Written: October 1970
Distributed: November 1970

LA-4539
UC-32, MATHEMATICS
AND COMPUTERS
TID-4500

LOS ALAMOS SCIENTIFIC LABORATORY
of the
University of California
LOS ALAMOS • NEW MEXICO

ANDYMG3, the Basic Program of a Series of Monte Carlo Programs for Time-Dependent Transport of Particles and Photons

by

D. R. Harris

BLANK PAGE

Contents

Tables

Figures

ANDYMG3, THE BASIC PROGRAM OF A SERIES OF MONTE CARLO PROGRAMS FOR TIME-DEPENDENT TRANSPORT OF PARTICLES AND PHOTONS

by

D. R. Harris

ABSTRACT

ANDYMG3 is the basic program of a series of Monte Carlo programs designed to solve applied problems in time-dependent particle and photon transport for general geometries. Particle or photon type and energy are identified by multienergy-group number. Cross sections are read in S_N format with scattering pattern components up to P_3. Particle splitting and termination routines permit negative weights. Particle and photon emission can be delayed. A library of reaction cross sections is provided so that practically useful results are computed after execution of the Monte Carlo. The ANDYMG3 program, in FORTRAN-IV for the CDC-6600 and UNIVAC-1108 computers, requires 0.5-2 msec per collision (CDC-6600) and a field length less than 60_8K for most problems.

I. INTRODUCTION

The ANDY series of Monte Carlo transport programs, in FORTRAN-IV for the CDC-6600 and UNIVAC-1108 computers, are variously designed for specific time-dependent particle and photon transport applications. These programs are intended to be small, transparently programmed, system-independent, and fast.

In this report is described ANDYMG3 (ANDY, Multigroup, General geometry, version 3), the basic program of a series of programs in which particle and photon type and energy are identified by multi-energy-group. Well-understood multigroup cross-section sets can be used in these programs which thus provide extension of familiar multigroup S_N and diffusion theory methods to complex geometries. Any complex geometry formed by segments of planes, spheres, cylinders, ellipsoids, and cones can be treated. Geometrical and real-time properties of particle and photon flight are not approximated. Scattering patterns in the simulation are continuous in scattering angles and treat scattering cross sections up to order P_3 in the laboratory coordinate system. Particles and photons from collisons can be delayed as from the decay of radioactive nuclei.

The applications of the ANDY programs are sufficiently varied, requiring different routines for various sources, collision products, geometry options, variance reducing devices, tallies, etc., that a series of ANDY programs rather than a single program with many options has been created for specific nuclear design applications. In consequence, problem inputs are simplified, the programs can be small and fast, and specialized modifications can be introduced simply into the programs. Derivative programs based on ANDYMG3 include ANDYMS1, including delayed particle and photon effects primarily for nuclear safeguards applications; ANDYMM1, treating moving material problems; ANDYMV1, for vulnerability studies; ANDYMP1, for nucleon-meson cascade calculations; and ANDYME1, for air transport and electromagnetic-pulse studies. These programs typically require a field length less than 60_8K and a running

time (CDC-6600) from 0.5 msec to 2 msec per particle collision, depending on the problem. Each program consists of approximately 1000 statements lines plus about 400 comment lines.

Considerable attention has been directed toward the development for the ANDY programs of a fast general geometry routine with simple input. The geometry routine is described in Section II-A and in Appendixes B and C. Several geometry-routine development problems and their resolutions are described in Section II-A. Problem input and output are described in Section III-A and Section IV, respectively. Programming is discussed in Section II-D.

The ANDY multigroup collision treatment, described in Section II-B, is a Monte Carlo simulation of the collision treatment used in S_N programs. This constraint results both from the objective that ANDY multigroup and S_N calculations be compatible and from the objective that the ANDY multigroup programs use well-understood S_N cross-section sets. It is felt that this constraint has been largely useful. For example, S_N cross-section sets often do not contain the fission cross section, but, instead, contain the fission neutron or photon production cross section. For this reason, the ANDY multigroup collision routine does not determine whether a collision has been a fission, but answers the more relevant question of whether a collision product is from fission. How then can the program yield physically useful quantities such as fission rate, $He^3(n,p)$ detector response, or biological dose? Many S_N cross-section sets contain no cross sections which are useful for physical tallies because total and scattering cross sections have been modified by transport approximations, because scattering cross sections include a variety of reactions, and because fission cross sections are absent. The ANDY multigroup program resolution of this problem is to introduce a summing library of physically useful cross sections which are applied after completion of the Monte Carlo transport calculation to the computation of physically useful quantities. The operation of this summing section is described in Section IV on output.

Specific design programs in the ANDY series, e.g., ANDYMS1, are supplied with a transport cross-section library and a summing library specific to the application. Changes in libraries can be effected, however, by reference to Section III-B on data library input. The cross-section set currently supplied with ANDYMG3 is a 25-group neutron cross-section set with P_0 and P_1 scattering components in the Bell-Hansen-Sandmeier[1] transport approximation. This cross-section library contains many negative cross sections for scattering from group IG to group IG', and the simulation[2] of such cross sections is described in Section II-B. Particles or photons are tracked, split, and terminated in ANDY with equal facility whether they have positive or negative weights. Splitting and termination are described in Section II-C.

Program tests, described in Section II-E, show that ANDYMG3 and the S_N program DTF-IV[3] are in good agreement. Other tests of program accuracy are described. Timing tests are described which intercompare ANDYMG3, DTF-IV, and the continuous-energy Monte Carlo program, MCN, for a test problem with spherical symmetry.

Input and output for a sample problem are listed in Appendixes D and E. The sample problem is described in Section III-A.

II. CALCULATIONS

In turn are described the ANDY general geometry routine, the ANDY collision routine, particle splitting and termination, programming, and program tests.

A. ANDY General Geometry Routine

The general geometry routine used in ANDYMG3 and its derivative programs is similar to that which has been described earlier for the ANDY1G2 and ANDY1R2 programs.[4] Some of this description is repeated here, and changes are noted. A flow chart of the ANDY general geometry routine is shown in Appendix B, and a listing of the routine is given in Appendix C. Geometry input is discussed in Section III.

The ANDY general geometry routine has been devised to be fast and to simplify problem input for complex geometries. In ANDY a topological entity, the surface segment, is interposed between regions and surfaces, the usual entities characterizing a Monte Carlo geometry routine. A region, from an operational point of view, is a spatial domain in which macroscopic cross sections are uniform or are specified by a single table or set of functions. A surface, from this operational point of view, is a set

of points in space which satisfy an algebraic equation, usually linear or quadratic. A region is bounded in ANDY, not by surfaces, but by surface segments. A surface segment is defined as a set of points all of which lie in a specified containing surface and which may be all or only a part of the containing surface. In the latter case, the segment is defined by its points having proper sense with respect to other surfaces. In the ANDY programs, sense is defined as +1 outside a closed surface such as a sphere, cylinder, or ellipsoid and as -1 inside. For a plane, cone, or other open surface, sense is defined as +1 on the side of the surface toward which its normal or axial vector points and as -1 on the other side.

For example, consider a uniform region* that is the union of two intersecting spheres numbered 1 and 2. In ANDY this single region is bounded by two surface segments numbered 1 and 2. Surface segment 1 is contained in spherical surface 1 and has sense +1 with respect to spherical surface 2. Surface segment 2 is contained in spherical surface 2 and has sense +1 with respect to spherical surface 1.

If a Monte Carlo geometry routine is topologically sound, it should be able to treat unambigiously (except for a set of trajectories with frequency measure zero) any configuration defined by surfaces included in the program (planes, spheres, cylinders, ellipsoids, and cones in ANDYMG3). A plausibility argument that the ANDY geometry routine is topologically sound is presented in Appendix C of Ref. 4.

When a particle emerges into a region from the source, from a collision, or from the bank, it is necessary to compute the distance D along the particle's trajectory to each surface segment surrounding the region. If D is complex or nonpositive, it is discarded, and by comparing each positive D with a precomputed distance to collision the particle is found to collide or to hit a surface segment. Similarly, when a particle hits a surface segment it is necessary to determine the distance D along the particle's trajectory to each surface segment bounding the new region about to be entered. At this point, there arise a number of alternatives of which three have been tested in the ANDY development. These are as follows.

(a) Present ANDY Surface Segment Crossing. Each surface used in defining surface segments bounding the new region about to be entered is tested to see if it also was used in bounding the region just left. If so, the distance to the surface has already been computed while the trajectory was in the region just left. This distance then is decremented by the flight distance in the region just left. This technique saves time and computations, and it has an additional advantage. The surface segment about to be crossed is surface held in common by the new and old regions, and this technique yields a distance, D, to it which is zero to the last bit. Hence, the surface segment about to be crossed can be rejected as a candidate for a hit following further flight because D is nonpositive.

(b) Another Surface Segment Crossing. A new array, ICALC(IS2), IS2 = 1, NSUR, is zeroed, except that ICALC(IS2) is set equal to 1 when a distance to a surface is calculated. When a particle is about to enter a new region, the array ICALC is examined and if the distance to a surface has ever been calculated along the uninterrupted trajectory in any previously entered region the distance is suitably decremented. This technique (b) is found to be several per cent slower than technique (a) for the problem illustrated in Fig. 1, presumably because the decrementing is more complicated and because ICALC must be rezeroed frequently in source and collision events and in bank withdrawals.

(c) Previous ANDY Surface Segment Crossing. In ANDY1G2 and ANDY1R2,[4] a particle arriving at a surface was "bumped" into the new region a distance ε along the trajectory. Then all flight distances to surface segments surrounding the new region were calculated, whether or not they had been calculated before. Not only is this technique (c) slower by 7% than technique (a) for the problem illustrated in Fig. 1, but technique (c) when used on the UNIVAC-1108 sometimes improperly calculated D to the surface segment just crossed. This failure resulted from loss of significance when ε was small compared to physical dimensions in the problem. No failures of technique (c) have been observed on the CDC-6600.

*This situation would require two regions with identical cross sections in some Monte Carlo programs.

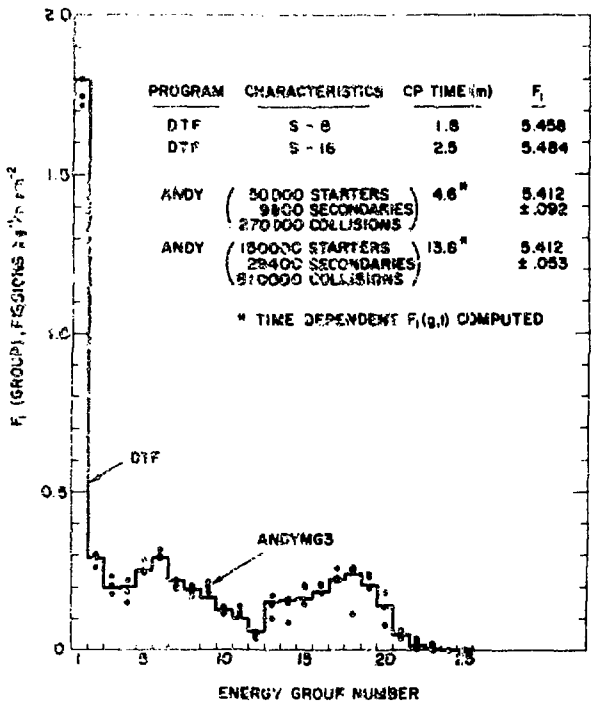


Fig. 1. F_1-number contributions from groups 1-25 calculated by DTF and by ANDYMG3.

Surface segment crossing technique (a) is used in current ANDY programs including ANDYMG3.

B. Collision Routine

If the computed distance to collision is less than any distance to hit a surface segment, then a collision occurs. The space and time coordinates of the particle or photon are translated to the point of collision, and collision tallies, if any, are incremented by the particle weight, W. If there are delayed particles or photons in the problem (NTPDEL positive), then quantities WDEL (ITPDEL) are incremented by W times the collision yield of delayed species of the type ITPDEL = 1, NTPDEL.

Collision products can be divided into two classes according as their phase space distribution (normalized per product) does ("scattering") or does not ("fission") depend significantly on the energy of the incident particle or photon. The nuclear fission process exemplifies the latter class, and, indeed, we shall refer to this alternative as "fission." These two alternatives are treated as different branches in the present ANDY collision routine. It may be objected that no collision process is really so exothermic and simple that the normalized product distribution is independent of the incident channel. Nevertheless, the present ANDY collison treatment conforms to current S_N program usage,[3] and such conformity is an immediate objective of the ANDY development. Of course, all prompt collision products can be placed into the "scattering" transfer matrix in ANDY, in which case the "fission" branch will be unused.

The first step in the ANDY treatment of promptly emitted collision products is the multiplication of the particle or photon weight, W, by the expected number, F_1, of prompt products per collision. Here the prompt products include particles and photons of positive or negative weights which are to be transported by ANDY. For a collision induced by a particle or photon in group g,

$$F_1 = \frac{\nu\Sigma_{fg} + \sum_{g'} |\Sigma_{sg\to g'}|}{\Sigma_g} , \qquad (1)$$

where Σ_g is the collision cross section in group g, $\nu\Sigma_{fg}$ is the "fission" particle or photon production cross section in group g, and $\Sigma_{sg\to g'}$ is the "scattering" cross section for transfer from group g to group g'. It may be recalled that group g identifies particle or photon type as well as energy; e.g., groups 1-25 might be neutrons and groups 26-37 might be gammas. In typical usage "scattering" includes, for example, (n,2n) cross sections, cross sections for electromagnetic slowing down of charged particles and gammas, and cross sections for production of other types of particles or photons such as $n \to \gamma$, $\gamma \to e^-$, $n \to p$, and $p \to \pi^+$.

The prompt collision product next is chosen to be from "scattering" or from "fission" according as a chosen random number in the interval (0.,1.) is smaller or larger than

$$F_2 = \frac{\sum_{g'} |\Sigma_{g\to g'}|}{\nu\Sigma_{fg} + \sum_{g'} |\Sigma_{g\to g'}|} . \qquad (2)$$

In the fission branch, a particle is emitted isotropically in the laboratory coordinate system into a group chosen at random using the cumulative "prompt fission spectrum" probability distribution, CHIP. In the "scattering" branch, the exit group g" is chosen from the probability distribution

$$F_3 = \frac{|\Sigma_{g\to g''}|}{\sum_{g'} |\Sigma_{g\to g'}|}, \qquad (3)$$

and the exit direction, $\underline{\Omega}''$, is chosen from some probability distribution, $p_{sim}(\underline{\Omega}')$, selected to improve problem statistics. Finally, the particle or photon weight is multiplied by

$$F_4 = \frac{\Sigma_{g\to g''}}{|\Sigma_{g\to g''}|} \times \frac{\int d\underline{\Omega}' p_{sim}(\underline{\Omega}')}{p_{sim}(\underline{\Omega}'')} \sum_{j=0}^{\hat{j}} (2j+1) \frac{\Sigma^j_{g\to g''}}{\Sigma_{g\to g''}} P_j(\underline{\Omega}\cdot\underline{\Omega}''), \qquad (4)$$

where $\underline{\Omega}$ is the incident direction, $P_j(\underline{\Omega}\cdot\underline{\Omega}'')$ is the Legendre polynomial of order j, $\hat{j}$ is the order of scattering treated, and $\Sigma^j_{g\to g''}$ is the j'th-order coefficient in the Legendre polynomial expansion of the "scattering" cross section,

$$\Sigma_{g\to g''}(\underline{\Omega}\cdot\underline{\Omega}'') = \sum_{j=0}^{\hat{j}} \frac{2j+1}{2} \Sigma^j_{g\to g''} P_j(\underline{\Omega}\cdot\underline{\Omega}''). \qquad (5)$$

Then the expected number of particles or photons transferred per collision from group g to group g'' through an angle whose cosine is $\underline{\Omega}\cdot\underline{\Omega}''$ is

$$F_1F_2F_3F_4 p_{sim}(\underline{\Omega}'')/\int d\underline{\Omega}' p_{sim}(\underline{\Omega}') = \Sigma_{g\to g''}(\underline{\Omega}\cdot\underline{\Omega}'')/\Sigma_g, \qquad (6)$$

as it should be.

There are two noteworthy features of this collision treatment, aside from the branch distinguishing "fission" and "scattering" which has been discussed already. In the first place, the "scattering" pattern, $p_{sim}(\underline{\Omega})$, used in the simulation is chosen to suit the application rather than to fit the physical nuclear or atomic scattering pattern. For example, if the design objective is penetration in the direction of the z-axis, then the simulation pattern can be chosen to be largely in the z direction. If the objective is scattering from a target to detectors at right angles to a beam moving in the z direction, then the simulation pattern might be, for example, $1 - \Omega_z^2$. If a wide variety of objectives are contemplated, then the simulation pattern can be taken to be isotropic, and this is the basic pattern found in ANDYMG3. Many physical cross sections contain a preponderance of forward scattering, so the basic isotropic pattern in ANDYMG3 is more suited for albedo and near-to-the-source applications. For deep penetration problems, the simulation angular pattern can be altered. However, directional splitting often can accomplish the same result.

In the second place, the ANDY collision treatment is devised to be able to deal with multigroup cross-section sets which may contain some negative "scattering" transfer cross sections, $\Sigma_{g\to g'}$. The Bell-Hansen-Sandmeier transport approximation,[1] for example, frequently leads to negative in-group "scattering" cross sections, $\Sigma_{g\to g}$.[2] When, in the ANDY collision treatment, the particle or photon weight, W, is multiplied by F_4 as defined in Eq. (4), W will change sign if $\Sigma_{g\to g''}$ is negative or if the scattering pattern is negative as a result of truncation to order $\hat{j}$ of the Legendre expansion of the scattering cross section. The truncation order $\hat{j}$ is 0, 1, 2, or 3 in ANDYMG3. Very little penalty in increased run time per collision is paid for the capability of treating negative cross sections. The factor $\Sigma_{g\to g''}/|\Sigma_{g\to g''}|$ appearing in F_4, Eq. (4), is stored as the algebraic sign, +1 or -1, of the nonnegative cummulative distribution of F_3, Eq. (3). Thus, no more storage is required than for the case where all cross sections can be guaranteed to be nonnegative. Of course, the ANDY collision routine does not require negative cross sections, and nonnegative cross-section sets may be preferred for operational reasons.

Delayed particles or photons of type ITPDEL, ITPDEL = 1, NTPDEL from collisons are stored in a bank when WDEL(ITPDEL) exceeds an input level, WDELF. This level may be set low so that every delayed particle is banked and subsequently tracked, or set high so that few delayed particles or photons are ever followed.

C. Particle Splitting and Termination

Negative and positive weight particles or photons are split when |W| exceeds an input-splitting level, WSPLT. In this event, one particle with weight W/2 continues, and one particle with weight W/2 is stored in a bank to be followed later when the continued particle is terminated. The particle weight, W, can increase in absolute value because F_1, Eq. (1), exceeds unity and/or because F_4, Eq. (4), exceeds unity in absolute value.

Negative and positive weight particles or photons are terminated when they leave the outer boundary of the geometry, when they live longer than the last tally time box, or when |W| falls below an input termination level, WCO. In the last case, the termination is made nearly unbiased by adding W to a quantity WCOC. When a particle termination causes |WCOC| to exceed an input level, WCOCF, the particle is continued with weight WCOC. This technique is unbiased except in that a small weight, < WCOCF, may still be in WCOC at the end of the problem, and this weight will not be continued. Typical values for WSPLT, WCØ, and WCUMF are 2, 0.0001, and 0.001.

One motivation for programming ANDY in the simplest manner consistent with speed and compactness, is to enable the user to easily add variance-reducing treatments pertinent to his problem. For example, statements can be placed anywhere in the Monte Carlo section of the form IF(.....) GØ TØ 210, whereupon the particle or photon will be split, one half being banked and the other half continued.

D. Programming

ANDYMG3 is transparently programmed in FORTRAN-IV for the CDC-6600 and UNIVAC-1108 computers. The program consists of about 1000 statement lines plus about 400 comment lines. All program variables are defined in comment lines at the front of the program; these are listed in Appendix A. All input and output quantities are labeled by these variable names. Also listed in Appendix A are comment lines detailing time box selection, surface descriptions, and sense conventions.

The program is variably dimensioned to reduce field length. The main program allocates storage, calls subroutine PREP to process and report input, and finally calls subroutine BUSY to execute the Monte Carlo and process and report results. The program uses more than 60 arrays and 20 dimensioning variables, but the CDC SCOPE 3 compiler will treat only about 60 arrays plus dimensioning variables, and the UNIVAC-1108 EXEC 8 compiler will treat only about 15 to 19 arrays through a subroutine, CALL. Hence, many small arrays are assigned fixed dimensions in labeled common. These fixed dimensions are identified by adjacent comment lines and must be altered to accommodate very large problems. Variably dimensioned arrays are stored in large arrays IA and A in blank common. Dimensions of these arrays and cumulative lengths (LØCINIA and LØCINA, respectively) of arrays stored in IA and A are edited. If these are incompatible, the program EXITS and the user should increase the dimensions of IA and/or A as indicated.

Program execution has been speeded by removing from the Monte Carlo section unnecessary divisions and multiplications and by placing the random number generator in line, i.e., as FORTRAN statements where required in BUSY, rather than as a FORTRAN or even an optimized machine language subroutine.[4] For those cases described in Ref. 4, removing unnecessary operations and placing the random number generator in line reduced running time by about 10% and 14%, respectively.

Certain systematics have been followed in the effort to render the programming transparent. For example, running indices begin with I with mnemonic suffixes; e.g., IG always identifies a multigroup. Upper limits on such indices have the I replaced by an N; e.g., IG ranges from 1 to NG. Temporaries are formed by suffix T. Read and numerical print formats are few in number and are collected after the storage section. Output identification formats are placed where required, and use Hollerith rather than * or ' to permit operation on various computers.

E. Program Tests

In Ref. 3 are described several tests of the ANDY geometry routine using one energy group. Of these the most convincing consists in construction of a very large and complicated geometry, assignment of the same cross sections to each region, and computation for one energy group of the mean-square distance $< r^2 >$ to collision. This should, and does, agree with the analytic result, $2/\Sigma_{tr}\Sigma_a$, where Σ_{tr} is the transport cross section and Σ_a is the absorption cross section. Comparisons with RZTRAN, a time-dependent S_N program developed by K. D. Lathrop, were less conclusive (refer to Figure 2 in Ref. 4), although agreement improved when space and time meshes were made finer in the S_N calculation.

In Figure 1 are compared ANDYMG3 and DTF[2] calculations of fissions in a fissile region enveloped by a poisoned hydrogeneous region and concentric with four other spherical annuli of various materials, in response to a plane incident wave of 14-MeV neutrons. The two programs are in good agreement in F-number, i.e., in total fissions per kg of fissile

material per incident neutron per square centimeter, and are in reasonable accord as to the spectral distribution of fissions. No special variance-reducing techniques were used in the ANDYMG3 calculation. The ANDY calculations yield front and back asymmetry of fissions and the time dependence of the F-number in a computing time not much greater than required for the spherical, time-independent DTF calculation.

These ANDYMG3 and DTF calculations utilized exactly the same cross sections, a 25-group set with P_0 and P_1 scattering components. Because these cross sections employ the Bell-Hansen-Sandmeier transport approximation,[1] many negative scattering cross sections are present. In Ref. 4 an unsuccessful Monte Carlo simulation of this problem is contrasted with the present successful simulation.

This problem was also calculated using a current version of the general-purpose, continuous-energy Los Alamos Monte Carlo program, MCN. As is shown in Table I, the product of running time per collision and field length is 2.8 times smaller for ANDY in this case. The cross sections used in the ANDYMG3 and MCN calculations were not all compatible, so the MCN calculation was not run long enough to compare the times required for a desired accuracy.

III. INPUT

Problem and library inputs conform in many respects to S_N program input formats and usage.[3]

A. Problem Input

Required problem input is listed in Table II. A sample input, listed in Appendix D, describes a Fluharty pulsed multiplier with two adjacent moderators in a cavity. A similar geometry with some dimensions altered is pictured in Fig. 2 with regions and surface segment numbers indicated.

The first two cards itemized in Table II are library cards that should not be changed unless the library is changed. Cards 3 to 24 +... are the actual problem input. Following the problem input are many lines of library data described in the next Section, III-B, but there is no more problem input. Surface descriptions, sense conventions, time box selection, and the notation used in Table II are detailed in Appendix A.

The input variable NKRN starts the pseudorandom number generator; NKRN can be taken to be a low positive prime number. Alternatively, if MØRE is greater than zero, then MØRE additional independent runs will be executed, NKRN being incremented between runs.

Input quantities for sums are defined in Appendix A, and are described more fully in Section IV, Output.

B. Data Library Input

The library cards 1 and 2 in Table II characterize the library and are required to fix its dimensions. In Table III is listed data library input for ANDYMG3. ANDYMG3 contains a generalized delayed particle and photon treatment with a rather clumsy input; this is made more efficient in the specialized program, ANDYMS1, and is dropped from other specialized programs.

Although decks for scattering components up to NLIBSC ≤ 3 may be included in the library, the order of scattering actually used in a problem is NSCAT, an input number less than or equal to NLIBSC. Note that the numbers of decks with scattering components P_0, P_1, P_2, or P_3 can differ; e.g., there might be MATLIB = 20 P_0 decks, NLIBS(1) = 8 decks with P_1 components, and NLIBS(2) = NLIBS(3) = 2 decks with P_2 and P_3 scattering components.

IV. OUTPUT

Input and output quantities and tallies are printed and/or punched. Printed quantities are labelled by their program variable names and defined in Appendix A and on comment cards at the beginning of the program. Microscopic cross sections and other library data are printed, as are time box limits, macroscopic cross sections, and the collision parameters described in Section II-B. Microscopic cross sections are not printed as read; instead, printed scattering cross sections for groups IG are in the form σ(from IG) rather than σ(to IG).

TABLE I

OPERATING COMPARISON OF ANDYMG3 AND MCN

	ANDYMG3	MCN
Object Time Field Length	53.1_8K	~100_8K
Run Time (msec/collision)	0.92	1.73

TABLE II

ANDYMG3 PROBLEM INPUT

Line or Order	Format	Contents*	
1	7A6,5I6	Library card 1: LIBRY,MATLIB,NG,NP,NING,NTPDEL	
2	12I6	Library card 2: (NLIBS(ISCAT),ISCAT=1,NLIBSC),NLIBSM	
3	16A5	TITLE	
4	12I6	NREG,NSUR,NSEG,NMIX,NSCAT,NSENMA	
5	12I6	NT,ITBl,NTAIR,NTALSS,NIT,NMATMA,NSUM	
6	12I6	NS,NKRN,MØRE,NPUNCH	
7	6E12.6	DELT1,DELT2,ØFFSET,TSPLT	
8	6E12.6	WSPLT,WCØ,WCØCF,WDELF	
9	12I6	ITP(IS)	A card triple for each surface IS=1,NSUR
10	6E12.6	AS(IS),BS(IS),...,FS(IS)	
11	6E12.6	GS(IS),HS(IS)	
12+...	12I6	IDS(ISS),NSEN(ISS)	A card for each surface segment
13+...	12I6	(IDEN(ISS,IS1),IS1=1,NSEN(ISS))	No cards for NSEN(ISS)=0
14+...	12I6	(ISEN(ISS,IS1),IS1=1,NSEN(ISS))	
15+...	12I6	NAS(IR),IMIX(IR)	A card triple for each region IR=1,NREG
16+...	12I6	(IAS(IR,ISS),ISS=1,NAS(IR))	
17+...	12I6	(IDS(IR,ISS),ISS=1,NAS(IR))	
18+...	12I6	(ITALR(I),I=1,NTALR)	
19+...	12I6	(ITALSS(I),I=1,NTALSS)	
20+...	12I6	NMAT(IM)	A card triple for each mix IM=1,NMIX
21+...	12I6	(IMAT(I,IM),I=1,NMAT(IM))	
22+...	6E12.6	(DENS(I,IM),I=1,NMAT(IM))	
23+...	6E12.6	(DENSM(I,ISUM),I=1,NLIBSM)	A card pair for each sum ISUM=1,NSUM
24+...	12I6	IRØRS(ISUM),ISUMTY(ISUM)	

*Variables are defined in Appendix A and on comment cards at the beginning of the program.

Basic program tallies include: WIR(IT,ITALY, IG), the weight of particles or photons colliding in each time box, IT, in each group, IG, and in each region with identification number ITALR(ITALY) and order number ITALY=1,NTALR; WISP(IT,ITALY;IG), the weight in each time box, IT, of particles in each group, IG, crossing the surface segment with identification number ITALSS(ITALY) and order number ITALY=1,NTALSS, from a region with lower identification number (Roman numerals in Fig. 2) to one with higher number; and WISN(IT,ITALY,IG), the same quantity for particles or photons moving in the opposite direction. The printed WIR, WISP, and WISN arrays have been divided by the number, NS, of starters. In addition, an array WIT(IT,IW), IW=1,NIT, is dimensioned, initialized, printed, and/or punched for arbitrary tallies to be introduced at the discretion of the user.

Program execution registers are printed, such as ISPLC, the number of splits; NCØL, the number of collisions; and NDEL, the number of delayed particles followed. The termination and splitting parameters described in Section II-C are printed; in particular, the printed quantity WCØC represents the terminated particle weight untracked at the end of the problem. Similarly, the delayed particle or photon weights WDEL(ITPDEL), ITPDEL=1,NTPDEL untracked at the end of the problem are printed.

Punched output can be read into the auxiliary program ANDYAV (not described here) for computation

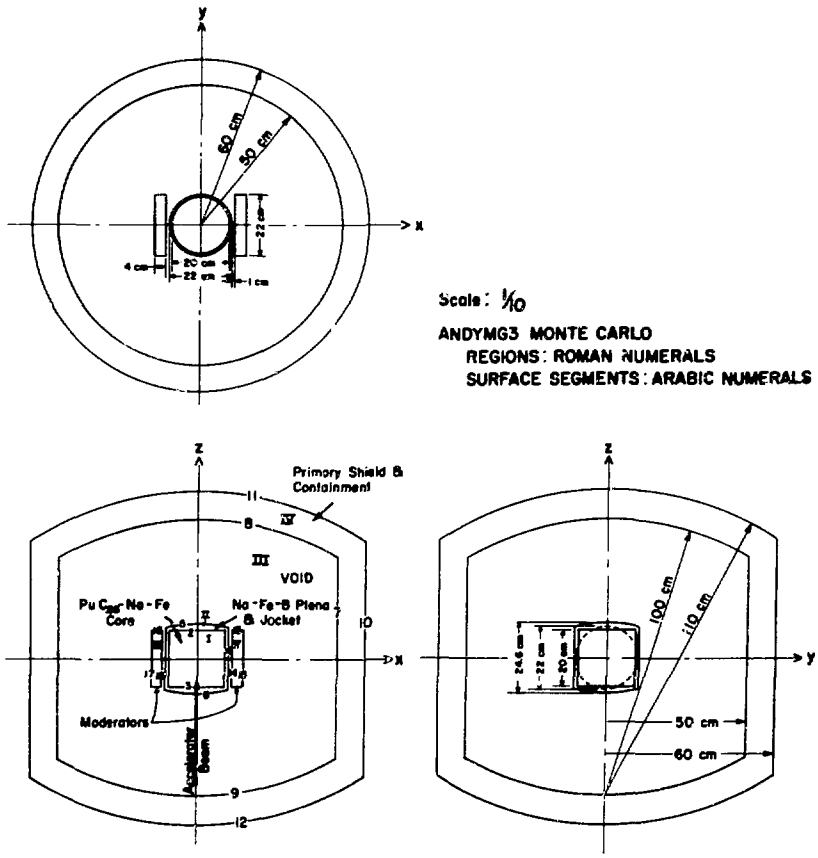


Fig. 2. Accelerator pulsed 3-MW reactor layout showing regions and surface segments for ANDYMG3 sample problem.

TABLE III

ANDYMG3 DATA LIBRARY INPUT

Line or Order	Format	Contents	
25+...	6E12.6	(V(IG),IG=1,NG)	
26+...	6E12.6	(CHIP(IG),IG=1,NG)	
		DO NOT INCLUDE CHID OR DELPC IF NTPDEL=0	
27+...	6E12.6	((CHID(ITPDEL,IG),IG=1,NG),ITPDEL=1,NTPDEL)	
28+...	6E12.6	(((DELPC(ITPDEL,IG,IMIX),IG=1,NG),ITPDEL=1,NTPDEL),IMIX=1,NMIX)	
29+...	6E12.6	(TD(ITPDEL),ITPDEL=1,NTPDEL)	
30+...	7A6,5I6	ALPHANUMERIC TITLE	FOR EACH OF SUMMING
31+...	6E12.6	(σ(I,IG),IG=1,NG)	DECKS I=1, NLIBSM.
32+...	7A6,5I6	ALPHANUMERIC TITLE, IDMAT	FOR EACH OF MATLIB DECKS IN LI-
33+...	6E12.6	MICROSCOPIC CROSS SECTIONS IN DTF FORMAT	BRARY FOR SCATTERING ORDER P_0.
34+...	7A6,5I6	ALPHANUMERIC TITLE, IDMAT	FOR EACH OF NLIBS(ISCAT) DECKS
35+...	6E12.6	MICROSCOPIC CROSS SECTIONS IN DTF-IV FORMAT	IN LIBRARY FOR SCATTERING ORDER P_{ISCAT} AND FOR ISCAT=1,NLIBSC.

of standard errors, for plotting, for computation of autocorrelation functions, etc.

The very large number of tallies in the WIR, WISP, and WISN arrays are reduced to useful design results by *summing* calculations after execution of the Monte Carlo section. A library of summing cross sections, $\sigma(I,IG), IG=1,NG, I=1,NLIBSM$, is provided for each applied program (refer to Section III-B). For example, $\sigma(1,IG)$ usually is unity for each group IG=1,NG, while $\sigma(2,IG)$ usually is $1/V(IG)$ for each group. Similarly, other summing cross sections might be $\sigma_{Fission}^{Pu239}$ or the biological dose in each multigroup. Macroscopic summing cross sections,

$$CSUM(ISUM,IG) = \sum_{I=1}^{NLIBSM} DENSM(I,ISUM)\sigma(I,IG), \qquad (7)$$

are formed from input densities and summing cross sections. Then, after completion of the Monte Carlo portion, sums ISUM=1, NSUM are computed. If IRØRS (ISUM)≠0, the computed and printed sums are

$$SUM(IT) = \sum_{IG=1}^{NG} WIR(1T,ISUMTY(ISUM),IG)*CSUM(ISUM,IG)/Macro-$$

scopic total cross section in the region with order number ISUMTY(ISUM) in the list of region tallies ITALY=1,NTALR, for the designated tally region.

(8)

If IRØRS(ISUM)=0, the computed and printed sums are

$$SUM(IT) = \sum_{IG=1}^{NG} WISP(IT,ISUMTY(ISUM),IG)*CSUM(ISUM,IG), \qquad (9)$$

and

$$SUM(IT) = \sum_{IG=1}^{NG} WISN(IT,ISUMTY(ISUM),IG)*CSUM(ISUM,IG), \qquad (10)$$

for the surface segment with order number ISUMTY (ISUM) in the list of surface segment tallies ITALY= 1,NTALSS. Printed with each sum, SUM(IT),IT=1,NT, are the identification numbers of the relevant regions and surface segments, i.e., those whose order numbers in tally lists have just been described. By suitable use of these sums, the output can yield directly useful quantities such as, fission rate, total flux, and biological dose.

Listed in Appendix E is the last section of output from the test problem whose input is listed in Appendix D. This problem required 61 seconds of CP time on the CDC-6600, of which about 19 seconds is required for compilation and input processing. In Figure 3 is displayed output from longer runs of this problem.

ACKNOWLEDGMENTS

The author is grateful to R. M. Frank, D. L. Hoffman, and L. L. Carter for assistance in various phases of the ANDY development and to D. W. Muir and G. D. Turner for their help in intercomparing DTF, MCN, and ANDY.

REFERENCES

1. G. I. Bell, G. E. Hansen, and H. A. Sandmeier, "Multitable Treatments of Anisotropic Scattering in S_N Multigroup Transport Calculations," Nucl. Sci. Eng., 28, 376 (1967).

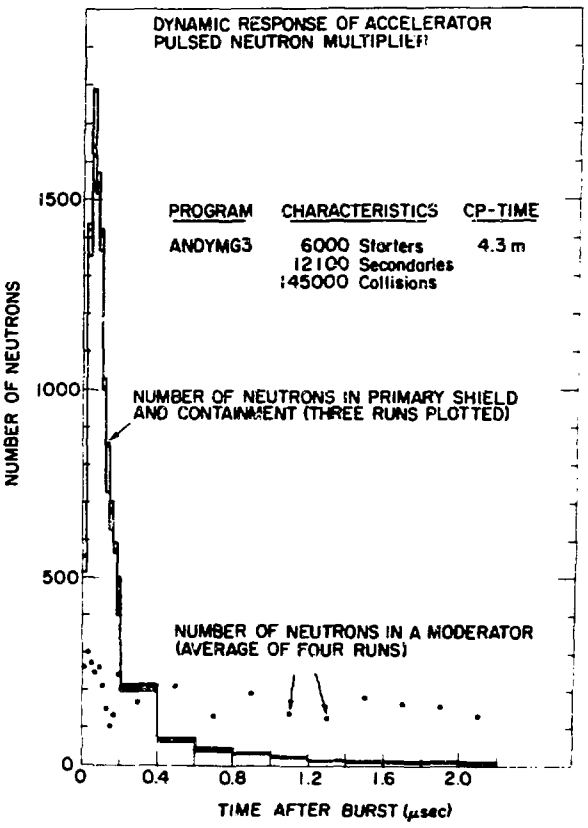


Fig. 3. Display of output from ANDYMG3 sample problem.

2. D. R. Harris, "The ANDY Monte Carlo Programs," Proc. Monte Carlo Seminar at Oak Ridge National Laboratory, October 5 to 7, 1970, to be published.

3. K. D. Lathrop, "DTF-IV, a FORTRAN-IV Program for Solving the Multigroup Transport Equation with Anisotropic Scattering," LA-3373, Los Alamos Scientific Laboratory (1965).

4. D. R. Harris, "ANDY1G2 and ANDY1R2, Monte Carlo Programs for Time-Dependent Monoenergetic Particle Transport in General Geometries and Repeating Arrays," LA-4410, Los Alamos Scientific Laboratory (1970).

APPENDIX A. NOTATION, TIME BOX SELECTION, SURFACE DESCRIPTIONS, SENSE CONVENTIONS, AND COLLISION DESCRIPTION.

```
C NOTATION
C      AS(IS),BS(IS),.....=PARAMETERS DEFINING SURFACE WITH ID NUMBER IS
C      C=PROBABILITY THAT SCATTERED PARTICLE IS EMITTED WITH SCATTERING ANGLE
C           WHOSE COSINE IS COSCAT
C      CHIP(IG)=PROMPT NON-SCATTER PARTICLE YIELD FRACTION PER COLLISION INTO
C           ENERGY GROUPS 1 THROUGH IG
C      CHID(ITPDEL,IG)=TYPE ITPDEL DELAYED PARTICLE YIELD FRACTION PER DECAY
C           INTO ENERGY GROUPS 1 THROUGH IG
C      CL(IP,IG)=MICROSCOPIC CROSS SECTION IN POSITION IP FOR ENERGY GROUP IG AS
C           READ FROM THE LIBRARY
C      CM(IP,IG,IM)=MACROSCOPIC CROSS SECTION OF TYPE IP IN ENERGY GROUP IG IN
C           MIX IM. THEN THESE QUANTITIES ARE PROCESSED TO THE FOLLOWING
C      CM(1,IG,IM)=NUMBER OF PROMPT SECONDARIES PER COLLISION FROM FISSION+SCAT
C      CM(2,IG,IM)=PROBABILITY SECONDARY PARTICLE IS FROM FISSION
C      CM(3,IG,IM)=TRANSPORT MEAN FREE PATH
C      CM (IP,IG,IM),IP=4,NG =PROBABILITY OF SCATTERING FROM ENERGY GROUP IG
C           INTO ENERGY GROUPS IGMIN(IG) THROUGH IP
C      CM1(IP,IG,IM)=MACROSCOPIC P1 COMPONENT FOR SCATTERING IN MIX IM FROM
C           GROUP IG TO GROUP IN POSITION IP
C      CM2(IP,IG,IM)=MACROSCOPIC P2 COMPONENT FOR SCATTERING IN MIX IM FROM
C           GROUP IG TO GROUP IN POSITION IP
C      CM3(IP,IG,IM)=MACROSCOPIC P3 COMPONENT FOR SCATTERING IN MIX IM FROM
C           GROUP IG TO GROUP IN POSITION IP
C      THEN THE CM1, CM2, AND CM3 COMPONENTS ARE CHANGED TO COEFFICIENTS OF
C           POWERS OF COSCAT
C      COSCAT=COSINE OF SCATTERING ANGLE IN LAB COORDINATE SYSTEM
C      CSUM(ISUM,IG)=MACROSCOPIN CROSS SECTION TO BE USED IN GROUPIG FOR SUM ISUM
C      D=PARTICLE FLIGHT PATH LENGTH TO SURFACE OR TO COLLISION POINT
C      D1(IAST)=MORE POSITIVE DISTANCE TO SURFACE SEGMENT WITH ID NUMBER IAST
C      D2(IAST)=LESS POSITIVE DISTANCE TO SURFACE SEGMENT WITH ID NUMBER IAST
C      DELPC(ITPDEL,IG,IM)=NUMBER OF DELAYED SECONDARY PARTICLES OF TYPE ITPDEL
C           EMITTED IN ENERGY GROUP IG PER COLLISION IN MIX IM
C      DELT1=WIDTH OF TIME BOX IT (2.LE.IT.LE.ITB1). DELT1I IS INVERSE
C      DELT2=WIDTH OF TIME BOX IT (IT.GT.ITB1.AND.IT.LE.NT). DELT2I IS INVERSE
C      DENS(I,IM)=NUCLEAR OR MOLECULAR DENSITY OF MATERIAL WITH ORDER NUMBER
C           I IN MIX IM
C      DENSM(I,ISUM)=DENSITY OF I-TH DECK TO BE USED IN SUM ISUM
C      DIRY=PARTICLE FLIGHT PATH LENGTH TO CURRENT SURFACE
C      FRN=REAL NUMBER IN (0.,1.) FORMED BY PSEUDORANDOM NUMBER GENERATOR
C      IAR(IR,ISS)=ID NUMBER OF REGION ON OTHER SIDE OF ISS-TH SURFACE SEGMENT
C           FROM REGION IR. IAR(IR,ISS) EXCEEDS NREG IF ISS IS ON SYSTEM BOUNDARY
C      IAS(IR,ISS)=ID NUMBER OF ISS-TH SURFACE SEGMENT ADJACENT TO REGION WITH ID
C           NUMBER IR. (IR=1,NREG),(ISS=1,NAS(IR)).
C      IDEN(ISS,IS1)=ID NUMBER OF THE IS1-TH SURFACE BOUNDING SURFACE SEGMENT ISS
C      IDS(ISS)=ID NUMBER OF SURFACE CONTAINING SURFACE SEGMENT WITH ID ISS
C      IGMAX(IG)=HIGHESTNUMBERED ENERGY GROUP FROM SCATTERING IN ENERGY GROUP IG
C      IGMIN(IG)=LOWEST NUMBERED ENERGY GROUP FROM SCATTERING IN ENERGY GROUP IG
C      IGSPL(ISPL)=ENERGY GROUP OF ISPL'TH BANKED PARTICLE
C      IHIT=ID NUMBER OF SURFACE SEGMENT HIT BY PARTICLE AND IS ZERO OTHERWISE
C      IMAT(I,IM)=ID NUMBER OF MATERIAL WITH ORDER NUMBER I IN MIX IM
C      IMTX(IR)=CROSS SECTION MIX NUMBER IN REGION IR
C      IRMULT= MULTIPLIER IN PSEUDORANDOM NUMBER GENERATOR
C      INDICES/IT FOR TIME BOX, IS FOR SURFACE, ISS FOR SURFACE SEGMENT,
C           IST FOR STARTER, IR FOR REGION, IG FOR ENERGY-TYPE GROUP, ITPDEL
C           FOR DELAYED PARTICLE TYPE, ISCAT FOR SCATTERING PATTERN COMPONENT,
```

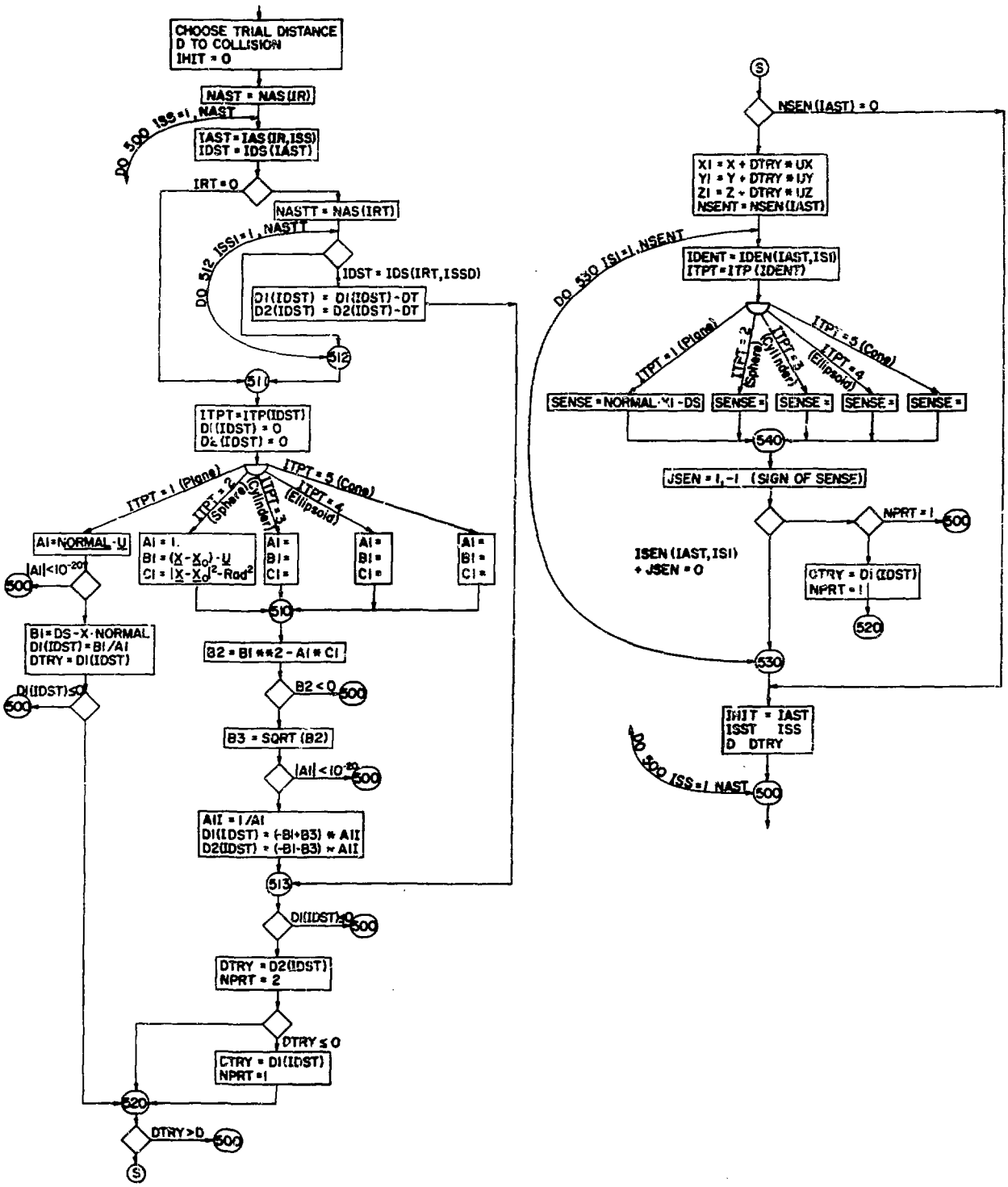
APPENDIX A. (Continued)

```
C          IRT FOR THE REGION JUST LEFT.  IW FOR INTEGRAL TALLY. ISUM FOR SUM
C      IRORS(ISUM)=1 IF A REGION TALLY IS TO BE USED IN SUM. 0 IF A SURFACE SEG-
C      IRORS(ISUM)=1 IF A REGION TALLY IS TO BE USED IN SUM. 0 IF A SURFACE SEG-
C          MENT TALLY IS TO BE USED IN SUM
C      IRSPL(ISPL)=REGION OF ISPL*TH BANKED PARTICLE
C      ISEN(ISS,IS1)=SENSE OF IS1-TH SURFACE BOUNDING SURFACE SEGMENT ISS
C      ISPL=NUMBER OF BANKED PARTICLE
C      ISPLC=CUMULATIVE NUMBER OF SECONDARY PARTICLES
C      ISUMTY(ISUM)=ORDER NUMBER OF INTEGRAL TALLY ITALY TO BE USED IN SUM
C      ISPLO=NUMBER OF SECONDARIES OVERFLOWING BANK
C      ITB1=LAST TIME BOX OF WIDTH DELT1 (1.LE.ITB1.LE.NT.LE.100)
C      ITALR(I)=ID NUMBER OF I-TH REGION FOR WHICH WIR IS TO BE TALLIED
C      ITALS(I)=ID NUMBER OF I-TH SURFACE SEGMENT FOR WHICH WISP AND WISN ARE
C          TO BE TALLIED
C      ITP(IS)=TYPE NUMBER OF SURFACE IS
C          WHETHER PLANE (1), SPHERE (2), CYLINDER (3), ELLIPSOID (4) , CONE (5)
C      KRN=INTEGER PSEUDORANDOM NUMBER
C      LENGA=DIMENSION OF STORAGE ARRAY A
C      LENGIA=DIMENSION OF STORAGE ARRAY IA
C      LIBRY=LIBRARY DESCRIPTION
C      LOCINA=NUMBER OF LOCATIONS REQUIRED TO SET UP ARRAYS TO BE STORED IN A
C      LOCINT =NUMBER OF LOCATIONS REQUIRED TO SET UP ARRAYS TO BE STORED IN IA
C      MATLIB=NUMBER OF MATERIALS IN CROSS SECTION LIBRARY
C      MORE+1=NUMBER OF CASES IN THIS JOB
C      NAS(IR)=NUMBER OF SURFACE SEGMENTS ADJACENT TO (BOUNDING) REGION IR
C      NBANK=BANK DIMENSION
C      NCOL=NUMBER OF COLLISIONS IN THIS JOB
C      NDEL=NUMBER OF DELAYED PARTICLES FOLLOWED IN JOB
C      NG=NUMBER OF ENERGY GROUPS
C      NING=POSITIONE OF IN-GROUP SCATTERING IN CROSS SECTION TABLE
C      NIT=NUMBER OF INTEGRAL TALLIES
C      NKRN=FACTOR (1,3,5,7,...) FOR STARTING PSEUDORANDOM NUMBER GENERATOR
C      NLIBS(ISCAT)=NUMBER OF MATERIALS IN LIBRARY WITH ANISOTROPIC SCATTERING
C          COMPONENT ISCAT=1,NLIBSC
C      NLIBSC =MAXIMUM NUMBER OF ANISOTROPIC SCATTERING COMPONENTS IN LIBRARY
C      NLIBSM=NUMBER OF DATA SETS IN SUMMING LIBRARY
C      NMAT(IM)=NUMBER OF MATERIALS IN CROSS SECTION MIX IM
C      NMATMA =MAXIMUM NUMBER OF MATERIALS PER CROSS SECTION MIX
C      NMIX=NUMBER OF CROSS SECTION MIXES
C      NP=NUMBER OF POSITIONS PER ENERGY GROUP IN CROSS SECTION TABLE
C      NREG=NUMBER OF REGIONS (1.LE.NREG.LE.20)
C      NS=NUMBER OF SOURCE PARTICLES
C      NSCAT=NUMBER OF ANISOTROPIC SCATTERING COMPONENTS TO BE USED IN PROBLEM
C      NSEG=NUMBER OF SURFACE SEGMENTS (1.LE.NSEG.LE.40)
C      NSEN(ISS)=NUMBER OF SURFACES BOUNDING SURFACE SEGMENT ISS
C      NSENMA =MAXIMUM NUMBER OF SENSE RELATIONS PER SURFACE SEGMENT
C      NSUM=DESIRED NUMBER OF SUMS
C      NSUR=NUMBER OF SURFACES (1.LE.NSUR.LE.20)
C      NT=NUMBER OF TIME BOXES (1,.LE.ITB1.LE.NT.LE.100)
C      NTALR=NUMBER OF REGIONS FOR WHICH WIR IS TO BE TALLIED GE.1
C      NTALS=NUMBER OF SURFACE SEGMENTS FOR WHICH WISP AND WISN ARE TALLIED GE.1
C      NTPDEL=NUMBER OF TYPES OF DELAYED PARTICLES
C      OFFSET=UPPER LIMIT OF FIRST TIME BOX (0.LE.OFFSET.LT.DELT1).  IF
C          OFFSET=0., TIME BOX IT=1 WILL BE EMPTY. IE. FIRST NON-ZERO TALLY
C          WILL BE IN TIME BOX IT=2
C      RMOD=PERIOD OF PSEUDORANDOM NUMBER GENERATOR
C      RNS=NUMBER OF SOURCE PARTICLES IN PROBLEM (RNS=NS*NB)
C      SUM(IT)=A SUM IN TIME BOX IT
C      SUMSCA =TEMPORARY SUM OF MACROSCOPIC OUTSCATERING FROM AN ENERGY GROUP
C      T=CUMULATIVE PARTICLE FLIGHT TIME=REAL TIME AGE OF PARTICLE AT EVENT TIME
C      TB(IT)=UPPER BOUND OF TIME BOX IT=1,2,...,NT
C      TD(ITPDEL)=MEAN LIFE FOR DELAYED PARTICLES OF TYPE ITPDEL
C      TITLE=PROBLEM DESCRIPTION
C      TSPL(ISPL)=REAL TIME AGE OF ISPL*TH BANKED PARTICLE
C      UX,UY,UZ=DIRECTION COSINES OF PARTICLE
C      UXSPL(ISPL),UYSPL(ISPL),UZSPL(ISPL)=DIRECTION COSINES OF ISPL*TH
C          BANKED PARTICLE
C      V(IG)=PARTICLE SPEED IN ENERGY GROUP IG. INVERSE SPEED AFTER PRECOMPUTE
C      WCO=A PARTICLE HISTORY IS TERMINATED IF ITS WEIGHT DROPS BELOW WCO
C      WCOCF=VALUE WHICH IF EXCEEDED BY WCOC PERMITS A LOW WEIGHT (W.LT.WCO)
```

APPENDIX A. (Continued)

```
C           PARTICLE TO CONTINUE WITH WEIGHT WCOC
C      WDEL(ITPDEL)=CUMULATIVE WEIGHT OF DELAYED PARTICLES OF TYPE ITPDEL
C      WDELF=A DELAYED PARTICLE IS FOLLOWED IF WDEL EXCEEDS WDELF
C      WIR(IT,ITALY,IG)=CUMULATIVE WEIGHT OF PARTICLES COLLIDING IN TIME BOX IT
C           IN ENERGY GROUP IG IN REGION ITALR(ITALY)
C      WISN(IT,ITALY,IG)=CUMULATIVE WEIGHT OF PARTICLES CROSSING SURFACE
C           SEGMENT ITALSS(ITALY) IN TIME BOX IT IN ENERGY GROUP IG FROM REGION
C           WITH HIGHER ID NUMBER TO REGION WITH LOWER ID NUMBER
C      WISP(IT,ITALY,IG)=CUMULATIVE WEIGHT OF PARTICLES CROSSING SURFACE
C           SEGMENT ITALSS(ITALY) IN TIME BOX IT IN ENERGY GROUP IG FROM REGION
C           WITH LOWER ID NUMBER TO REGION WITH HIGHER ID NUMBER
C      WIT(IT,IW)=IW-TH INTEGRAL TALLY IN TIME BOX IT
C      WSPL(ISPL)=WEIGHT OF ISPL*TH BANKED PARTICLE
C      WSPLT=PARTICLE WEIGHT MINIMUM FOR SPLITTING
C      X,Y,Z=RECTANGULAR COORDINATES OF PARTICLE
C      X(ISPL),Y(ISPL),Z(ISPL)=RECTANGULAR COORDINATES OF ISPL*TH BANKED PARTICLE
C      XU,YU,XYU,R2U ARE TEMPORARIES IN DIRECTION FINDER
C      A1,B1,C1,....,ETC=TEMPORARIES IN GEOMETRY ROUTINE.  OTHER TEMPORARIES
C           ARE FORMED BY ADDING SUFFIX T
C
C TIME BOXES
C      AN EVENT AT TIME T IS TALLIED IN TIME BOX IT IF TB(IT-1).LE.T.LT.TB(I).
C      WHERE TB(IT) IS THE UPPER LIMIT OF TIME BOX IT.  TIME BOX IT=1 COVERS THE
C      INTERVAL (0.,OFFSET). TIME BOXES IT=2,ITB1 ARE OF WIDTH DELT1. AND TIME
C      BOXES IT=ITB1+1,NT ARE OF WIDTH DELT2
C
C SURFACE DESCRIPTIONS
C      PLANE (1). A VECTOR (AS,BS,CS) IS NORMAL TO PLANE AND IS DIRECTED GENER-
C      ALLY OUT FROM ORIGIN.  LEAST DISTANCE FROM ORIGIN TO PLANE IS
C      DS/SQRT(AS**2+BS**2+CS**2).
C      SPHERE (2). RADIUS DS CENTERED AT (AS,BS,CS)
C      CIRCULAR CYLINDER (3). RADIUS GS WITH AXIS PASSING THRU (AS,BS,CS) IN
C      DIRECTION (DS,ES,FS)
C      ELLIPSOID (4). CENTERED AT (AS,BS,CS) WITH AXES PARALLEL TO X,Y,Z COOR-
C      DINATE AXES AND WITH RADII DS,ES,FS, RESPECTIVELY.
C      CONE(5). APEX AT (AS,BS,CS) WITH AXIS PARALLEL TO (DS,ES,FS) AND OPENING
C           ANGLE 2.*GS WHERE GS IS IN UNITS OF RADIANS
C
C SENSE CONVENTIONS
C      A POINT IN SPACE HAS POSITIVE SENSE WITH RESPECT TO A PLANE IF THE SPACE
C           POINT IS ON THE SIDE OF THE PLANE TOWARD WHICH THE NORMAL (AS,BS,CS)
C           POINTS, WITH RESPECT TO A SPHERE, CYLINDER, OR ELLIPSOID IF THE SPACE
C           POINT IS OUTSIDE THE SURFACE, WITH RESPECT TO A CONE
C
C MULTIGROUP CROSS SECTION LIBRARY
C      NEGATIVE SCATTERING CROSS SECTIONS AND LEGENDRE COMPONENTS ARE OK
C
C COLLISION PROCESSES
C      WHEN A COLLISION OCCURS IT IS TALLIED IN WIR, DELAYED PARTICLE TALLIES ARE
C      INCREMENTED,AND THE CONTINUING PARTICLE WEIGHT IS MULTIPLIED BY THE PROMPT
C      SECONDARIES PER COLLISION YIELD CM(1,IG,IM).  THE CONTINUING PARTICLE
C      EMERGES PROMPTLY AND ISOTROPICALLY AND IS CHOSEN TO BE A FISSION PARTICLE
C      (WITH PROBABILITY CM(2,IG,IM)) OR A SCATTERED PARTICLE.  IF FROM FISSION
C      ITS ENERGY SPECTRUM IS CHOSEN FROM CHIP.  IF FROM SCATTERING THE
C      CONTINUING PARTICLES SPECTRUM IS CHOSEN FROM CM(IP,IG,IM),IP.GE.4.  ITS
C      WEIGHT IS MULTIPLIED BY A FACTOR PROPORTIONAL TO THE SCATTERING CROSS
C      SECTION AS A FUNCTION OF SCATTERING ANGLE.  IF THIS FACTOR IS NEGATIVE THE
C      PARTICLE IS TERMINATED BY WCO AND WCOCF IS INCREMENTED NEGATIVELY.
```

APPENDIX B. FLOW CHART OF ANDY GEOMETRY TREATMENT.



```
C     CHOOSE TRIAL DISTANCE TO COLLISION
  507 KRN=TRMULT*KRN
      FRN=KRN*RMOD
      IMIXT=IMIX(IR)
      D=-ALOG(FRN)*CM(3,IG,IMIXT)
      IHIT=0
C
C     DEBUG PRINT NNNN=2 GOES HERE
C
C     GEOMETRY SECTION
C
C     NAST IS THE NUMBER OF SURFACE SEGMENTS ADJACENT TO REGION IR
  505 NAST=NAS(IR)
      DO 500 ISS=1,NAST
C     IAST IS THE ID NO. OF THE SURFACE SEGMENT WITH ORDER NO. ISS ADJACENT TO
C     REGION IR
      IAST=IAS(IR,ISS)
C     IDST IS THE ID NO. OF THE SURFACE CONTAINING SURF SEG WITH ID NO. IAST
      IDST=IDS(IAST)
      IF (IPT.EQ.0) GO TO 511
      NASTT=NAS(IRT)
      DO 512 ISST=1,NASTT
      IAST2=IAS(IRT,ISST)
      IF (IDST.NE.IDS(IAST2)) GO TO 512
      D1(IDST)=D1(IDST)-DT
      D2(IDST)=D2(IDST)-DT
      GO TO 513
  512 CONTINUE
C     ITPT IS THE TYPE NO. OF SURFACE WITH ID NO. IDST
  511 ITPT=ITP(IDST)
      D1(IDST)=0.
      D2(IDST)=0.
      GO TO (501,502,503,504,506                              ),ITPT
C     PLANE SURFACE WITH NORMAL (AS,BS,CS) AND WITH CLOSEST DISTANCE TO
C     ORIGIN DS/SQRT(AS**2+BS**2+CS**2)
  501 A1=AS(IDST)*UX+BS(IDST)*UY+CS(IDST)*UZ
      IF (ABS(A1).LT.1.E-20) GO TO 500
      B1=DS(IDST)-AS(IDST)*X-BS(IDST)*Y-CS(IDST)*Z
      D1(IDST)=B1/A1
      IF (D1(IDST).LE.0.0) GO TO 500
      DTRY=D1(IDST)
      NPRT=1
      GO TO 520
C     SPHERE OF RADIUS DS CENTERED AT (AS,BS,CS)
  502 A1=1.
      B1=(X-AS(IDST))*UX+(Y-BS(IDST))*UY+(Z-CS(IDST))*UZ
      C1=(X-AS(IDST))**2+(Y-BS(IDST))**2+(Z-CS(IDST))**2-DS(IDST)**2
      GO TO 510
C     CIRCULAR CYLINDER OF RADIUS GS WITH AXIS PASSING THRU (AS,BS,CS) IN
C          DIRECTION (DS,ES,FS).  NOTE (DS,ES,FS) WAS NORMALIZED IN INITIALIZE
  503 V2=UX*DS(IDST)+UY*ES(IDST)+UZ*FS(IDST)
      V3=(X-AS(IDST))*UX+(Y-BS(IDST))*UY+(Z-CS(IDST))*UZ
      V4=(X-AS(IDST))**2+(Y-BS(IDST))**2+(Z-CS(IDST))**2
      V5=(X-AS(IDST))*DS(IDST)+(Y-BS(IDST))*ES(IDST)+(Z-CS(IDST))*
     1FS(IDST)
      A1=1.-V2**2
      B1=V3-V5*V2
      C1=V4-V5**2-GS(IDST)**2
      GO TO 510
C     ELLIPSOID CENTERED AT (AS,BS,CS) WITH AXES PARALLEL TO X,Y,Z AXES WITH
C          RADII DS,ES,FS, RESPECTIVELY.  THEN IN INITIALIZE DS,ES,FS ARE
C          REPLACED BY THEIR RECIPROCALS SQUARED
  504 A1=UX**2*DS(IDST)+UY**2*ES(IDST)+UZ**2*FS(IDST)
      B1=UX*(X-AS(IDST))*DS(IDST)+UY*(Y-BS(IDST))*ES(IDST)
     1+UZ*(Z-CS(IDST))*FS(IDST)
      C1=(X-AS(IDST))**2*DS(IDST)+(Y-BS(IDST))**2*ES(IDST)
     1+(Z-CS(IDST))**2*FS(IDST)
      GO TO 510
C     CONE WITH APEX AT (AS,BS,CS) AND AXIS PARALLEL TO (DS,ES,FS) WITH
C          OPENING ANGLE 2.*GS.  NOTE (DS,ES,FS) WAS NORMALIZED AND (COSGS)**2
```

APPENDIX C. (Continued)

```
C           WAS STORED IN GS IN INITIALIZE
  510 V3=UX*GS(IDST)+U*ES(IDST)+UZ*FS(IDST)
      V5=(X-AS(IDST))*UX+(Y-BS(IDST))*UY+(Z-CS(IDST))*UZ
      V4=(X-AS(IDST))**2+(Y-BS(IDST))**2+(Z-CS(IDST))**2
      V6=(X-AS(IDST))*DS(IDST)+(Y-BS(IDST))*ES(IDST)+(Z-CS(IDST))*
     1FS(IDST)
      A1=V3**2-GS(IDST)
      B1=V3*V5-GS(IDST)*V6
      C1=V5**2-GS(IDST)*V4
  520 B2=B1**2-A1*C1
C     ARE THE DISTANCE ROOTS COMPLEX
      IF (B2.LT.0.0) GO TO 500
      B3=SQRT(B2)
      IF (ABS(A1).LT.1.E-20) GO TO 500
      A11=1./A1
      D1(IDST)=(-B1+B3)*A11
      D2(IDST)=(-B1-B3)*A11
  530 CONTINUE
C
C     DEBUG PRINT NNNN=3 GOES HERE
C
C     ARE THE DISTANCE ROOTS BOTH NEGATIVE
      IF (D1(IDST).LE.0.0) GO TO 500
      DTRY=D2(IDST)
      NPRI=2
      IF (DTRY.LE.0.0) GO TO 540
      GO TO 520
  540 DTRY=D1(IDST)
      NPRI=1
  520 IF (DTRY.GT.D) GO TO 500
C
C     IF THIS POINT IS REACHED THEN WE HAVE A CANDIDATE DTRY FOR THE SHORTEST
C     FLIGHT TO A SURFACE SEGMENT ADJACENT TO REGION IR. NOW TEST SENSES TO
C     SEE IF X+DTRY*U IS ACTUALLY IN THE SURFACE SEGMENT WITH ID IAST.
      DO 550 ISEN=1,NSEN
      X1=X+DTRY*UX
      Y1=Y+DTRY*UY
      Z1=Z+DTRY*UZ
      JSEN=ISENSE(IAST)
      DO 560 IS=1,NSEN
      IDENT=IDENT(IAST,IS)
      ITPT=ITPT(IDENT)
      GO TO (561,562,563,564,565                                    ),ITPT
  561 SENSE=AS(IDENT)*X1+BS(IDENT)*Y1+CS(IDENT)*Z1-DS(IDENT)
      GO TO 560
  562 SENSE=(X1-AS(IDENT))**2+(Y1-BS(IDENT))**2+(Z1-CS(IDENT))**2
     1 -DS(IDENT)**2
      GO TO 560
  563 V4=(X1-AS(IDENT))**2+(Y1-BS(IDENT))**2+(Z1-CS(IDENT))**2
      V5=(X1-AS(IDENT))*DS(IDENT)+(Y1-BS(IDENT))*ES(IDENT)
     1+(Z1-CS(IDENT))*FS(IDENT)
      SENSE=V4+V5**2-GS(IDENT)**2
      GO TO 560
  564 SENSE=(X1-AS(IDENT))**2*DS(IDENT)    +(Y1-BS(IDENT))**2*
     1ES(IDENT)    +(Z1-CS(IDENT))**2*FS(IDENT)    -1.
      GO TO 560
  565 V4=(X1-AS(IDENT))**2+(Y1-BS(IDENT))**2+(Z1-CS(IDENT))**2
      V5=(X1-AS(IDENT))*DS(IDENT)+(Y1-BS(IDENT))*ES(IDENT)
     1+(Z1-CS(IDENT))*FS(IDENT)
      SENSE=V5**2-GS(IDENT)**2*V4
  560 JSEN=1
      IF (SENSE.LT.0.0) JSEN=-1
C
C     DEBUG PRINT NNNN=4 GOES HERE
C
      IF (ISEN(IAST,IS1)*JSEN.EQ.0) GO TO 541
C     THIS SENSE TEST HAS BEEN PASSED
      GO TO 550
C     THIS SENSE TEST HAS BEEN FAILED
```

APPENDIX C. (Continued)

```
  510 IF (NPRT.EQ.1) GO TO 500
      DTRY=DI(ITOST)
      NPRT=1
      GO TO 520
  530 CONTINUE
C     ALL TESTS HAVE BEEN PASSED SO IHIT IS THE ID NUMBER OF THE CLOSEST STRUCK
C     SURFACE SEGMENT OF THOSE YET TESTED
  550 IHIT=ITAST
      ISST=ISS
      D=DTRY
  500 CONTINUE
```

APPENDIX D. SAMPLE INPUT FOR ANDYMG3.

```
25 GROUP NEUTRONS. P1. B-H-T TRANSPORT          12    25    17     4     0
     1     1     6
PULSED MULTIPLIER IN CAVITY
     6    17    18     5     1     2
    20    19     4     3     1     7     4
 10000    19     0     0
2.           20.          2.          100.
2.           .0001        .01         1.
     3
0.           0.           0.          0.          0.          1.
4.           0.
     1
0.           0.           1.          4.          0.          0.
0.           0.
     1
0.           0.           -1.         4.          0.          0.
0.           0.
     3
0.           0.           0.          0.          0.          1.
5.           0.
     2
0.           0.           -4.         10.         0.          0.
0.           0.
     2
0.           0.           4.          10.         0.          0.
0.           0.
     3
0.           0.           0.          0.          0.          1.
50.          0.
     2
0.           0.           -50.        100.        0.          0.
0.           0.
     2
0.           0.           50.         100.        0.          0.
0.           0.
     3
0.           0.           0.          0.          0.          1.
56.          0.
     2
0.           0.           -50.        106.        0.          0.
0.           0.
     2
0.           0.           50.         106.        0.          0.
0.           0.
     3
0.           0.           0.          1.          0.          0.
5.           0.
     1
1.           0.           0.          6.          0.          0.
0.           0.
     1
```

APPENDIX D. (Continued)

```
1.          0.          0.          10.         0.          0.
0.          0.
    1
-1.         0.          0.          10.         0.          0.
0.          0.
    1
-1.         0.          0.          6.          0.          0.
0.          0.
     1      2
     2      3
    -1     -1
     2      1
     1
    -1
     3      1
     1
    -1
     4      2
     5      6
    -1     -1
     5      2
     4      2
    -1      1
     6      2
     4      3
    -1      1
     7      2
     8      9
    -1     -1
     8      1
     7
    -1
     9      1
     7
    -1
    10      0
    11      0
    12      0
    13      2
    14     15
     1     -1
    14      1
    13
    -1
    15      1
    13
    -1
    13      2
    16     17
    -1      1
    16      1
    13
    -1
    17      1
    13
    -1
     3      1
     1      2      3
     2      2      2
     6      2
     1      2      3      4      5      6
     1      1      1      3      3      3
    12      3
     4      5      6      7      8      9     13     14     15     16     17     18
     2      2      2      4      4      4      5      5      5      6      6      6
     6      4
     7      8      9     10     11     12
     3      3      3      9      9      9
     3      5
    13     14     15
```

APPENDIX D. (Continued)

```
      3      3      3
      3      5
     16     17     18
      3      3      3
      1      4      5      6
      7     15     16
      6
    303    306    307    350    342    331
.0142857     .000767723  .00001       .0129459     .0135952     .00736668
      5
    342    331    345    346    350
.02          .008         .018         .0018        .005
      2
    342    331
.000001      .000001
      5
    342    394    345    346    350
.04          .02          .038         .0018        .01
      7
    342    394    345    346    350    351    347
.0007        .12          .0           .0           .03          .0
.0
0.           0.           0.           0.           1.           0.
      1      1
0.           1.           0.           0.           0.           0.
      1      2
0.           1.           0.           0.           0.           0.
      1      3
0.           1.           0.           0.           0.           0.
      1      4
```

APPENDIX E. LAST PART OF OUTPUT FOR ANDYMG3 SAMPLE PROBLEM.

```
      RESULTS FOR TIME INTERVAL     20  TO TB(IT)=  .220000E+03

      WIR(IT,ITALY,IG),IG=1,NG FOR REGION      1
0.           0.           0.           0.           0.           0.
0.           0.           0.           0.           0.           0.
0.           0.           0.           0.           0.           0.
0.           0.           0.           0.           0.           0.
0.

      WIR(IT,ITALY,IG),IG=1,NG FOR REGION      4
0.           0.           0.           0.           0.           0.
0.           0.           0.           0.           0.           0.
0.            .160058E-03  .261632E-03  .121823E-02  .147282E-02  .332858E-02
 .117046E-02  .105316E-03 -.259763E-03  .464013E-06 -.850899E-06  0.
0.

      WIR(IT,ITALY,IG),IG=1,NG FOR REGION      5
0.           0.           0.           0.           0.           0.
0.           0.           0.           0.           0.           0.
0.           0.           0.           0.           0.           0.
0.           0.            .173160E-06 -.517399E-03 -.183005E-02  .133207E-01
 .256575E-02

      WIR(IT,ITALY,IG),IG=1,NG FOR REGION      6
0.           0.           0.           0.           0.           0.
0.           0.           0.           0.           0.           0.
0.           0.           0.           0.           0.           0.
0.           0.           0.            .660105E-03  .389335E-02  .125642E-01
-.596383E-03
```

APPENDIX E. (Continued)

```
      WISP(IT,ITALY,IG),IG=1,NG FOR SURFACE SEGMENT       7
0.                0.                0.                0.                0.                0.
0.                0.                0.                0.                0.                0.
0.                 .395609E-04     -.104334E-03       .217137E 02       0.                0.



0.                0.                0.                0.                0.                0.
0.

      WISN(IT,ITALY,IG),IG=1,NG FOR SURFACE SEGMENT       7
0.                0.                0.                0.                0.                0.
0.                0.                0.                0.                0.                0.
0.                0.                 .424741E-06       .647501E-03       .119099E-04      -.121417E-04
0.                0.                0.                0.                0.                0.
0.

      WISP(IT,ITALY,IG),IG=1,NG FOR SURFACE SEGMENT      15
0.                0.                0.                0.                0.                0.
0.                0.                0.                0.                0.                0.
0.                0.                0.                0.                0.                0.
0.                0.                0.                0.                0.                0.
0.

      WISN(IT,ITALY,IG),IG=1,NG FOR SURFACE SEGMENT      15
0.                0.                0.                0.                0.                0.
0.                0.                0.                0.                0.                0.
0.                0.                0.                0.                0.                0.
0.                0.                0.                0.                0.               -.329896E-04
 .214595E-06

      WISP(IT,ITALY,IG),IG=1,NG FOR SURFACE SEGMENT      16
0.                0.                0.                0.                0.                0.
0.                0.                0.                0.                0.                0.
0.                0.                0.                0.                0.                0.
0.                0.                0.                0.                0.                0.
0.

      WISN(IT,ITALY,IG),IG=1,NG FOR SURFACE SEGMENT      16
0.                0.                0.                0.                0.                0.
0.                0.                0.                0.                0.                0.
0.                0.                0.                0.                0.                0.
0.                0.                0.                0.                0.               -.176652E-04
0.

      WIT(IT,IW),IW=1,NIT
0.

      NS    ISPLC    ISPLO    NHS    NCOL    NDEL
1000       2505        0      3505     26458        0

      WCO    WCOC    WCOCF    WSPLT
.100000E-03      .235741E-02      .100000E-01      .200000E+01

      WDEL(ITPDEL),ITPDEL=1,NTPDEL
.461762E+5

      REGION SUM ISUM=       1 FOR TALLY ITALY=       1 FOR REGION IR=       1

      WIR SUM(IT),IT=1,NT
.302467E+02      .247497E+00      .773301E-01      .741328E-02      .229960E-01      .144269E+00
.489820E-01      .458651E-02      0.               .267514E-02      .466523E-01     -.213505E-03
.108616E-01      0.               0.              -.172905E-04      .870930E-03      0.
0.               0.

      REGION SUM ISUM=       2 FOR TALLY ITALY=       2 FOR REGION IR=       4

      WIR SUM(IT),IT=1,NT
.192383E+00      .448562E+00      .552372E+00      .524211E+00      .407877E+00      .304626E+00
```

APPENDIX E. (Continued)

```
 .254372E+00      .210575E+00      .193422E+00      .201244E+00      .765364E+00      .335344E+00
 .191902E+00      .151973E+00      .628064E-01      .447508E-01      .229587E-01      .617394E-01
 .187332E-01      .217380E-01

      REGION SUM ISUM=       3 FOR TALLY ITALY=       3 FOR REGION IR=       5

      WIR SUM(IT),IT=1,NT
 .144390E+00      .294435E+00      .274591E+00      .146536E+00      .498529E-01      .168554E+00
 .102305E+00      .103942E+00      .895665E-01     -.222353E-01      .954626E+00      .101354E+01
 .101370E+01      .957336E+00     -.502855E+00     -.400151E+00     -.255398E+00      .478337E+00
-.668645E+00      .220705E+01

      REGION SUM ISUM=       4 FOR TALLY ITALY=       4 FOR REGION IR=       6

      WIR SUM(IT),IT=1,NT
 .105419E+00      .151694E+00      .345635E-01      .942177E-01     -.390135E-01     -.188502E+00
 .553846E-01      .925431E-01      .136420E+00      .290826E+00      .365703E+00      .110149E+01
 .205448E+01      .133424E+01     -.288299E+00      .473617E+00      .760466E+00      .176741E+01
 .180468E+01      .164770E+01
```

KT/sv: 313 (50)