N70-32598

NASA TECHNICAL MEMORANDUM

NASA TM X-2048

NASA TM X-2048

UNAMIT - A ONE-DIMENSIONAL 4π SPHERICAL MULTILAYER REACTOR-SHIELD-WEIGHT OPTIMIZATION CODE

by
Eugene S. Troubetzkoy
Columbia University

and
Millard L. Wohl
Lewis Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JULY 1970

1. Report No. NASA TM X-2048	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle UNAMIT - A ONE-DIMENSIONAL 4π SPHERICAL MULTILAYER REACTOR-SHIELD-WEIGHT OPTIMIZATION CODE		5. Report Date July 1970
		6. Performing Organization Code
7. Author(s) Eugene S. Troubetzkoy, Columbia Univ., New York, N. Y.; and Millard L. Wohl, Lewis Research Center		8. Performing Organization Report No. E-5619
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		10. Work Unit No. 126-15
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The computer code UNAMIT is described. The code generates 4π multilayer spherical reactor shields of minimum weight subject to a fixed shield surface dose rate constraint. The code uses an exponential attenuation - secondary-production analytic model. Methods are presented for determining required input parameters for attenuation of primary neutrons, primary gamma rays, and secondary gamma rays, and for production of secondary gamma rays. Discussion of the pertinent theory and operation of the code is presented in addition to listings of the code in Fortran IV and Fortran 63. Full input instructions and a sample problem output listing are presented.

17. Key Words (Suggested by Author(s)) Nuclear engineering; Nuclear propulsion; Computer codes; Radiation shielding		18. Distribution Statement Unclassified - unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 21	22. Price* $3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

UNAMIT - A ONE-DIMENSIONAL 4π SPHERICAL MULTILAYER REACTOR-SHIELD-WEIGHT OPTIMIZATION CODE

by Eugene S. Troubetzkoy,* and Millard L. Wohl

Lewis Research Center

SUMMARY

The computer code UNAMIT allows the computation of total neutron and gamma-ray dose rate at the surface of a multilayer spherical shield surrounding a spherical reactor model whose leakage is known. It computes this dose rate subject to a minimum total shield weight constraint. The code utilizes an exponential attenuation - secondary-gamma-ray production model with a transport-determined dose rate and artificial source term to generate the variation of dose rate through the shield and obtain its value at the shield surface.

The user must specify a set of parameters characterizing the geometry and composition of the reactor-shield configuration. These are (1) the reactor outer radius, (2) the dose rate convergence criterion, (3) minimum values for all shield layer radii, (4) maximum values for all shield layer radii, (5) step sizes for shield layer radii, and (6) shield layer material densities.

A set of parameters characterizing the materials specified in the shield layers is also required. These must be specified by the user and are for each shield layer: (1) attenuation parameters for primary gamma rays, p, (2) attenuation parameters for neutrons, y, (3) attenuation parameters for secondary gamma rays, λ, and (4) secondary gamma-ray production parameters, z. These parameters depend not only on the shielding materials in question, but also on an assumed preliminary shield configuration.

The model assumes exponential attenuation and secondary production in each shield layer, and is designed to match the neutron dose rate at the shield surface as determined by a transport calculation. The parameters used by the calculational model are obtained from preliminary transport analyses so that the calculational model gives a reasonable approximation of the attenuation and secondary production of radiation.

The UNAMIT code adjusts the thicknesses of the specified shield layers by finite increments within layer boundary limits prescribed by the user. It generates, by a stepping search procedure, the minimum weight shield configuration satisfying the shield surface dose rate constraint specified by the user. The minimum weight configuration obtained lies within the set of possible configurations defined by the specified shield layer materials and their order, and the minimum and maximum prescribed shield layer radii.

---

*Formerly at United Nuclear Corporation, Elmsford, New York; presently at Columbia University, New York, New York.

INTRODUCTION

The design of 4π unit nuclear reactor shields to permit the achievement of low dose rates in the near vicinity of the powerplant is an involved, time-consuming process. Detailed neutron and gamma-ray transport calculations are an important part of the overall design procedure. If the constraint of minimum unit shield weight is added to the required dose rate constraint, the shield design becomes more difficult.

Weight-optimization of even first-order unit shield configurations is a highly involved procedure if iterative neutron and gamma-ray transport analyses are done. These are very time consuming and the probability of error is high.

An alternative to iterative transport procedures is to use a highly simplified computational model. Such models were first systematically employed in the Military Compact Reactor (MCR) Program where system constraints necessitated minimum shield weight. During the course of this program, a series of simplified shield weight-optimization codes was developed.

These codes used a model starting with a reactor leakage source term and an exponential attenuation - secondary-production description. Thicknesses of prescribed ordered shield layers were systematically varied to achieve minimum shield weight.

The latest variant of these codes is called UNAMIT. This code was used extensively in the nuclear airplane studies being conducted by the NASA Lewis Research Center. The code accepts an ordered set of shield materials, nominal inner and outer layer radii, and radial step size increments. It then generates the minimum-weight layered unit shield configuration consistent with the prescribed shield surface dose rate.

In order to generate a lowest-weight shield configuration, UNAMIT requires attenuation and production parameters characteristic of the shield materials and their order in the shield. The required parameters are attenuation parameters for primary radiation; attenuation parameters for secondary-producing radiation; attenuation parameters for secondary radiation; and secondary-production parameters. These parameters depend upon an initial assumed shield configuration and are generated from preliminary transport analyses for such a configuration.

This report will discuss the operation of the UNAMIT code and the pertinent theory involved. Listings of the code in both Fortran IV and Fortran 63 are presented. In addition, full input instructions and a sample problem output listing are included.

ANALYSIS

The code UNAMIT computes the total neutron and gamma-ray dose rate at the surface of a multilayer-unit shield as described below in equation (1). It weight-optimizes the shield subject to a fixed dose rate constraint at the shield surface. The following section describes the computational method, including the determination of primary and secondary attenuation and production parameters.

Calculational Procedure

The calculational model uses an arbitrary number of neutron groups, each of which produces secondary gamma rays. An arbitrary number of primary gamma-ray groups is also specified. The dose rate at the shield surface is the sum of the neutron dose rate and the primary and secondary gamma-ray dose-rate contributions.

For a spherical shield consisting of N layers of distinct materials between radii $r_0, r_1, r_2, \ldots, r_n$, the dose rate is given by

$$D = \sum_{i=1}^{N} \sum_{K=1}^{NGS_i} GS_i^K \exp\left[-\sum_{j=1}^{i-1} Y_{ji}^K(r_j - r_{j-1})\right] \int_{r_{i-1}}^{r_i} \exp\left[-Y_{ii}^K(r - r_{i-1})\right] Z_i^K$$

$$\times \exp\left[-\lambda_{ii}^K(r_i - r)\right] dr \exp\left[-\sum_{j=i+1}^{N} \lambda_{ji}^K(r_j - r_{j-1})\right] + \sum_{K=1}^{NGP} GP^K \exp\left[-\sum_{i=1}^{N} P_i^K(r_i - r_{i-1})\right] \tag{1}$$

where

- i outer summation index denoting region with inner and outer radii r_{i-1} and r_i
- j inner summation index for regions internal to i^{th} region, which affect production of secondary gamma rays in i^{th} region
- K energy group summation index for secondary-producing neutrons and primary gamma rays
- GS_i^K source intensity for neutrons emitted at r_0 which are responsible for secondary gamma rays produced in region i; for each region denoted by i, K runs from 1 to NGS_i.
- Y_{ji}^K attenuation parameter for K^{th} neutron group in region j for fixed i; it is defined only for $j \le i$
- λ_{ji}^K attenuation parameter for gamma rays produced in region i by K^{th} neutron group; it is defined only for $j \ge i$
- Z_i^K secondary gamma-ray production parameter, photons/(source neutron-cm) for K^{th} neutron group in region i

GP^K source intensity for primary neutrons and gamma rays emitted at r_0 which contribute to external dose

NGS_i number of secondary gamma-ray producing groups in region i

P_i^K attenuation parameter of K^{th} primary gamma-ray group in region i

NGP number of primary radiation groups

N number of layers of distinct materials

The shield weight is then given by

$$W = \frac{4\pi}{3} \sum_{i=1}^{N} \rho_i \left(r_i^3 - r_{i-1}^3\right) \tag{2}$$

where ρ_i is the i^{th} region material density.

Discussion of equation (1). - The first sequence of terms in equation (1), within the double summation, deal with the production and subsequent attenuation of secondary gamma radiation.

GS_i^K is the source intensity for reactor leakage neutrons which are responsible for secondary gamma rays produced in region i. The exponential term

$$\exp\left[-\sum_{j=1}^{i-1} Y_{ji}^K (r_j - r_{j-1})\right]$$

describes the attenuation of these neutrons in the outward radial sense through shield regions up to, but not including region i, where secondary gamma rays are produced.

The exponential term $\exp\left[-Y_{ii}^K(r - r_{i-1})\right]$ describes the leakage neutron attenuation through region i, in which secondary gamma rays are produced. The term Z_i^K is the production strength for secondary gamma rays produced in region i.

The exponential term $\exp\left[-\lambda_{ii}^K(r_i - r)\right]$ describes the attenuation of secondary gamma rays produced in region i through the remainder of region i; the product of doubly subscripted terms (subscripts ii) must be included in the integral over region i because the secondary production may take place anywhere in this region.

The exponential term

$$\exp\left[-\sum_{j=i+1}^{N} \lambda_{ji}^K (r_j - r_{j-1})\right]$$

describes the attenuation of secondary gamma rays produced in region i through shield regions external to i.

The last term in equation (1)

$$GP^K \exp\left[-\sum_{i=1}^{N} P_i^K(r_i - r_{i-1})\right]$$

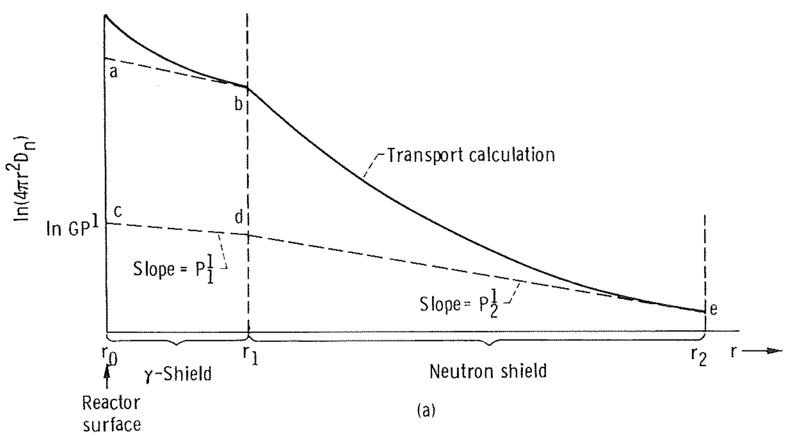
describes the source strength and attenuation of primary radiation, both neutrons and gamma rays.

Discussion of attenuation and secondary-production parameters. - The model described by equation (1) assumes that a given shielding material is described by a number of parameters. These are the attenuation parameters for primary radiation P, the attenuation parameters for secondary producing radiation Y, attenuation parameters for the secondary radiation λ, and secondary production parameters Z. These parameters depend not only on the shielding materials in question but also on the shield configuration. It is, therefore, important to obtain the model parameters from transport calculations so that the model gives a reasonable approximation of the attenuation and secondary production of radiation.

The methods of determining the primary and secondary radiation attenuation and production parameters will be discussed using a two-layer shield model consisting of an inner layer of high-atomic number gamma-ray shielding material followed by a layer of hydrogenous neutron shield material.

Primary radiation. -

Neutron dose rate contribution: In order to determine the neutron attenuation parameters, let us consider a single group of neutrons responsible for the neutron dose rate at the shield surface. This will be the first category of primary radiation. A transport (Monte Carlo or Sn) calculation of the total primary neutron dose rate as a function of r, the distance from the reactor center, might yield the following plot.



(a)

The dotted lines are straight lines having the same slopes as the solid curves at r_1 and r_2. The slopes are P_1^1 and P_2^1 respectively, and serve as the attenuation parameters for primary neutrons in the model. The ordinate intercept, $\ln GP^1$, is obtained by appending to the dotted line segment $\overline{de}$ a segment $\overline{cd}$ parallel to $\overline{ab}$.

Given all the attenuation parameters, P_i^1, the source term GP^1 is uniquely determined as indicated and is described, for the configuration of sketch (a), in the equation

$$GP^1 \, e^{\left[-P_1^1(r_1-r_0)\right]} \, e^{\left[-P_2^1(r_2-r_1)\right]} = D^1$$

where $D^1 = 4\pi r^2 x$ the primary neutron dose rate at the shield surface.

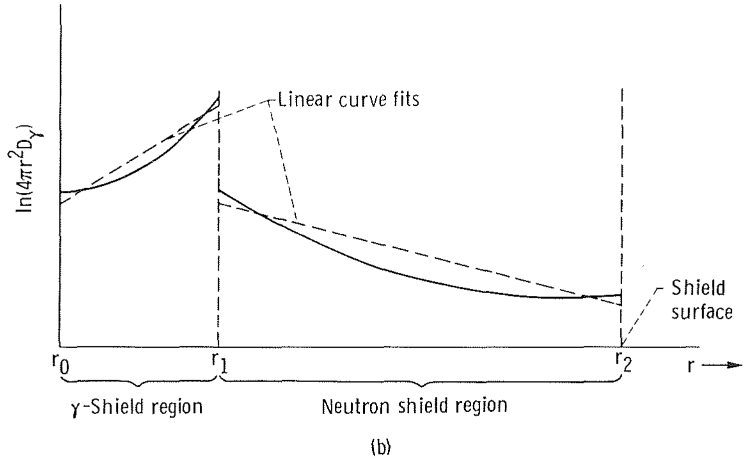
Primary gamma-ray dose rate contribution: The primary gamma-ray contribution is designed by the index $K = 2$ in equation (1). The parameters P_i^2 for primary gamma-ray attenuation can be determined in a manner similar to the method just discussed for obtaining primary neutron attenuation parameters. An alternative would be to use the mass absorption coefficient, for an appropriate gamma-ray energy, for the material in region i as P_i^2.

Secondary radiation. - In order to determine the secondary gamma-ray attenuation parameters, let us assume that a single group of neutrons is responsible for the production of a single group of secondary gamma rays.

All of the secondary gamma-ray attenuation coefficients λ_{ji}^K can be assumed to be given by the mass absorption coefficients in the material for a representative energy of gamma rays produced in region i.

From the results of a transport calculation, the representative energy of neutrons responsible for secondary production in region i can be determined. By fitting the model of the attenuation of the neutron group in a manner similar to the one described under "Primary radiation," the secondary-producing neutron attenuation parameters Y_{ji}^K in region j may be determined.

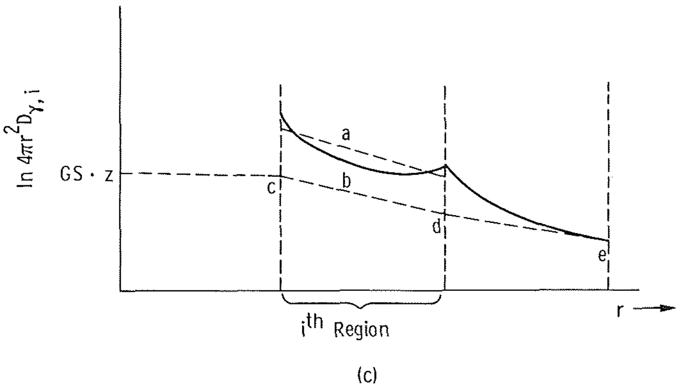
A special procedure can be applied to determine the attenuation coefficient Y_{ii}^K of neutrons in region i (either region shown in sketch (b)) responsible for secondary production in the same region i. A transport calculation can give D_γ, the contribution to the shield surface dose rate due to secondary production at all positions r in the shield. By plotting $\ln(4\pi r^2 x$ this contribution) against r, a curve which should be fit by a piecewise linear curve (according to our model) is obtained as follows:



(b)

In each shield region, the slope of the straight line fit is obtained from Y_{ii} = slope + λ_{ii}. Having obtained λ_{ii} from the mass absorption coefficients in the manner already prescribed, one can obtain Y_{ii} from the slope.

Finally, the combination of parameters $GS_i^K \cdot Z_i^K$ can be determined by back-extrapolating the total secondary dose rate due to region i as shown in sketch (c).



(c)

In sketch (c), $D_{\gamma,i}$ is the secondary dose rate from region i. As in sketch (a), $\overline{cd}$ is parallel to $\overline{ab}$.

As has been mentioned throughout this discussion, useful application of the attenuation-production model is dependent on an accurate transport calculation for a shield similar to the set of shields to be studied with the UNAMIT code. It is recommended that the accurate calculation be performed by either Monte Carlo or Sn methods employing carefully prepared cross sections and/or transfer matrices.

ASSUMPTIONS AND LIMITATIONS OF UNAMIT

As has been mentioned, UNAMIT utilizes an exponential attenuation - secondary-production model. The input parameters characterizing the initial assumed shield layer configuration are derived from transport analyses for an assumed physical shield layer configuration. If, using this assumed initial configuration, UNAMIT cannot obtain the surface dose rate constraint prescribed by the user, it may be necessary to assume a second initial configuration from which new attenuation and production parameters must be obtained. Shield calculations made to date have never required a third initial configuration.

As an adjunct to the previous statements, the user should be careful not to assume that attenuation and production parameters which were successful in generating optimum shield weight configurations in a given reactor power regime would be successful in another regime. Changing reactor power regimes is equivalent to changing attenuation regimes, and generally new parameters are required when this is done.

PREPARATION OF INPUT DATA

The user specifies minimum and maximum values of all radii and step sizes for each radius. UNAMIT systematically varies each radius within the prescribed range, adjusting them to give the prescribed dose. The shield weights for all configurations within the variation considered are compared with one another, and the configuration yielding the lightest shield is retained.

The input description is as follows:

INPUT

PART A 1st Card: Shield configuration and specifications
Title (any 80 Hollerith characters)

2nd Card: N, number of regions
r_0, core radius
$\overline{D}$, dose specification - left blank for UNAMIT FORMAT (I 12, 2E12. 5)

The next group of cards <u>must be repeated for regions</u> $i = 1, 2, 3, \ldots, N$:

1st Card: i, region number
NGS_i, number of distinct secondary production processes occurring in region i
ρ_i, density of material in i^{th} region (g/cm^3) FORMAT (2I5, E12. 5)

2nd Card: GS_i^K, source term for group K in region i

Z_i^K, secondary production parameter for group K in region i

K = 1, 2, . . . , NGS_i, five pairs of numbers to a card

FORMAT (10E8.4)

3rd Card: Y_{li}^K, neutron attenuation parameter

λ_{li}^K, gamma-ray attenuation parameter (blank if $i > l$)

K = 1, 2, . . . , NGS_i, five pairs per card. Note: for each K value, a set of values of Y and λ is specified for $i + 1 \leq l \leq N$.

FORMAT (10E8.4)

3 + jth Card: Y_{ji}^K, neutron attenuation parameter (blank if $j > i$)

λ_{ji}^K, gamma-ray attenuation parameter (blank if $j < i$)

K = 1, 2, . . . , NGS_i, five pairs per card)

FORMAT (10E8.4)

After the N groups of cards have been entered, enter the following information on primary radiation:

1st Card: NGP, number of primary groups

FORMAT (I12)

2nd Card: GP^K, primary source terms, K = 1, NGP (10E8.4)

3rd Card: P_i^K, attenuation parameter of Kth primary radiation in region i

K = 1, 2, 3, . . . , NGP

FORMAT (10E8.4)

3 + jth Card: P_j^K, attenuation parameter of Kth primary radiation in region j. K = 1, 2, 3, . . . , NGP

FORMAT (10E8.4)

j runs from 1 to i

PART B 1st Card: EPS, convergence criterion

NITMAX, maximum number of iterations permitted

ISW; 0, no intermediate answers

1, answers for all shields calculated

FORMAT (E12.4, 2I6)

2nd Card: RMI(1) RMT(2), . . ., minimum values for all radii
FORMAT (6E12.4)

3rd Card: RMS(1), RMA(2), . . ., maximum values for all radii
FORMAT (6E12.4)

This can be followed by PART A and PART B for as many shields as desired.

OUTPUT

The input information is printed out.
If ISW = 1, radii and weights of all shields calculated are printed out.
The lowest weight shield obtained is edited.

SAMPLE PROBLEM

Monte Carlo Analysis of Reactor-Shield Configuration

A spherical homogeneous 375-megawatt reactor with a layered uranium-water spherical shell 4π unit shield was analyzed with the SANE-2M and SAGE 4 Monte Carlo codes. SANE-2M is used to perform neutron transport calculations and generate secondary gamma rays. SAGE 4 is used to perform primary and secondary gamma ray transport calculations.

The configuration analyzed with SANE-2M and SAGE 4 is indicated in table I.

TABLE I. - CONFIGURATION FOR MONTE CARLO REACTOR-SHIELD ANALYSIS

Physical region	Type	Outer radius, cm	Physical region	Type	Outer radius, cm
1	Core	82.38	14	H_2O	150
2	Ba reflector	90	15	U	152
3	U	93	16	H_2O	160
4	H_2O	100	17	U	162
5	U	103	18	H_2O	170
6	H_2O	110	19	U	172
7	U	113	20	H_2O	190
8	H_2O	120	21	U	192
9	U	123	22	H_2O	210
10	H_2O	130	23	U	212
11	U	132	24	H_2O	230
12	H_2O	140	25	H_2O	320
13	U	142	26	Air	1000

TABLE II. - REACTOR-SHIELD MATERIAL

COMPOSITIONS

Component	Element	Atom density atoms/cm^3
Core	Hydrogen	1.976×10^{22}
	Oxygen	1.184×10^{22}
	Aluminum	5.12×10^{21}
	Zirconium	1.744×10^{22}
	Uranium-235	9.79×10^{20}
Reflector	Beryllium	1.20×10^{23}
Depleted uranium	Uranium-238	4.82×10^{22}
Water (borated)	Hydrogen	6.45×10^{22}
	Oxygen	3.37×10^{22}
	Boron-10	1.73×10^{20}
	Boron-11	7.85×10^{20}
Air	Nitrogen	4.17×10^{19}
	Oxygen	9.0×10^{18}

The material compositions for the configuration specified in table I are listed in table II.

A Monte Carlo analysis of this reactor shield configuration yielded a dose rate of 0.0224 millirem per hour at a detector point in air 30 feet from the reactor center.

Optimum Shield Weight Determination With UNAMIT Code

The Monte Carlo analysis was performed with specific uranium-water configurations represented by discrete uranium layers separated by water. The uranium layers were of 2- to 3-centimeter thickness to allow the benefit of self-shielding effects. The thickness of the water layers was chosen to yield effective mixture densities in the range of 3 to 6.5 grams per cubic centimeter.

In performing shield optimization analysis with UNAMIT, three homogenized uranium-water (borated) mixtures were considered in the shield in addition to an outer layer of borated water. The mixtures were

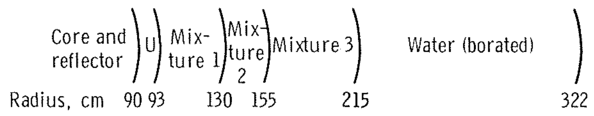
(1) 30 Percent depleted uranium plus 70 percent borated water, giving a density of 6.4 grams per cubic centimeter

(2) 20 Percent depleted uranium plus 80 percent borated water, giving a density of 4.6 grams per cubic centimeter

(3) 10 Percent depleted uranium plus 90 percent borated water, giving a density of 2.8 grams per cubic centimeter

Mixtures 1, 2, and 3 correspond to homogenized combinations of physical regions 3 to 10, 11 to 18, and 19 to 24, respectively, in table I.

The weight-optimized configuration generated by UNAMIT, for a dose rate constraint of 0.025 millirem per hour 30 feet (9.14 m) from the reactor center, is shown schematically in sketch (d).



(d)

The weight of this optimized configuration is 543 000 pounds (247 000 kg) for the prescribed 30-foot (9.14-m) dose rate of 0.025 millirem per hour. This is very close to the Monte Carlo-determined dose rate of 0.0224 millirem per hour at the same detector location. Details of the computational results are listed in the following output listing.

```
 UNAMIT  U-H20 SHIELD          375 MWE

N=            5 RZERO= 0.90000E 02 DBAR= 0.25000E-01

KR=     1 NG=     2 RU= 0.19050E 02
 GS
0.162C0E C7 (.74560E 08
  Z
0.10CCCE 01 (.10000E 01
PAR
0.150C0E 0C (.94000E C0 0.273C0E 00 0.90000E 00
0.15CC0E 00 (.31000E 00 0.27300E 00 0.30000E 00
0.133C0E 00 (.23000E 00 0.15000E 00 0.22000E 00
0.115C0E 00 C.13000E 00 0.13000E 00 0.13000E 00
0.97CC0E-01 C.48000E-01 0.97000E-01 0.50000E-01

KR=     2 NG=     2 RO= 0.64000E 01
 GS
0.53740E C6 C.25790E C9
  Z
0.10CC0E 01 C.10000E 01
PAR
0.150C0E C( (.94000E 00 0.27300E 00 0.90000E 00
0.15CC0E 0C (.31000E 00 0.27300E 00 0.30000E 00
0.133CCE 0C (.23000E 00 0.15000E 00 0.22000E 00
0.115C0E 00 (.13000E 00 0.13000E 00 0.13000E 00
0.97CC0E-01 (.48000E-01 C.97000E-01 0.50000E-01

KR=     3 NG=     2 RO= 0.46000E 01
 GS
0.37250E C6 (.15290E C9
  Z
0.10CC0E 01 (.1C000E C1
PAR
0.15CC0E 00 C.94000E 00 0.27300E 00 0.90000E 00
0.150C0E 00 (.31000E 00 0.27300E 00 0.30000E 00
0.133C0E CC (.23000E 00 0.15000E 00 0.22000E 00
0.115C0E 0C (.13000E 00 0.13000E 00 0.13000E 00
0.97C00E-01 (.48000E-01 0.97000E-01 0.50000E-01

KR=     4 NG=     3 RO= 0.28000E 01
 GS
0.33170E C6 (.86320E C8 0.18270E 08
  Z
0.10CC0E C1 (.10000E C1 0.10000E 01
PAR
0.150C0E 0( (.94000E C0 0.27300E 00 0.90000E 00 0.27300E 00-0.
0.15000E 00 (.31000E 00 0.27300E 0C 0.30000E 00 0.27300E 00-0.
0.133C0E C0 (.23000E C0 0.150C0E 00 0.22000E 00 0.15000E 00-0.
0.11500E C0 (.13000E 00 0.13000E 00 0.12980E 00 0.13000E 00 0.18000E 00
0.97CC0E-01 (.4800CE-01 0.97000E-01 0.50000E-01 0.99000E-01 0.40000E-01

KR=     5 NG=     3 RO= 0.10200E 01
 GS
C.24930E C6 C.4260CE 06 0.19010E 07
  Z
0.10CC0E C1 (.10000E 01 0.10000E 01
```

```
PAR
C.15CCOE 0C (.94000E 00 0.273C0E 00 0.90000E 00 0.27300E 00-0.
C.15CCCE 00 (.31000E 00 0.273C0E 0C 0.30000E 00 0.27300E 00-0.
0.13300E C0 (.23000E 00 0.15000E 00 0.22000E 00 0.15000E 00-0.
0.115C0E CC (.13000E C0 0.13000E 0C 0.13000E 00 0.13000E 00 0.18000E 00
C.97CC0E-01 (.48000E-01 0.97000E-01 0.50000E-01 0.99000E-01 0.40000E-01

NG=          2
G
0.33720E C9 (.18200E 13
PAR
0.1735CE CC (.90000E 00
0.118C0E 00 (.3000CE C0
0.11CC0E 00 (.22000E 00
0.1C2C0E 00 (.13000E C0
0.10CC0E 00 (.50000E-C1
 0.9300E C2  0.1300E C3  0.1550E 03  0.2000E 03  0.2900E 03
 0.93C0E C2  0.1300E C3  C.1700E 03  0.2200E 03  0.3000E 03
 C.1CC0E C1  C.5000E C1  0.5000E 01  0.5000E 01  0.1000E 02

RO= C.90000E 02<--REFLECTOR OUTER RADIUS (CM)
R(I)
C.930C0E C2 (.13000E 03 0.15500E 03 0.21500E 03 0.32245E 03<--SHIELD REGION OUTER RADII (CM)

DOS(I)
0.10246E-C6 C.61601E-05 0.62330E-04 0.84887E-03 0.73617E-03 0.14609E-02 0.67880E-02 C.42179E-02 0.82309E-03 0.26181E-02
0.729C2E-05 C.76247E-04 0.77118E-02 0.

W= 0.54329E C6 D= 0.25357E-01

SHIELD WEIGHT     DOSE RATE
    (LB)          (MREM/HR)
```

FORTRAN IV COMPUTER CODE LISTING

```
C     PROGRAM UNAMIT
      COMMON/MAX/N,Z(2),R(19),X(2),CON,W
      DIMENSION  RMI(20),RMA(20),DER(20),ROPT(20),RNG(20)
  100 CALL INITAL
      READ(5,101) EPS,NITMAX,ISW
      READ(5,102) (RMI(I),I=1,N)
      WRITE(6,1C2)(RMI(I),I=1,N)
      READ (5,102)(RMA(I),I=1,N)
      WRITE(6,102)(RMA(I),I=1,N)
      READ (5,102)(DER(I),I=1,N)
      WRITE(6,1C2)(DER(I),I=1,N)
  101 FORMAT (E12.4,2I6      )
  102 FORMAT (6E12.4)
      WMAX=-1.0E+25
      NM1=N-1
      DO 1 I=1,NM1
      R(I)=RMI(I)
    1 RNG(I)=RMI(N)
      R(1)=R(1)-DER(1)
    2 I=1
    3 R(I)=R(I)+DER(I)
      IF(R(I)-RMA(I))4,4,15
    4 IF(R(I)-R(I+1))5,5,15
    5 RN1 =RNG(I)
      R(N)=RN1
      NIT=NITMAX
      CALL DR
      CON1=CCN-1.0
      IF (ABS (CON1)-EPS)10,10,6
    6 RN2=      RN1+DER(N)
      R(N)=RN2
      CALL DR
      CON2=CCN-1.0
      IF(ABS (CON2)-EPS)10,10,7
```

```
    7 RN=      RN1-CON1*(RN1-RN2)/(CON1-CON2)
      R(N)=RN
      CALL DR
      CON=CON-1.0
      IF(ABS (CON )-EPS)10,10,8
    8 NIT=NIT-1
      IF(NIT)99,99,9
   99 STOP
    9 RN2=RN1
      CON2=CON1
      RN1=RN
      CON1=CON
      GO TO 7
   10 RNG(I)=R(N)
      IF(R(N)-R(N-1))2,11,11
   11 CALL WR
      IF(ISW)12,12,111
  111 WRITE(6,112) W,(R(J),J=1,N)
  112 FORMAT (10E12.4)
   12 IF(W-WMAX)2,2,13
   13 WMAX=W
      DO 14 J=1,N
   14 ROPT(J)=R(J)
      GO TO 2
   15 R(I)=RMI(I)
      IF(I-1)99,18,16
   16 IF(R(I)-R(I-1))17,18,18
   17 R(I)=R(I-1)
   18 I=I+1
      IF(I-N)3,19,19
   19 DO 20 I=1,20
   20 R(I)=ROPT(I)
      CALL EDIT
      GO TO 100
      END
```

```
$IBFTC INITUN  DECK

      SUBROUTINE INITAL
      COMMON/MAX/N,MNOP,ALAM,R(19),DZZZ,CSQ,CON,W
      DIMENSION RO(19),GS(10),Z(10),PAR(10),G(100),PARP(10),P(100,19),
     1Q(19),DOS(100)
      DIMENSION TITLE(10)
  999 FORMAT(1H1)
      WRITE(6,999)
      ALPHA=(4.0*3.14159)/(453.5924E+5*3.)
 1000 FORMAT(10A6)
      READ  (5,1000)            (TITLE(I),I=1,10)
      WRITE(6,1000)             (TITLE(I),I=1,10)
 1002 FORMAT(3HON=I12,7H RZERO=E12.5,6H DBAR=E12.5)
 2002 FORMAT(I12,2E12.5)
      READ (5,2002)             N,RZERO,DBAR
      WRITE(6,1002)             N,RZERO,DBAR
      L=0
      M=0
      KP=0
      DO 17 I=1,N
 1003 FORMAT(4HOKR=I5,4H NG=I5,4H RO=E12.5)
      READ (5,2003)             KR,NG,ROKR
 2003 FORMAT(2I5,E12.5)
      RO(KR)=ROKR
```

```
      WRITE(6,1C03)              KR,NG,RC(KR)
      IF(KR-I) 901,1,901
 901  WRITE(6,3901)
3901  FORMAT(31H REGION NUMBERS NOT CONSECUTIVE)
      STOP
   1  READ (5,1005)            (GS(K),Z(K),K=1,NG)
1004  FORMAT(5E12.5)
      WRITE(6,998)
 998  FORMAT( 4H  GS)
      WRITE(6,1C04)(GS(K),K=1,NG)
      WRITE(6,997)
 997  FORMAT(4H   Z)
      WRITE(6,1C04)(Z(K),K=1,NG)
      WRITE(6,996)
 996  FORMAT(4H PAR)
      NG=2*NG
      DO 16 J=1,N
      READ (5,10C5)            (PAR(K),K=1,NG)
1CO5  FORMAT(10E8.4)
      WRITE(6,1006)              (PAR(K),K=1,NG)
1006  FORMAT(          10E12.5)
      IF(J-1) 902,2,4
 902  WRITE(6,3902)
3902  FORMAT(16H J LESS THAN ONE)
      STOP
   2  DO 3 K=1,NG,2
      KP=KP+1
      ZZZ=EXP(RZERO*PAR(K))
      IF (ZZZ.GT.1.0E+27) GO TO 111
      IF(GS(KP).GT.1.CE+10) GO TO 111
   3  GS(KP)=GS(KP)*ZZZ
      GO TO 199
 111  GS(KP)=1.0E+37
 199  CONTINUE
      KP=0
   4  IF(J-I) 5,7,12
   5  DO 6 K=1,NG,2
   6  PAR(K+1)=PAR(K)
      GO TO 9
   7  DO 8 K=1,NG,2
      K=K
      M=M+1
      KP=KP+1
      DEBUG K,A, (PAR(JD),JD=1,10)
      A=     -GS(KP)*Z(KP)/(PAR(K )-PAR(K +1))
      DEBUG A
      G(M)=A
      M=M+1
      IF( I-1)902,9C3,904
 903  XXX=EXP((RZERO*(PAR(K+1)-PAR(K))))
      IF.(XXX.GT.1.0E+27) GO TO 777
      IF (A.GT.1.0E+10) GO TO 777
      G(M)=-A*XXX
      GO TO 779
 777  G(M)=1.CE+37
 779  CONTINUE
      GO TO 8
 904  G(M)=-A
   8  CONTINUE
      KP=0
   9  IF(J-1) 9C2,10,14
  10  DO 11 K=1,NG
  11  PARP(K)=PAR(K)
      GO TO 16
  12  DO 13 K=1,NG,2
```

```
   13 PAR(K)=PAR(K+1)
   14 DO 15 K=1,NG
      L=L+1
      P(L,J-1)=PARP(K)-PAR(K)
   15 PARP(K)=PAR(K)
      L=L-NG
   16 CONTINUE
      DO 17 K=1,NG
      L=L+1
   17 P(L,N)=PAR(K)
      READ(5,2002)NG
 1C07 FORMAT(4HCNG=I10)
      WRITE(6,1007)NG
      READ( 5,1C05)(GS(K),K=1,NG)
      WRITE(6,1008)(GS(K),K=1,NG)
 1008 FORMAT(6H G     /10E12.5)
      WRITE(6,996)
      READ( 5,1005)(PARP(K),K=1,NG)
      WRITE(6,1009)(PARP(K),K=1,NG)
 1C09 FORMAT(             10E12.5)
      DO 18 K=1,NG
      M=M+1
      YYY=EXP(RZERO*PARP(K))
      IF (YYY.GT.1.0E+27) GO TO 888
      IF (GS(K).GT.1.CE+10) GO TO 888
   18 G(M)=GS(K)*YYY
      GO TO 189
  888 G(M)=1.0E+37
  189 CONTINUE
      WZERO=ALPHA*RO(1)*RZERO**3
      DO 20 J=2,N
      READ( 5,10C5)(PAR(K),K=1,NG)
      WRITE(6,1009)(PAR(K),K=1,NG)
      DO 19 K=1,NG
      L=L+1
      P(L,J-1)=PARP(K)-PAR(K)
   19 PARP(K)=PAR(K)
      Q(J-1)=ALPHA*(RO(J)-RO(J-1))
   20 L=L-NG
      DO 21 K=1,NG
      L=L+1
   21 P(L,N)=PAR(K)
      Q(N)=-ALPHA*RO(N)
      GO TO 100
      ENTRY CR
      D=0.0
      DO 32 K=1,L
      BAD=0.C
      DO 31 I=1,N
   31 BAD=BAD+R(I)*P(K,I)
   32 D=D+G(K)*EXP (-BAD)
      CON=ALCG(D/DBAR)+1.0
      GO TO 100
      ENTRY WR
      W=WZERC
      DO 41 I=1,N
   41 W=W+Q(I)*R(I)**3
      GO TO 100
      ENTRY EDIT
      WRITE(6,1010)            RZERC,(R(I),I=1,N)
 1010 FORMAT(4HCRO=E12.5/5H R(I)/(10E12.5))
      D=0.0
      W=WZERC
      J=0
      M=M-NG
```

```
      MP=M+1
      MPP=M/2+NG
      DO 42 K=1,L
      BAD=0.C
      DO 46 I=1,N
   46 BAD=BAD+R(I)*P(K,I)
      A=G(K)*EXP(-BAD)
      DOS(K)=A
   42 D=D+A
      DO 43 K=1,M,2
      J=J+1
   43 DOS(J)=DOS(K)+DOS(K+1)
      DO 44 K=MP,L
      J=J+1
   44 DOS(J)=DOS(K)
 1011 FORMAT(7HCDOS(I)/(10E12.5))
      WRITE(6,1011)              (DOS(I),I=1,MPP)
      DO 45 I=1,N
   45 W=W+Q(I)*R(I)**3
      W=-W*1.0E+5
 1012 FORMAT(/3H W=E12.5,3H D=E12.5)
      WRITE(6,1012)W,D
  10C RETURN
      END
```

FORTRAN 63 COMPUTER CODE LISTING

```
     COMMON/MAX/N,Z(2),R(19),X(2),CON,W
     DIMENSION  RMI(20),RMA(20),DER(20),ROPT(20),RNG(20)
 100 CALL INITIAL
     READ 101,EPS,NITMAX,ISW
     READ 102,(RMI(I),I=1,N)
     PRINT102,(RMI(I),I=1,N)
     READ 102,(RMA(I),I=1,N)
     PRINT102,(RMA(I),I=1,N)
     READ 102,(DER(I),I=1,N)
     PRINT102,(DER(I),I=1,N)
 101 FORMAT (E12.4,2I6       )
 102 FORMAT (6E12.4)
     WMAX=-1.E+200 $ NM1=N-1 $ DO 1 I=1,NM1 $R(I)=RMI(I)
   1 RNG(I)=RMI(N) $ R(1)= R(1)-DER(1)
   2 I=1
   3 R(I)=R(I)+DER(I)
     IF(R(I)-RMA(I))4,4,15
   4 IF(R(I)-R(I+1))5,5,15
   5 R(N)=RN1=RNG(I) $NIT=NITMAX $CALL DR  $CON1=CON-1
     IF (ABSF(CON1)-EPS)10,10,6
   6 R(N)=RN2=RN1+DER(N)  $CALL DR  $CON2=CON-1
     IF(ABSF(CON2)-EPS)10,10,7
   7 R(N)=RN=RN1-CON1*(RN1-RN2)/(CON1-CON2) $CALL DR $CON=CON-1
     IF(ABSF(CON )-EPS)10,10,8
   8 NIT=NIT-1 $ IF(NIT)99,99,9
  99 STOP
   9 RN2=RN1 $CON2=CON1 $ RN1=RN $ CON1=CON  $ GO TO 7
  10 RNG(I)=R(N) $ IF(R(N)-R(N-1))2,11,11
  11 CALL WR $ IF(ISW)12,12,111
 111 PRINT 112,(W,(R(J),J=1,N))
 112 FORMAT (10E12.4)
  12 IF(W-WMAX)2,2,13
  13 WMAX=W  $ DO 14  J=1,N
  14 ROPT(J)=R(J) $GO TO 2
  15 R(I)=RMI(I)  $ IF(I-1)99,18,16
  16 IF(R(I)-R(I-1))17,18,18
  17 R(I)=R(I-1)
  18 I=I+1  $ IF(I-N) 3,19,19
```

```
   19 DO 20 I=1,20
   20 R(I)=ROPT(I) $ CALL EDIT  $GO TO 100
      END
```

```
      SUBROUTINE INITIAL
      COMMON/MAX/N,MNOP,ALAM,R(19),DZZZ.CSQ.CON.W
      DIMENSION RO(19),GS(10),Z(10),PAR(10),G(100),PARP(10),P(100,19),
     1Q(19),DOS(100)
      DIMENSION TITLE(10)
  999 FORMAT(1H1)
      WRITE OUTPUT TAPE 6,999
      ALPHA=(4.0*3.14159)/(453.5924E+5*3.)
 1000 FORMAT(10A8)
      READ INPUT TAPE  5,1000,(TITLE(I),I=1,10)
      WRITE OUTPUT TAPE 6,1000,(TITLE(I),I=1,10)
 1002 FORMAT(3HON=I12,7H RZERO=E12.5,6H DBAR=E12.5)
 2002 FORMAT(I12,2E12.5)
      READ INPUT TAPE 5,2002,N,RZERO,DBAR
      WRITE OUTPUT TAPE 6,1002,N,RZERO,DBAR
      L=M=KP=0
      DO 17 I=1.N
 1003 FORMAT(4HOKR=I5,4H NG=I5,4H RO=E12.5)
      READ INPUT TAPE 5,2003,KR,NG,ROKR
 2003 FORMAT(2I5,E12.5)
      RO(KR)=ROKR
      WRITE OUTPUT TAPE 6,1003,KR,NG,RO(KR)
      IF(KR-I) 901,1,901
  901 PRINT 901
  901 FORMAT(31H REGION NUMBERS NOT CONSECUTIVE)
      STOP
    1 READ INPUT TAPE 5,1005,(GS(K),Z(K),K=1.NG)
 1004 FORMAT(5E12.5)
      WRITE OUTPUT TAPE 6,998
  998 FORMAT( 4H  GS)
      WRITE(6,1004)(GS(K).K=1,NG)
      WRITE OUTPUT TAPE 6,997
  997 FORMAT(4H   Z)
      WRITE(6,1004)(Z(K),K=1,NG)
      WRITE(6,996)
  996 FORMAT(4H PAR)
      NG=2*NG
      DO 16 J=1,N
      READ INPUT TAPE 5,1005,(PAR(K),K=1,NG)
 1005 FORMAT(10E8.4)
      WRITE OUTPUT TAPE 6,1006,(PAR(K),K=1,NG)
 1006 FORMAT(             ,10E12.5)
      IF(J-1) 902,2,4
  902 PRINT 902
  902 FORMAT(16H J LESS THAN ONE)
      STOP
    2 DO 3 K=1,NG,2
      KP=KP+1
    3 GS(KP)=GS(KP)*EXPF(RZERO*PAR(K))
      KP=0
    4 IF(J-I) 5,7,12
    5 DO 6 K=1,NG,2
    6 PAR(K+1)=PAR(K) $GO TO 9
    7 DO 8 K=1,NG,2
      M=M+1   $KP=KP+1
      A=G(M)=-GS(KP)*Z(KP)/(PAR(K )-PAR(K +1))
```

```
      M=M+1
      IF(I-1)902,903,904
  903 G(M)=-A*EXPF(RZERO*(PAR(K+1)-PAR(K)))  $GO TO 8
  904 G(M)=-A
    8 CONTINUE
      KP=0
    9 IF(J-1) 902,10,14
   10 DO 11 K=1,NG
   11 PARP(K)=PAR(K)  $GO TO 16
   12 DO 13 K=1,NG,2
   13 PAR(K)=PAR(K+1)
   14 DO 15 K=1,NG
      L=L+1
      P(L,J-1)=PARP(K)-PAR(K)
   15 PARP(K)=PAR(K)   $ L=L-NG
   16 CONTINUE
      DO 17 K=1,NG
      L=L+1
   17 P(L,N)=PAR(K)
      READ(5,2002)(NG)
 1007 FORMAT(4HONG=I10)
      WRITE(6,1007) (NG)
      READ( 5,1005)(GS(K),K=1,NG)
      WRITE(6,1008)(GS(K),K=1,NG)
 1008 FORMAT(6H G     /10E12.5)
      WRITE(6,996)
      READ( 5,1005)(PARP(K),K=1,NG)
      WRITE(6,1009)(PARP(K),K=1,NG)
 1009 FORMAT(              10E12.5)
      DO 18 K=1,NG
      M=M+1
   18 G(M)=GS(K)*EXPF(RZERO*PARP(K))  $WZERO=ALPHA*RO(1)*RZERO**3
      DO 20 J=2,N
      READ( 5,1005)(PAR(K),K=1,NG)
      WRITE(6,1009)(PAR(K),K=1,NG)
      DO 19 K=1,NG $ L=L+1
      P(L,J-1)=PARP(K)-PAR(K)
   19 PARP(K)=PAR(K)   $ Q(J-1)= ALPHA*(RO(J)-RO(J-1))
   20 L=L-NG
      DO 21 K=1,NG   $ L=L+1
   21 P(L,N)=PAR(K)   $ Q(N)=-ALPHA*RO(N)
      GO TO 100
      ENTRY DR
      D=0.0
      DO 32 K=1,L
      BAD=0.0
      DO 31 I=1,N
   31 BAD=BAD+R(I)*P(K,I)
   32 D=D+G(K)*EXPF(-BAD)
      CON=LOGF(D/DBAR)+1
      GO TO 100
      ENTRY WR
      W=WZERO
      DO 41 I=1,N
   41 W=W+Q(I)*R(I)**3
      GO TO 100
      ENTRY EDIT
      WRITE OUTPUT TAPE 6,1010,RZERO,(R(I),I=1,N)
```

```
1010 FORMAT(4HORO=E12.5/5H R(I)/(10E12.5))
     D=0.0 $ W=WZERO $ J=0 $ M=M-NG $ MP=M+1 $ MPP=M/2+NG
     DO 42 K=1,L
     BAD=0.0
     DO 46 I=1,N
  46 BAD=BAD+R(I)*P(K,I)
     A=DOS(K)=G(K)*EXPF(-BAD)
  42 D=D+A
     DO 43 K=1,M,2
     J=J+1
  43 DOS(J)=DOS(K)+DOS(K+1)
     DO 44 K=MP,L
     J=J+1
  44 DOS(J)=DOS(K)
1011 FORMAT(7HODOS(I)/(10E12.5))
     WRITE OUTPUT TAPE 6,1011,(DOS(I),I=1,MPP)
     DO 45 I=1.N
  45 W=W+O(I)*R I)**3
     W=-W*1.0E+5
1012 FORMAT(/3H W=E12.5,3H D=E12.5)
     WRITE OUTPUT TAPE 6,1012,W,D
 100 RETURN
     END
```

Lewis Research Center,

National Aeronautics and Space Administration,

Cleveland, Ohio, April 9, 1970,

126-15.

NASA-Langley, 1970 —— 22 E-5619

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

OFFICIAL BUSINESS

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546