NASA TECHNICAL MEMORANDUM

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THERMAL CONTROL OF HIGH ENERGY NUCLEAR WASTE, SPACE OPTION

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Program Development

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Marshall Space Flight Center, Alabama

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ACKNOWLEDGMENTS

This study resulted from the expertise of several persons who shared their knowledge in the solution of a specialized problem statement provided by Dr. Rowland E. Burns, EL24. Dr. Burns' challenge was to develop an approach for cooling high energy density nuclear waster material and provide a computerized thermal model which could give quick turnaround for configuration changes. First, a discussion with Mr. Kearns resulted in the verification of the engineering soundness of the technical approach. Second, Messrs. Carl Colley, PD23, and Dave Mercier, PD33, developed the mathematics of geodetic structures relating to the thermal model. Finally, all of these ideas were coordinated by two computer programs discussed herein. The models for data output were computerized by Patricia Sage, CSC.

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LIST OF SYMBOLS

A	Waste surface area — ft^2
E	Specific energy generation — Btu/hr-lbm
k	Conductivity of waste — Btu/hr-ft-°F
M	Waste mass — lbm
N	Number of rods
Q	Total energy rate generated — Btu/hr
$\dot{q}$	Waste energy rate — Btu/hr-ft^3
R	Radius at which generalized temperature occurs —°R
R_o	Radius of waste package — ft
r_o	Cooling rod radius — ft
T	Generalized temperature — °R
T_o	Waste package surface temperature — °R
ϵ	Waste surface emittance (0.80)
ρ	Waste mass density — lbm/ft^3
σ	Stefan-Boltzmann constant — Btu/hr-ft^2-$°R^4$
ν	Geodetic frequency (number of subdivision of an icosahedron)
ℓ	Element length of subdivided icosahedron — in.

TECHNICAL MEMORANDUM

THERMAL CONTROL OF HIGH ENERGY NUCLEAR WASTE, SPACE OPTION

INTRODUCTION

The space option for nuclear waste disposal presents some thermal problems which must be solved and assessed before feasibility by space disposal can be established. Primarily, the thermal problem is one of maintaining the waste temperature below the melt conditions. This is especially true for those waste compounds having very high energy densities (≥ 0.2 W/g). Studies thus far have resulted in development of the spherical waste configuration. Thus, the thermal problem is associated with the inner core of the waste package. The core temperature is[1]

$$T = T_o + \frac{\dot{q} R_o^2}{4k} \quad . \tag{1}$$

The core temperature T is, therefore, greatly affected by the surface temperature, T_o. On the ground where convection cooling can be made available, the core temperature is easier to maintain at acceptable levels. However, in space, the surface temperature is determined by the radiation properties of the waste surface. The surface temperature is established by its area and emittance. Increasing the surface area decreases the surface temperature but increases the second term, $\dot{q} R_o^2/4k$. The net result is always an increase in the core temperature with an increase in R_o.

Thus, in space, very little control can be exercised over the core temperature. For a homogeneous waste distribution, the temperature is best limited by limiting the energy generating characteristics and mass size. However, this is self-defeating since nuclear waste has an inherently low conductivity and some of the most desirable waste to be disposed of has high energy content. Also, it is desirable to use the Shuttle payload capability for each launch.

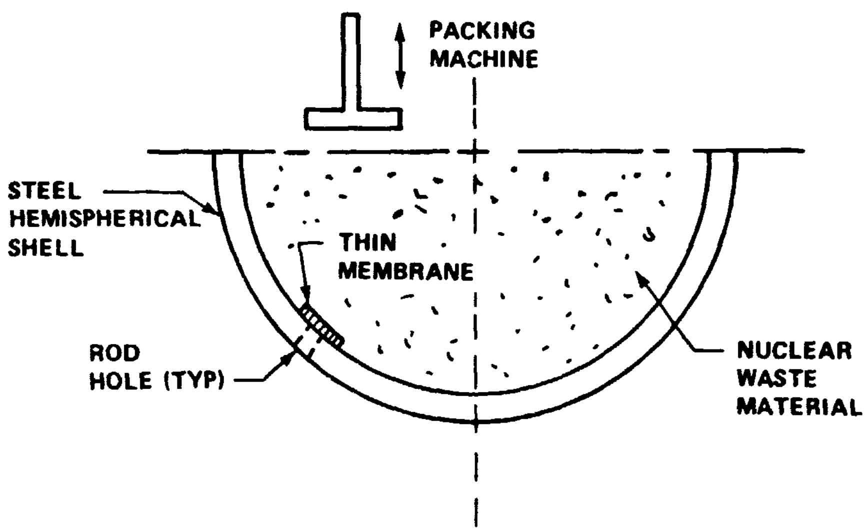
1. Kreith, Frank: Principles of Heat Transfer. Dun-Donnelley, New York, 1976.

The purpose of this study is to suggest a technique whereby the effective conductivity of the waste can be increased. This allows core temperature control with larger masses having larger energy contents. The concept is to bring the energy within the core to the surface by means of cylindrical rods having high conductivity. This does not reduce the surface temperature but does reduce the temperature difference occurring between the surface and core.

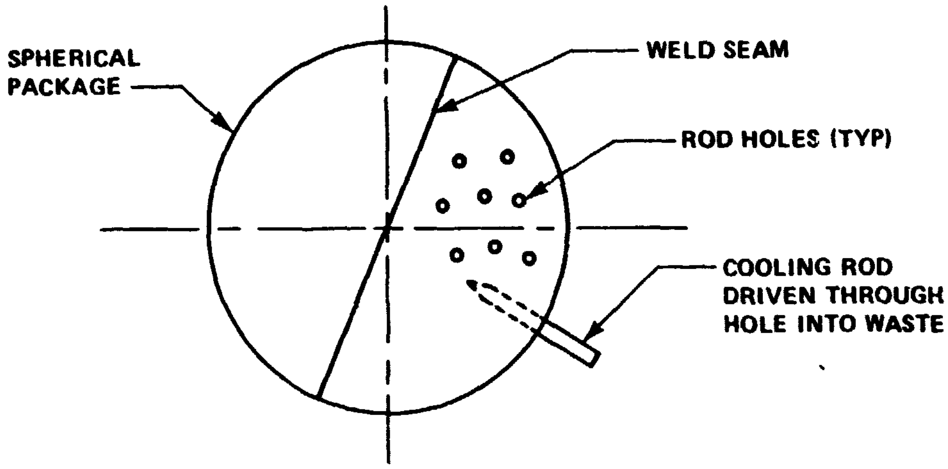
The objective herein is to evaluate this concept and to establish the effectiveness of the cooling rods as greater waste masses having greater energy densities are considered. Also, the effects of the number of rods and their size will be assessed.

The cooling rod concept is also important because of the way it lends itself to manufacture of the nuclear waste package. This advantage is very important and is the motivation for studying the rod concept in detail. This cooling rod packaging process consists of three basic steps (in order):

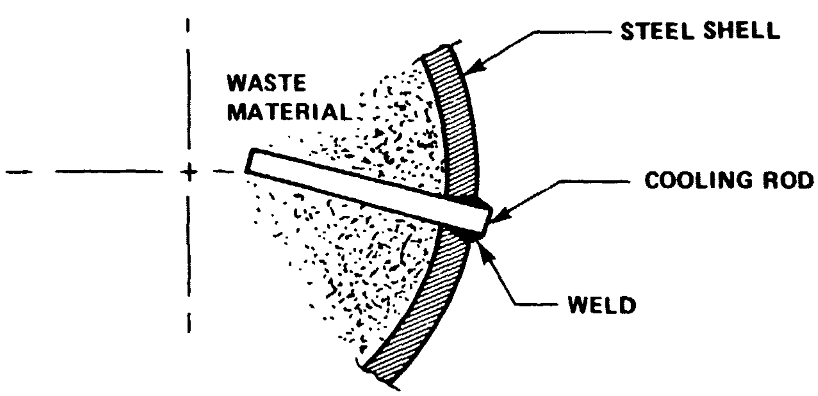
1) A steel hemispherical shell with rod holes located on its surface, which will later receive the rods, is packed with waste material by a suitable packing mechanism. There are thin membranes over the rod holes to contain the material during the packing process.



2) After packing two hemispheres, they are brought together and welded. The cooling rods are then inserted through the rod holes. There may be as many as 300 to 500 rod holes. The cooling rod pierces the membrane as it is driven into the waste material.



3) After each rod is driven flush, it is welded to the sphere's surface. The package is now complete for deportation into space.



There are several advantages to this technique besides the symmetrical configuration which lessens the thermal analysis problem. First, there is less chance of waste spillage and tool contamination. This is an important advantage and motivates use of this concept. Second, the extra packing of the waste material as a result of driving the rods reduces the contact resistance between the rod and waste material.

GENERAL THERMAL CHARACTERISTICS

The temperature distribution within a spherical waste package having a homogeneous mass distribution can be found in Footnote 1,

$$T = T_o + \frac{\dot{q} R_o^2}{4k} \left[1 + \left(\frac{R}{R_o} \right)^2 \right] . \qquad (2)$$

The temperature, T, occurs at Radius R, with R_o being the radius of the spherical package. At the core, R/R_o equals zero and equation (2) reduces to equation (1). At the surface, R/R_o is unity, and the temperature in question if equal to the surface temperature is determined by the radiation characteristics at the surface:

$$T_o = \left[\frac{Q}{\sigma \epsilon A} \right]^{1/4} . \qquad (3)$$

Equation (3) states that in the steady state the total energy rate generated must be radiated at the surface. The required surface temperature is T_o.

Equations (2) and (3) are very simple to apply but are not in terms of the variables which the nuclear material is usually specified. In general a waste mass, M, is given which has a given energy density, E, and a mass density, ρ. Noting that:

$$q = E\rho$$

$$R_o = \left[\frac{3M}{4\pi\rho} \right]^{1/3}$$

$$Q = EM \quad .$$

Equation (2) can be manipulated to give a more useful form in terms of stated characteristics. These substitutions in equation (2) give

$$T = \left\{ \frac{EM}{4\,\pi\sigma\epsilon \left[\frac{3M}{4\pi\rho}\right]^{2/3}} \right\}^{1/4} + \frac{E\rho}{4k} \left[\frac{3M}{4\pi\rho}\right]^{2/3} \left[1 - \left(\frac{R}{R_o}\right)^2\right] \quad . \qquad (4)$$

A typical temperature distribution resulting from this equation is given in Figure 1. In this particular example the energy density of 0.002 W/g is sufficiently low that cooling conduction rods are not required.

Most of the time, only the core temperature is of interest since therein lies the highest temperature. Additional characteristics for just the core temperature are given in Figure 2. Waste mass is the independent variable with energy density as an argument. A density of 2.88 g/cm³ and conductivity of 1.8 W/m-°K are taken as typical waste characteristics. It is noted that density and conductivity are illusive parameters. The conductivity is particularly difficult to characterize.

Figure 2 illustrates the difficulty of keeping the core temperature below 1800°F for energy densities above 0.004 W/g. Yet, some nuclear waste has densities above 0.2 W/g. Cooling rods are necessary for these energy levels.

Figure 3 has been included to illustrate the importance of conductivity. This figure emphasizes the importance of achieving an effective conductivity of at least 4 or 5 W/m-°K. From equation (4), it is realized that as the conductivity becomes greater, the core temperature approaches the surface temperature. The objective herein is to demonstrate how the cooling rod increases the effective conductivity of the waste material.

The effective conductance can be found by solving equation (4) for k and taking the value of T as the core temperature which results from application of the cooling rods:

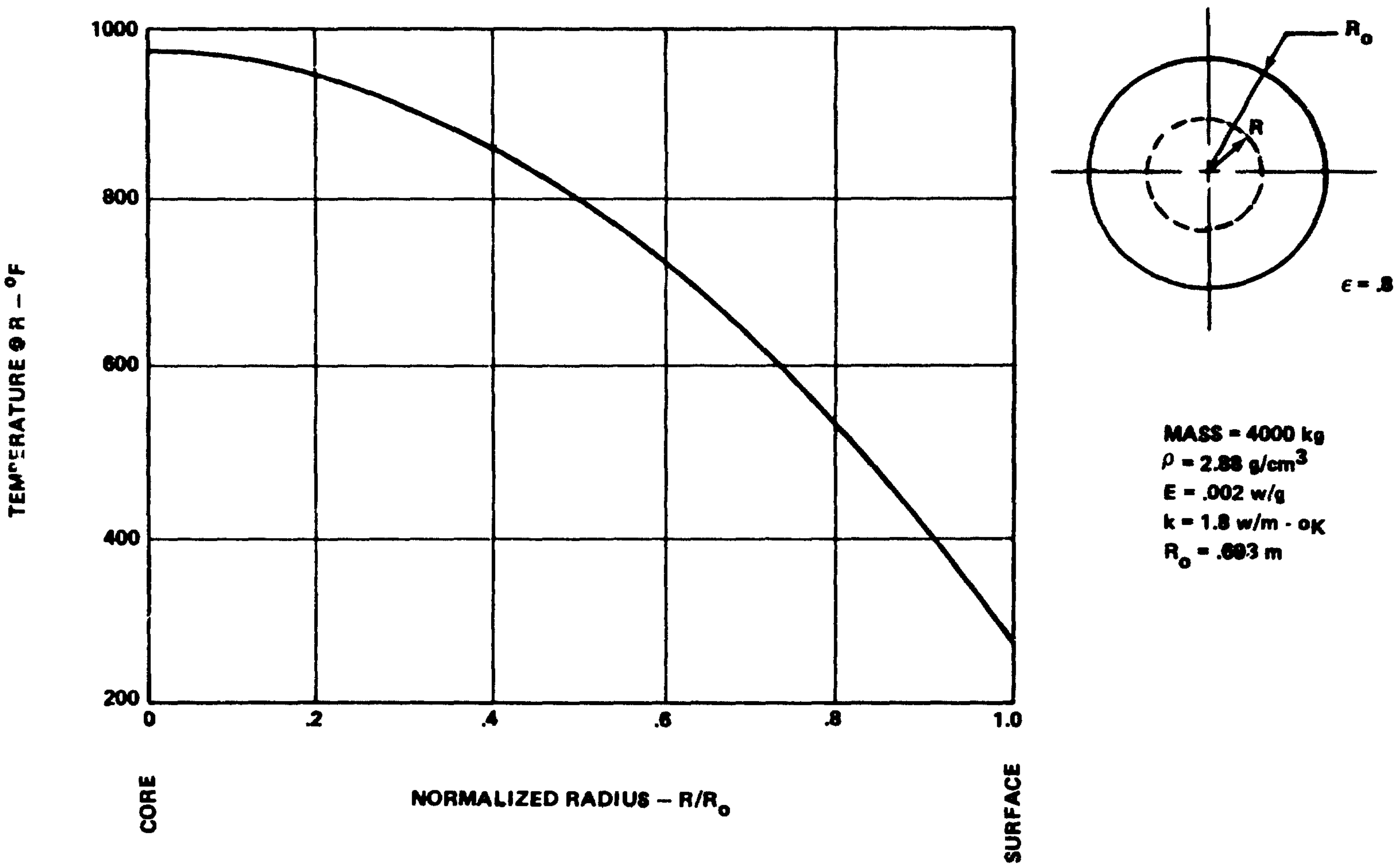


Figure 1. Temperature distribution for a spherical waste configuration having a homogeneous mass distribution.

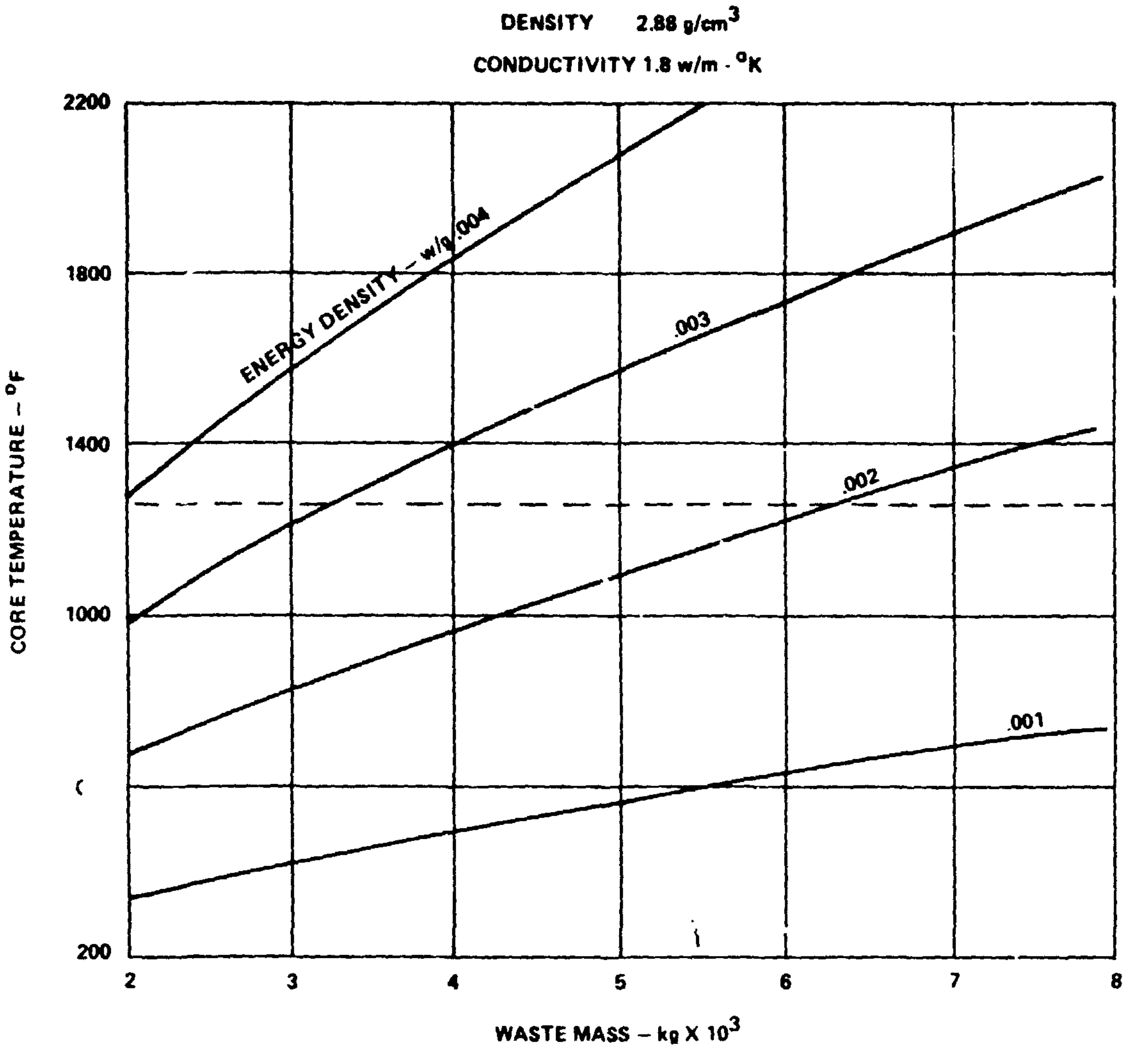


Figure 2. Core temperature as computed from equation (4).

$$k_{eff} = \frac{E\rho\left[\frac{3M}{4\pi\rho}\right]^{2/3}}{T_{CORE} - \left\{\frac{EM}{4\pi\sigma\epsilon\left[\frac{3M}{4\pi\rho}\right]^{2/3}}\right\}^{1/4}} \quad . \qquad (5)$$

Equation (5) will be utilized later to compute the effective waste conductivity resulting from cooling rods.

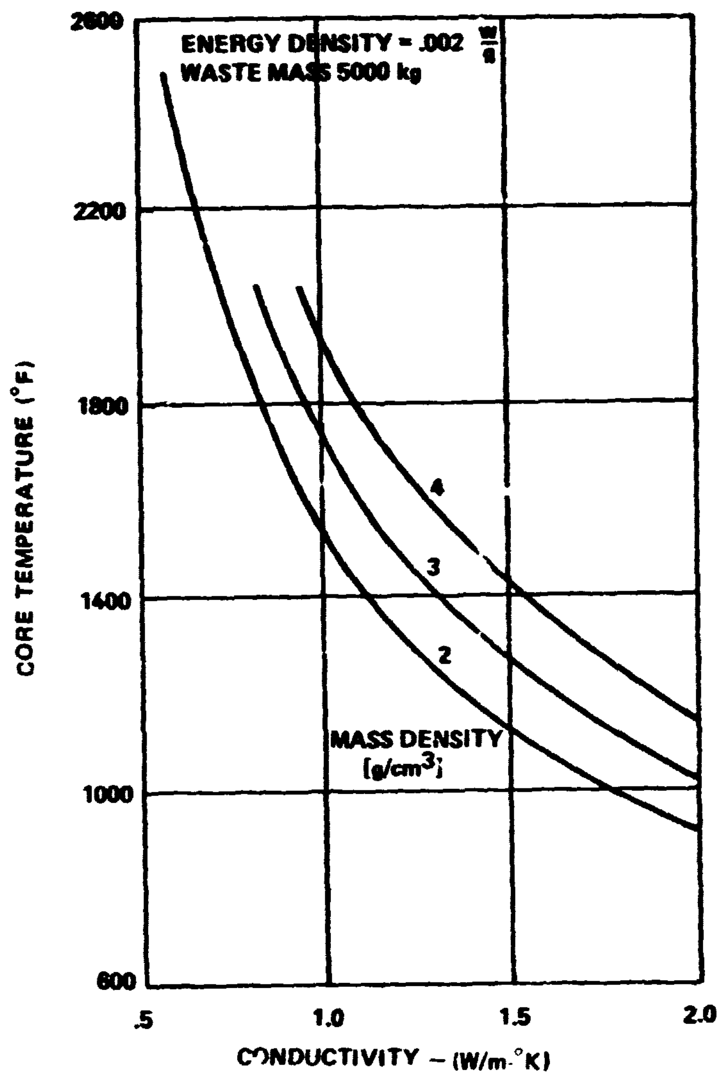


Figure 3. Core temperature sensitivity to nuclear waste conductivity.

Equation (4) has been computerized for quick assessment of core temperature. Also, if the effective conductivity is known, the core temperature can be quickly computed without resorting to the SINDA system numerical difference analyzer program. A typical output from this program is given in Table 1. The program iterates waste mass up to 10 000 kg and energy densities up to 0.008 W/g. The values of these selected ranges can be easily changed as is discussed in Appendix A. In some material, the temperature which can be tolerated is not known. For this reason, a tool for quick evaluation of any proposed nuclear waste package can be made available to those whose expertise are with nuclear material.

TABLE 1. DATA OBTAINED FROM EQUATION (4)

WASTE DENSITY: G/CM3 2.00
WASTE CONDUCTIVITY: WATTS/DEG.K M 1.00
SURFACE EMITTANCE .80

CORE TEMP [KELVIN]	CORE TEMP [DEG. F]	SURFACE TEMP [DEG. F]	WASTE MASS [KG]	WASTE RADIUS [M]	TOTAL ENERGY [WATTS]	ENERGY DENSITY [WATTS/G]
448.9	348.4	130.8	2000	.550	2000.0	.0010
497.7	436.2	151.1	3000	.629	3000.0	.0010
539.4	511.2	166.0	4000	.693	4000.0	.0010
576.7	578.3	177.7	5000	.746	5000.0	.0010
610.9	639.8	187.5	6000	.793	6000.0	.0010
642.7	697.1	195.9	7000	.834	7000.0	.0010
672.7	751.1	203.3	8000	.872	8000.0	.0010
701.1	802.4	209.8	9000	.907	9000.0	.0010
728.4	851.4	215.7	10000	.940	10000.0	.0010
631.9	677.8	242.5	2000	.550	4000.0	.0020
720.3	836.9	266.7	3000	.629	6000.0	.0020
797.0	975.0	284.4	4000	.693	8000.0	.0020
866.3	1099.6	298.4	5000	.746	10000.0	.0020
930.2	1214.7	310.0	6000	.793	12000.0	.0020
990.1	1322.5	320.0	7000	.834	14000.0	.0020
1046.3	1424.5	328.7	8000	.872	16000.0	.0020
1100.8	1521.7	336.5	9000	.907	18000.0	.0020
1152.5	1614.9	343.6	10000	.940	20000.0	.0020
794.5	970.3	317.5	2000	.550	6000.0	.0030
921.8	1199.5	344.2	3000	.629	9000.0	.0030
1033.0	1399.7	363.8	4000	.693	12000.0	0030
1133.8	1581.1	379.3	5000	.746	15000.0	.0030
1227.1	1749.2	392.2	6000	.793	18000.0	.0030
1314.8	1906.9	403.2	7000	.834	21000.0	.0030
1397.9	2056.5	412.9	8000	.872	24000.0	.0030
1477.2	2199.2	421.5	9000	.907	27000.0	.0030
1553.3	2336.3	429.3	10000	.940	30000.0	.0030
947.6	1245.9	375.5	2000	.550	8000.0	.0040
1113.5	1544.6	404.2	3000	.629	12000.0	.0040
1258.9	1806.4	425.2	4000	.693	16000.0	.0040
1391.1	2044.3	441.9	5000	.746	20000.0	.0040
1513.8	2265.1	455.7	6000	.793	24000.0	.0040
1629.0	2472.6	467.6	7000	.834	28000.0	.0040
1738.4	2669.4	478.0	8000	.872	32000.0	.0040
1842.9	2857.5	487.3	9000	.907	36000.0	.0040
1943.3	3038.2	495.6	10000	.940	40000.0	.0040
1095.1	1511.5	423.4	2000	.550	10000.0	.0050
1299.4	1879.2	453.8	3000	.629	15000.0	.0050
1479.0	2202.5	476.0	4000	.693	20000.0	.0050
1642.4	2496.7	493.6	5000	.746	25000.0	.0050
1794.2	2769.9	508.3	6000	.793	30000.0	.0050
1937.1	3027.0	520.8	7000	.834	35000.0	.0050
2072.7	3271.1	531.8	8000	.872	40000.0	.0050
2202.3	3504.4	541.6	9000	.907	45000.0	.0050
2326.9	3728.7	550.4	10000	.940	50000.0	.0050

THERMAL MODEL GEOMETRY

As already mentioned, the core temperature cooling mechanism consists of conductive rods which penetrate the waste radically within a few inches of the spherical center. The rod radius, r_o, results in interference between rods as they approach the center (Fig. 4). The radius of the resulting sphere at the center can be found by equating the area of the inner sphere with the sum of the cross-sectional areas of the rods plus 10.7 percent:

$$4\pi r_o^2 = 1.107\ \pi N r_c^2$$

$$r_c = \frac{r_o}{2} \sqrt{1.107\ N} \quad .$$

For 362 rods, the inner core diameter will be 2.5 in. for 0.25-in. radius rods. This core will probably be made of steel to provide structural integrity to the waste package. In any event, the allowable rod length must be accounted for by this method. The first step to be taken is to define a relationship for the number of rods. At first, it may appear that any arbitrary number could be used. However, this is not the case if the rods are to be equally distributed throughout the sphere.

It is necessary to establish the relationship between the number of rods and the distance between rod tips as they enter the spherical surface. Finally, the distance between all adjacent rod tips would be equal. The basis for establishing these relationships is a surface constructed of 20 equilateral triangles. The solid figure formed by a single triangle is known as an icosahedron. Representation of a spherical surface by 20 icosahedrons is shown in Figure 5.

Each equilateral triangle can be subdivided into small triangles as illustrated in Figures 6 and 7. Each intersection lies on the surface of the sphere. As the number of triangles increases each icosahedron surface approaches an equilateral spherical surface. In Figure 6 the basic icosahedron leg is divided equally into two elements. This results in formation of four triangles. The number of equal subdivisions in each icosahedron sides is known as the geodetic frequency. Figure 7 has a geodetic frequency of six.

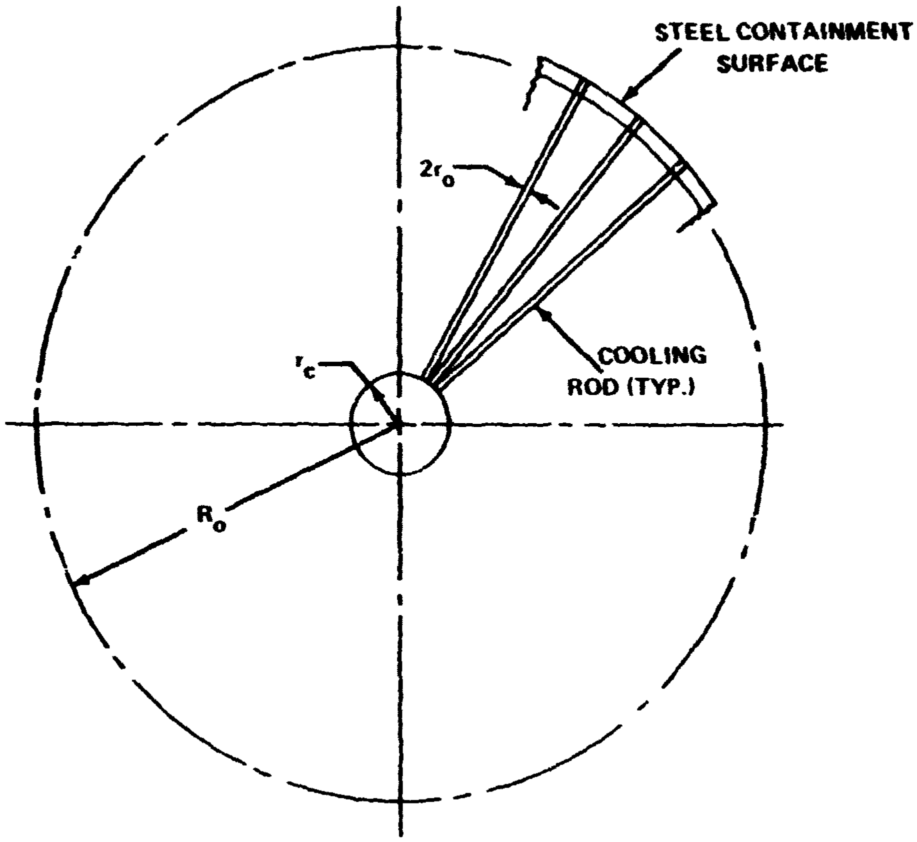


Figure 4. Cooling rod concept which conducts heat energy from the core to radiating surface of the waste.

For purposes of the thermal control mechanism, a rod would be located at each interaction. The relationship between the geodetic frequency and the surface characteristics are:

Number of Vertices $10\,\nu^2 + 2$

Number of Faces $20\,\nu^2$.

For example, a geodetic frequency of 6 results in 362 rods and 720 triangles formed by each rod end. Since the frequency must be an integer, the possible number of rods grows as 12, 42, 92, 162, 252, 362, 492, etc. All intermediate numbers of rods are not possible with this configuration.

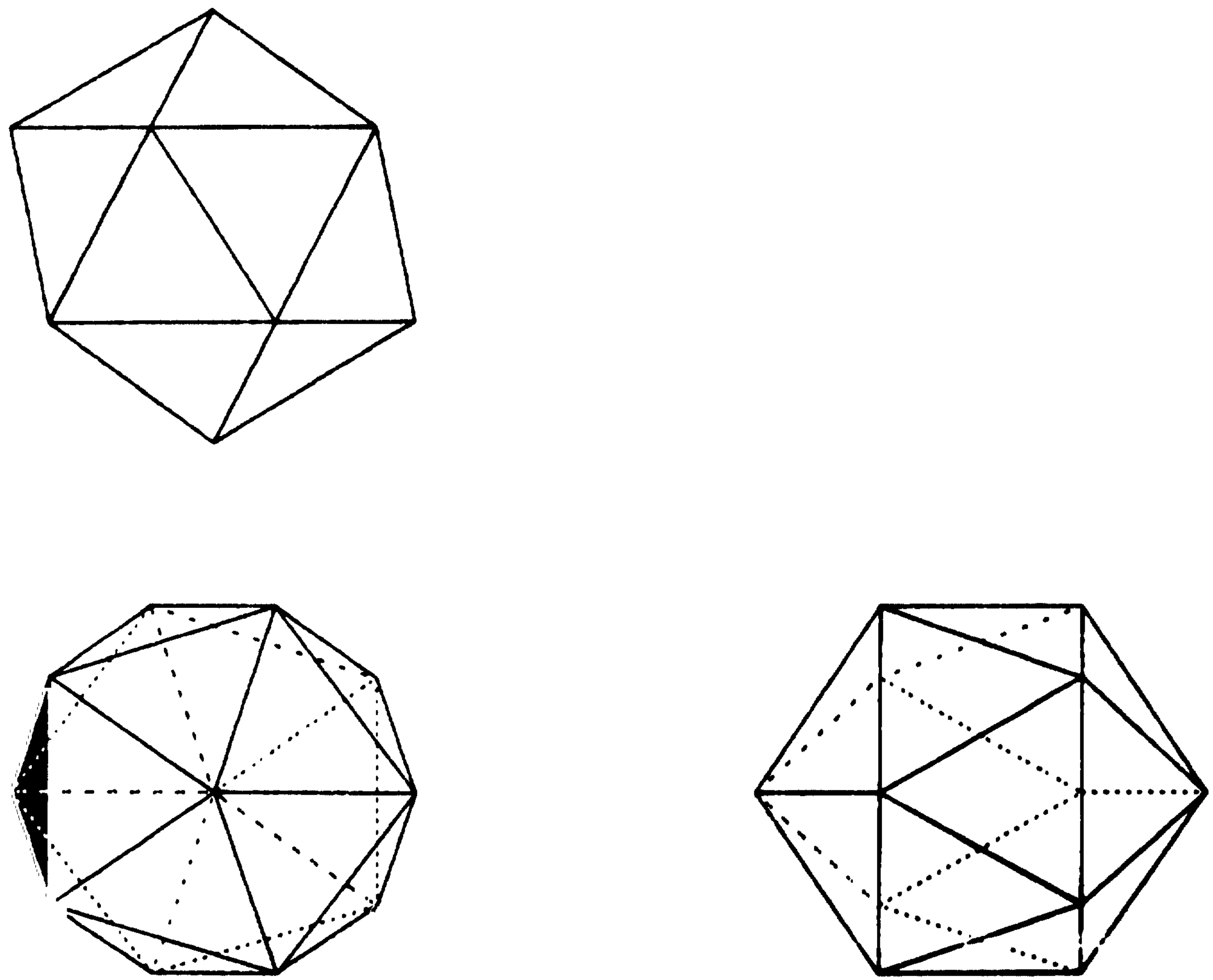


Figure 5. A solid spherical surface formed by 20 icosahedrons.

INPUT NO. OF SIDE SEGMENTS DESIRED

>2

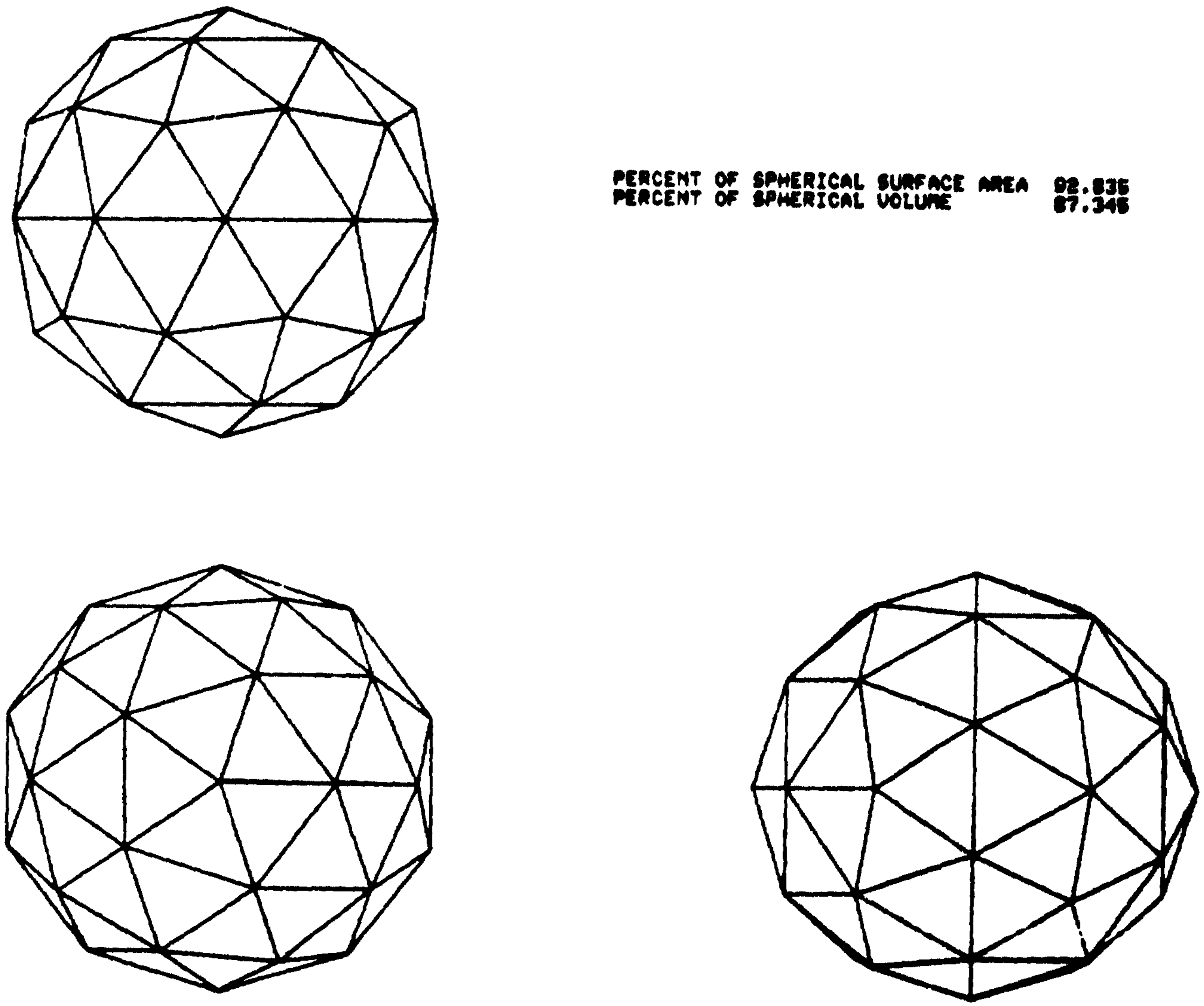


Figure 6. A spherical surface generated by a geodetic frequency of 2.

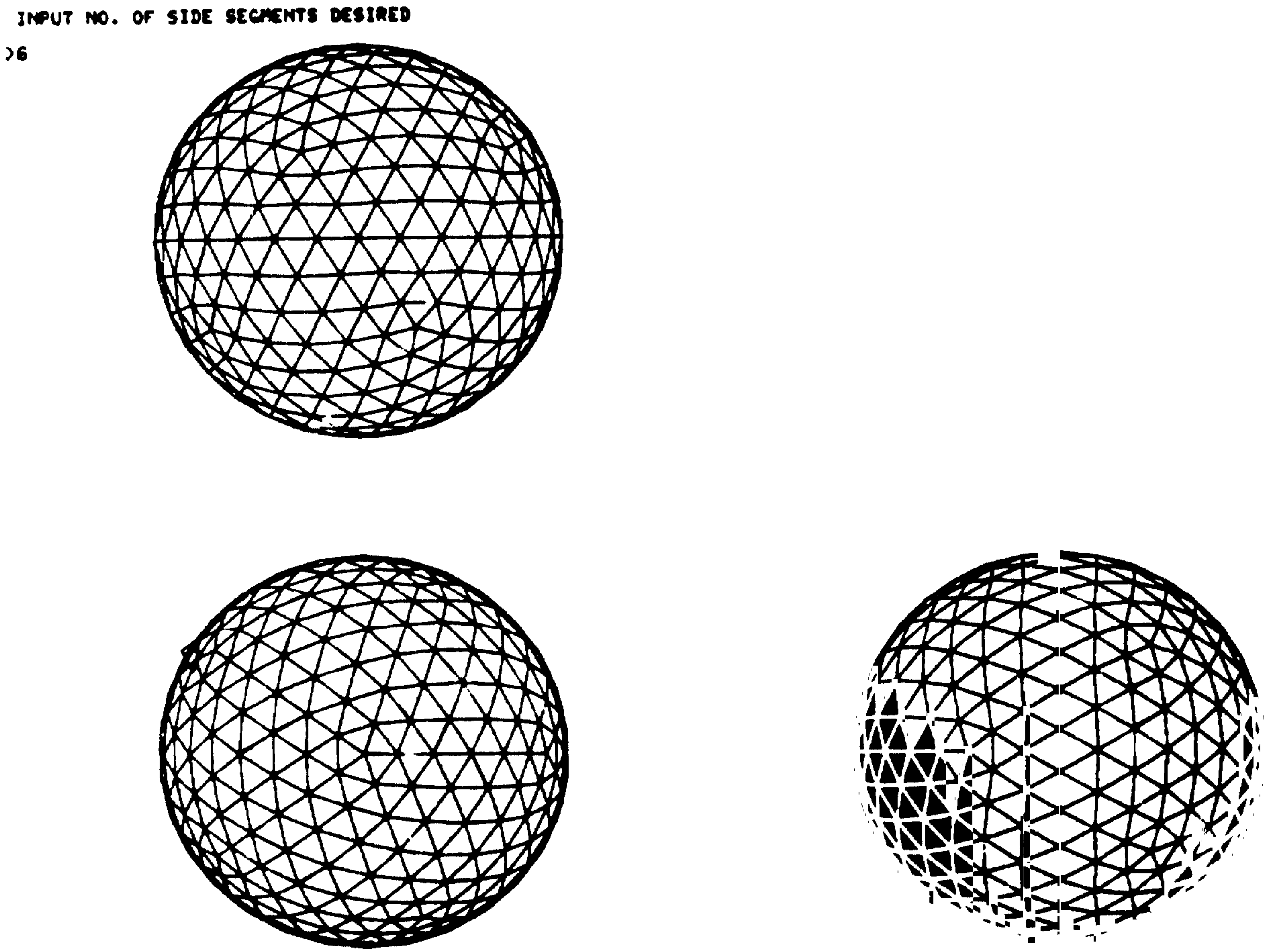


Figure 7. A spherical surface generated by a geodetic frequency of 6.

For a frequency of one, the geometry reduces to the basic 20 equilateral triangles. Sides which form the surface of the icosahedron are equal. However, geodetic frequencies above one do not produce all equilateral triangles. The subdivided triangles do not result in equilateral triangles, although some sides are repeated. Consider the icosahedron surface of Figure 8 where the sides have been subdivided with a frequency of four. Letters indicate members of the same length. The length of each member can be found by multiplying the encompassing sphere radius by a correction factor, CF. Some of these correction factors are given in Table 2. For an example, the length of the "c" member for a frequency of 4 is the radius times 0.294530. It is unfortunate that this situation exists; however, for purposes of the thermal model and rod placement, the problem becomes greatly simplified by generalizing on a single relation between the sphere radius and element length. For purposes of the thermal model, the following generalization has been made:

$$\frac{R_o}{\ell} = \nu^{0.8684} \qquad . \tag{6}$$

Equation (6) is based upon the length trends occurring within the icosahedron. It is noted that this equation cannot be used for actual design construction but does allow thermal analysis of a single rod to represent all rods.

Figure 9(a) is a plain view projection of a portion of an equilateral spherical triangle. All of the element lengths are equal as per equation (6). Each intersection is the location of a rod. Around each rod is a prescriber circle of diameter, ℓ , the element length. Each of these circles represent a cone, each having identical thermal distribution.

An element cone is shown in Figure 9(b). This cone is defined by dimensions ℓ and R_o as related by equation (6). The number of cones is equal to the number of vertices which is, $10\nu^2 + 2$. Thus, the mass element to be thermally modeled is defined. The complex thermal and mechanical configuration has been reduced to a simple cone with a single rod located on its radius centerline. The thermal distribution in this cone characterizes the thermal characteristics of the entire nuclear waste package. It is noted that a small area exists outside of the prescribed circles of Figure 9(a).

The energy represented by this area is distributed proportionally within each cone. Thus, the temperature at the outer surface of the cone is considered to be representative of the temperature between intersecting cones. This deviation from the actual configuration is considered to be minor and the simplicity it brings to the model is warranted.

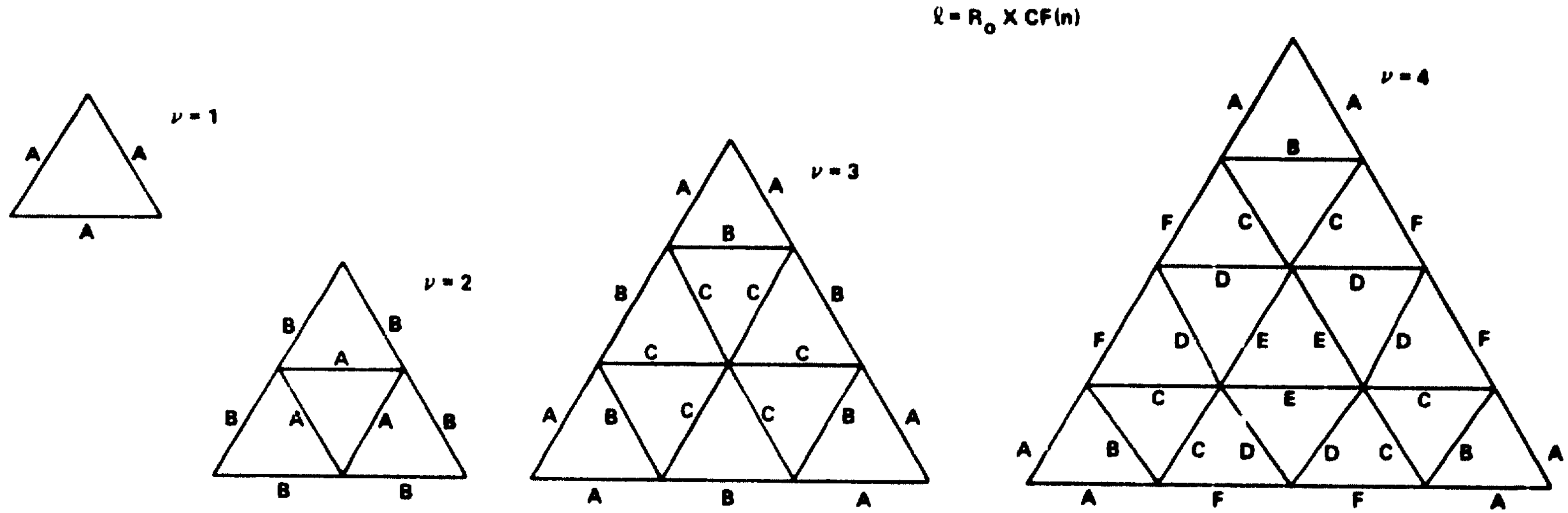


Figure 8. Subdivision of an icosahedron to form an equilateral spherical surface.

TABLE 2. ELEMENTS LENGTHS, ℓ, CORRECTION FACTORS (CF)

FREQUENCY - ν	CF (A)	CF (B)	CF (C)	CF (D)	CF (E)	CF (F)
1	1.0514622					
2	.6180339	.546533				
3	.348615	.403548	.4124114			
4	.253184	.295241	.294530	.3128689	.3249196	.2915881

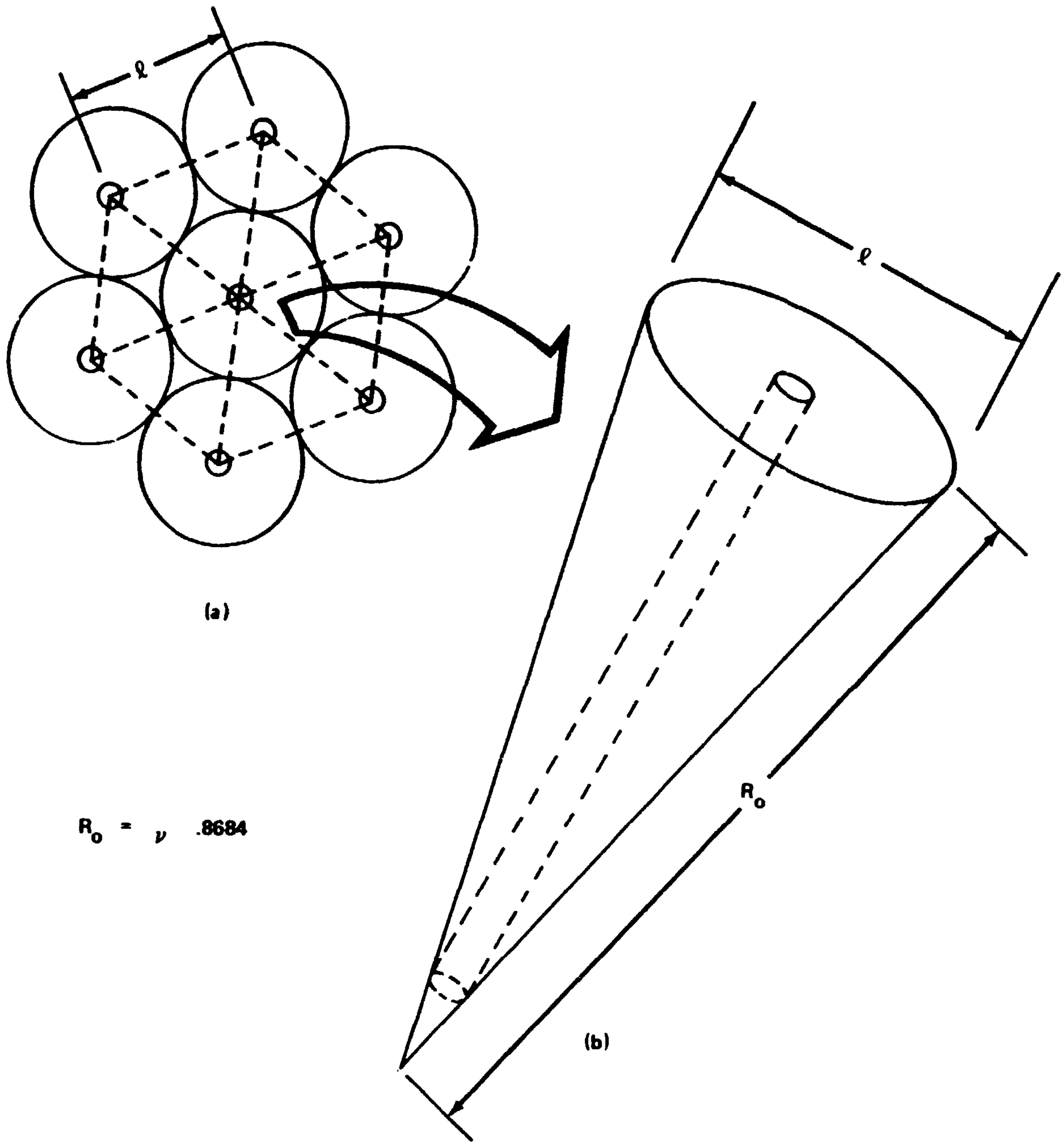


Figure 9. Definition of a characteristics mass element for a spherical nuclear waste package.

THERMAL MODEL NODE LOCATIONS

Now that the mass element to be thermally modeled has been defined, the node location and their respective capacitance and conductance are to be determined. Since each node representing the nuclear waste is an energy generating node, it became an intuitive guideline to give each node equal mass. In this way, the energy generated would be distributed equally within the model network. This approach reinforces the fidelity of the model since a finite number of nodes represents an infinite number of energy generating points. To accomplish this guideline the sphere was divided into four concentric shells each having the same mass. This subdivision of the element cone is illustrated in Figure 10. Each shell is numbered 1 to 4 and they cut through the cone as shown. For proper location of the shells, each section of the cone will have the same mass. If n is taken as the shell number, the necessary relationship between the first shell, $n = 1$, radius, R_1, and the radius R_n, at n is

$$\frac{4}{3}\pi R_n^3 = n\frac{4}{3}\pi R_1^3$$

$$R_n = n^{1/3} R_1 \quad . \tag{7}$$

The spherical radius, R_o, will be taken as the independent variable with $n = 4$. Therefore, R_1 becomes

$$\frac{R_{n=4}}{(4)^{1/3}} = R_1 \tag{8}$$

where

$$R_{n=4} = R_o \quad .$$

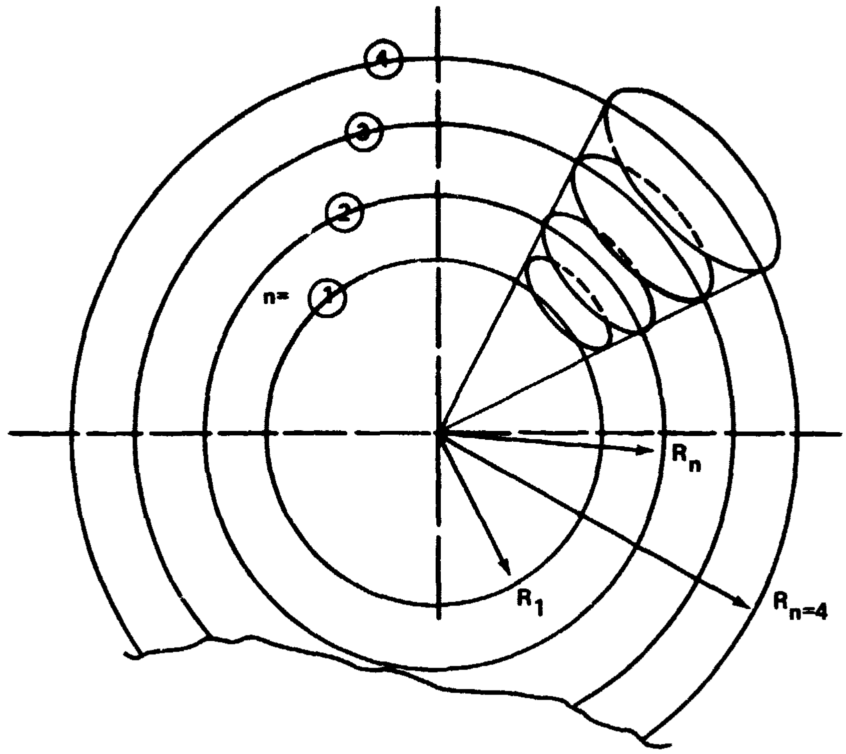


Figure 10. Spherical shells having equal mass.

For an example, if the waste radius is 2.4 ft, R_1 becomes 1.5119 ft. From this value equation (7) can be used to find R_n at other shell locations. A scaled sketch of the waste package divided into shells as above is given in Figure 11.

To complete the thermal model, the mass within the top three shells is divided into doughnuts as shown in Figure 12. The generalized radius of the outside doughnut is r_{n2}. The inside doughnut radius is r_{n1}. For equal mass within each doughnut, the following relationship exists:

$$2r_{n1}^2 = r_{n2}^2 + r_o^2 \quad . \tag{9}$$

For similar triangles,

$$\frac{\ell/2}{R_o} = \frac{r_{n2}}{R_n} \quad .$$

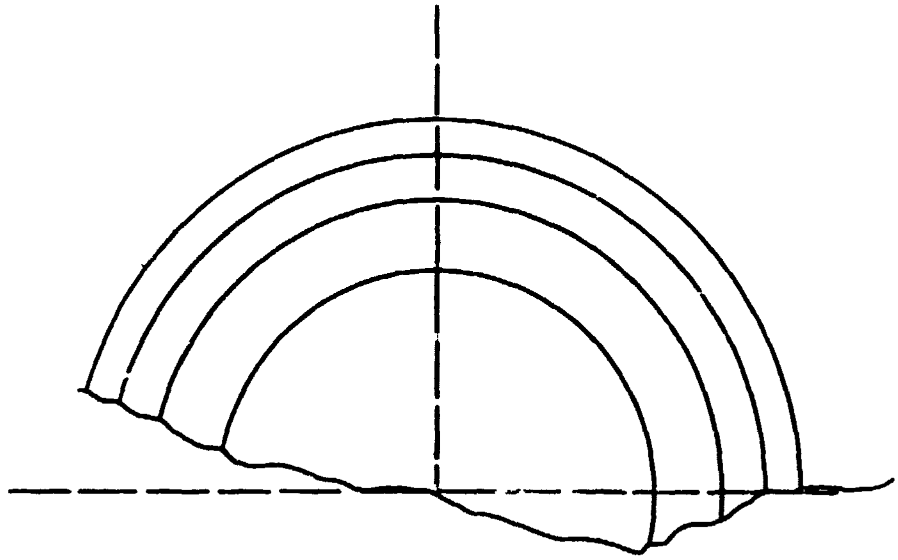


Figure 11. Scale drawing of four shells with radii determined by $R_n = n^{1/3} R_1$.

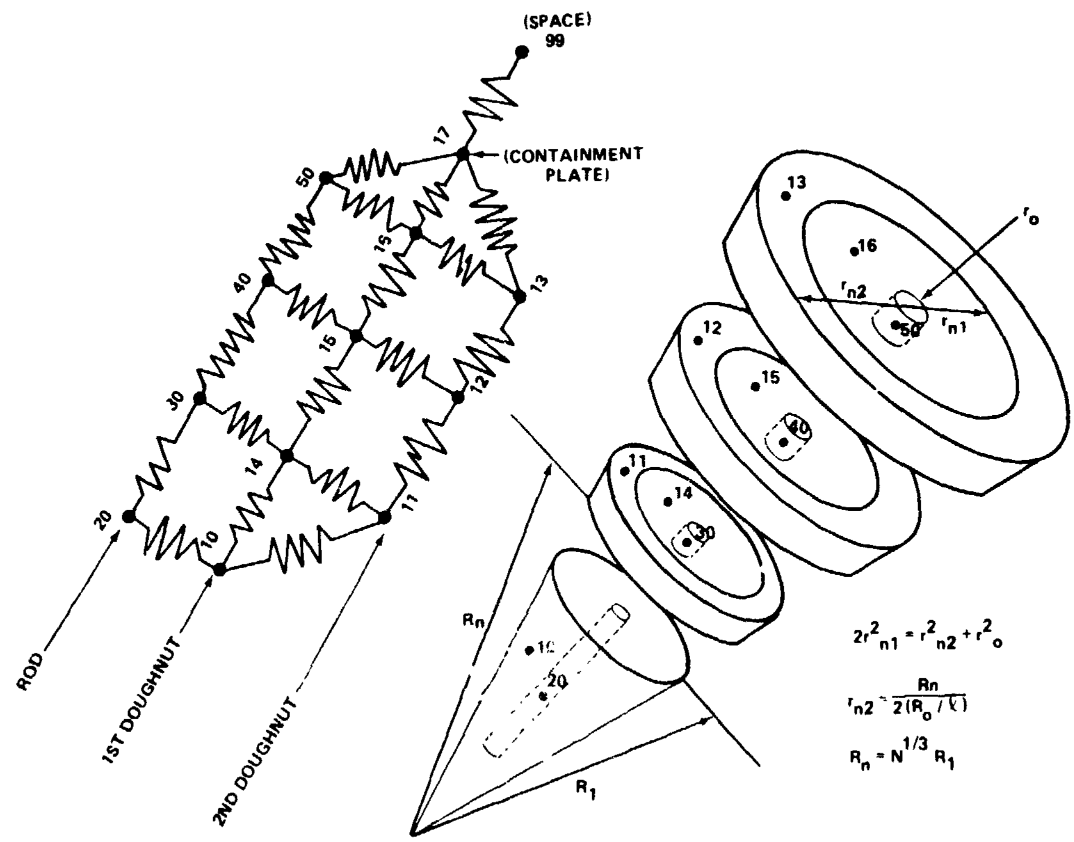


Figure 12. Nodal structure of characteristic mass element.

Thus

$$r_{n2} = \frac{R_n}{2(R_o/\ell)} \tag{10}$$

which determines r_{n1} of equation (9). Equations (7) through (10) completely describe the geometry of the mass element. A summary of these dimensions are given in Figure 13.

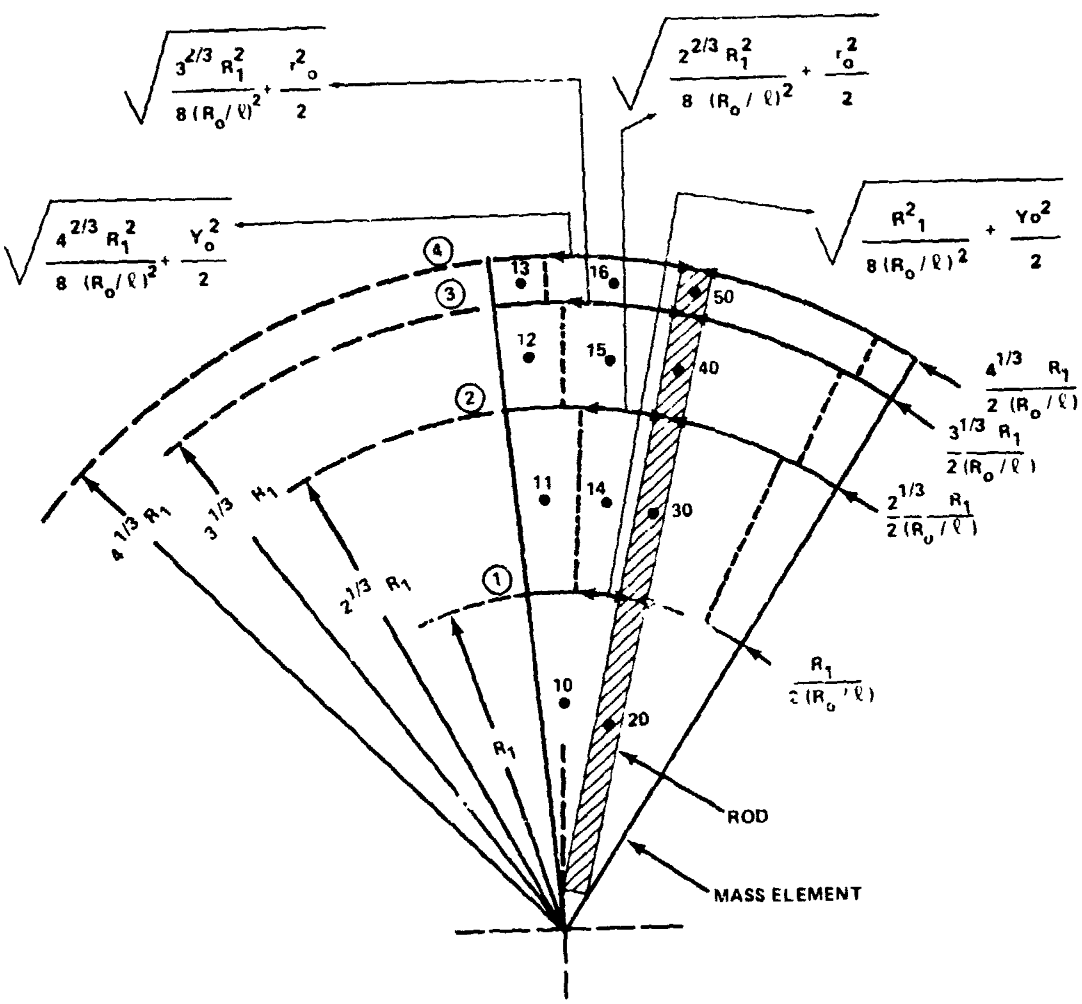


Figure 13. General dimensions of the mass element.

The nodal system consists of six doughnuts, each having different dimensions as given in Figure 13. Also, there is node 10 which represents a cone shape. The mass in the cone is twice the mass in any single doughnut. The cooling rod common to each set of doughnuts and cone has nodes 50, 40, 30, and 20, respectively. The R-C network representing the model is illustrated in Figure 12. The nodal system consists of 13 nodes with 99 being a space node and node 17 the plate which contains the waste material.

It is noted that the model as described here has not been presented to the depth where as equations are available for computing the capacitance and conductance between nodes. The intention is to describe the model in sufficient detail that the modeling approach can be understood. Since it was anticipated that the model would have to be integrated many times, the model was completely computerized and the output was made compatible with the SINDA data block forms. A typical output from this program is given in Figure 14. This program is discussed in Appendix B.

DATA RESULTS

Before the computerized thermal model was complete, it was difficult to speculate upon the effectiveness of the cooling rods. The entire purpose was to assess the capability of the rods in controlling the core temperature. Results from one of the first sample cases are shown in Figure 15. While the specific temperatures obtained from this sample problem are of an academic interest only, it indicated that the cooling rod concept can be very effective in reducing core temperature. For this sample case, a mass of 10 480 lb was chosen with 362 half inch rods. The energy density was 0.2071 W/g. Without the cooling rods the core temperature was over 80 000°F. With the cooling rods the core temperature dropped to 8500°F. This is a factor of 10, a result worth noting. The surface temperature is about 1900°F. The surface temperature is the same with and without the rods since, in the steady state, the same energy must be radiated at the surface. The cooling rods used in this example were molybdenum which has a conductivity of 72 Btu/hr-ft-°F at 3000 °F.

To establish the limit of capability of the cooling rods, the passive molybdenum rods were replaced with heat pipes. These results are indicated in Figure 16. Most of these temperatures can be tolerated. Thus, in the limit, the rod cooling concept can maintain core temperature for large masses and high energy densities. It is of interest to note that the reduction in core temperature with the number of rods is not significant. That is, the reduction in

```
     WASTE DENSITY  LB/FT3:                                      179.0000
     RADIUS OF CONDUCTING ROD:  FT                                  .0200
     GEODETIC FREQUENCY                                            8.0000
     WASTE RADIUS:  FT                                             2.4000
   * HEAT CAPACITY, WASTE:  BTU/LB  F                               .2200
     HEAT CAPACITY, ROD:  BTU/LB  F                                 .2200
     CONDUCTIVITY, WASTE:  BTU/HR-FT  F                            3.5000
     CONDUCTIVITY, ROD:  BTU/HR-FT  F                             46.2000
     ROD DENSITY:  LB/FT3                                        170.0000
     ENERGY DENSITY:  BTU/HR LB                                  320.0000
     NUMBER OF VERTICES                                          642.0000
     TOTAL MASS:  LBM                                          10409.0311
     RADIUS OF FIRST SHELL:  FT                                    1.5119
     RATIO OF GEODETIC ELEMENTS                                    6.0873

BCD 3NODE DATA
     11,200.,  .4459
     12,200.,  .4459
     13,200.,  .4459
     14,200.,  .4459
     15,200.,  .4459
     16,200.,  .4459
     17,200.,  .0874
     10,200.,  .8917
     20,200.,  .0536
     30,200.,  .0200
     40,200.,  .0140
     50,200.,  .0111
BCD 3SOURCE DATA
     11, 648.5378
     12, 648.5378
     13, 648.5378
     14, 648.5378
     15, 648.5378
     16, 648.5378
     10,1297.0755
BCD 3CONDUCTOR DATA
     1112,11,12,  .39[illegible]3
     1213,12,13,  .7024
     1415,14,15,  .4095
     1516,15,16,  .7217
     1114,11,14,12.3856
     1215,12,15, 8.6442
     1316,13,16, 6.8675
     1011,10,11, 1.0529
     1014,10,14, 1.1136
     1020,10,20,11.5998
     1430,14,30, 4.3188
     1540,15,40, 3.0295
     1650,16,50, 2.4118
     1317,13,17, 1.9244
     1617,16,17, 1.9244
     5017,50,17,  .5720
     2030,20,30,  .0659
     3340,30,40,  .1877
     4050,40,50,  .2535
     -1799,17,99, 1.673189-10
```

Figure 14. Typical computer output which generates nodal data for SINDA.

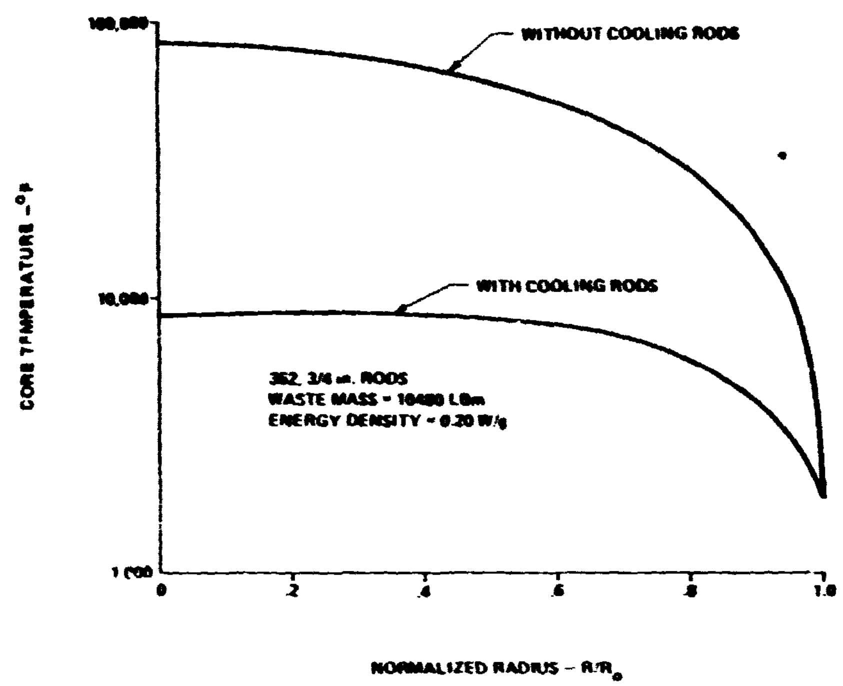


Figure 15. Effectiveness of cooling rods upon the temperature distribution for high density nuclear waste material.

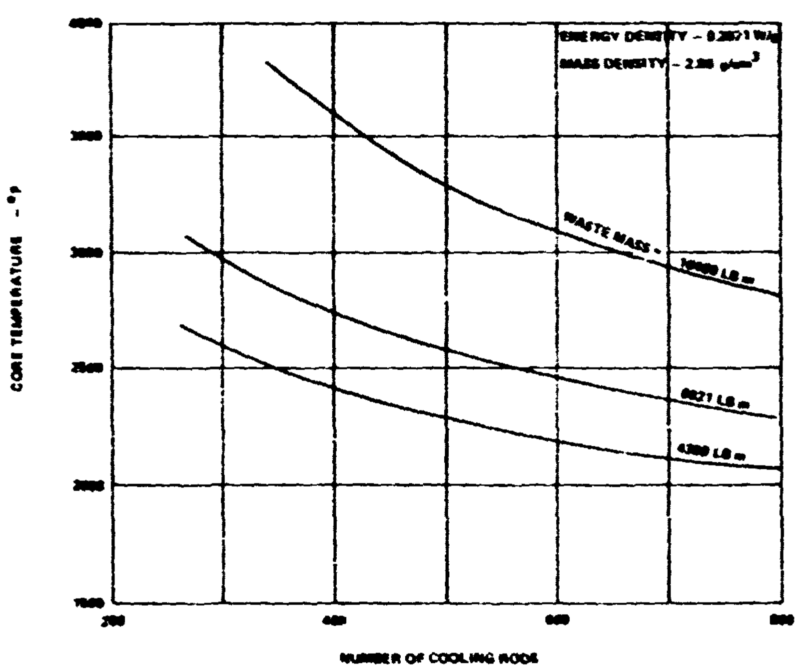


Figure 16. Core temperature results from heat pipe cooling rods.

core temperature by using 810 rods is not significant from that of 492 rods. This is especially true for waste masses below 10 480 lb. Thus, geodetic frequencies greater than 7 (492 rods) is not warranted in view of the additional complexity of building the waste package. The effective conductivity of the entire package was calculated for the 10 480-lb package using equation (5). The effective conductivity was computed at 122 W/m-°K.

It became of particular interest to assess the performance of the cooling rods by reducing the waste mass while keeping the same high energy density. These results are shown in Figure 17. Three cases are shown for different diameters of rods. Since most waste temperatures must be less than 3500°F, the waste mass must be limited to 2000 to 3000 lb. This implies that waste material which has high energy density must consist of multiple packages of relatively low mass.

Figure 18 corresponds to Figure 2 except that much higher energy densities are considered as the argument. To approach a single waste package of 10 000 lb, the energy density must be below 0.1 W/g to keep the core temperature below 3500°F.

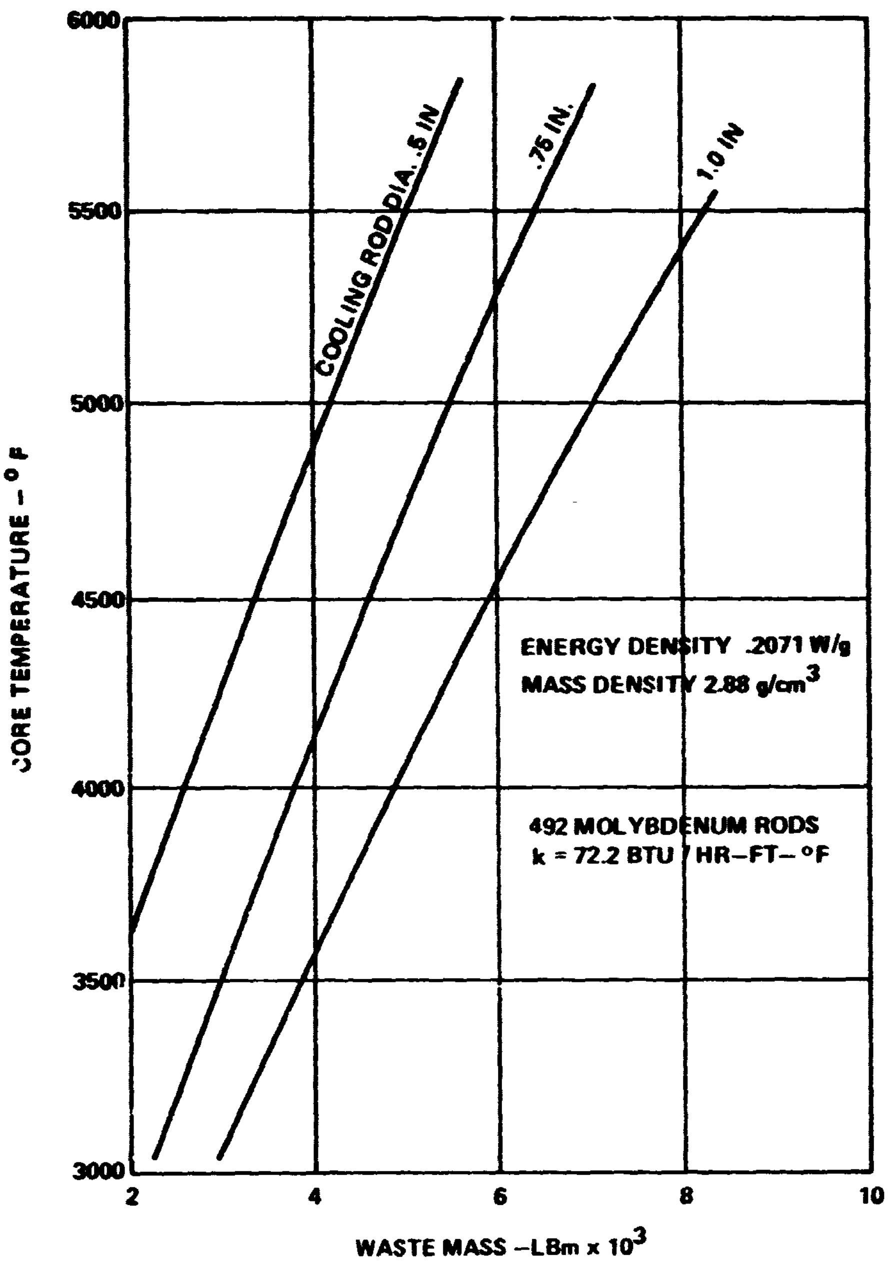


Figure 17. Core temperature using molybdenum rods.

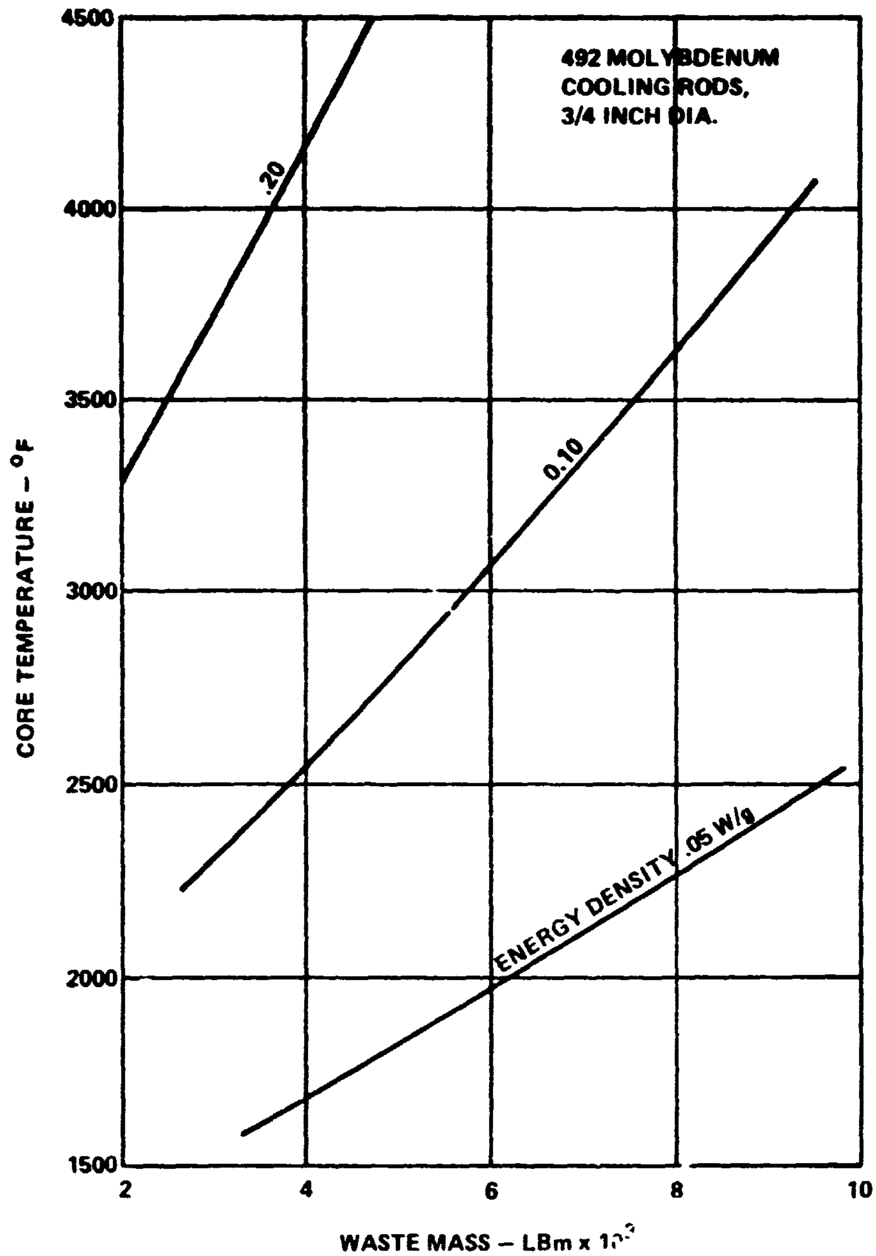


Figure 18. Core temperature with energy density as an argument.

APPENDIX A

TEMPERATURE DISTRIBUTION FOR A SPHERICAL HOMOGENEOUS MASS

The computer program presented in this appendix represents the solution to Equation (4). There are three inputs: waste density, waste conductivity, and surface emittance. These parameters are noted as RHO, XK, and EMISS, respectively per statement 17 of the main program. Density has units in g/cm^3 and conductivity in W/m-°K. An emittance value of 0.80 has been selected for all calculations herein. The range of mass is controlled by state 19 of subroutine PRNT. As shown the mass is iterated in increments of 2000 kg, beginning with 1000 kg up to 10 000 kg.

For each mass the energy density is initiated from 0.001 to 0.005 W/g as controlled by statements 44 through 48 of the same subroutine. The mass and energy values can be alternated to achieve any combination of mass and energy density desired. It is noted that SIG, the Stefan Boltzmann constant, has units of W/m^2-°R.

Vol — Volume - m^3

RADI — Radius — m

QDOT — Energy Rate — W/m^3

QT — Total Energy Rate — W/kg

```
JPEEPS*IN20B*JPFILE2(1).COMDEK
        COMDEK PROC
        C
        C      COMMON VARIABLES
        C
               COMMON RHO,XK,EMISS,E,M,T,TF,TO,RADI,QT
        C
         END
>
```

```
FURPUR 27R3AH4     E33 SL73R1 04/17/79 10:05:00

JPEEPS*IN20B*JPFILE2(1).NEWMAN
        C  **NUCLEAR ENERGY WASTE MANAGEMENT (NEWMAN)**
        C
              INCLUDE COMDEK
        C
        C     INITIALIZE TEKTRONIX GRAPHICS PACKAGE
              CALL INITT(120)
              CALL TERM(3,1024)
              CALL CHRSIZ(4)
              CALL TSEND
        C
        C     LOOP - UNTIL ALL CASES HAVE BEEN DONE
        C
        C     VARIABLES ARE AS FOLLOWS
        C     RHO   - WASTE DENSITY
        C     XK    - WASTE CONDUCTIVITY
        C     EMISS - SURFACE EMITTANCE
           10 READ (5,100,END=999) RHO,XK,EMISS
        C
        C     PRINT AND COMPUTE DATA
              CALL PRNT
        C
        C     LOOP - BACK TO NEXT CASE
              GO TO 10
        C
          100 FORMAT ( )
          999 STOP
              END
>
```

```
      SUBROUTINE PRNT
C
C     PRINTS OUT ALL DATA FOR NEWMAN
C
      INCLUDE COMDEK
C
      CALL NEWPAG
C
C     PRINT OUT INPUT DATA
      PRINT 101,RHO
      PRINT 102,XK
      PRINT 103,EMISS
C
C     LC - LINE COUNT
      LC=6
C
C     E - ENERGY PER UNIT MASS
      E=.001
   30 DO 60 M=2000,10000,1000
C
C     DO COMPUTATIONS
      CALL COMP
C
C     TEST NUMBER OF LINES ON PAGE
      IF (LC-63) 50,40,50
C     IF THERE ARE 63 LINES THEN
   40       CALL HDCOPY
            CALL NEWPAG
            CALL TSEND
C
C           RESET COUNTER TO COUNT NEXT PAGE
            LC=0
C
C           PRINT HEADINGS
            PRINT 104
            PRINT 105
            PRINT 106
            LC=LC+5
C
C     ELSE PRINT ANOTHER LINE ON PAGE
   50       PRINT 107,T,TF,TO,M,RADI,QT,E
            LC=LC+1
   60 CONTINUE
      E=E+.001
C
C     TEST E TO SEE WHEN TO STOP
C     PRINTING DATA
      IF (E-.005) 30,30,70
C     IF E IS GREATER THAN .005 THEN
   70 CALL HDCOPY
      CALL TSEND
C     ELSE REBEGIN DO LOOP
C
  100 FORMAT ( )
  101 FORMAT (10X,35H WASTE DENSITY: G/CM3                ,F10.2)
  102 FORMAT (10X,35H WASTE CONDUCTIVITY: WATTS/DEG.K   M,F10.2)
```

```
 103 FORMAT (10X,35H SURFACE EMITTANCE                    ,F10.2,///)
 104 FORMAT (12X,4HCORE,14X,4HCORE,12X,7HSURFACE,11X,5HWASTE,11X,
    *5HWASTE,11X,5HTOTAL,12X,6HENERGY)
 105 FORMAT (12X,4HTEMP,14X,4HTEMP,14X,4HTEMP,13X,4HMASS,10X,6HRADIUS,
    *10X,6HENERGY,12X,7HDENSITY)
 106 FORMAT (10X,8H[KELVIN],10X,8H[DEG. F],10X,8H[DEG. F],11X,4H[KG],
    *12X,3H[M],11X,7H[WATTS],10X,9H[WATTS/G],//)
 107 FORMAT (F17.1,F18.1,F17.1,I17,F16.3,F17.1,F18.4)
C
     RETURN
     END
EOF:67 SCAN:10
@:)
```

```
FURPUR 27R3AH4     E33 SL73R1 04/17/79 10:08:14

JPEEP$BIN208*JPFILE2(1).COMP
            SUBROUTINE COMP
       C
       C    COMPUTES EQUATIONS FOR NEWMAN
       C
            INCLUDE COMDEK
       C
       C    VARIABLES ARE AS FOLLOWS
       C    VOL  - VOLUME
       C    RADI - RADIUS
       C    QDOT - ENERGY RATE PER VOLUME
       C    QT   - ENERGY RATE
       C    SIG  - STEFAN-BOLTZMANN CONSTANT
       C    TO   - SURFACE TEMPERATURE
       C    TK   - SURFACE TEMPERATURE - KELVIN
       C    T    - CORE TEMPERATURE - KELVIN
       C    TF   - CORE TEMPERATIRE - FAHRENHEIT
            VOL=(M/RHO)*1.0E-03
            RADI=(3.*VOL/(4.*3.14))**.333
            QDOT=E*RHO/1.0E-06
            QT=1000.*E*M
            SIG=5.407E-09
            TO=(QT/(4.*3.14*RADI**2*SIG*EMISS))**.25-460.
            TK=(TO-32.)*(5./9.)+273.16
            T=TK+QDOT*RADI**2/(4.*XK)
            TF=9.*(T-273.16)/5.+32.
       C
            RETURN
            END
>
```

APPENDIX B

PRESINDA, SINDA, DATA BLOCK DEVELOPMENT

This appendix presents the PRESINDA program. This program computes the conductance, compacitance, and energy rate of energy generating nodes. There are 10 inputs as noted in statement 24 of the main program. Units are given in SUBROUTINE PRNT statements 136 through 145.

```
JPEEPSB:N208:JPFILE9(1).PRESINDA
      C  **PRESINDA**
      C
            INCLUDE COMDEK
      C
      C     INITIALIZE TEKTRONIX GRAPHICS PACKAGE
            CALL INITT(120)
            CALL TERM(3,1024)
            CALL CHRSIZ(3)
            CALL TSEND
      C
            REWIND 8
      C
      C     LOOP - UNTIL ALL CASES HAVE BEEN DONE
      C     RHW - WASTE DENSITY
      C     RC  - RADIUS OF CONDUCTING ROD
      C     XMU - GEODETIC FREQUENCY
      C     R   - WASTE RADIUS
      C     CPW - HEAT CAPACITY, WASTE
      C     CPR - HEAT CAPACITY, ROD
      C     XKW - CONDUCTIVITY, WASTE
      C     XKR - CONDUCTIVITY, ROD
      C     RHO - ROD DENSITY
      C     ED  - ENERGY DENSITY
         10 READ (5,100,END=999) RHW,RC,XMU,R,CPW,CPR,XKW,
           *XKR,RHO,ED
      C
      C     DO COMPUTATIONS
            CALL COMP
      C
      C     PRINT OUT DATA
            CALL PRNT
      C
      C     LOOP - BACK TO NEXT CASE
            GO TO 10
      C
        100 FORMAT ( )
        999 STOP
            END
>
```

```
      SUBROUTINE PRNT
C
      INCLUDE COMDEK
C
      CALL NEWPAG
C
C     PRINT INPUT DATA
      PRINT 101,RHW
      PRINT 102,RO
      PRINT 103,XMU
      PRINT 104,R
      PRINT 105,CPW
      PRINT 106,CPR
      PRINT 107,XKW
      PRINT 108,XKR
      PRINT 109,RHO
      PRINT 110,ED
      PRINT 111,XN
      PRINT 112,XM
      PRINT 113,RIR
      PRINT 114,RL
C
C     PRINT NODE DATA HEADINGS
      WRITE (8,116)
      WRITE (8,117)
      WRITE (8,118)
      WRITE (8,119)
      PRINT 119
      FD=200.
C
C     SET ND EQUAL TO NUMBER OF NODE
C     FOR USE IN VARIABLE FORMAT
      ND=10
      DO 10 N=1,7
      ND=ND+1
C
C     WRITE NODE DATA TO A
C     FILE AND ON TO SCREEN
      WRITE (8,140) ND,FD,DN(N)
   10 PRINT 140,ND,FD,DN(N)
C
C     SET ND EQUAL TO NUMBER OF NODE
C     FOR USE IN VARIABLE FORMAT
      ND=0
      DO 20 N=8,12
      ND=ND+10
C
C     WRITE NODE DATA TO A
C     FILE AND ON TO SCREEN
      WRITE (8,140) ND,FD,DN(N)
   20 PRINT 140,ND,FD,DN(N)
      WRITE (8,141)
      WRITE (8,118)
C
C     PRINT SOURCE DATA HEADING
      PRINT 120
      WRITE (8,120)
C
C     WRITE SOURCE DATA TO A
C     FILE AND ON TO SCREEN
      DO 30 IS=1,6
      WRITE (8,142) IS,S(IS)
   30 PRINT 142,IS,S(IS)
C
C     SET IS EQUAL TO NUMBER OF NODE
C     FOR USE IN A VARIABLE FORMAT
      IS=10
      WRITE (8,143) S(7)
      PRINT 143,S(7)
      WRITE (8,118)
C
C     PRINT CONDUCTOR DATA HEADING
      WRITE (8,121)
      PRINT 121
C
C     SET IC AND JC EQUAL TO
C     NUMBER OF CONDUCTOR NODES
C     FOR USE IN VARIABLE FORMAT
      IC(1)=11
      JC(1)=12
      IC(2)=12
      JC(2)=13
      IC(3)=14
      JC(3)=15
      IC(4)=15
      JC(4)=16
      IC(5)=11
      JC(5)=14
      IC(6)=12
      JC(6)=15
      IC(7)=13
      JC(7)=16
      IC(8)=10
      JC(8)=11
      IC(9)=10
      JC(9)=14
      IC(10)=10
      JC(10)=20
      IC(11)=14
      JC(11)=30
      IC(12)=15
      JC(12)=40
      IC(13)=16
      JC(13)=50
      IC(14)=13
      JC(14)=17
      IC(15)=16
      JC(15)=17
      IC(16)=50
      JC(16)=17
      IC(17)=20
      JC(17)=30
      IC(18)=30
      JC(18)=40
```

```
      IC(19)=40
      JC(19)=50
      IC(20)=17
      JC(20)=99
C
C     WRITE CONDUCTOR DATA TO
C     A FILE AND ON TO SCREEN
      DO 40 I=1,19
      WRITE (8,144) IC(I),JC(I),IC(I),JC(I),C(I)
   40 PRINT 144,IC(I),JC(I),IC(I),JC(I),C(I)
      WRITE (8,145) IC(20),JC(20),IC(20),JC(20),C(20)
      PRINT 145,IC(20),JC(20),IC(20),JC(20),C(20))
      WRITE (8,118)
C     PRINT *'S TO SEPARATE DATA
C     CASES WRITTEN ON FILE
      WRITE (8,146)
C
C     CALL HDCOPY
      CALL NEWPAG
      CALL TSEND
C
  101 FORMAT (10X,35H WASTE DENSITY  LB/FT3:                ,F20.4)
  102 FORMAT (10X,35H RADIUS OF CONDUCTING ROD:  FT         ,F20.4)
  103 FORMAT (10X,35H GEODETIC FREQUENCY                    ,F20.4)
  104 FORMAT (10X,35H WASTE RADIUS:  FT                     ,F20.4)
  105 FORMAT (10X,35H HEAT CAPACITY, WASTE:  BTU/LB  F      ,F20.4)
  106 FORMAT (10X,35H HEAT CAPACITY, ROD:  BTU/LB  F        ,F20.4)
  107 FORMAT (10X,35H CONDUCTIVITY, WASTE:  BTU/HR-FT  F    ,F20.4)
  108 FORMAT (10X,35H CONDUCTIVITY, ROD:  BTU/HR-FT  F      ,F20.4)
  109 FORMAT (10X,35H ROD DENSITY:  LB/FT3                  ,F20.4)
  110 FORMAT (10X,35H ENERGY DENSITY:  BTU/HR LB            ,F20.4)
  111 FORMAT (10X,35H NUMBER OF VERTICES                    ,F20.4)
  112 FORMAT (10X,35H TOTAL MASS:  LBM                      ,F20.4)
  113 FORMAT (10X,35H RADIUS OF FIRST SHELL:  FT            ,F20.4)
  114 FORMAT (10X,35H RATIO OF GEODETIC ELEMENTS            ,F20.4,/)
  116 FORMAT (6X,18H BCD 3THERMAL SPCS)
  117 FORMAT (6X,12H BCD 9NEWMAN)
  118 FORMAT (6X,4H END)
  119 FORMAT (6X,15H BCD 3NODE DATA)
  120 FORMAT (6X,17H BCD 3SOURCE DATA)
  121 FORMAT (6X,20H BCD 3CONDUCTOR DATA)
C 122 FORMAT (6X,20H BCD 3CONSTANTS DATA)
C 123 FORMAT (9X,12H TIMEND=120.)
C 124 FORMAT (9X,10H OUTPUT=6.)
C 125 FORMAT (6X,16H BCD 3ARRAY DATA)
C 126 FORMAT (6X,15H BCD 3EXECUTION)
C 127 FORMAT (22HF      DIMENSION X(200))
C 128 FORMAT (14HF      NDIM=200))
C 129 FORMAT (11HF      NTH=0)
C 130 FORMAT (9X,7H CNFRWD)
C 131 FORMAT (6X,17H BCD 3VARIABLES 1)
C 132 FORMAT (6X,17H BCD 3VARIABLES 2)
C 133 FORMAT (6X,18H BCD 3OUTPUT CALLS)
C 134 FORMAT (9X,7H TPRINT)
C 135 FORMAT (6X,17H BCD 3END OF DATA)
  140 FORMAT (11X,I2,',',F4.0,',',F7.4)
  141 FORMAT (11X,13H-99,-460.,.00)
  142 FORMAT (11X,1H1,I1,',',F9.4)
  143 FORMAT (11X,3H10,,F9.4)
  144 FORMAT (11X,I2,I2,',',I2,',',I2,',',F7.4)
  145 FORMAT (11X,'-',I2,I2,',',I2,',',I2,',',1PE12.6
)
  146 FORMAT ('*************')
C
      RETURN
      END
EOF:179 SCAN:64
0:>
```

```
                                                57:)
      SUBROUTINE COMP
C
      INCLUDE COMDEK
C
C     COMPUTE EQUATIONS FOR VARIABLES NOT READ IN
C     XN  - NUMBER OF VERTICES
C     XM  - TOTAL MASS
C     RIR - RADIUS OF FIR   SHELL
C     RL  - RATIO OF GE .  IC ELEMENTS
      XN=19.*XMU**2+2.
      XM=(4.1887*R**3-(3.14*RO**2*R*XN/RHO))*RHW
      RIR=R/4.**(1./3.)
      RL=XMU**.8686
C
C     SET VARIABLES EQUAL TO EQUATIONS USED IN COMPUTING
C     NODE, SOURCE, AND CONDUCTOR DATA EQUATIONS
      A1=(2.**(2./3.))*(RIR**2)/(4.*(RL**2))
      A2=(2.**(2./3.))*(RIR**2)/(8.*(RL**2))
      A3=(3.**(2./3.))*(RIR**2)/(4.*(RL**2))
      A4=(3.**(2./3.))*(RIR**2)/(8.*(RL**2))
      A5=(RIR**2)/(8.*(RL**2))
      A6=(RIR**2)/(4.*(RL**2))
      A7=((4.**(2./3.))*(RIR**2))/(4.*(RL**2))
      A8=((4.**(2./3.))*(RIR**2))/(8.*(RL**2))
      B1=((3.**(1./3.))*RIR)
      B2=((4.**(1./3.))*RIR)
      B3=((2.**(1./3.))*RIR)
      B4=RIR/(4.*RL)
      B5=((2.**(1./3.))*RIR)/(4.*RL)
      B6=((3.**(1./3.))*RIR)/(4.*RL)
      B7=(RO**2)/2.
      B8=(3.14/4.)*((2.*RO)**2)
C
C     COMPUTE EQUATIONS FOR NODE DATA
C     SET NODES 11 THRU 16 EQUAL TO SAME EQUATION
      DO 10 N=1,6
   10 DN(N)=XM*.75*CPU/(XN*6.)                    $  ND 11-16
      DN(7)=3.14*A7*179.*.02*.2                    $  ND 17
      DN(8)=XM*.25*CPU/XN                          $  ND 10
      DN(9)=3.14*(RO**2)*(RIR-SQRT(3.*XN)*
     *((2.*RO)/4.))*RHO*CPR                        $  ND 20
      DN(10)=3.14*(RO**2)*(B3-RIR)*RHO*CPR         $  ND 30
      DN(11)=3.14*(RO**2)*(B1-B3)*RHO*CPR          $  ND 40
      DN(12)=3.14*(RO**2)*(B2-B1)*RHO*CPR          $  ND 50
C
C     COMPUTE EQUATIONS FOR SOURCE DATA
C     SET NODES 11 THRU 16 EQUAL TO SAME EQUATION
      DO 20 IS=1,6
   20 S(IS)=XM*ED*.75/(XN*6.)                      $  SD 11-16
      S(7)=XM*ED*.25/XN                            $  SD 10
C
C     COMPUTE EQUATIONS FOR CONDUCTOR NODES
      C(1)=3.14*(A1-A2-B7)/(.5*(B1-RIR))*XKU       $  CN 1112
      C(2)=3.14*(A3-A4-B7)/(.5*(B2-B3))*XKU        $  CN 1213
      C(3)=3.14*(A2+B7)/(.5*(B1-RIR))*XKU          $  CN 1415
      C(4)=3.14*(A4+B7)/(.5*(B2-B3))*XKU           $  CN 1516
      C(5)=(2.*(3.14)*SQRT(A5+B7)*(B3-RIR)/B4)*XKU $  CN 1114
```

```
      C(6)=(2.*(3.14)*SQRT(A2+B7)*(B1-B3)/B5)*XKW      @  CN 1215
      C(7)=(2.*(3.14)*SQRT(A4+B7)*(B2-B1)/B6)*XKW      @  CN 1316
      C(8)=(3.14*(A6-A5-B7)/B5)*XKW                    @  CN 1011
      C(9)=(3.14*(A5+B7)/B5)*XKW                       @  CN 1014
      C(10)=3.14*(RIR-SQRT(3.*XN)*
     *((2.*RO)/4.))*XKW                                @  CN 1020
      C(11)=(3.14*(B3-RIR))*XKW                        @  CN 1430
      C(12)=(3.14*(B1-B3))*XKW                         @  CN 1540
      C(13)=(3.14*(B2-B1))*XKW                         @  CN 1650
      C(14)=(3.14*(A7-A8-B7)/(.5*(B2-B1)))*XKW         @  CN 1317
      C(15)=(3.14*(A7-A8-B7)/(.5*(B2-B1)))*XKW         @  CN 1617
      C(16)=(B8/(.5*(B2-B1)))*XKR                      @  CN 5017
      C(17)=(B8/(B3/2.))*XKR                           @  CN 2030
      C(18)=(B8/((B1-RIR)*.5))*XKR                     @  CN 3040
      C(19)=(B8/((B2-B3)*.5))*XKR                      @  CN 4050
      C(20)=1.714E-9*.8*3.14*((4.**(2./3.))*
     *(?IR**2)/(4.*(RL**2)))                           @  CN 1799
      RETURN
      END
EOF:76 SCAN:18
0:>
```

APPROVAL

THERMAL CONTROL OF HIGH ENERGY NUCLEAR WASTE, SPACE OPTION

By Jerry A. Peoples

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

C. R. DARWIN
Director, Preliminary Design Office

JAMES T. MURPHY
Director, Program Development