}) = \frac{4 f_{\text{KE}} \epsilon_e}{\epsilon_1 (3E_t - \epsilon)}$$

where

$$f_{\text{KE}} = \frac{E_t - \epsilon/3}{E_t + \epsilon} .$$

2. Partition the neutral species from elastic collisions. The (fast) particle densities from the elastic-energy cascade are

$$[\text{N}]_c = \frac{2[\text{N}_2]}{n} n_c$$

$$[\text{O}]_{c2} = \frac{2[\text{O}_2]}{n} n_c$$

$$[\text{O}]_{c1} = \frac{[\text{O}]}{n} n_c$$

$$[\text{O}]_c = [\text{O}]_{c2} + [\text{O}]_{c1} .$$

The (slow) particle densities from the elastic-energy cascade are

$$[\text{N}]_{cs} = [\text{N}]_c$$

$$[\text{O}]_{c2s} = [\text{O}]_{c2} .$$

3. Partition among excited states the (total) particle densities from the elastic-energy cascade.

$$[\text{N}(^4\text{S})] = F_9[\text{N}]_c + [\text{N}]_{cs}$$

$$[\text{N}(^2\text{D})] = (1 - F_9) [\text{N}]_c$$

$$[\text{O}(^3\text{P})] = (1 - F_{10}) [\text{O}]_c + [\text{O}]_{c2s}$$

$$[\text{O}(^1\text{D})] = F_{10}[\text{O}]_c .$$

4. Partition the energy from elastic collisions into four modes.

Heavy-particle thermal energy:

$$K(\text{eV}/\text{cm}^3) = f_{\text{KE}} \epsilon_e / \epsilon_1$$

$$K_1(\text{erg}/\text{g}) = \epsilon_1 K$$

Dissociation energy:

$$D_e(\text{eV}/\text{cm}^3) = 9.76[\text{N}]_c + 5.12[\text{O}]_{c2}$$

Excitation energy:

$$X_e(\text{eV}/\text{cm}^3) = 2.37 (1 - F_9)[\text{N}]_c + 1.96 F_{10} [\text{O}]_c$$

$$X_{e1}(\text{erg}/\text{g}) = \epsilon_1 X_e$$

Radiation energy:

$$R(\text{eV}/\text{cm}^3) = 12 \{ [\text{N}]_c + [\text{O}]_c \} .$$

We can now combine the results from inelastic and elastic collisions.

1. Add the contributions from the inelastic and elastic collisions to obtain the total values of dissociation and radiation energies.

$$D(\text{eV}/\text{cm}^3) = D_i + D_e$$

$$D_1(\text{erg}/\text{g}) = \epsilon_1 D$$

$$R(\text{eV}/\text{cm}^3) = R_i + R_e$$

$$R_1(\text{erg/g}) = \epsilon_1 R \quad .$$

2. Compute the total fractional partitions of energy for the six modes.

$$f_K = \epsilon_1 K / (\epsilon_i + \epsilon_e)$$

$$f_E = \epsilon_1 E / (\epsilon_i + \epsilon_e) \quad .$$

$$f_D = \epsilon_1 D / (\epsilon_i + \epsilon_e)$$

$$f_{X_e} = \epsilon_1 X_e / (\epsilon_i + \epsilon_e)$$

$$f_I = \epsilon_1 I / (\epsilon_i + \epsilon_e)$$

$$f_R = \epsilon_1 R / (\epsilon_i + \epsilon_e) \quad .$$

The fractional error in energy conservation is

$$F = f_K + f_E + f_D + f_{X_e} + f_I + f_R - 1 \quad .$$

3. Compute (and collate) the changes in species densities.

$$\delta[N_2] = - \frac{2[N_2]}{n} \{ [e] + n_c \}$$

$$\delta[O_2] = - \frac{2[O_2]}{n} \{ [e] + n_c \}$$

$$\delta[N(^4S)] = [N^+] + (1 + F_9) \frac{2[N_2]}{n} n_c$$

$$\delta[\text{N}(^2\text{D})] = (1 - F_9) \frac{2[\text{N}_2]}{n} n_c$$

$$\delta[\text{O}] = -\frac{[\text{O}]}{n} [e] + [\text{O}^+]_2 + 2 \frac{2[\text{O}_2]}{n} n_c$$

$$\delta[e] = [e]$$

$$\delta[\text{N}_2^+] = \frac{1}{1.35} \frac{2[\text{N}_2]}{n} [e]$$

$$\delta[\text{O}_2^+] = \frac{1}{1.35} \frac{2[\text{O}_2]}{n} [e]$$

$$\delta[\text{N}^+] = 0.35 \delta[\text{N}_2^+]$$

$$\delta[\text{O}^+] = 0.35 \delta[\text{O}_2^+] + \frac{[\text{O}]}{n} [e]$$

4. Compute the sums of changes in densities of nitrogen nuclei, oxygen nuclei, and charged species as measures of conservation errors.

$$\sum \delta\text{N} = 2 \{ \delta[\text{N}_2] + \delta[\text{N}_2^+] \} + \delta[\text{N}(^4\text{S})] + \delta[\text{N}(^2\text{D})] + \delta[\text{N}^+]$$

$$\sum \delta\text{O} = 2 \{ \delta[\text{O}_2] + \delta[\text{O}_2^+] \} + \delta[\text{O}] + \delta[\text{O}^+]$$

$$\sum \delta\text{C} = \delta[\text{N}_2^+] + \delta[\text{O}_2^+] + \delta[\text{N}^+] + \delta[\text{O}^+] - \delta[e] .$$

5. Compute the sum of electron thermal and  $\text{O}(^1\text{D})$  excitation energies per newly-formed electron.

$$E_{pe} (\text{eV/electron}) = \left( E + 1.96 F_{10} \{ [\text{O}_2] + 0.5[\text{O}] \} \frac{2n_c}{n} \right) / [e] .$$



6. Store changes in cell quantities in temporary scratch area (BUF2).

$\text{BUF2}(1) = \delta[e]$	$\text{BUF2}(7) = \delta[\text{N}^+]$
$\text{BUF2}(2) = \delta[\text{N}({}^4\text{S})]$	$\text{BUF2}(8) = \delta[\text{O}^+]$
$\text{BUF2}(3) = \delta[\text{N}({}^2\text{D})]$	$\text{BUF2}(9) = E_{\text{pe}}$
$\text{BUF2}(4) = \delta[\text{O}]$	$\text{BUF2}(10) = K_1$
$\text{BUF2}(5) = \delta[\text{N}_2]$	$\text{BUF2}(11) = \delta[\text{N}_2^+]$
$\text{BUF2}(6) = \delta[\text{O}_2]$	$\text{BUF2}(12) = \delta[\text{O}_2^+]$

## 8. ORGANIZATION OF THE HEAVY-PARTICLE RELATED ROUTINES

An outline of the portion of the HAG module for kinetic-yield partitioning, heavy-particle energy deposition, and generation of consequent chemical species is shown in Fig. 9. The interface with the rest of the HAG module is through three calls by Subroutine PROMPG.

The first call (for debris) from Subroutine PROMPG is to Subroutine DEBRIS which serves as a control routine for seven subsequent steps. Subroutine HDPART is called in Step 1 for the partitioning of the kinetic yield, given the kinetic yield, event-point magnetic field, and event-point mass density. Step 1 is accomplished with the aid of Subroutines LOSCON, IONLEK, and CHXLOS. A return to Subroutine DEBRIS occurs with values for the downward-moving *loss-cone* energy (WLCD), the downward-moving ion-leak energy (WILD), the charge-exchange energy (WCHEX), the characteristic magnetic tube radii for loss-cone particles ( $R_{lc}$ ) and ion-leak particles ( $R_{il}$ ), the minimum ( $v_1$ ) and maximum ( $v_2$ ) velocities in the loss-cone energy spectrum, and the residual energy available for UV and thermal energies.

If  $WLCD > 10^{-4}$  MT, then Step 2 is a call to Subroutine CONSPC to compute the histogram energy distribution for the loss-cone particles and Step 3 is a call to Subroutine BLINE to deposit the loss-cone particle energies in a spatial tube centered about the event-point field line. Subroutines CONJUG, BFIELD, and INDEX aid in the field-line tracing while Subroutine DEPO does the particle energy deposition in a grid cell and detects the stopping locations of the monoenergetic energy groups. Subroutine XYZGEO performs the necessary transformation from tangent-plane cartesian coordinates to geocentric cartesian coordinates. When

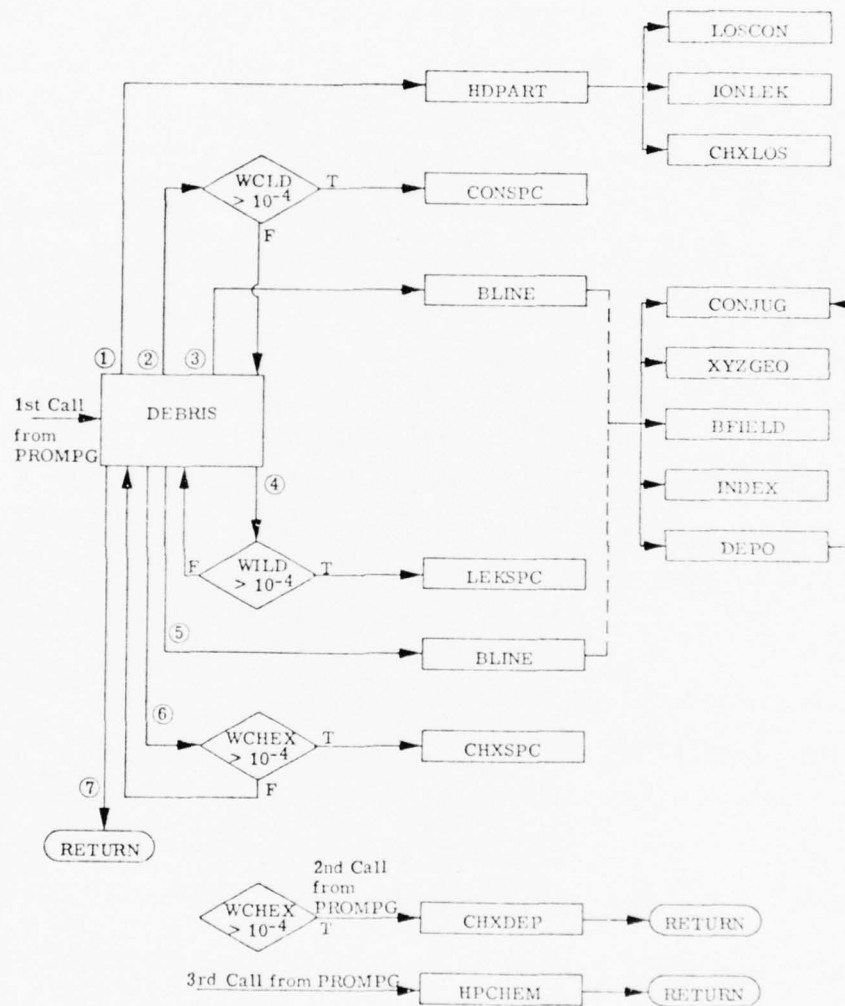


Fig. 9. Simplified Flow Chart of Debris-Related Routines.

control returns from Subroutine BLINE to Subroutine DEBRIS, every cell that is intersected by the loss-cone magnetic tube has a contribution to its specific energy.

If  $WILD > 10^{-4}$  MT, then Step 4 is a call to Subroutine LEKSPC to compute the histogram energy distribution for the ion-leak particles and Step 5 is a call to Subroutine BLINE to deposit the ion-leak particle energies in a spatial tube centered about the event-point field line. The operational procedure of Subroutine BLINE is identical to the loss-cone case except that the heavy particles are considered to have mass number 16 rather than the mass number 27 of the loss-cone particles. After specific-energy contributions are added to cells intersected by the ion-leak tube, control is returned from Subroutine BLINE to Subroutine DEBRIS.

If  $WCHEX > 10^{-4}$  MT, then Step 6 is a call to Subroutine CHXSPC to compute the histogram energy distribution of the CHEX particles for later use by Subroutine CHXDEP. Step 7 is the return to Subroutine PROMPG.

The second call from Subroutine PROMPG to the debris module is to Subroutine CHXDEP, provided  $WCHEX > 10^{-4}$  MT; otherwise the call is bypassed. Contributions to the specific energy by CHEX particles are assigned to every grid cell, provided the areal density to the cell is less than the range of the most energetic CHEX particle.

The third call from Subroutine PROMPG is then made. Contributions to cell specific energy by the three particle sources are summed for the production of changes in the chemical species, thermal energy, and excitation energy. These latter two calls from Subroutine PROMPG are conveniently made just prior to the UV photon deposition since the necessary cell-calling logic is the same.

Detailed flow charts for Subroutines BLINE, DEPO, and CHXDEP are given in Figs. 10, 11, and 12, respectively.

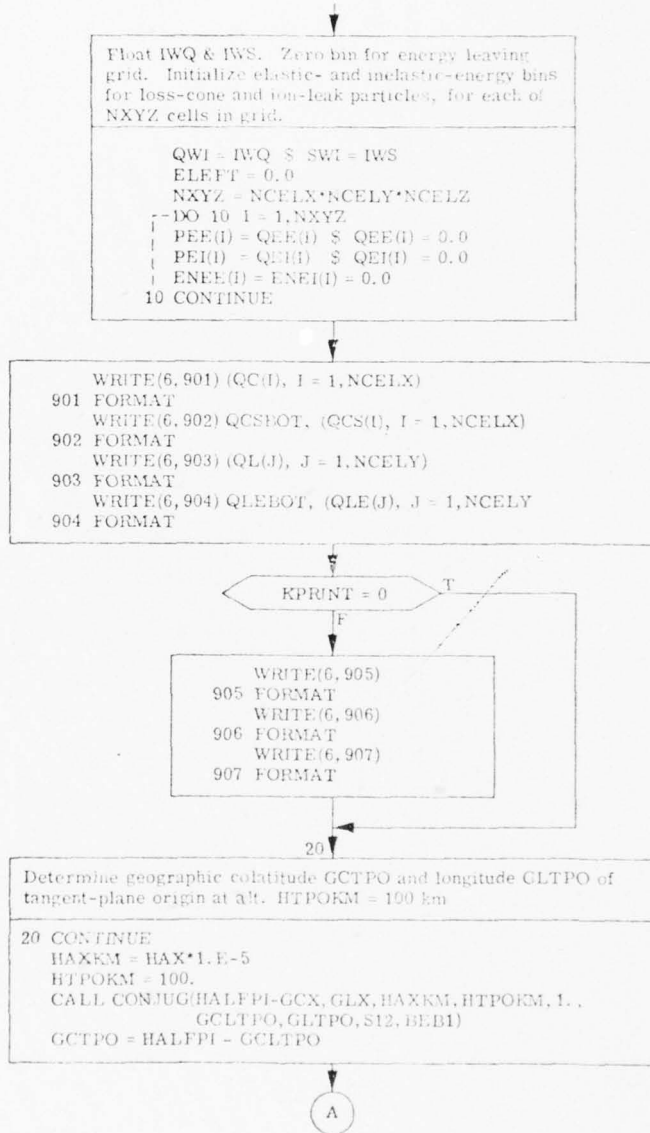


Fig. 10. Flow Chart for Subroutine BLINE(NXCEL, RR).



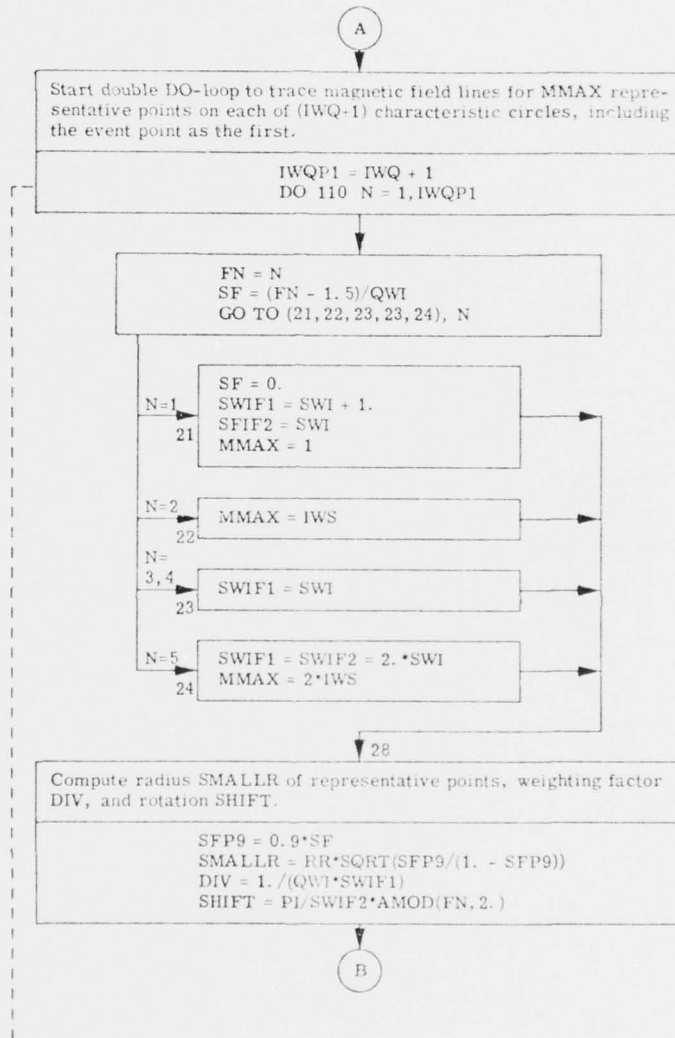


Fig. 10. (Continued).

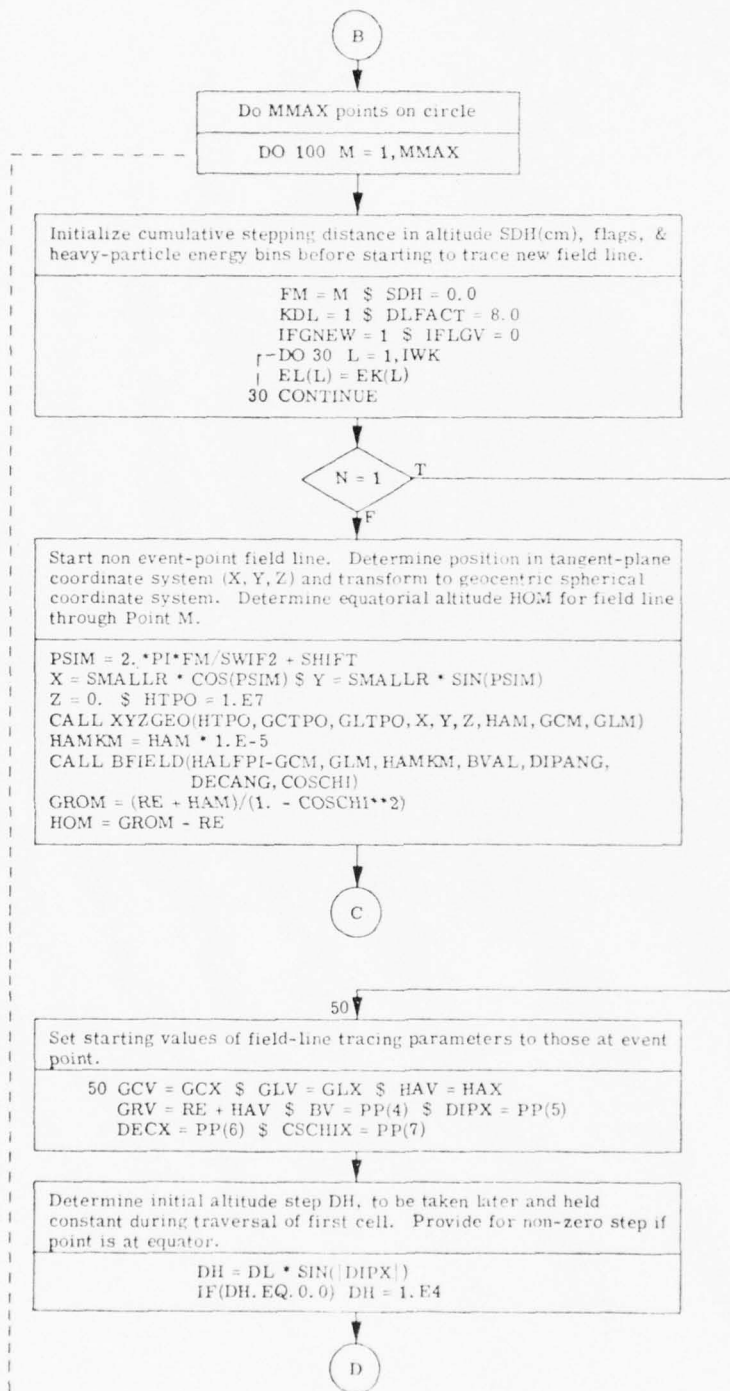


Fig. 10. (Continued).

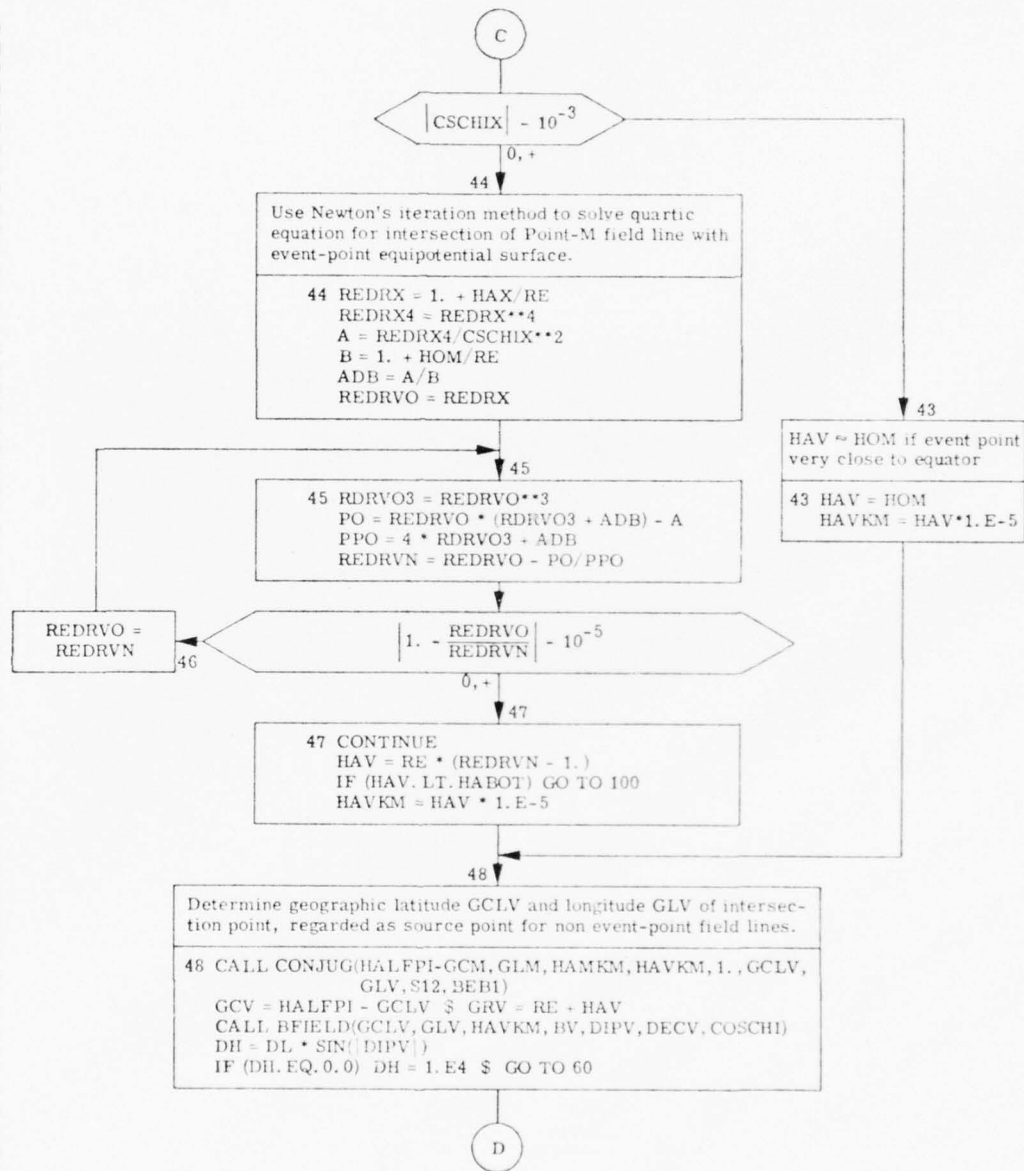


Fig. 10. (Continued).

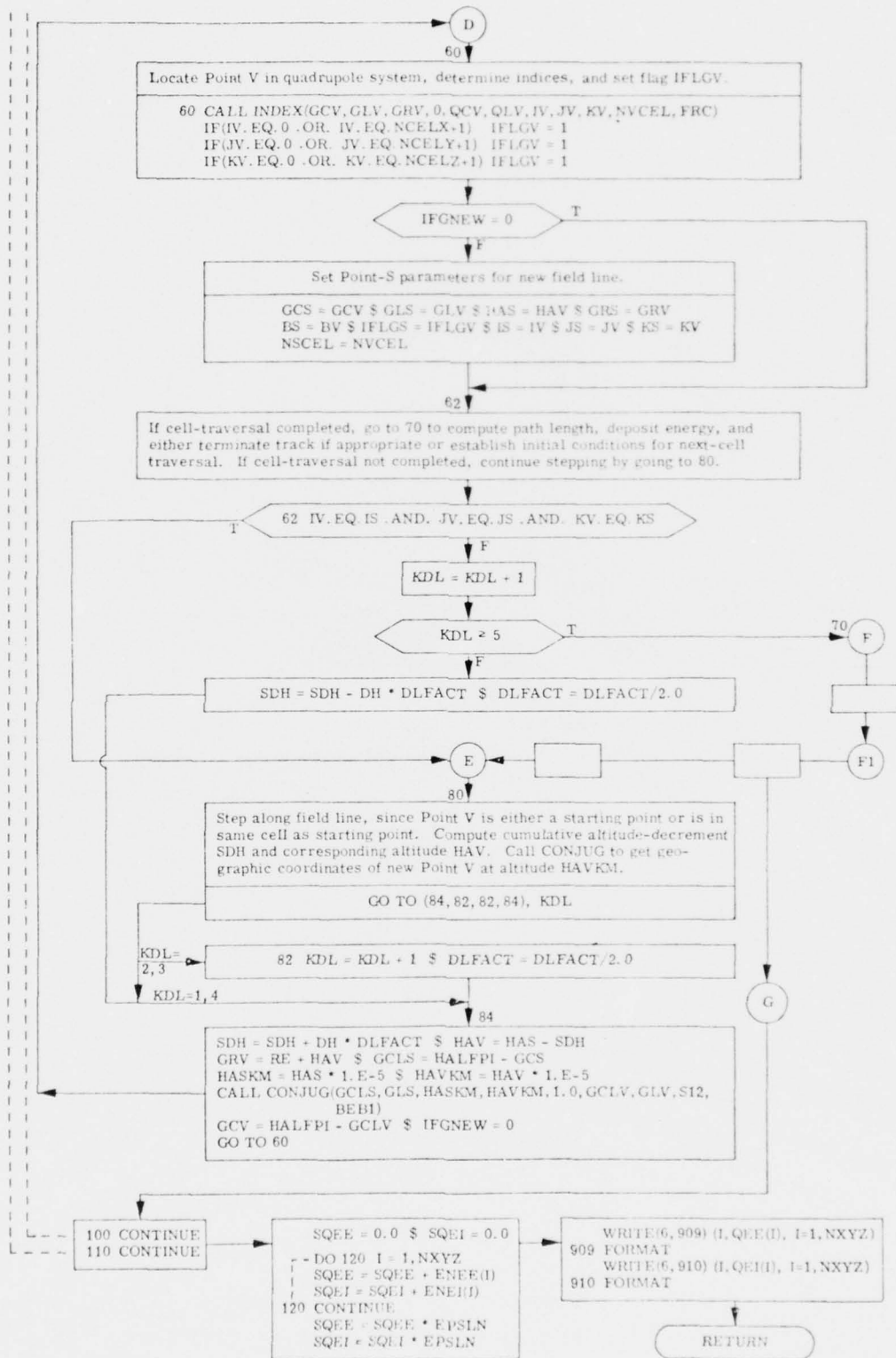


Fig. 10. (Continued).

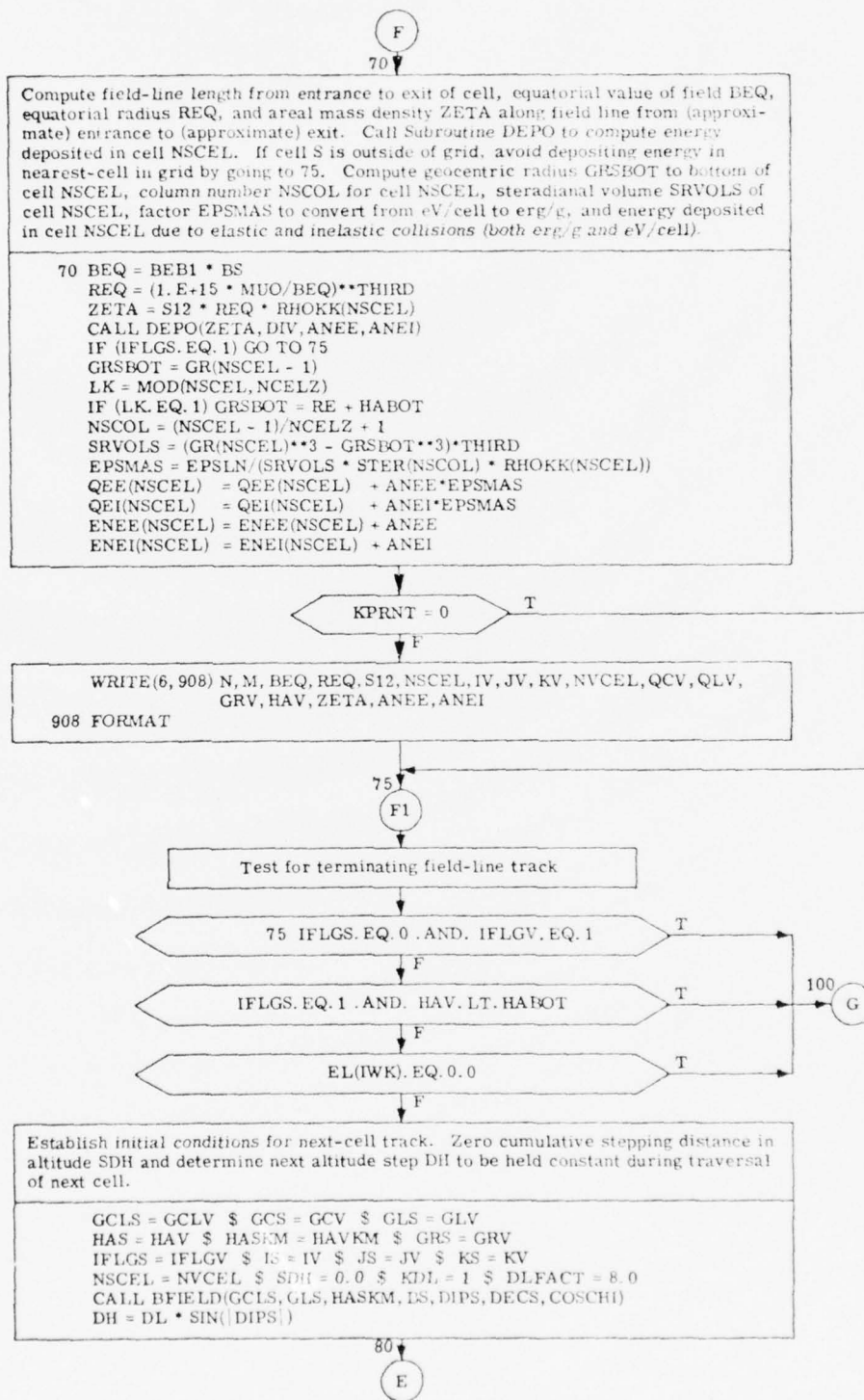


Fig. 10. (Continued).

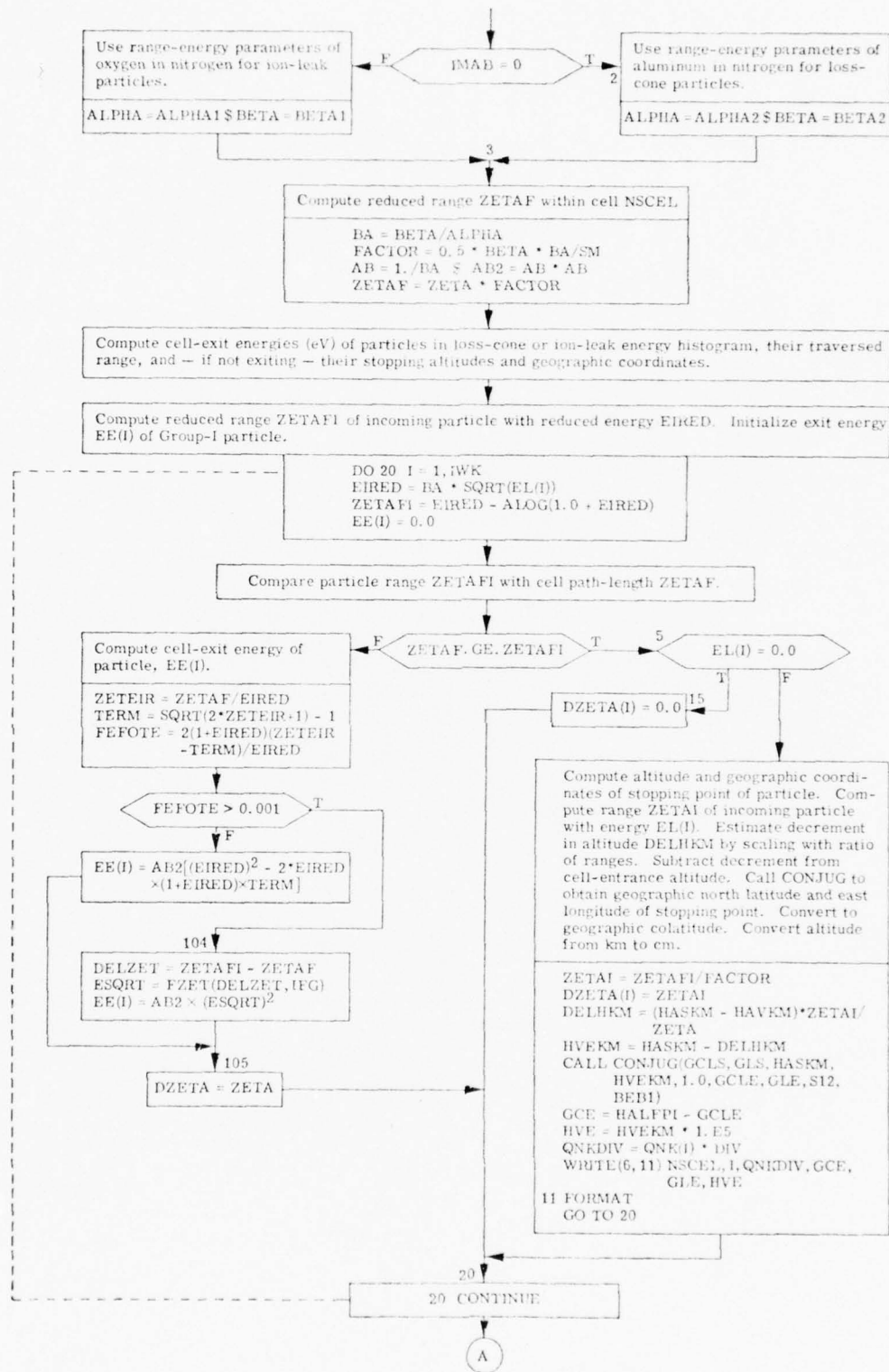


Fig. 11. Flow Chart for Subroutine DEPO(ZETA, DIV, ANEE, ANEI).



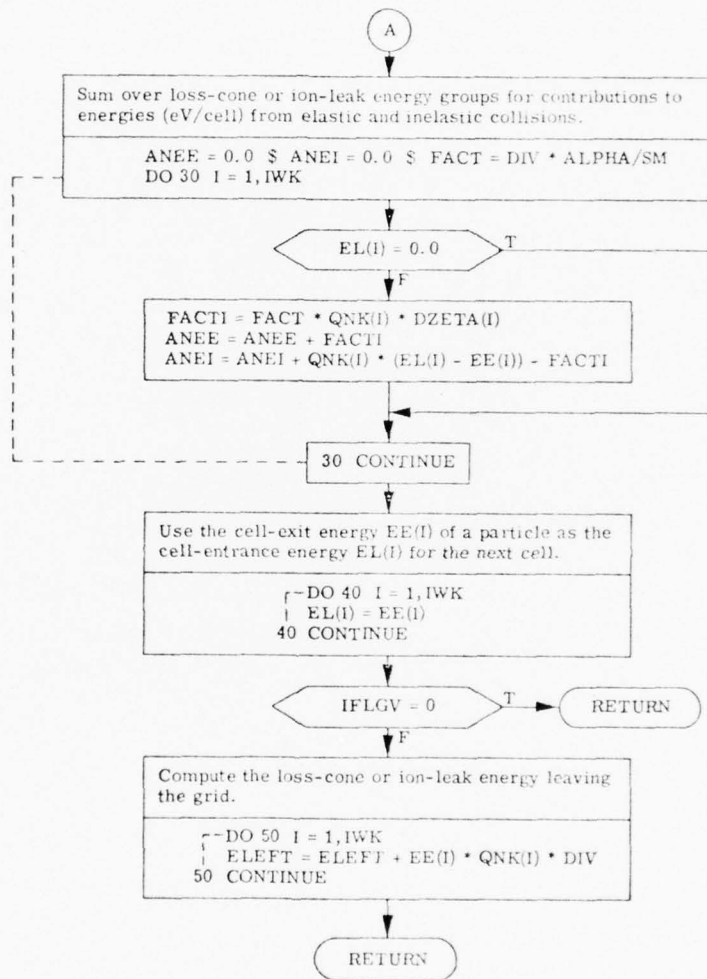


Fig. 11. (Continued)

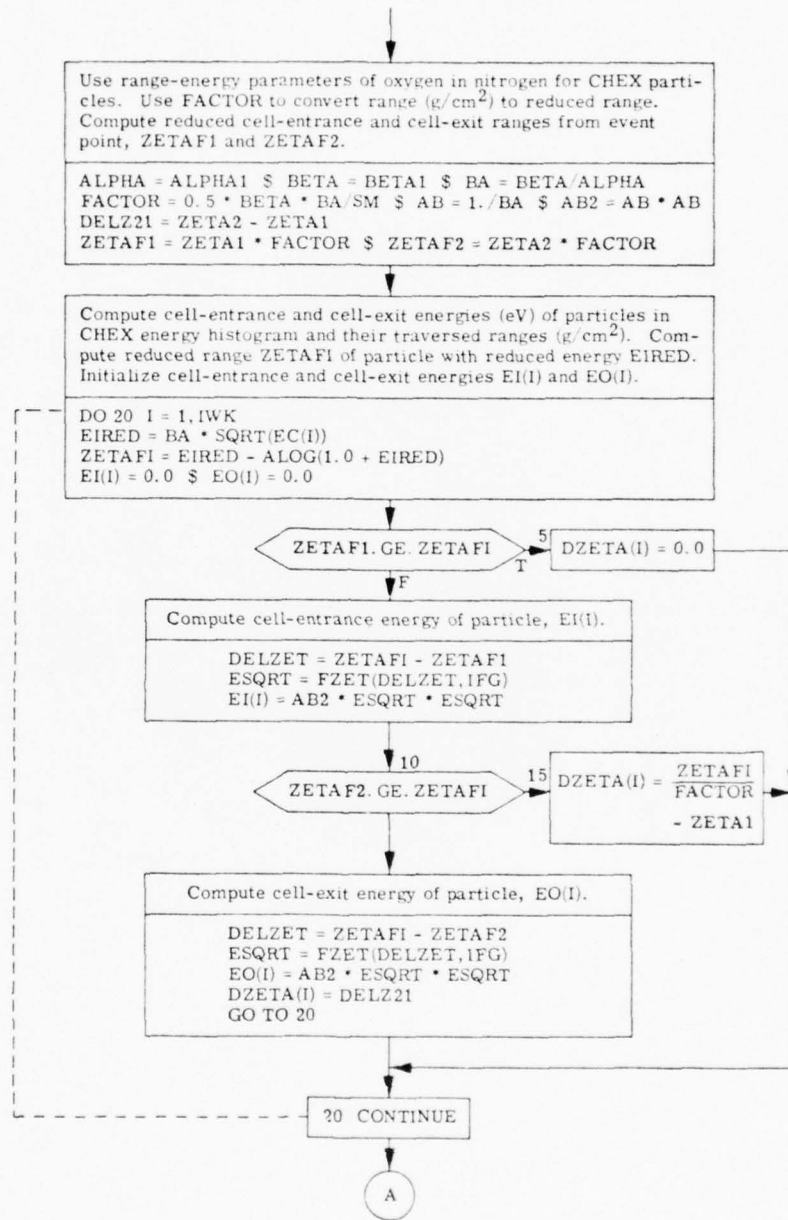


Fig. 12. Flow Chart for Subroutine CHXDEP(NCEL).

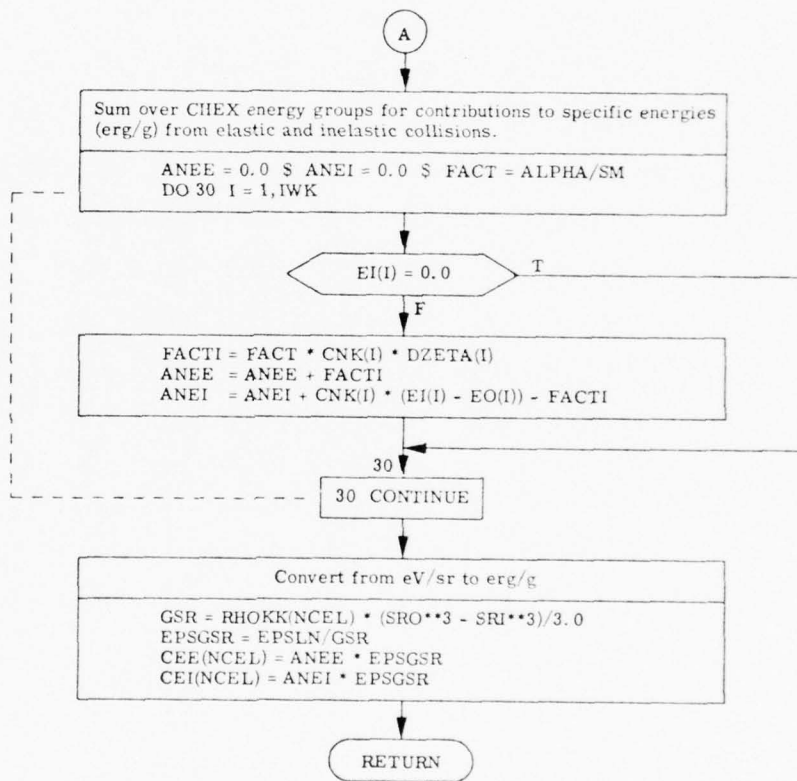


Fig. 12. (Continued).

## 9. UV DEPOSITION

The total computation of UV deposition requires Subroutine EUXFIT for finding the energy in each of the five Group-U subgroups, Subroutine PLINE for tracing ray paths from the event point through the center of each of the cells in the HAG, Subroutine PINT to compute integrals of mass density and species number densities along these ray paths, Subroutine BEDGE to find the radius (B-edge) within which only atomic ions are formed and to compute line integrals of species densities within the B-edge, Subroutine PHEAT to compute the photon fluences of the Group-U subgroups and to compute the total pressure due to the Group-U energy deposition (and to combine it with the original pressure and that due to Groups X and H), and Subroutine PCHEM to compute the prompt chemistry associated with the Group-U deposition (and to combine these results with those due to Groups X and H).

### 9.1 COMPUTATION OF RAY PATHS THROUGH THE HAG (SUBROUTINE PLINE)

#### 9.1.1 Introduction

Subroutine PLINE traces ray paths through the HAG. A ray path starts at the event point, passes through the center of a selected HAG cell regarded as a target cell, and ends as the ray leaves the target cell. We must compute the length of each of the line segments formed by the intersection of the ray with the intervening cell boundary surfaces. Target cells are selected by Subroutine PROMPG by systematically looping over all the cells in the HAG.

### 9.1.2 Transformation from the Quadrupole Coordinate System to the Associated Geocentric Cartesian System

In Volume 16, we have introduced the quadrupole coordinate system and given many of the details. Here, as shown in Fig. 13, we need to convert from quadrupole coordinates (quadrupole colatitude  $\varphi$  and quadrupole east longitude  $\theta$ ) and geocentric radius  $r$  to the corresponding geocentric cartesian system in which the Z axis is through the quadrupole north pole and the X axis is through the quadrupole west pole.

The required transformation equations are

$$x = r \sin a \cos \theta$$

$$y = r \sin a \sin \theta$$

$$z = r \cos a ,$$

where  $\sin a$  is obtained by first applying the law of sines to triangle P-QN-QW to obtain

$$\begin{aligned} \sin a &= \sin \varphi \sin 90^\circ / \sin \lambda \\ &= \sin \varphi / (1 - \cos^2 \lambda)^{\frac{1}{2}} \end{aligned}$$

and then the law of cosines for angles to obtain

$$\cos \lambda = - \cos \varphi \cos \theta$$

so that

$$\sin a = \sin \varphi / (1 - \cos^2 \varphi \cos^2 \theta)^{\frac{1}{2}} .$$

We also have

$$\cos a = \text{SIGN}(1.0, \cos \varphi) (1 - \sin^2 a)^{\frac{1}{2}} .$$

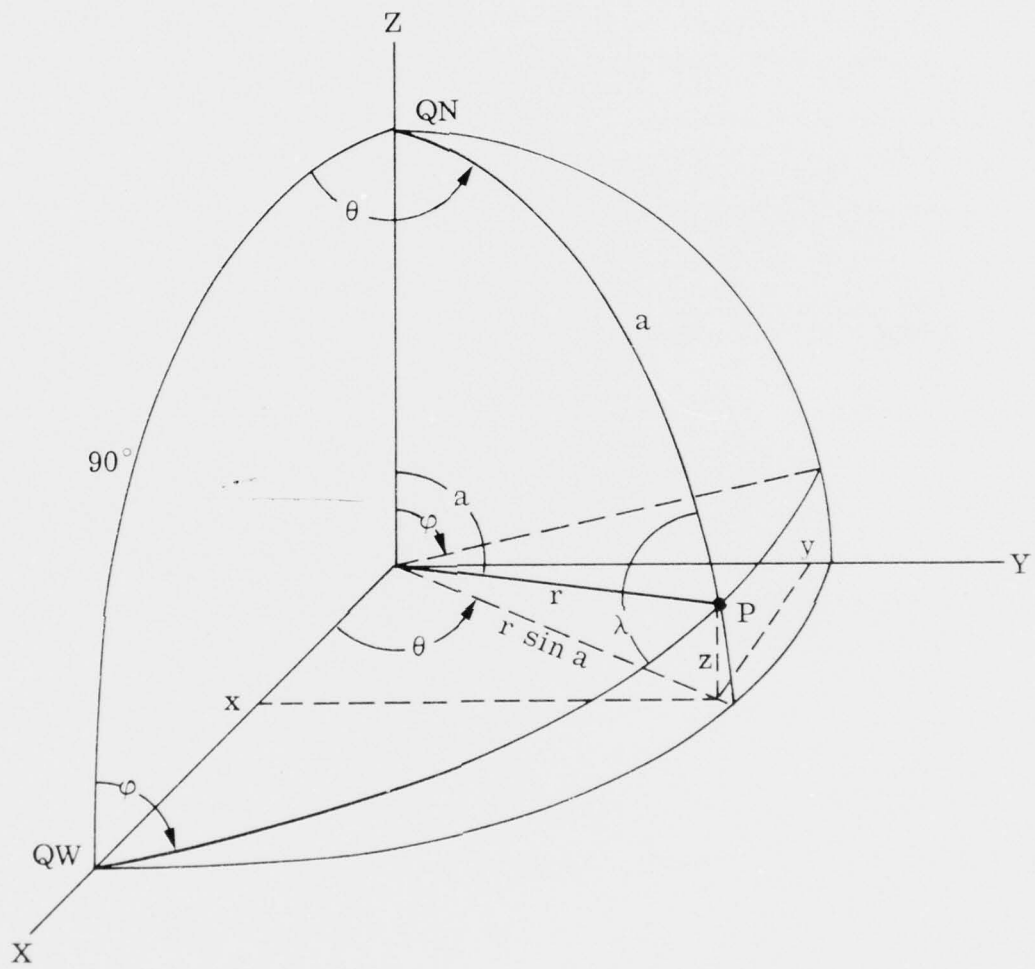


Fig. 13. Diagram Illustrating the Transformation from the Quadrupole Coordinate System to the Corresponding Geocentric Cartesian System.



### 9.1.3 Cell Shape

As explained in Volume 16, for a cell in the HAG, the top and bottom surfaces are geocentric spherical surfaces and the four sides are meridian planes.

### 9.1.4 Basic Formulas for Slant Range from a Given Point to a Cell Boundary

There are three basic formulas, each one corresponding to the intersected boundary being (a) a top or bottom boundary, (b) a quadrupole colatitude boundary, or (c) a quadrupole east longitude boundary. The first case affords more complication than either of the remaining two, each of which is similar to the other.

The quantities we have as input are:

- a. Event-point quadrupole coordinates and, hence, cartesian coordinates
- b. Target-point quadrupole coordinates and, hence, cartesian coordinates
- c. Lateral cell-boundary quadrupole coordinates and top and bottom geocentric radii.

In each of the three types of boundary cases, the ray from the starting point (usually the event point, denoted by  $\vec{r}_1$ ) through the target-cell center (denoted here by  $\vec{r}_3$ ) is specified by its direction cosines,

$$\cos \alpha = (x_3 - x_1)/r_{13}$$

$$\cos \beta = (y_3 - y_1)/r_{13}$$

$$\cos \gamma = (z_3 - z_1)/r_{13} ,$$

where

$$r_{13} = \left[ (x_3 - x_1)^2 + (y_3 - y_1)^2 + (z_3 - z_1)^2 \right]^{\frac{1}{2}} .$$

9.1.4.1 Slant Range of a Ray Intersecting a Cell Top- or Bottom-Boundary. Consider a Point 2 with geocentric radius  $r_2$  on the ray  $P_1P_3$ , shown in Fig. 14. The angle  $\delta$  between the vectors  $\vec{r}_1$  and  $\vec{r}_{12} = \vec{r}_2 - \vec{r}_1$  is specified in terms of the direction cosines of the unit vectors  $\hat{r}_1$  and  $\hat{r}_{12}$  by the relation

$$\begin{aligned} \hat{r}_1 \cdot \hat{r}_{12} = \cos \delta &= \frac{x_1}{r_1} \cos \alpha + \frac{y_1}{r_1} \cos \beta + \frac{z_1}{r_1} \cos \gamma \\ &= \frac{x_1 \cos \alpha + y_1 \cos \beta + z_1 \cos \gamma}{(x_1^2 + y_1^2 + z_1^2)^{\frac{1}{2}}} \end{aligned}$$

From the right triangle  $OPP_2$  in Fig. 14, we have

$$(r_1 \sin \delta)^2 + (r_1 \cos \delta + r_{12})^2 = r_2^2$$

or

$$DSRR \equiv r_{12} = -S2 + FGR \sqrt{WS2}$$

where

$$WS2 = (S2)^2 + (GR2)^2 - GR12$$

$$S2 = r_1 \cos \delta$$

$$GR2 = r_2$$

$$GR12 = r_1^2$$

and FGR is chosen to select the positive root or the smaller of the two positive roots.

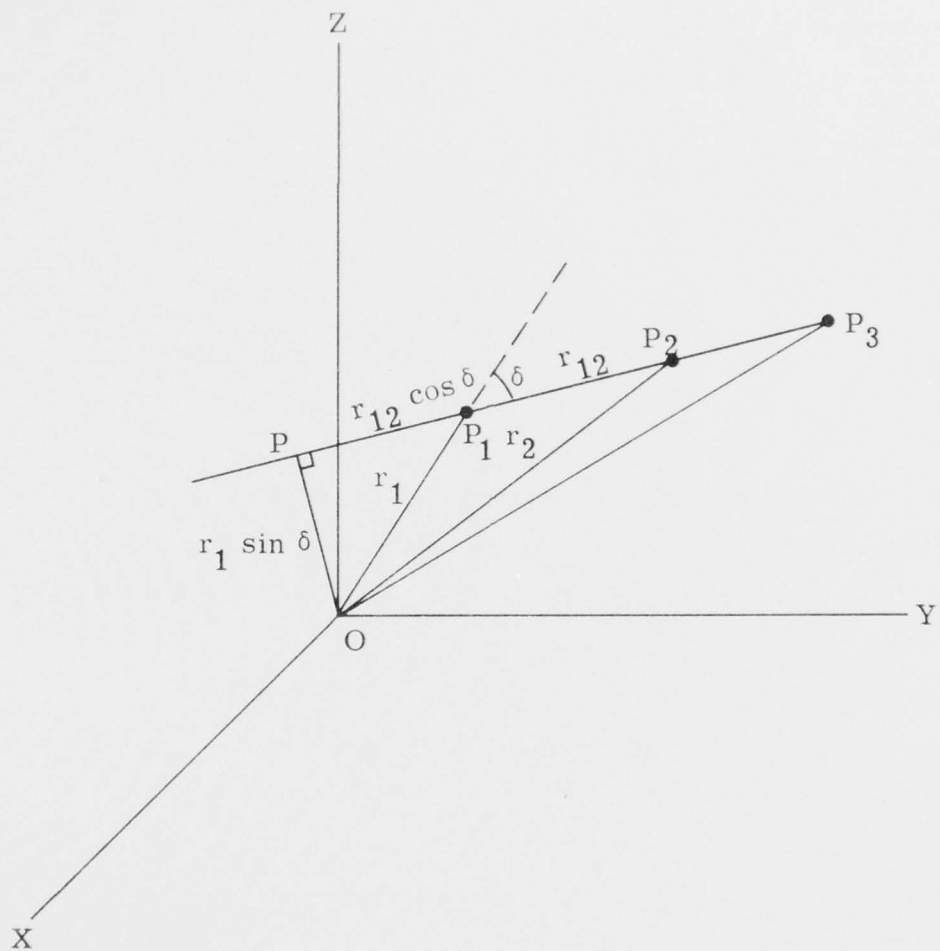


Fig. 14. Geometry Used in Deriving Slant Range of a Ray Intersecting a Cell Top- or Bottom-Boundary.

9.1.4.2 Slant Range of a Ray Intersecting a Cell North- or South-Boundary (Specified by Quadrupole Colatitude). In this case we are given the quadrupole colatitude ( $\varphi_2$ ) of the Point 2. In Fig. 15, the line segment  $P_1P_2$  is projected onto the YZ plane. Thus,

$$\tan \varphi_2 = \frac{\sin \varphi_2}{\cos \varphi_2} = \frac{y_2}{z_2} = \frac{y_1 + r_{12} \cos \beta}{z_1 + r_{12} \cos \gamma}$$

or

$$\text{DSRC} \equiv r_{12} = \frac{y_1 \cos \varphi_2 - z_1 \sin \varphi_2}{\cos \gamma \sin \varphi_2 - \cos \beta \cos \varphi_2}$$

9.1.4.3 Slant Range of a Ray Intersecting a Cell East- or West-Boundary (Specified by Quadrupole East Longitude). In this case we are given the quadrupole east longitude ( $\theta_2$ ) of the Point 2. In Fig. 16, the line segment  $P_1P_2$  is projected onto the XY plane. Thus,

$$\tan \theta_2 = \frac{\sin \theta_2}{\cos \theta_2} = \frac{y_2}{x_2} = \frac{y_1 + r_{12} \cos \beta}{x_1 + r_{12} \cos \alpha}$$

or

$$\text{DSRL} \equiv r_{12} = \frac{y_1 \cos \theta_2 - x_1 \sin \theta_2}{\cos \alpha \sin \theta_2 - \cos \beta \cos \theta_2}$$

#### 9.1.5 A Caution for Energy Deposition in the Event-Point Cell

The nominal cell heights for both SAIHYD and NRLHYD, under both initial and rezone conditions, are given in Tables 2 and 4 of Volume 16. From these tables it is seen that the cell thicknesses for most of the cells (and especially for the lower-altitude cells) are much smaller than the typical horizontal dimensions of the columns which may

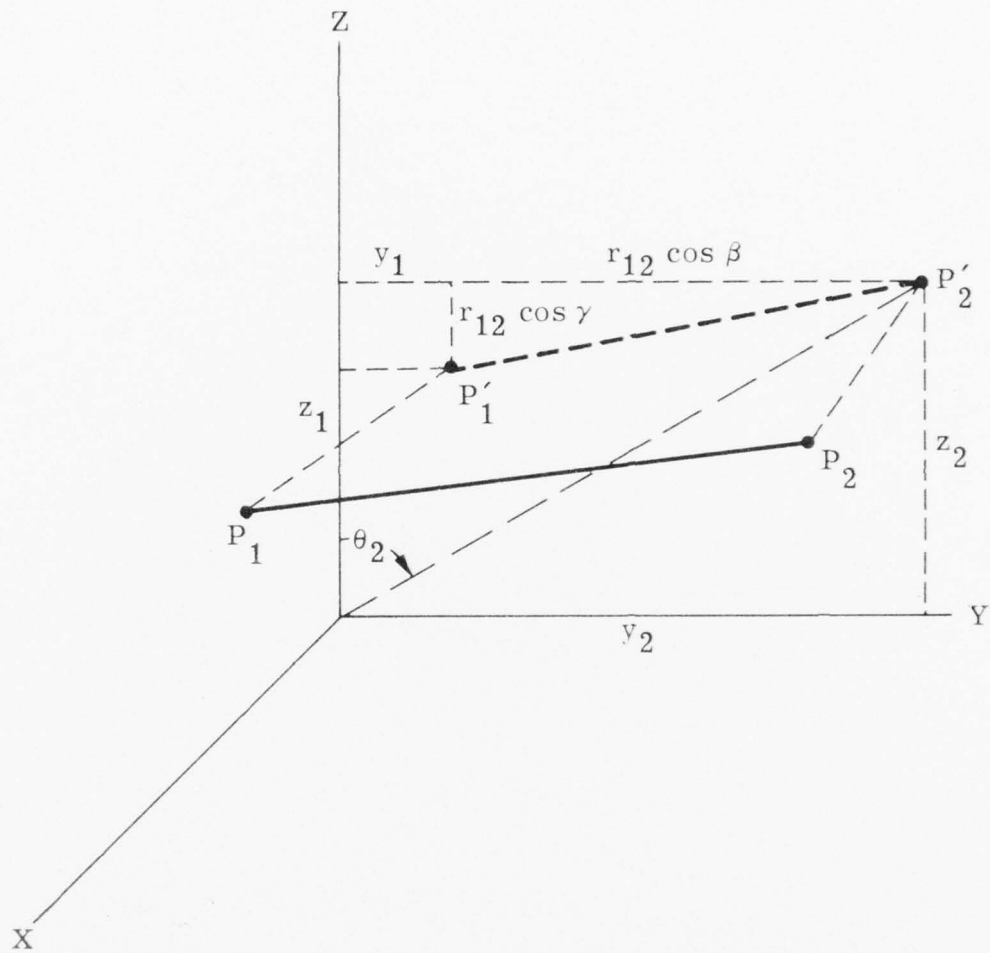


Fig. 15. Geometry Used in Deriving Slant Range of a Ray Intersecting a Cell North- or South-Boundary (Specified by Quadrupole Colatitude  $\theta_2$ ). The segment  $P_1P_2$  is projected onto the YZ plane.

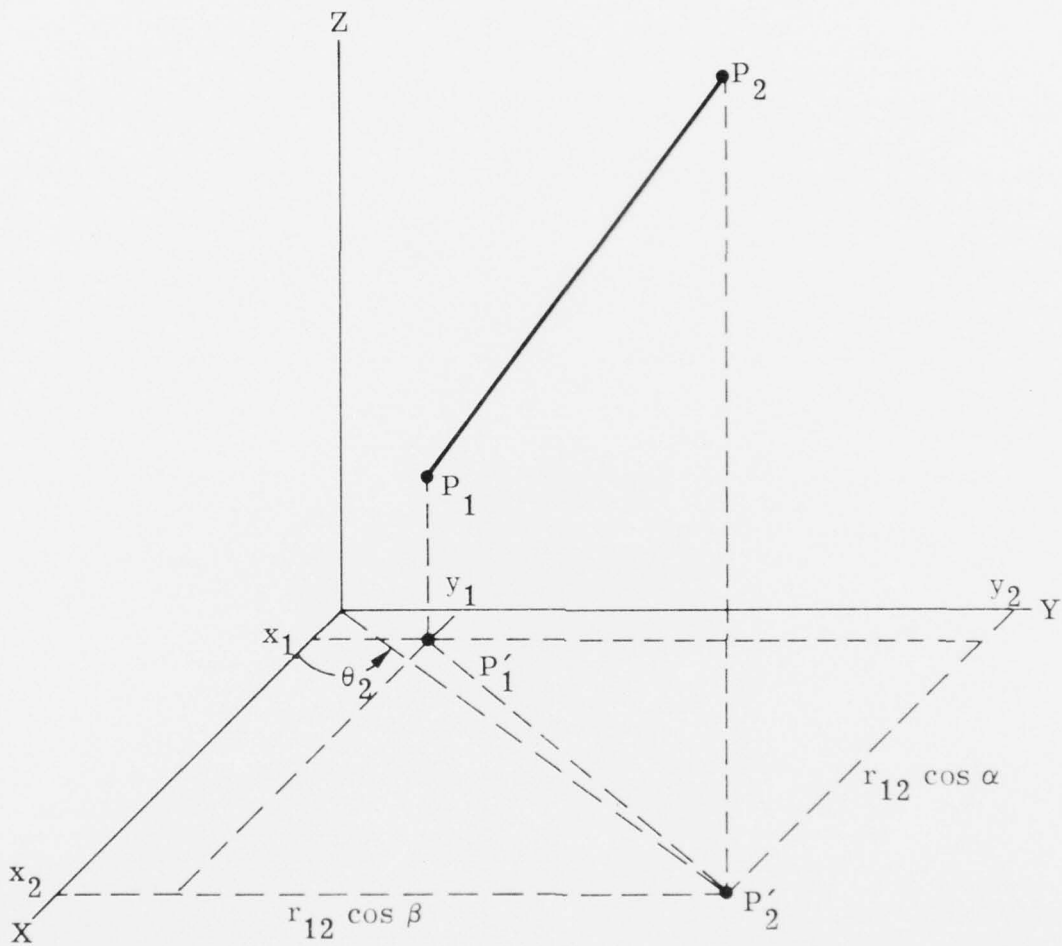


Fig. 16. Geometry Used in Deriving Slant Range of a Ray Intersecting a Cell East- or West-Boundary (Specified by Quadrupole East Longitude  $\theta_2$ ). The segment  $P_1P_2$  is projected onto the XY plane.



be on the order of 100 km. For a small-energy event in the lower-altitude cells, it would be quite possible to put more energy into a cell than was available from the event, owing to using a path length that was unrepresentatively small. We tried an interim procedure to relieve this situation, but the undesirable side effects led us to delete the procedure. Thus, we alert the user to this potential problem which deserves review and more study.

#### 9.1.6 Directional Flags and Indices of Next Set of Boundaries to be Intersected

In Subroutine PLINE we use the following directional flags:

<u>Index</u>	<u>Value</u>	<u>Ray Moves</u>
IINC	{ +1 -1	southward northward
JINC	{ +1 -1	eastward westward
KINC	{ +1 -1	upward downward

The initial value of KINC is saved as the variable KINC0.

The indices I, J, K are used to denote the next possible set of boundaries to be intersected by the ray. In starting from the event cell (IEC, JEC, KEC), these boundary indices are initially defined as

$$\begin{aligned}
 I &= IEC - (1 - IINC)/2 \\
 J &= JEC - (1 - JINC)/2 \\
 K &= KEC - (1 - KINC)/2 .
 \end{aligned}$$

A value of 1 (instead of 0) for the flag IEND denotes that the last step in the line integral has been reached.

The index  $II$  is used to denote the number of boundaries intersected by the ray from the event point to the exit boundary of the target cell.

#### 9.1.7 Flow Charts of Subroutine PLINE

Figure 17 is a simplified flow chart of Subroutine PLINE which includes calls to Subroutines PINT and BEDGE. Figure 18 is another simplified flow chart of Subroutine PLINE that gives information only about the computation of the ray-path segments.

#### 9.1.8 Miscellaneous Functions of Subroutine PLINE

Other miscellaneous related tasks performed by Subroutine PLINE include the following:

- a. Set Group-U subgroup index (IGROUP) to 5.
- b. Zero integrals (SNR2(L), FLUX(L), L=1, 5) computed in Subroutine BEDGE.
- c. Zero integrals (SN2INT, SO2INT, SNINT, SOINT, RHOINT, O2INT) computed in Subroutine PINT.
- d. Set flag (IUFLAG) denoting whether or not the B-edge has been passed.
- e. Zero integral (SR) for distance from event point to cell entry-point.

#### 9.2 COMPUTATION OF INTEGRALS OF SPECIES NUMBER DENSITIES AND MASS DENSITIES ALONG THE RAY PATH (SUBROUTINE PINT)

For the line path SRN calculated by Subroutine PLINE, Subroutine PINT integrates the species number densities and mass densities as follows:

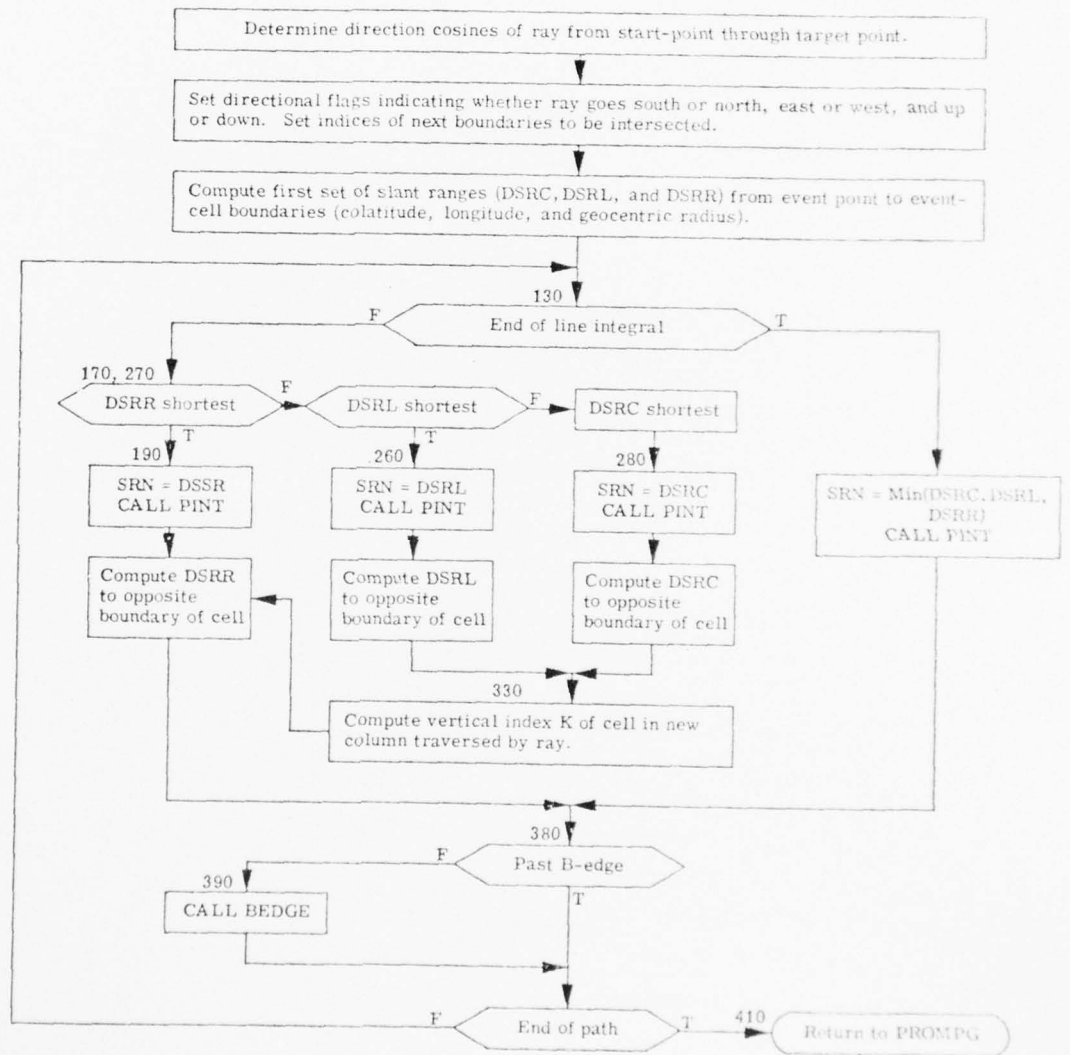


Fig. 17. Simplified Flow Chart of Subroutine PLINE, Including Calls to Subroutines PINT and BEDGE.

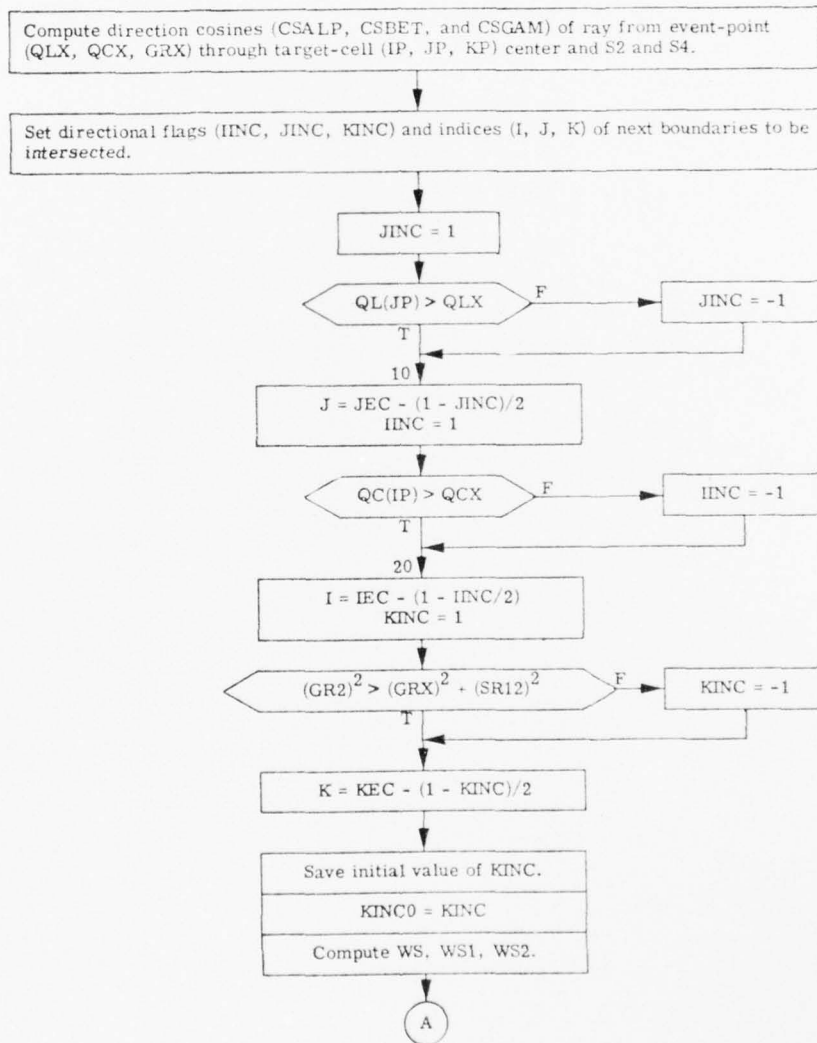


Fig. 18. Simplified Flow Chart of Subroutine PLINE. Only steps pertaining to ray-path segments are shown.

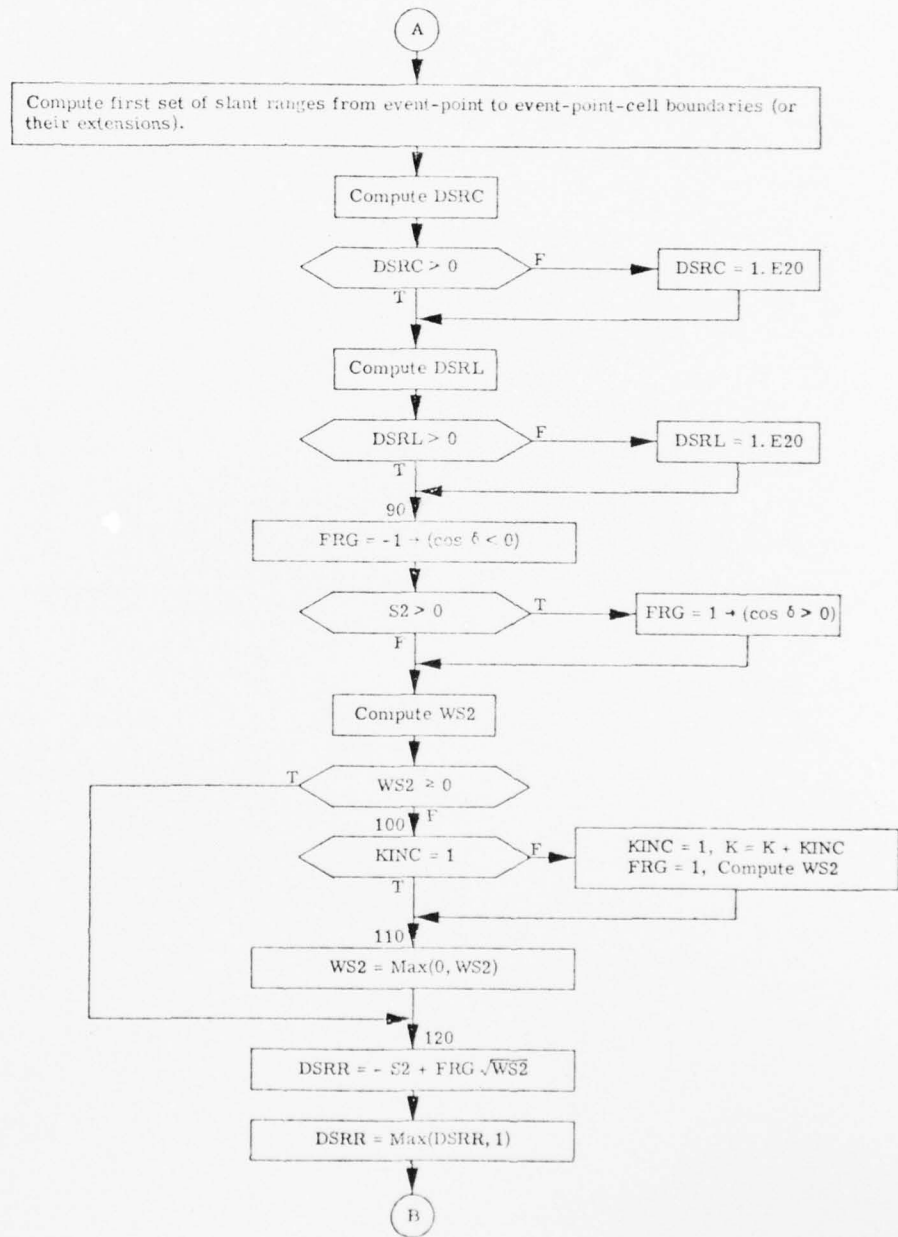


Fig. 18. (Continued).

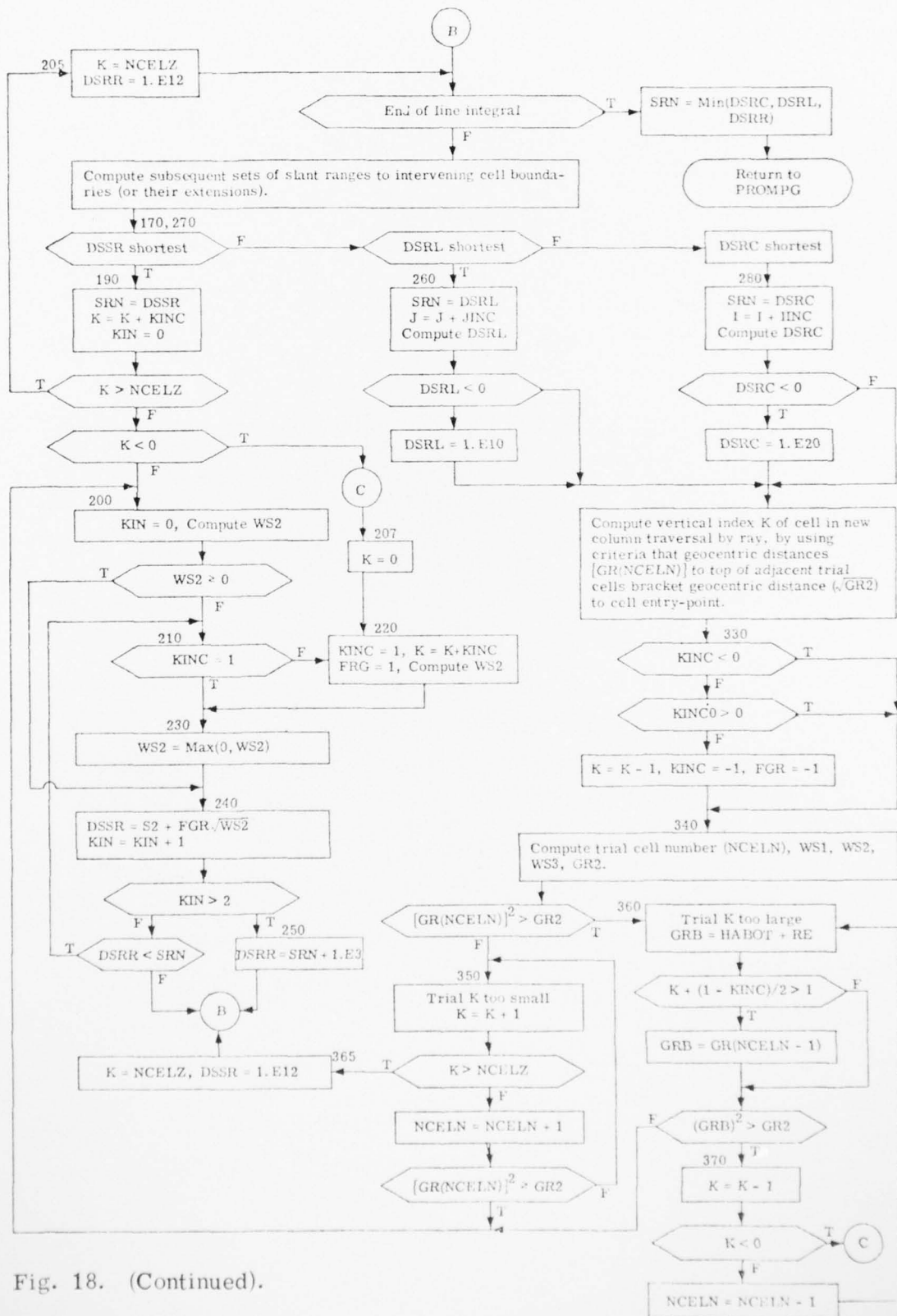


Fig. 18. (Continued).



$$\text{SN2INT} = \int_0^{\text{SRN}} [\text{N}_2] \text{ dr} , \quad \text{cm}^{-2}$$

$$\text{SO2INT} = \int_0^{\text{SRN}} [\text{O}_2] \text{ dr} , \quad \text{cm}^{-2}$$

$$\text{SNINT} = \int_0^{\text{SRN}} [\text{N}] \text{ dr} , \quad \text{cm}^{-2}$$

$$\text{SOINT} = \int_0^{\text{SRN}} [\text{O}] \text{ dr} , \quad \text{cm}^{-2}$$

$$\text{RHOINT} = \int_0^{\text{SRN}} \rho \text{ dr} , \quad \text{g/cm}^2$$

$$\text{O2INT} = \int_0^{\text{SRN}} \rho_{\text{O}_2} \text{ dr} , \quad \text{g/cm}^2$$

The variables for these integrals are zeroed in Subroutine PLINE. Over a ray segment between SR and SRN, the corresponding contributions to the integrals are, respectively, DSN2I, DSO2I, DSNI, DSOI, DHR0I, and DO2INT. SPECIE(I) denotes the concentration of  $\text{N}_2$ ,  $\text{O}_2$ , N, and O, respectively, for  $I = 1, 2, 3$ , and 4.

When the properties of a particular cell are needed to perform the integrals Subroutine PINT calls Subroutine ECRD and transfers quantities 2 through 11 from large core memory to small core memory.

### 9.3 COMPUTATION OF THE ATOMIC-ION REGION (B-EDGE) FOR GROUP-U PHOTONS (SUBROUTINE BEDGE)

#### 9.3.1 Introduction

As Subroutine PLINE computes the ray path from the event point to a target point, Subroutine BEDGE is employed to determine the radius (SRR(2)) of the edge (B-edge) of the region within which Group-U ionizing photons are very strongly absorbed and produce entirely atomic ions. Subroutine BEDGE also computes (a) the line integrals, from the event point to the B-edge, of the  $O_2$ -mass density (O2U) and of the species densities of  $N_2$  (SN2U),  $O_2$  (SO2U), N (SNU), and O (SOU), and (b) the number of ionizing-photon absorptions per steradian that are required to produce atomic ions alone for Group-U Subgroup-L (SNR2(L)).

#### 9.3.2 Simplified Description of the Essence of Subroutine BEDGE

To simplify the description of the essence of Subroutine BEDGE, we introduce some terms, not all of which are used in the routine.

PHOTON(L) = Number of Subgroup-L photons emitted per steradian from the source.

PHOTAB(L) = Number of Subgroup-L photons per steradian used in developing the radius of the B-edge up to its current radius  $R_c$ .

ABSORP = Number of ionizing-photon absorptions per steradian required to increase the radius of the B-edge from its current value  $R_c$  to R.

XMUBAR(L) = Mass attenuation coefficient ( $cm^2/g$ ) for Subgroup-L photons in Cell NCELS with neutral-particle mass-density RHON(NCELS).

$$= \frac{\sum_{I=1}^4 \text{SPECIE}(I) \times \text{SIGU}(L, I)}{\text{RHON}(\text{NCELS})}$$

(I = 1, 2, 3, 4 denotes  $N_2$ ,  $O_2$ , N, O).

EVEN = Number of absorptions per cubic centimeter required to get atomic ions.

$$= 3 \sum_{I=1}^2 \text{SPECIE}(I) + \sum_{I=3}^4 \text{SPECIE}(I)$$

EVNPG = Number of absorptions per gram required to get atomic ions.

$$= \text{EVEN}/\text{RHON}(\text{NCELS})$$

If we want the Subgroup-L photons to produce all atomic ions at radius R, then the condition to be satisfied is

$$\frac{\text{PHOTON}(L) - \text{PHOTAB}(L) - \text{ABSORP}}{R^2} \times \text{XMUBAR}(L) = \text{EVNPG} .$$

Now, multiply both sides of the equation by  $R^2/(\text{XMUBAR}(L) \times \text{EVEN})$  and define a new function EDGE(L) to be the difference between the right- and left-hand sides:

$$\text{EDGE}(L) = \frac{R^2 \times \text{EVNPG}}{\text{XMUBAR}(L)} - \frac{[\text{PHOTON}(L) - \text{PHOTAB}(L) - \text{ABSORP}]}{\text{EVEN}} .$$

A positive value for EDGE(L) is the steradianal volume in excess of that for which the Subgroup-L photons can produce all atomic ions. A negative value for EDGE(L) is the steradianal volume beyond radius R that the Subgroup-L photons can produce all atomic ions. A zero value for EDGE(L) means that the Subgroup-L photons have produced atomic ions exactly to the radius R.

If we recognize the fact that

$$\frac{\text{ABSORP}}{\text{EVEN}} = \frac{R^3 - R_c^3}{3} ,$$

then we can write EDGE(L) as

$$\text{EDGE}(L) = A_3 R^3 + A_2 R^2 + A_0$$

where

$$A_3 = 1/3$$

$$A_2 = 1/[\text{RHON}(\text{NCELS}) \times \text{XMUBAR}(L)]$$

$$A_0 = \frac{\text{PHOTAB}(L) - \text{PHOTON}(L)}{\text{EVEN}} - \frac{R_c^3}{3}$$

The equation

$$3 \times \text{EDGE}(L) = 0$$

is solved for the radius R by using the standard Newton-Raphson iteration formula:

$$R_{i+1} = R_i - \frac{\text{EDGE}(L, R_i)}{d[\text{EDGE}(L, R_i)]/dR_i}$$

### 9.3.3 Flow Charts of Subroutine BEDGE

Figures 19 and 20 are simplified and detailed flow charts of Subroutine BEDGE.

### 9.4 COMPUTATION OF GROUP-U SUBGROUP FLUENCES AND PROMPT HEATING (SUBROUTINE PHEAT)

For each cell in the HAG, Subroutine PHEAT computes the photon fluences of the Group-U subgroups and the total pressure due to the Group-U energy deposition and then combines this pressure with the pre-event pressure and the pressures due to Group-X and -H energy depositions.

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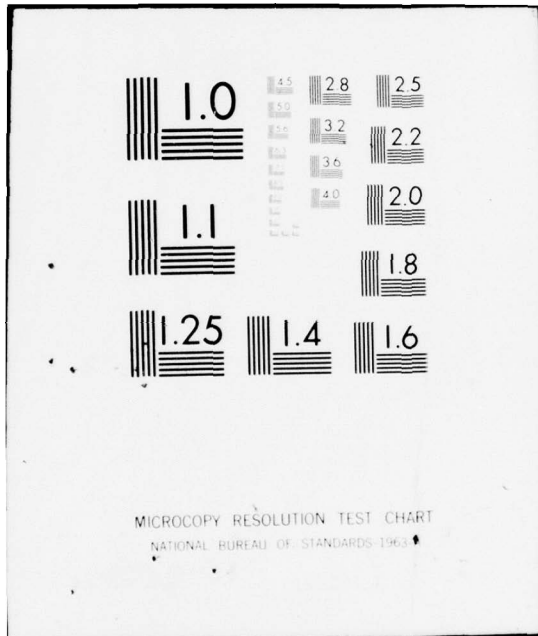
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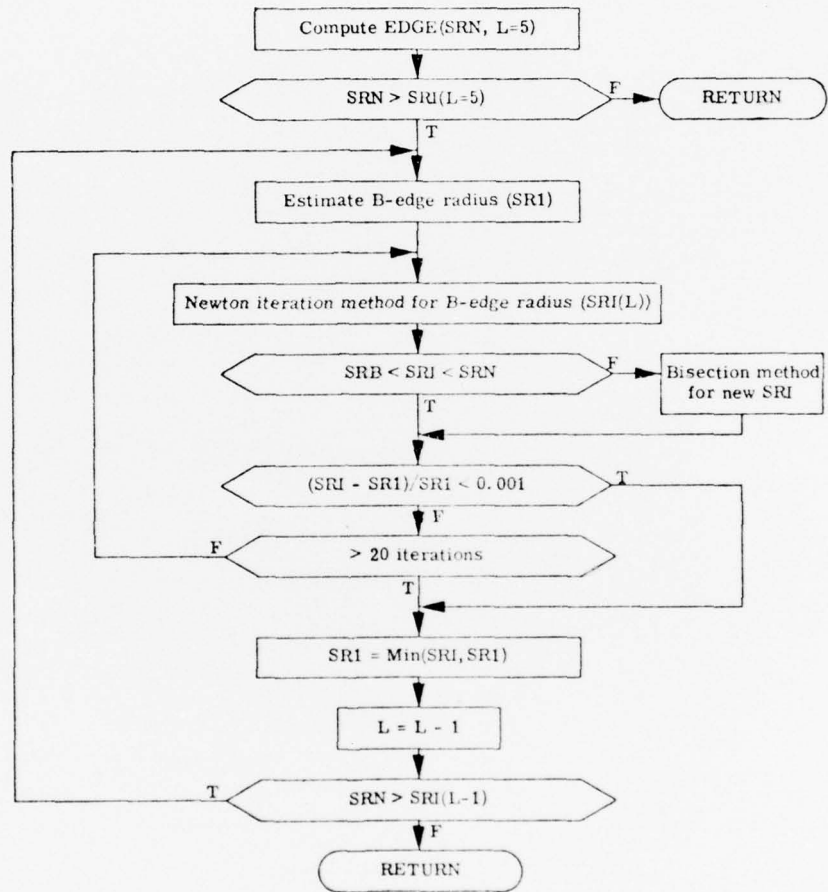


Fig. 19. Simplified Flow Chart of Subroutine BEDGE.

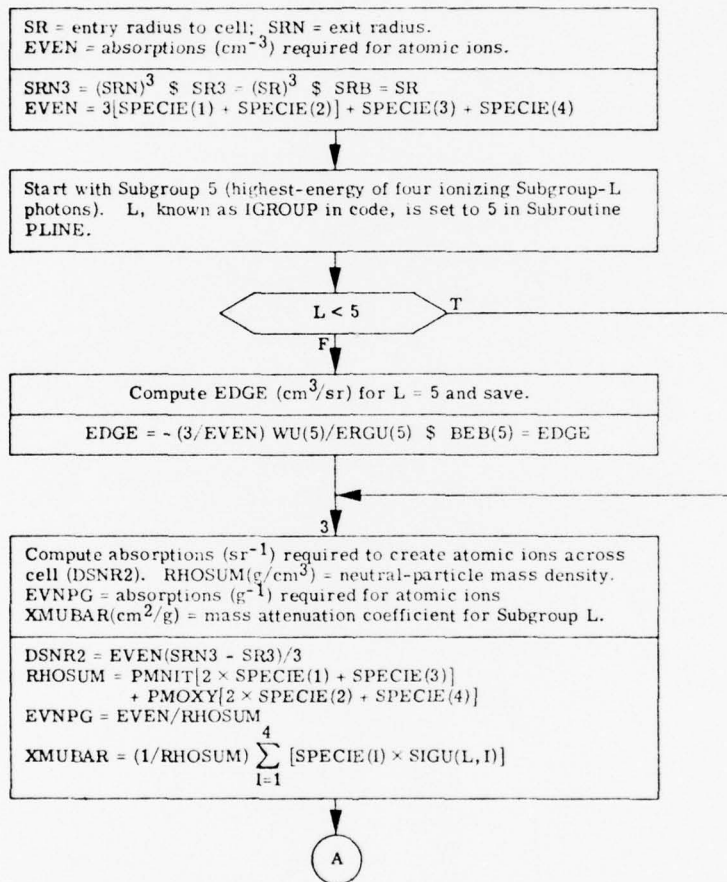


Fig. 20. Detailed Flow Chart of Subroutine BEDGE.

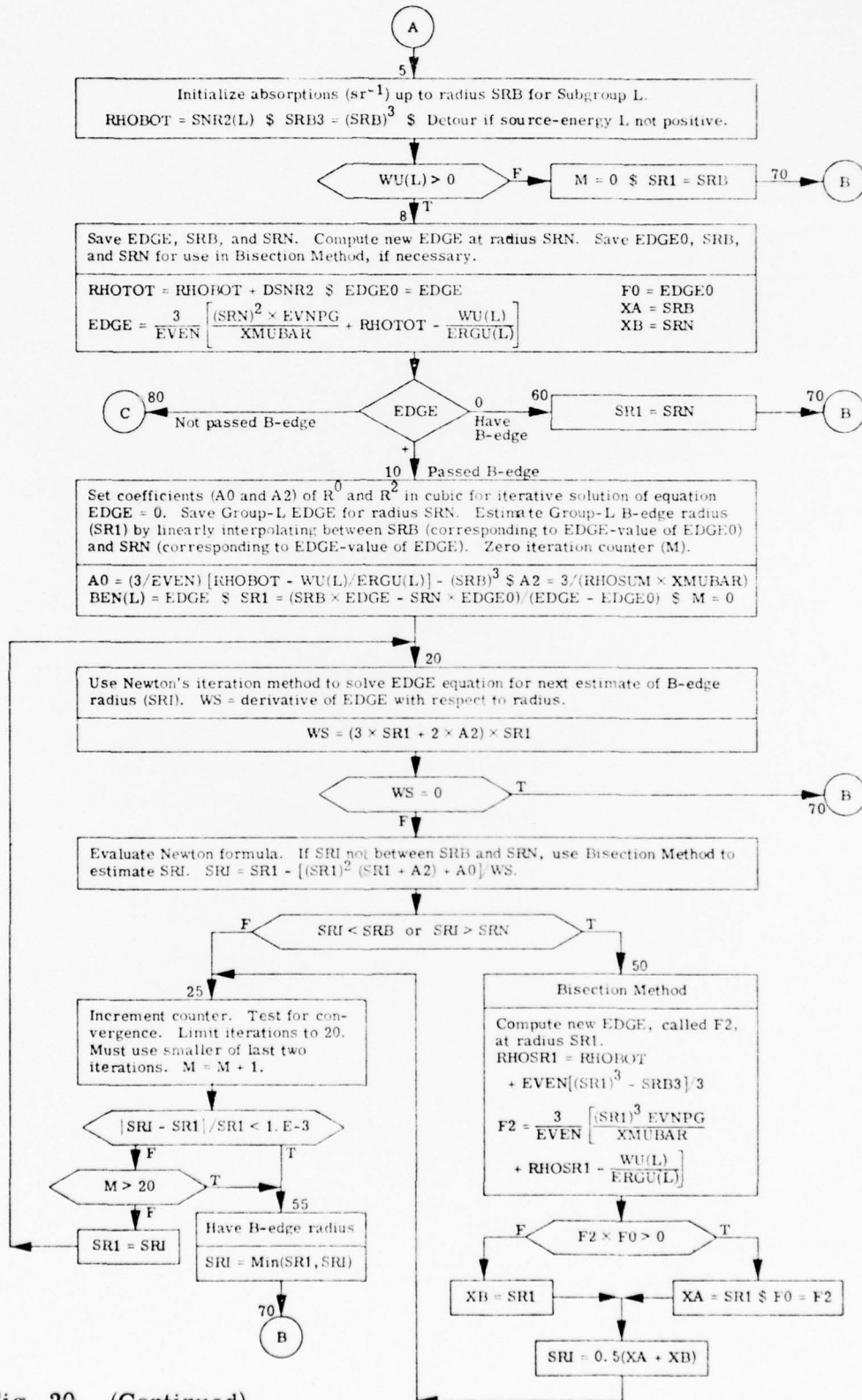


Fig. 20. (Continued).

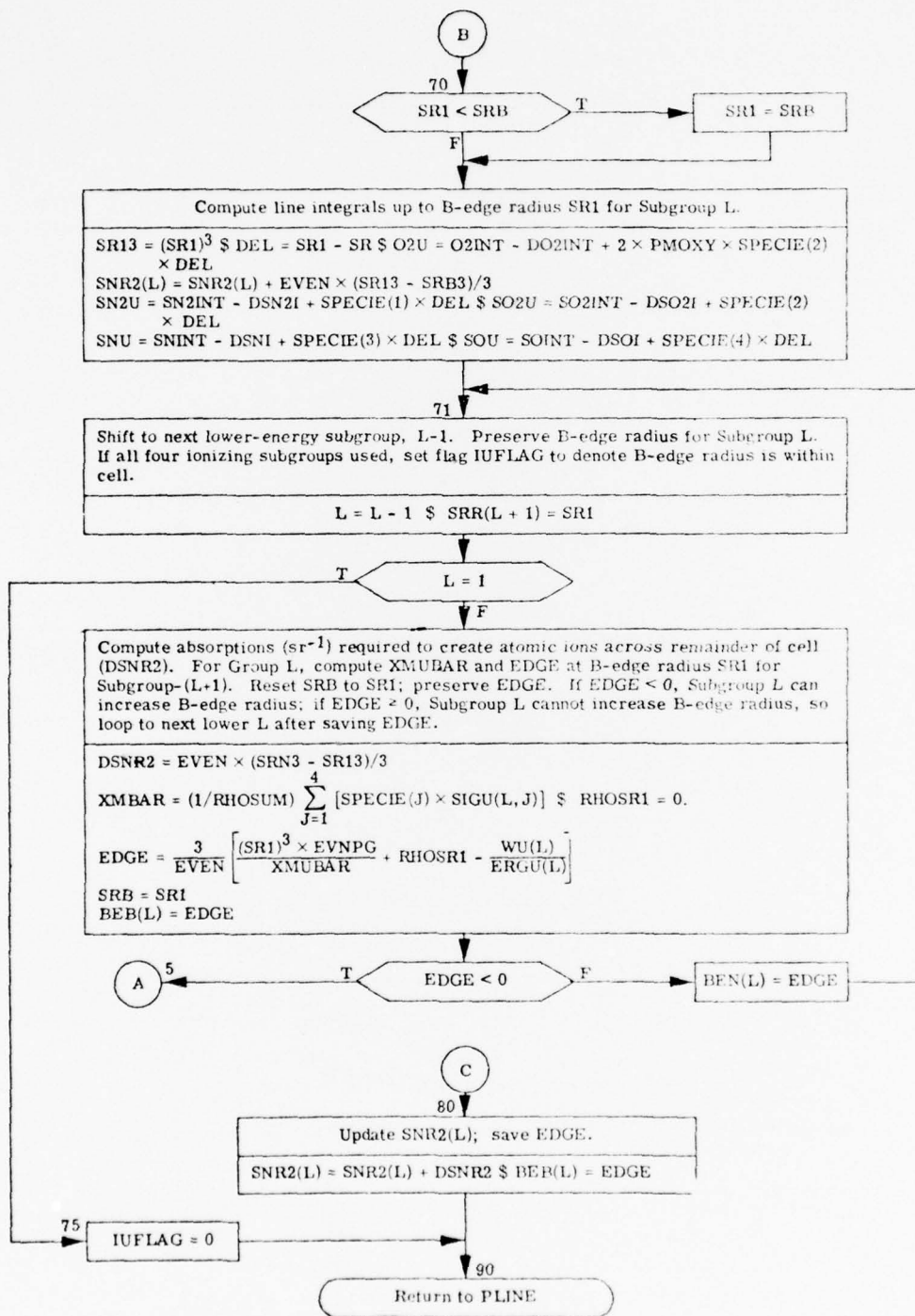


Fig. 20. (Continued).

#### 9.4.1 Group-U Energy Deposition and Fluences

In computing the Group-U energy deposition (erg/g) in a target cell and the Group-U photon fluences (photons/cm<sup>2</sup>), we treat three cases:

Case 1 (B-edge radius (SRR(2)) smaller than target-cell entry-radius (SR))

We use the difference of the incident and exit values of the steradian energy fluence for each Group-U subgroup, divided by the corresponding steradian mass for the cell. We treat dissociating (Subgroup 1) and ionizing (Subgroups 2-5) separately.

For Subgroup 1,

$$DAIX(1) = \frac{WU(1)}{(\rho/3)(R_{out}^3 - R_{in}^3)} \left\{ e^{-XMU1 \times O2IN} - e^{-XMU1 \times O2OUT} \right\} ,$$

where  $XMU1(\text{cm}^2/\text{g})$  is the mass attenuation coefficient of  $O_2$  for Subgroup-1 photons,  $O2IN$  and  $O2OUT$  are the areal mass densities of  $O_2$  from the B-edge to the entry and exit points of the target cell.

The energy available for hydro due to Subgroup-1 absorption is

$$DAIXU(1) = PREFF(1, 2) \times DAIX(1) ,$$

where  $PREFF(1, 2)$  is the pressure efficiency of  $O_2$  (Species 2) absorbing Subgroup-1 photons.

For the target cell, the effective photon fluence for Subgroup 1, consistent with the energy deposition, is

$$\begin{aligned} FLUX(1) &= \frac{\rho}{\rho_{O_2}} \frac{DAIX(1) \times 2 \times PMOXY}{ERGU(1) \times SIGU(1, 2)} \\ &= \frac{\rho}{[O_2]} \frac{DAIX(1)}{ERGU(1) \times SIGU(1, 2)} , \end{aligned}$$

since

$$\frac{1}{[O_2]} = \frac{2 \times \text{PMOXY}}{\rho_{O_2}} .$$

For Subgroups 2 through 5, the Subgroup-L energy absorbed per gram is

$$\text{DAIX(L)} = \frac{\text{WU(L)} - \text{ERGU(L)} \times \text{SNR2(L)}}{(\rho/3)(R_{\text{out}}^3 - R_{\text{in}}^3)} \left\{ e^{-\text{SUMIN(L)}} - e^{-\text{SUMOUT(L)}} \right\} ,$$

where

$$\text{SUMIN(L)} = \sum_{J=1}^4 \text{SPECIN(J)} \times \text{SIGU(L, J)}$$

$$\text{SUMOUT(L)} = \sum_{J=1}^4 \text{SPECOUT(J)} \times \text{SIGU(L, J)}$$

and SPECIN(J) and SPECOUT(J) are the areal densities of the J-species from the B-edge to the cell entry-point and exit-point.

For Subgroup L, the average pressure efficiency for a target cell is defined as

$$\text{PEFBAR(L)} = \frac{\sum_{J=1}^4 \text{PREFF(L, J)} \times \text{SPECIE(J)} \times \text{SIGU(L, J)}}{\sum_{J=1}^4 \text{SPECIE(J)} \times \text{SIGU(L, J)}} .$$

The energy available for hydro due to Subgroup L is

$$\text{DAIXU(L)} = \text{DAIX(L)} \times \text{PEFBAR(L)} .$$



For the target cell the effective fluence for Subgroup-L photons, consistent with the energy deposition, is

$$\text{FLUX}(L) = \frac{\rho}{4 \sum_{J=1}^4 \rho_J} \frac{\text{DAIX}(L)}{\text{ERGU}(L) \times \text{XMU}(L)}$$

where

$$\text{XMU}(L) = \frac{\sum_{J=1}^4 \text{SIGU}(L, J) \times \text{SPECIE}(J)}{\sum_{J=1}^4 \rho_J} .$$

The total Group-U energy available for hydro is the sum of that for Subgroup-1 and that for Subgroups 2 to 5, i. e. ,

$$\text{DAIXU} = \sum_{L=1}^5 \text{DAIXU}(L) .$$

Case 2 (B-edge radius (SRR(2)) greater than target-cell exit-radius (SRN))

Inside the B-edge the internal energy is set by the expression

$$\text{DAIXU} = \text{SPINT}$$

where SPINT is set in Block Data BLOCKH. The HARC code used a value of  $2.07 \times 10^{12}$  erg/g, which we have reduced by a factor of 10, since  $2.07 \times 10^{12}$  erg/g corresponds to

$$\begin{aligned} \frac{2.07 \times 10^{12} \text{ erg/g}}{1.6 \times 10^{-12} \text{ erg/eV}} \cdot 2.325 \times 10^{-23} \text{ g/nitrogen atom} &= 30.08 \frac{\text{eV}}{\text{nitrogen atom}} \\ &= 15.04 \frac{\text{eV}}{\text{charged particle}} \end{aligned}$$

where [charged particle] =  $\{[N^+] + [e]\}$ . This energy per charged particle corresponds to a temperature of about 10 eV since the kinetic energy per particle is  $(3/2) kT$ . Thus, we have assumed that the particles inside the B-edge have a temperature equal to nearly 1 eV. We are neglecting the difference between the oxygen and nitrogen mass, but this approximation is satisfactory since the assumed value of about 1 eV is somewhat arbitrary.

We have no need for the Group-U fluences at a point inside the B-edge since it is assumed that only atomic ions exist there.

Case 3 (B-edge radius (SRR(2)) between target-cell entry-radius (SR) and exit-radius (SRN))

To obtain the specific energy available for hydro, we use a volume-weighted average of the values for the two portions of the cell inside and outside the B-edge. For the cell portion inside the B-edge, the specific energy is equal to SPINT, as in Case 2. For the cell portion outside the B-edge, the specific energy is determined in a manner similar to that for Case 1.

Again, we treat dissociating and ionizing subgroups separately.

For Subgroup 1 in the cell portion outside the B-edge, we have

$$DAIX(1) = \frac{WU(1)}{(\rho/3)(R_{out}^3 - R_{edge}^3)} \left\{ 1 - e^{-X_{MU1} \times O_{2OUT}} \right\}$$

where the subscript 'edge' denotes B-edge and the subscript 'out' has the same meaning as in Case 1.

For Subgroups 2 through 5 in the cell portion outside the B-edge, the Subgroup-L energy absorbed per gram is

$$\text{DAIX(L)} = \frac{\text{WU(L)} - \text{ERGU(L)} \times \text{SNR2(L)}}{(\rho/3)(R_{\text{out}}^3 - R_{\text{edge}}^3)} \left\{ 1 - e^{-\text{SUMOUT(L)}} \right\}$$

where SUMOUT(L) is computed just as in Case 1.

The energy available for hydro due to Subgroup L is computed just as in Case 1.

The total Group-U energy available for hydro in the cell portion outside the B-edge is, as in Case 1, the sum of that due to the five subgroups.

The weighted average of the values of the deposited energy available for hydro in the two portions of the cell is taken to be

$$\text{DAIXU}_{\text{average}} = \text{W1} \times \text{SPINT} + (1 - \text{W1}) \times \text{DAIXU}_{\text{total}}$$

where

$$\text{W1} = \left( R_{\text{edge}}^3 - R_{\text{in}}^3 \right) / \left( R_{\text{out}}^3 - R_{\text{in}}^3 \right) .$$

For the cell portion outside the B-edge, the effective photon fluences for Subgroup 1 and for Subgroups 2 through 5, consistent with the energy deposition, are computed just as in Case 1.

#### 9.4.2 Pressure To Be Used for Hydro

In Subroutine PHEAT, the pressure computed from the equation of state  $[p = (\gamma-1)\rho\epsilon]$  by using the total specific energy available for hydro from the deposition of the Group-X, -H, and -U energies, is currently interpreted as the total pressure. However, an electron pressure,  $p_e \equiv n_e kT_e$ , is implied by the computation in Subroutine PCHEM where a common temperature is found for the electron kinetic temperature, the  $\text{N}_2$  vibrational temperature, and the  $\text{O}(^1\text{D})$ -to- $\text{O}(^3\text{P})$  population ratio.

It is possible that a negative value for the heavy-particle temperature obtains when the electron pressure is subtracted from the total pressure. Our interim procedure in Subroutine PCHEM by which we insure no negative value for the heavy-particle temperature needs to be reviewed and improved.

As an interim measure we have adopted the HARC procedure for limiting the amount of specific energy when the various contributions are added to obtain SPINTN; however, the limiting term has not been derived and needs to be reviewed and improved. Another possible shortcoming is that the current procedure permits adding energy to a region within a B-edge for a previous event.

#### 9.4.3 Flow Chart for Subroutine PHEAT

Figure 21 is a detailed flow chart for Subroutine PHEAT.

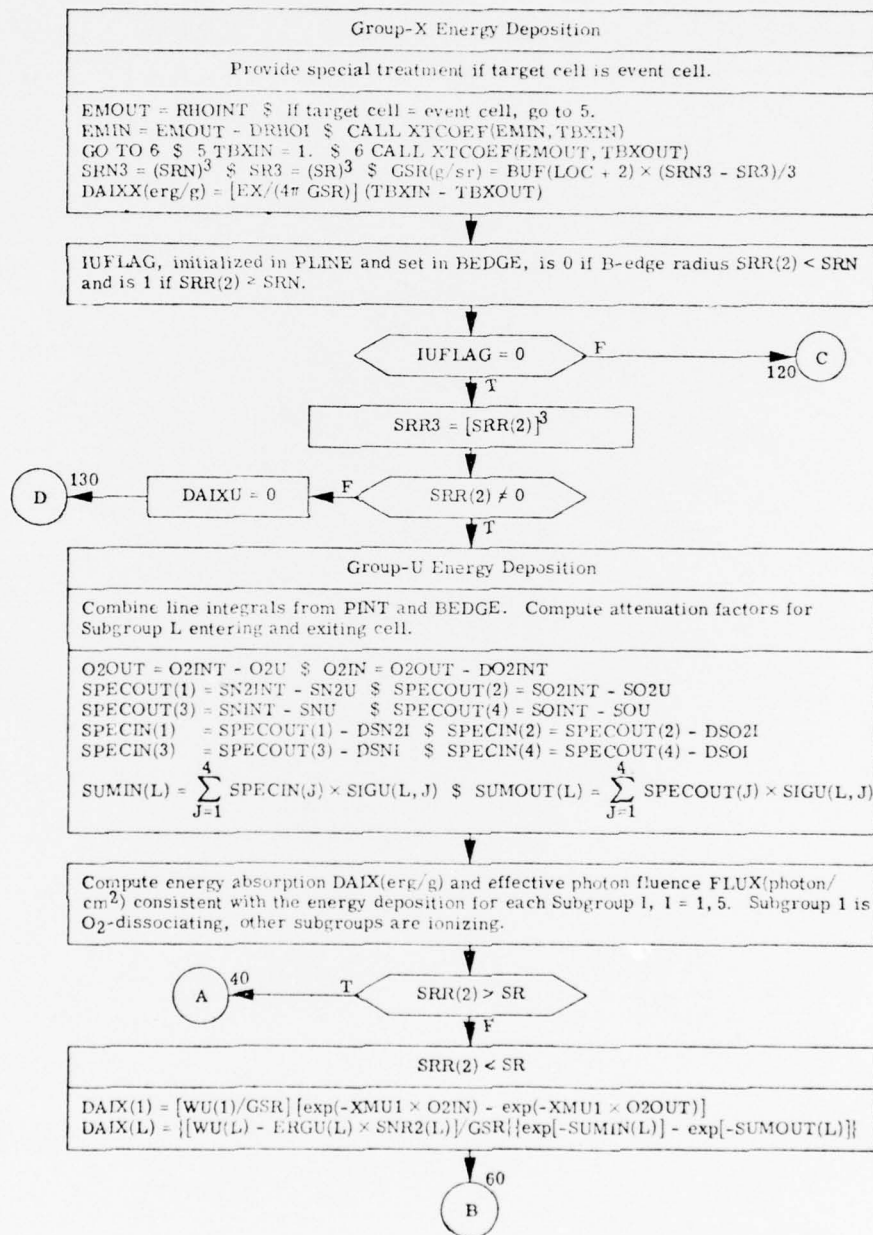


Fig. 21. Flow Chart of Subroutine PHEAT.



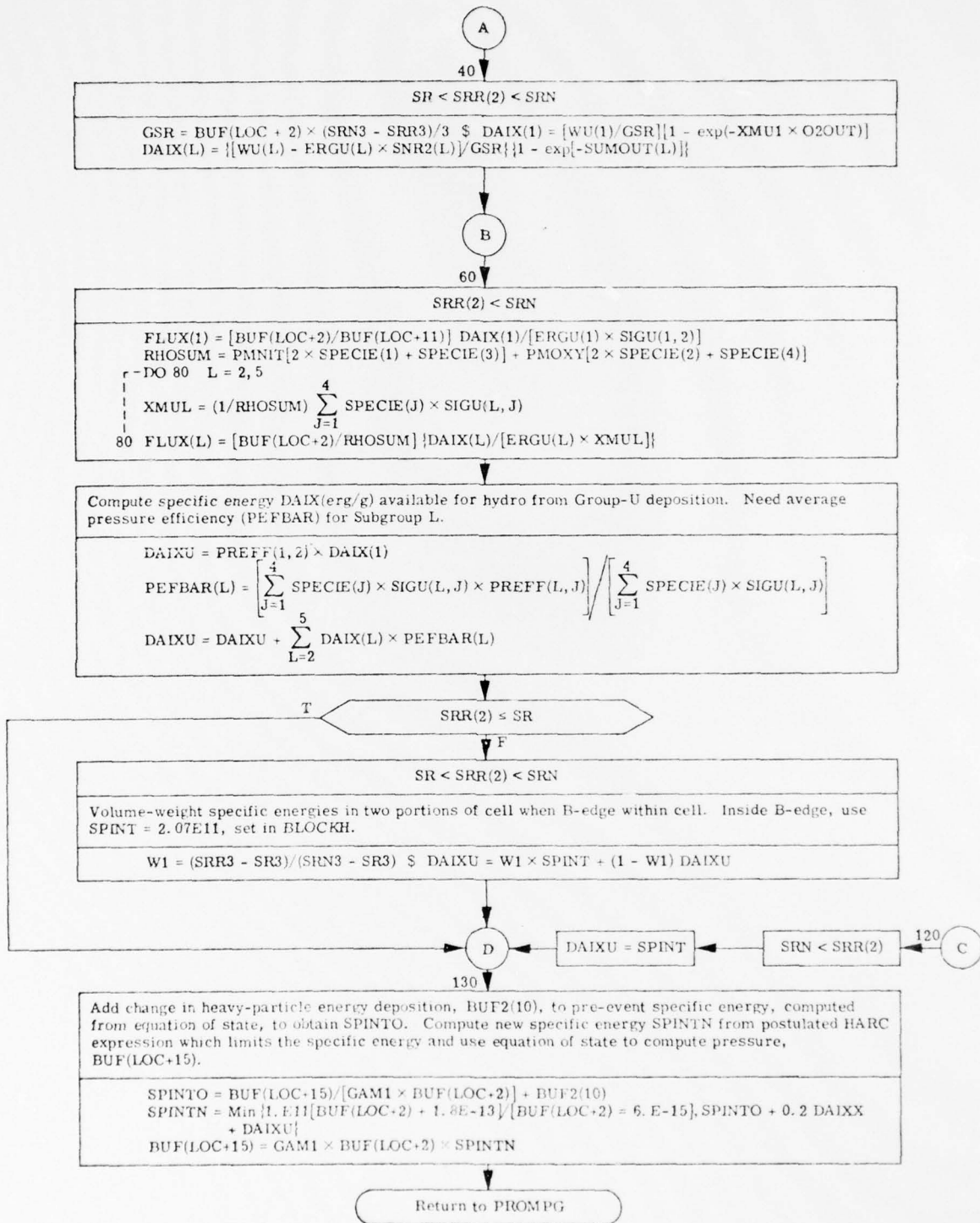


Fig. 21. (Continued).



## 10. PROMPT CHEMISTRY ASSOCIATED WITH GROUP-X AND GROUP-U ENERGY DEPOSITION (SUBROUTINE PCHEM)

Subroutine PCHEM first combines (a) the changes in species densities due to debris deposition, computed in Subroutine HPCHEM, with (b) the previous species densities of a cell and then computes the ionization and species densities from the Group-X and Group-U energy depositions.

Subroutine PCHEM contains numerous compromises and adjustments made necessary by using energy deposition models that are (a) instantaneous and (b) mismatched with the late-time chemistry modules.

### 10.1 DETERMINATION OF INITIAL SPECIES FOR COMPUTING THE PROMPT CHEMISTRY ASSOCIATED WITH GROUP-X AND GROUP-U ENERGY DEPOSITIONS

Before computing the prompt chemistry associated with the energy depositions of Groups X and U, we must combine the changes in species densities due to debris deposition with the previous species densities.

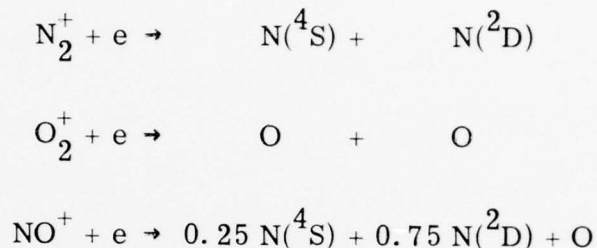
The changes in the species densities and electronic thermal and excitation energy are stored in the BUF2 array by Subroutine HPCHEM. These variables are defined in Table 3.

The incorporation of these changes may seem trivial, but it is complicated by the facts that (a) the late-time chemistry for the HAG treats all molecular ions as if they are  $\text{NO}^+$  and (b) it is necessary to appropriately convert the  $\text{N}_2^+$  and  $\text{O}_2^+$  produced by the heavy-particle deposition into  $\text{NO}^+$ . This conversion is made so as to conserve nuclei

Table 3. Inputs to Subroutine PCHEM from BUF2 Array for Those Cell Quantities Updated by Subroutine HPCHEM as a Result of Debris Deposition.

I	BUF2(I)
1	Change in [e], $\text{cm}^{-3}$
2	Change in [ $\text{N}(^4\text{S})$ ], $\text{cm}^{-3}$
3	Change in [ $\text{N}(^2\text{D})$ ], $\text{cm}^{-3}$
4	Change in [O], $\text{cm}^{-3}$
5	Change in [ $\text{N}_2$ ], $\text{cm}^{-3}$
6	Change in [ $\text{O}_2$ ], $\text{cm}^{-3}$
7	Change in [ $\text{N}^+$ ], $\text{cm}^{-3}$
8	Change in [ $\text{O}^+$ ], $\text{cm}^{-3}$
9	Change in O excitation energy and electron thermal energy per new electron (eV/electron)
10	Not used
11	Change in [ $\text{N}_2^+$ ], $\text{cm}^{-3}$
12	Change in [ $\text{O}_2^+$ ], $\text{cm}^{-3}$

of a given mass number and electronic state but with only partial regard to energy considerations. The appropriate mass conversion coefficients are based on the same dissociative recombination products of  $N_2^+$ ,  $O_2^+$ , and  $NO^+$  used in the later treatment of Group-X and -U energy depositions. The assumed dissociative recombination products are as follows [Volume II]:



To illustrate this conversion process, we note that if we have a  $NO^+$  molecular-ion density equal to  $[N_2^+]$ , the number of  $N(^4S)$  atoms we get from dissociative recombination of  $NO^+$  is only one-fourth as many as from dissociative recombination of  $N_2^+$ . Thus, to the initial density of  $N(^4S)$  we must add a number equal to  $0.75[N_2^+]$ . Similarly, if we have a  $NO^+$  density equal to  $[O_2^+]$ , the number of  $N(^4S)$  atoms we get from dissociative recombination of  $NO^+$  is  $0.25[NO^+]$  whereas we would get no  $N(^4S)$  atoms from the dissociative recombination of  $[O_2^+]$ . Thus, to the initial density of  $N(^4S)$  we must subtract a number equal to  $0.25[O_2^+]$ .

To prevent the density of  $N(^4S)$ ,  $N(^2D)$ , or  $O$  from becoming negative as a result of converting  $N_2^+$  and  $O_2^+$  to  $NO^+$ , we appropriately reduce either the  $N_2^+$  or  $O_2^+$  (produced by the heavy particles) and correspondingly increase  $N_2$  or  $O_2$ . Of course, the electron density must be reduced to maintain charge conservation when we reduce the density of either  $N_2^+$  or  $O_2^+$ .

More details of the steps in converting  $N_2^+$  and  $O_2^+$  to  $NO^+$  are given on the first page of the flow chart for Subroutine PCHEM (Fig. 22).

We assume that  $[CO_2]$  and  $[He]$  are reduced by the debris deposition in proportion to the  $[N_2]$  reduction.

## 10.2 IONIZATION AND SPECIES DENSITIES FROM GROUP-X DEPOSITION

Computation of the species densities from Group-X deposition is done very simply.

1. Use the specific energy absorbed from Group-X deposition ( $DAIXX(\text{erg/g})$ ) computed in Subroutine PHEAT and the mass density ( $RHO(\text{g/cm}^3)$ ) to get the corresponding energy density ( $DELEX(\text{eV/cm}^3)$ ).
2. Assume 35-eV of energy is expended in forming an ion-pair.
3. Distribute the ions in proportion to the neutral species, but allow no more than one ion pair per neutral particle. Such a prescription is perhaps unduly simplistic in view of the considerable amount of information available concerning x-ray and electron energy degradation in the atmosphere (see, e. g., MS-75, SK-75, TA-74); however, no reliable prescription is yet available to predict the species for an arbitrary initial mix of species.
4. Assume the molecular ions undergo instantaneous dissociative recombination in accordance with the prescription in Section 10. 1.
5. Assume that  $[CO_2]$  and  $[He]$  are reduced in proportion to the  $[N_2]$  reduction.

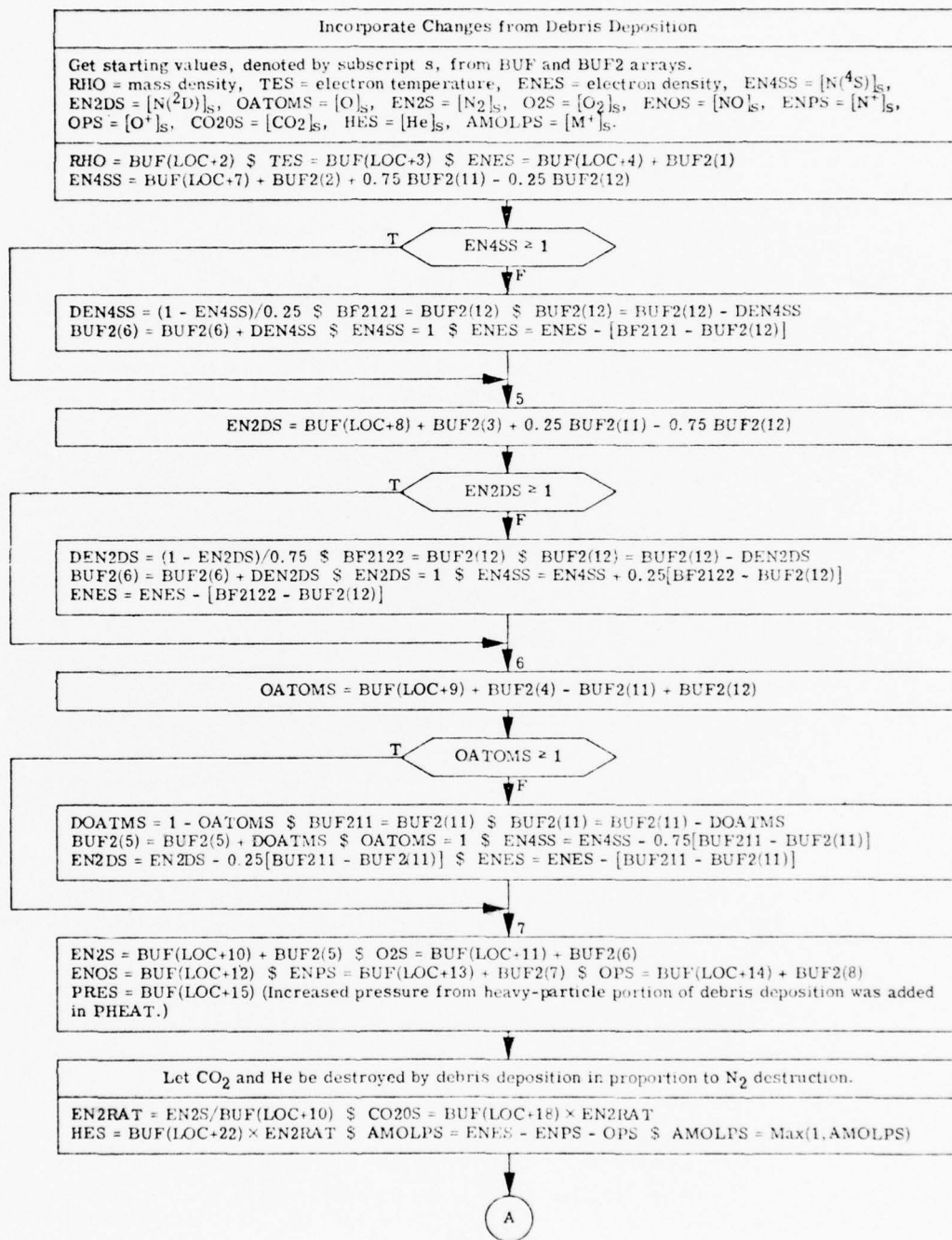


Fig. 22. Flow Chart of Subroutine PCHEM.



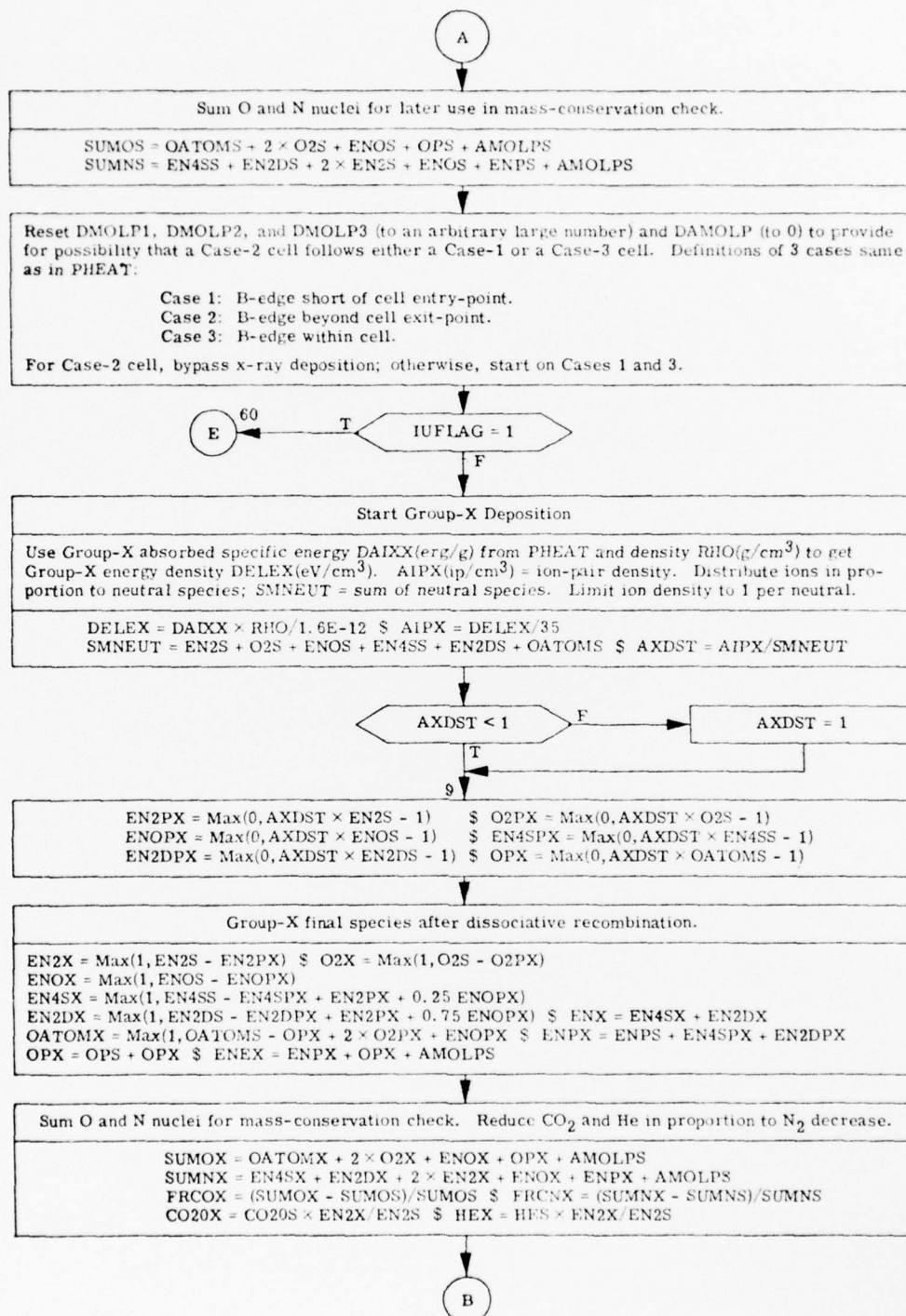


Fig. 22. (Continued).



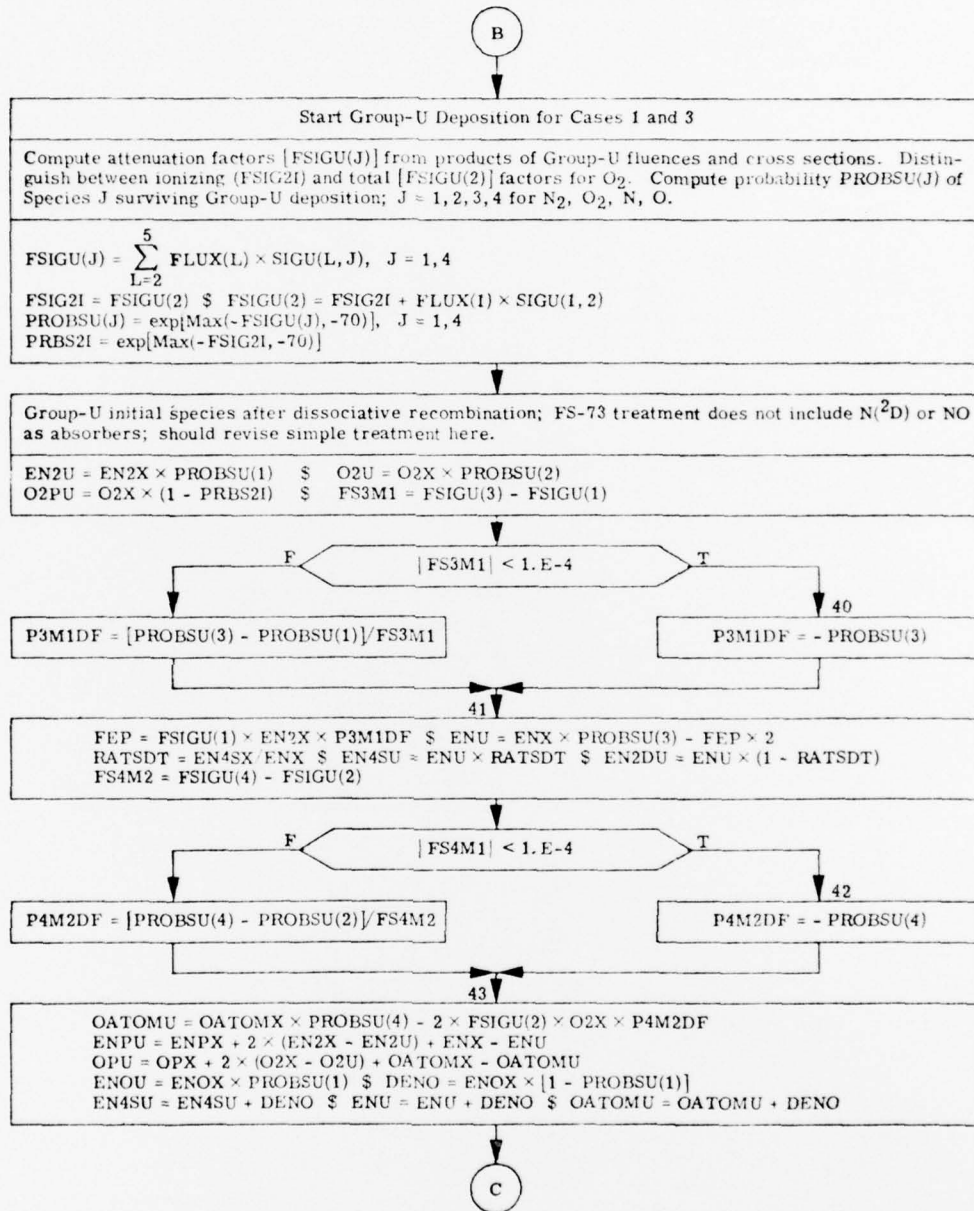


Fig. 22. (Continued).

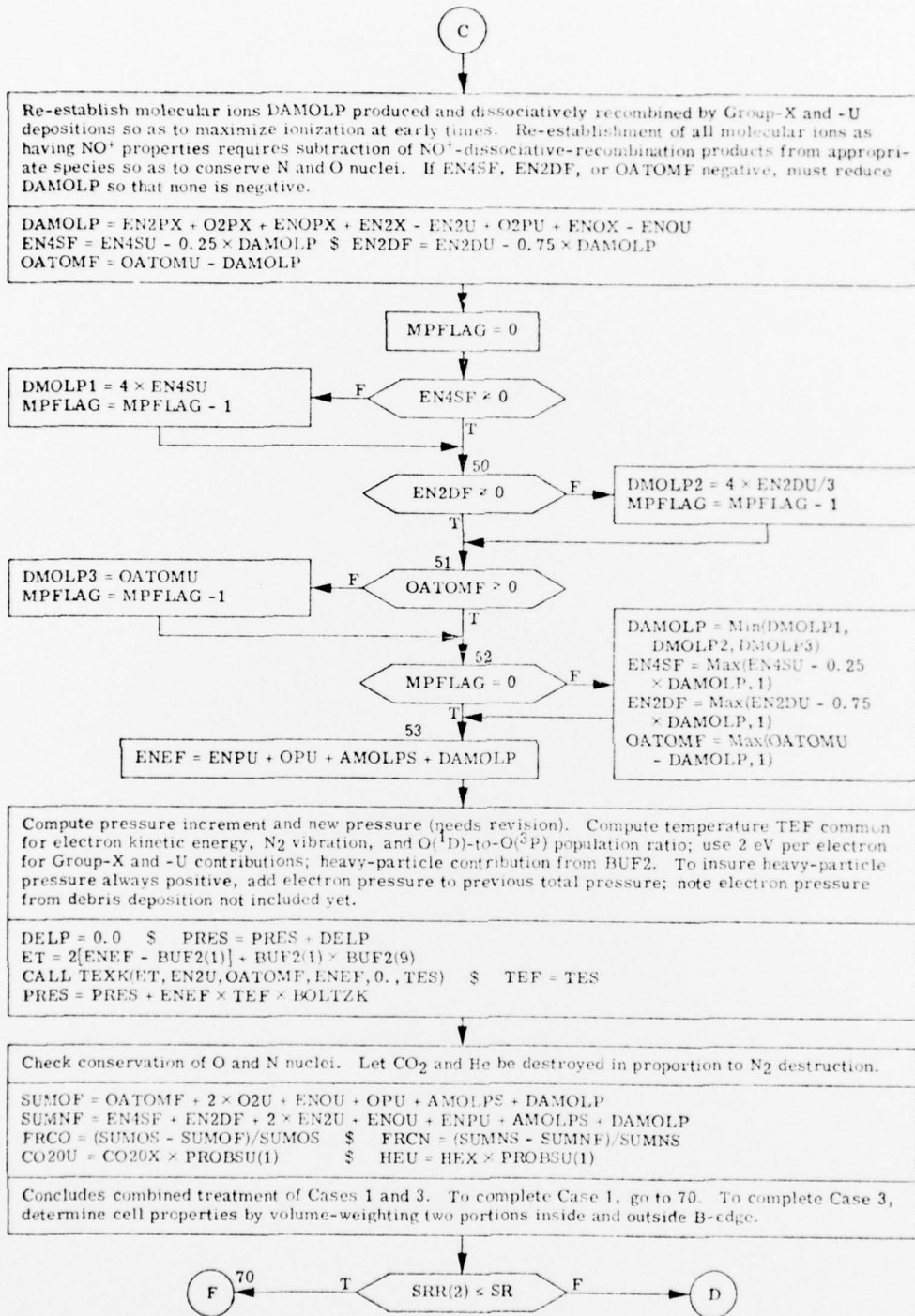


Fig. 22. (Continued).

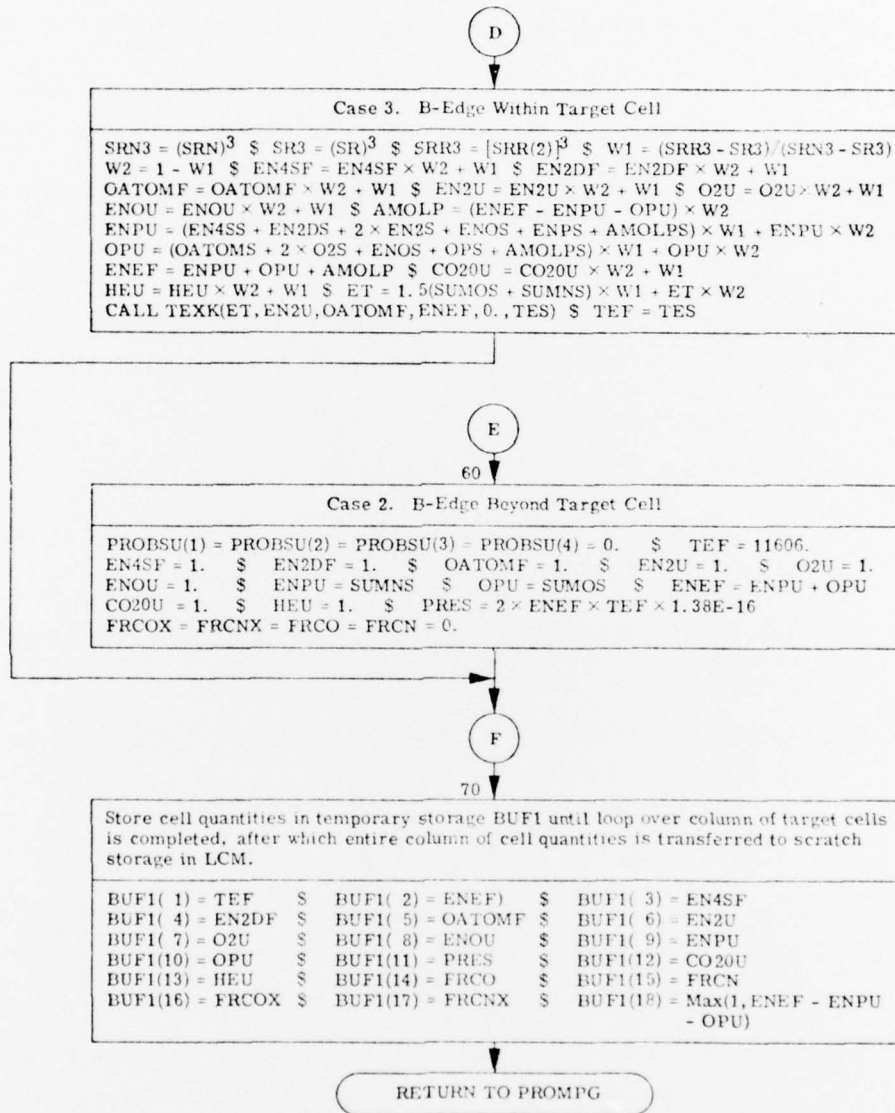


Fig. 22. (Continued).

As one of the mass conservation checks during development, we have compared the sums of the O and N nuclei after the computation of the species resulting from Group-X deposition with the sums before the deposition.

If the target cell is a Case-2 cell as defined in Section 9.4 and again below in Section 10.3, no computation is made of species resulting from Group-X deposition.

### 10.3 IONIZATION, SPECIES DENSITIES, AND RESULTANT PRESSURE FROM GROUP-U DEPOSITION

In computing the species from Group-U deposition, we consider three cases, just as we did in Subroutine PHEAT:

Case 1: B-edge radius (SRR(2)) is smaller than the target-cell entry radius (SR).

Case 2: B-edge radius (SRR(2)) is greater than the target-cell exit radius (SRN).

Case 3: B-edge radius (SRR(2)) is between the target-cell entry radius (SR) and the exit radius (SRN).

The total attenuation factors (FSIGU(J)) are computed from the summed products of Group-U fluences (FLUX(L), photons/cm<sup>2</sup>) and cross sections (SIGU(L, J), cm<sup>2</sup>). (Recall that the Group-U fluences computed in Subroutine PHEAT are effective fluences, consistent with the absorbed energy computed as the difference of the (steradianal) energy entering and leaving the cell.) The attenuation factors are

$$\text{FSIGU}(J) = \sum_{L=2}^5 \text{FLUX}(L) \times \text{SIGU}(L, J) , \quad J = 1, 4$$

$$\text{FSIG2I} = \text{FSIGU}(2)$$

$$\text{FSIGU}(2) = \text{FSIG2I} + \text{FLUX}(1) \times \text{SIGU}(1,2) ,$$

where  $\text{SIGU}(L, J)$  is the absorption cross-section of Species  $J$  for Subgroup- $L$  photons, tabulated in Table 4 and entered as data in Block Data BLOCKH, and where we have distinguished between the ionizing ( $\text{FSIG2I}$ ) and total ( $\text{FSIGU}(2)$ ) attenuation factors for  $\text{O}_2$ .

The total survival probability of Species  $J$  is

$$\text{PROBSU}(J) = e^{-\text{FSIGU}(J)} .$$

The probability of  $\text{O}_2$  not being ionized is

$$\text{PRBS2I} = e^{-\text{FSIG2I}} .$$

If the species densities after the Group- $X$  deposition (but before the Group- $U$  deposition) are denoted by a subscript  $x$ , the initial species after the Group- $U$  deposition, with provision for instantaneous dissociative recombination of the molecular ions but without production of  $\text{N}(^2\text{D})$ , are [FS-73]

$$[\text{N}_2]_{\text{u}} = [\text{N}_2]_{\text{x}} \times \text{PROBSU}(1)$$

$$[\text{O}_2]_{\text{u}} = [\text{O}_2]_{\text{x}} \times \text{PROBSU}(2)$$

$$[\text{N}]_{\text{u}} = [\text{N}]_{\text{x}} \times \text{PROBSU}(3) + 2 \times [\text{N}_2]_{\text{x}} \times \text{FSIGU}(1) \times \frac{\text{PROBSU}(1) - \text{PROBSU}(3)}{\text{FSIGU}(3) - \text{FSIGU}(1)}$$

$$[\text{O}]_{\text{u}} = [\text{O}]_{\text{x}} \times \text{PROBSU}(4) + 2 \times [\text{O}_2]_{\text{x}} \times \text{FSIGU}(2) \times \frac{\text{PROBSU}(2) - \text{PROBSU}(4)}{\text{FSIGU}(4) - \text{FSIGU}(2)}$$

$$[\text{N}^+]_{\text{u}} = [\text{N}^+]_{\text{x}} + 2 \{ [\text{N}_2]_{\text{x}} - [\text{N}_2]_{\text{u}} \} + [\text{N}]_{\text{x}} - [\text{N}]_{\text{u}}$$

$$[\text{O}^+]_{\text{u}} = [\text{O}^+]_{\text{x}} + 2 \{ [\text{O}_2]_{\text{x}} - [\text{O}_2]_{\text{u}} \} + [\text{O}]_{\text{x}} - [\text{O}]_{\text{u}} .$$



Table 4. UV Absorption Cross-Sections SIGU(L, J)<sup>a</sup>  
(in units of 10<sup>-18</sup> cm<sup>2</sup>).

Species	J	SIGU(L, J)				
		L = 1 11.0 eV	L = 2 14.8 eV	L = 3 16.2 eV	L = 4 22.0 eV	L = 5 36.0 eV
N <sub>2</sub>	1	0	8	20	25	20
O <sub>2</sub>	2	2	16	20	25	20
N	3	0	10	10	10	10
O	4	0	3.2	3.2	9	9

<sup>a</sup>From Table A-1 of FS-73, in turn from DD-70b.

Since the Group-U deposition procedure does not provide for either N(<sup>2</sup>D) or NO, as an interim measure we partition the N atoms between N(<sup>4</sup>S) and N(<sup>2</sup>D) according to the prescription

$$[N(^4S)]_u = [N]_u [N(^4S)]_x / [N]_x$$

$$[N(^2D)]_u = [N]_u \left\{ 1 - [N(^4S)]_x / [N]_x \right\} ,$$

decrease the NO in proportion to the N<sub>2</sub> decrease, and increase N and O correspondingly:

$$[NO]_u = [NO]_x \times \text{PROBSU}(1)$$

$$\delta[NO] = [NO]_x \left\{ 1 - \text{PROBSU}(1) \right\}$$

$$[N(^4S)]_u \rightarrow [N(^4S)]_u + \delta[NO]$$

$$[N]_u \rightarrow [N]_u + \delta[NO]$$

$$[O]_u \rightarrow [O]_u + \delta[NO] .$$



To maximize the ionization at early time, as suggested by W. Knapp, we re-establish the molecular ions produced and dissociatively recombined by the Group-X and -U depositions (and allow the molecular ion decay to be predicted by the later-time chemistry module). The increment in such molecular ions is

$$\begin{aligned} \text{DAMOLP} \equiv \delta M^+ &= [N_2^+]_X + [O_2^+]_X + [NO^+]_X + [N_2]_X - [N_2]_U \\ &+ [O_2^+]_U + [NO]_X - [NO]_U \end{aligned}$$

where

$$[O_2^+]_U = [O_2]_X (1 - \text{PRBS2I}) .$$

The re-establishment of all molecular ions as having the properties of  $NO^+$  requires subtraction of all the products of  $NO^+$  dissociative recombination from the appropriate species so as to conserve N and O nuclei:

$$[N(^4S)]_f = [N(^4S)]_u - 0.25 \times \delta M^+$$

$$[N(^2D)]_f = [N(^2D)]_u - 0.25 \times \delta M^+$$

$$[O]_f = [O]_u - \delta M^+ .$$

However, if  $[N(^4S)]_f$ ,  $[N(^2D)]_f$ , or  $[O]_f$  is negative, we must reduce  $\delta M^+$  so that none of them is negative.

The final values for the species densities after Group-X and -U depositions and re-establishment of the molecular ions are  $[N_2]_u$ ,  $[O_2]_u$ ,  $[NO]_u$ ,  $[N(^4S)]_f$ ,  $[N(^2D)]_f$ ,  $[O]_f$ ,  $[N^+]_u$ ,  $[O^+]_u$ , and  $[e]$ , the electron density,

$$[e] = [N^+]_u + [O^+]_u + \delta M^+ + M_s^+$$

where  $M_S^+$  is the molecular-ion density prior to Group-X deposition.

There remains the task of devising a truly satisfactory procedure for computing a pressure increment in addition to that computed in Subroutine PHEAT. The treatment in Subroutine PHEAT is incomplete because the Group-U subgroups are deposited independently of each other across an appreciable path length without accounting for either species depletion by other subgroups or additional absorbers resulting from the (instantaneous) dissociative recombination that is included in Subroutine PCHEM. (Note, however, that the partial heating computed in Subroutine PHEAT does serve the purpose of defining effective fluences for the Group-U subgroups that are used in Subroutine PCHEM.) Any additional pressure increment computed in Subroutine PCHEM must be consistent with (1) that computed in Subroutine PHEAT and with (2) the return of pressure computed by the later-time chemistry in CHEMEF. The problem is further complicated because the molecular ions which are produced by the Group-X and -U depositions and which undergo dissociative recombination as part of the modeling in Subroutine PCHEM are  $N_2^+$  and  $O_2^+$  whereas the molecular ions that are re-established are  $NO^+$  ions which are carried in CHEMEF. As an interim measure we set the pressure increment DELP equal to zero.

To ensure that the heavy-particle pressure will always be positive, we have added the electron pressure (computed below) to the previously-found value for the total pressure. This interim measure needs to be reviewed and improved.

To compute the temperature TEF taken to be common to the thermal electrons, the  $N_2$  vibrational states, and the  $O(^1D)$ -to- $O(^3P)$  population ratio, we use the GET-prepared Subroutine TEXK [Vol. 11] which determines such a temperature when given  $[N_2]$ ,  $[O]$ ,

[e], and the energy per cubic centimeter (ET) to be divided among the three modes. As an interim measure we compute ET from

$$ET = 2 \times \delta[e]_{x,u} + \delta[e]_{HP} \times E_{pe}$$

where  $\delta[e]_{x,u}$  is the incremental electron density produced by the Group-X and -U depositions, the factor 2 is an interim assumption for the energy in the three modes per newly-formed electron in the Group-X and -U depositions,  $\delta[e]_{HP}$  is the incremental electron density produced by the heavy-particle depositions, and  $E_{pe}$  is the sum of the electron thermal and O(<sup>1</sup>D) excitation energies per newly-formed electron in the heavy-particle deposition, obtained from Subroutine HPCHEM.

As another of the mass conservation checks during development, we have compared the sums of the O and N nuclei after the computation of the species resulting from Group-U deposition with the sums before the deposition.

As with the Group-X deposition, we assume as an interim measure that [CO<sub>2</sub>] and [He] are reduced in proportion to the [N<sub>2</sub>] decrease.

The foregoing describes the combined treatment of target cells that are Case 1 or Case 3. For Case 1, the treatment is complete, but for Case 3, the final cell properties are determined by volume-weighting the two portions, one of which is inside the B-edge and the other is outside the B-edge.

For Case 2, the entire cell is inside the B-edge and the only remaining species are assumed to be N<sup>+</sup>, O<sup>+</sup>, and e. The temperature of both electrons and heavy particles is taken to be 1 eV.

The final step in Subroutine PCHEM is to store the cell quantities in temporary storage BUF1 until the loop over the entire column of target cells is completed, after which the entire column of cell quantities is transferred to scratch storage in large-core memory.

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