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A Computer Program to Determine the Specific Power of Prismatic- Core Reactors



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A COMPUTER PROGRAM TO DETERMINE THE SPECIFIC
POWER OF PRISMATIC-CORE REACTORS

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ABSTRACT

A computer program has been developed to determine the maximum specific power for prismatic-core reactors as a function of maximum allowable fuel temperature, core pressure drop, and coolant velocity. The prismatic-core reactors consist of hexagonally shaped fuel elements grouped together to form a cylindrically shaped core. A gas coolant flows axially through circular channels within the elements, and the fuel is dispersed within the solid element material either as a composite or in the form of coated pellets. Different coolant, fuel, coating, and element materials can be selected to represent different prismatic-core concepts. The computer program allows the user to divide the core into any arbitrary number of axial levels to account for different axial power shapes. An option in the program allows the automatic determination of the core height that results in the maximum specific power. The results of parametric specific power calculations using this program are presented for various reactor concepts.

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APPENDIX - COMPUTER PROGRAM LISTING

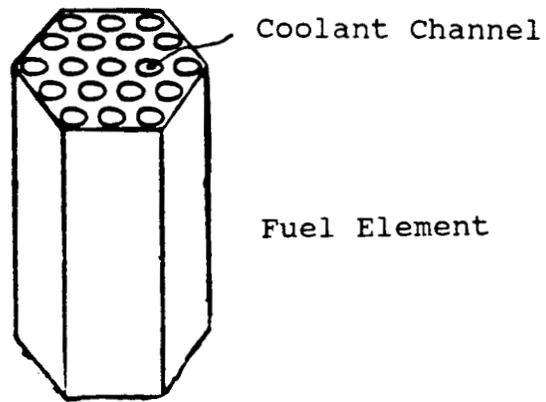
1.0 INTRODUCTION

The prismatic-core reactors consist of hexagonally shaped fuel elements grouped together to form a cylindrically shaped core. A gas coolant flows axially through circular channels within the elements, and the fuel is dispersed within the solid element (matrix) material either as a composite or in the form of coated spherical pellets. Figure 1.0.1 provides a diagram of a typical fuel element for a prismatic core along with examples of the coated pellets and composite fuel forms.

The specific power is defined as the amount of power that can be produced per unit of fuel mass (power/mass). Thus, higher values of specific power result in less massive reactor cores for a given power level. Two constraints that must be considered when determining the maximum specific power that a reactor core can achieve are criticality and heat removal. To satisfy the criticality constraint, the size, composition, and geometry of the core must be such that criticality can be achieved over the entire reactor lifetime. Satisfying this constraint dictates the mass of fuel required. To satisfy the heat removal constraint, the amount of power produced must be such that it can be removed without exceeding the maximum allowed core temperatures or the maximum allowed coolant velocity or core pressure drop.

A computer program has been written to calculate the core power for any given fuel mass and core length. Used in conjunction with criticality calculations, this program allows one to determine the specific power for a prismatic-core reactor. The program includes approximate models to account for the thermal resistance associated with the coolant, matrix, coating, and fuel. Different coolant, matrix, coating, and fuel materials can be selected to represent different prismatic-core concepts. The computer program allows the user to divide the core into any arbitrary number of axial levels to account for different axial power shapes. Also, an option in the code allows the automatic determination of the core height that results in the maximum specific power.

This report contains a description of the models used in the computer program along with some examples of the application of the program.



FUEL FORMS

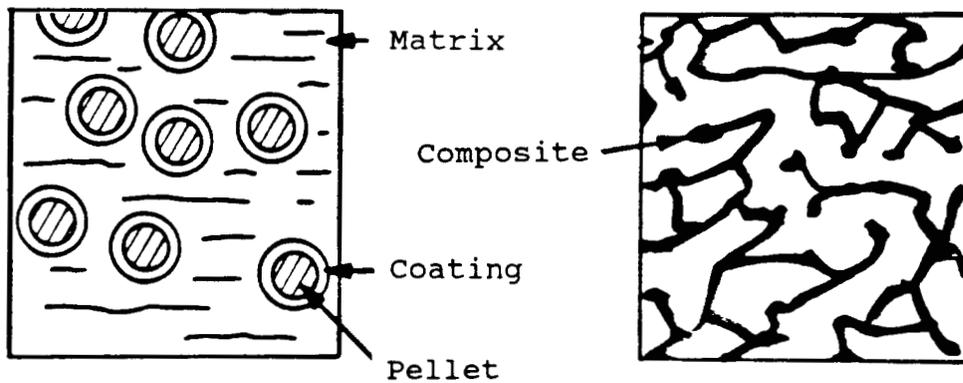


Figure 1.0.1 Typical Prismatic-Core Fuel Element

2.0 COMPUTER PROGRAM DESCRIPTION

The program was written to allow the user to specify the material for the coolant, matrix, coating, and fuel. Presently, properties for the following core materials are available:

- 1 - uranium carbide
- 2 - uranium dioxide
- 3 - uranium boride
- 4 - reactor grade graphite
- 5 - boron carbide
- 6 - beryllium oxide
- 7 - zirconium carbide
- 8 - tungsten
- 9 - molybdenum

Also, two gases are available for the coolant:

- 1 - helium
- 2 - hydrogen

The thermophysical properties for these materials are built into the program as a function of temperature. These properties were taken from References 1 through 4; curve fits (linear, logarithmic, or power) to the data were made to allow easy evaluation of the properties at any temperature. The property functions are provided in the appendix, which contains a FORTRAN listing of the entire program. Figures 2.0.1 through 2.0.5 are graphs of the resulting property functions. The ideal gas law was used to calculate the coolant density as a function of pressure and temperature.

A cross-sectional view of a prismatic-core fuel element is provided in Figure 2.0.6. In this example, there are seven channels within the element. The variable S denotes the maximum conduction length within the element; this represents the greatest distance that heat must travel from the fuel to the channel wall. If the fuel is in the form of coated pellets dispersed uniformly within the matrix, a pellet is assumed to reside at this location to provide a conservative (worst case) estimate of the fuel maximum temperature. The input variable S can be calculated for N uniformly spaced channels using the following equation:

$$S = D / (2N_d \cos^e(30^\circ)) - d_c / 2 - d_p / 2 - t \quad (1)$$

where: D = hexagon flat-to-flat width,
 N_d = number of channels across the element diagonal,
 $e = 1$ if $N = 1$; $e = 2$ for $N > 1$,
 d_c = channel diameter,
 d_p = pellet diameter, and
 t = coating thickness.

If the fuel is in the form of a composite, the fuel is dispersed within the matrix material and there are no pellets or

coating; d_p and t would be set equal to zero in this case. For uniformly spaced channels, Table 2.0.1 provides the value of N_d for various values of the number of channels per element, N . If the channels are not uniformly spaced, S must be calculated in a manner appropriate with the spacing.

Table 2.0.1 Number of Diagonal Channels

N	N_d
1	1
7	3
19	5
37	7
61	9

Specific power, defined as the total power produced in the core divided by the total fuel mass, is determined by the core criticality constraints and by the core heat transfer and hydraulic constraints. The total core power, P , is given by:

$$P = mc_p(T_O - T_I) \quad (2)$$

with: $m = \rho VA$

where: m = core mass flow rate,

ρ = coolant density,

V = coolant velocity,

A = core flow area,

c_p = coolant average specific heat,

T_O = core outlet coolant temperature, and

T_I = core inlet coolant temperature.

For a given fuel element geometry (i.e., number of channels, channel diameter, and hexagon width), only the velocity in Equation (2) is unknown (T_I and T_O are input variables). The computer program calculates the maximum coolant velocity such that a prescribed maximum fuel, coating, or matrix temperature is not exceeded (heat transfer limit) or a maximum core pressure drop (hydraulic limit) is not exceeded. Also, a maximum-allowed coolant Mach number can be established as a limiting criteria.

Based on the specified core pressure, and coolant inlet and outlet temperatures, the coolant sonic speed is calculated at the core inlet and outlet. Using the maximum of the inlet and outlet sonic speeds and the specified maximum allowed Mach number, the coolant velocity (and hence, core mass flow rate) is determined. Equation (2) is then used to calculate the core power based on this velocity. However, if this calculated power results in core temperatures or a core pressure drop that exceeds

specified limits, the velocity is reduced and a new power and associated core temperatures and pressure drop are determined. The velocity is reduced until the limits are no longer exceeded.

For any arbitrary axial power profile, the axial location at which the maximum core temperature occurs is not known. Therefore, the computer program allows the core to be divided into any number of equally spaced axial levels. Relative power factors for each level are then specified to define the axial power profile. (A program option allows the user to specify either a flat or cosine power profile in which the relative power factors are automatically calculated.) Equation (2) is used to determine the coolant temperature at the ends of the axial levels. The average specific heat for each level is calculated as the algebraic average of that level's inlet and outlet specific heats. The average specific heat must be determined iteratively with Equation (2) because the outlet temperature for each level is unknown.

Using the average coolant temperature for each level, the coolant properties are evaluated from which the Reynolds and Prandtl numbers are determined. The velocity for each core level, V_z , is determined based on continuity such that $V_z = m/\rho A$ where m is the core mass flow rate and ρ is that level's coolant density. (If a value of zero is specified as the number of core levels, then the coolant properties and velocity for the heat transfer calculations are based on the core exit temperature.) Now, enough information is available to determine the temperature drop from the coolant, through the matrix and coating, to the fuel. (If the fuel is in the form of a composite, the temperature drop associated with the coating and the fuel pellet is not applicable.)

To determine the temperature drop from the coolant to the channel wall, the Taylor equation [4] for the coolant heat transfer coefficient, h , is used. This equation is:

$$h = 0.023 Ck/d_c Re^{0.8} Pr^{0.4} \quad (3)$$

with,

$$C = (T_w/T_c)^E$$

$$E = (1.59d_c/x - 0.57)$$

where: k = coolant conductivity,
 d_c = channel diameter,
 Re = Reynold's number,
 Pr = Prandtl's number,
 T_w = wall temperature,
 T_c = coolant bulk temperature, and
 x = distance from channel entrance.

This equation is for turbulent flow in circular channels and is a function of the channel wall temperature; thus, it must be solved iteratively with Newton's law of cooling, given by:

$$P = hA_w(T_w - T_c) \quad (4)$$

where: A_w = total channel wall area.

If the core is divided into axial levels, then Equation (4) is solved for each level. (This equation does not account for aerodynamic heating effects that would be expected to occur at very high coolant velocities.)

Next, the temperature drop across the matrix material of the element (ΔT_m) is determined. As already mentioned, the variable S represents the maximum distance that heat must travel from the fuel to the channel wall. An estimate of the temperature drop across this distance can be made by using the conduction relation for heat flow in a hollow cylinder of inside radius equal to one-half the channel diameter and outside radius equal to the inside radius plus the distance S . Thus,

$$\Delta T_m = (P_z/N) \ln[(2S + d_c)/d_c] / (2\pi\Delta z k_m) \quad (5)$$

where: P_z = core axial level power,
 N = number of coolant channels,
 S = maximum conduction length,
 d_c = channel diameter,
 Δz = axial level length, and
 k_m = matrix thermal conductivity.

This equation has been derived assuming that the matrix thermal conductivity is constant. A crude estimate of an average thermal conductivity for the matrix is found by first solving Equation (5) using k_m evaluated at the previously calculated (Equations (3) and (4)) channel wall temperature. Then, a first guess for the maximum matrix temperature, T_m , is calculated as $T_w + \Delta T_m$. Now, k_m is evaluated at the algebraic average of T_w and T_m , and Equation (5) is solved again to provide a better estimate of T_m . If the fuel is in the form of a composite, k_m is determined as a volume average of the fuel and matrix conductivities.

If pellet fuel is used, the temperature drop across the coating and the pellet must next be calculated. The temperature drop across the coating, ΔT_c , is given by:

$$\Delta T_c = (P_z/N_{p,z}) t / [2\pi d_p k_c (d_p/2 + t)] \quad (6)$$

where: P_z = core axial level power,
 $N_{p,z}$ = number of fuel pellets per core level,
 t = coating thickness,
 d_p = pellet diameter, and
 k_c = coating thermal conductivity.

The temperature drop from the center of the spherical fuel pellet to the coating inside surface, ΔT_p , is given by:

$$\Delta T_p = P_z / N_{p,z} / (4 \pi d_p k_p) \quad (7)$$

where: k_p = pellet thermal conductivity.

The next task is to determine the pressure drop from the core inlet to the core outlet. This is just the sum of the pressure drops across all core levels. The pressure drop for a core level, Δp_z , is calculated using:

$$\Delta p_z = f \Delta z / d_c (\rho/2) v_z^2 \quad (8)$$

with: $f = 0.184 \text{ Re}^{-0.2} \text{ Pr}^{-0.6}$

The core pressure specified in the input is assumed to be the core inlet pressure. The pressure for each level (which is used in the calculation of the coolant density) is taken as the pressure at the level inlet based on the pressure drop for the preceding level. Thus, $p_{i+1} = p_i - \Delta p_i$. The subscripts refer to the pressure for level $i+1$ and the preceding level i .

Although this computer program can be used for any prismatic-core reactor, it was originally developed to perform parametric calculations for the NERVA reactor [5]. It therefore contains provisions to account for the effects of internal support structure within the core on the core flow rate and pressure drop.

NERVA fuel elements are grouped into clusters; each cluster contains six fueled elements and one centrally located unfueled element. Some of the clusters have central unfueled elements that contain a moderating material such as ZrH_2 ; these clusters are referred to as moderated clusters and the elements in these clusters are referred to as moderated elements. The central elements in the moderated clusters contain an inner can and can holes that could be used to provide flow paths for coolant. The unmoderated clusters contain an inner and outer can in the central element that could also be used for coolant flow. Figure 2.0.7 shows a diagram of the two types of clusters.

Two support structure cooling options are available in the program for the NERVA reactor. In one option, coolant first flows through the central elements to provide cooling of the support structure. The coolant then turns and flows through the fueled elements of the core. Thus, two core coolant passes are made and the pressure drop associated with each pass is calculated. The program user can also specify that the coolant makes only one core pass; i.e., the support structure and fueled elements are treated as parallel flow paths. For this option, the program calculates the additional coolant flow rate needed for support structure cooling assuming the pressure drops across both flow paths are equal. For the single-pass option, the input parameters describing the central element geometry can be neglected without effecting the specific power calculations.

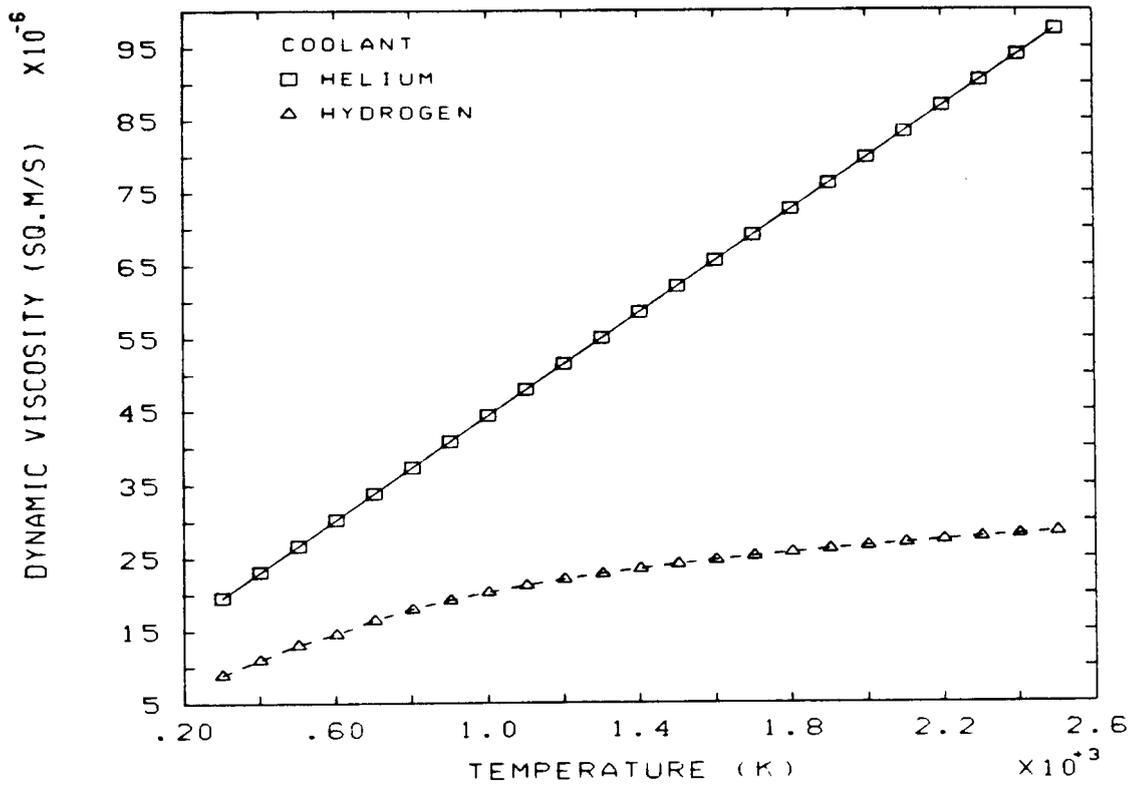


Figure 2.0.1 Coolant Dynamic Viscosity

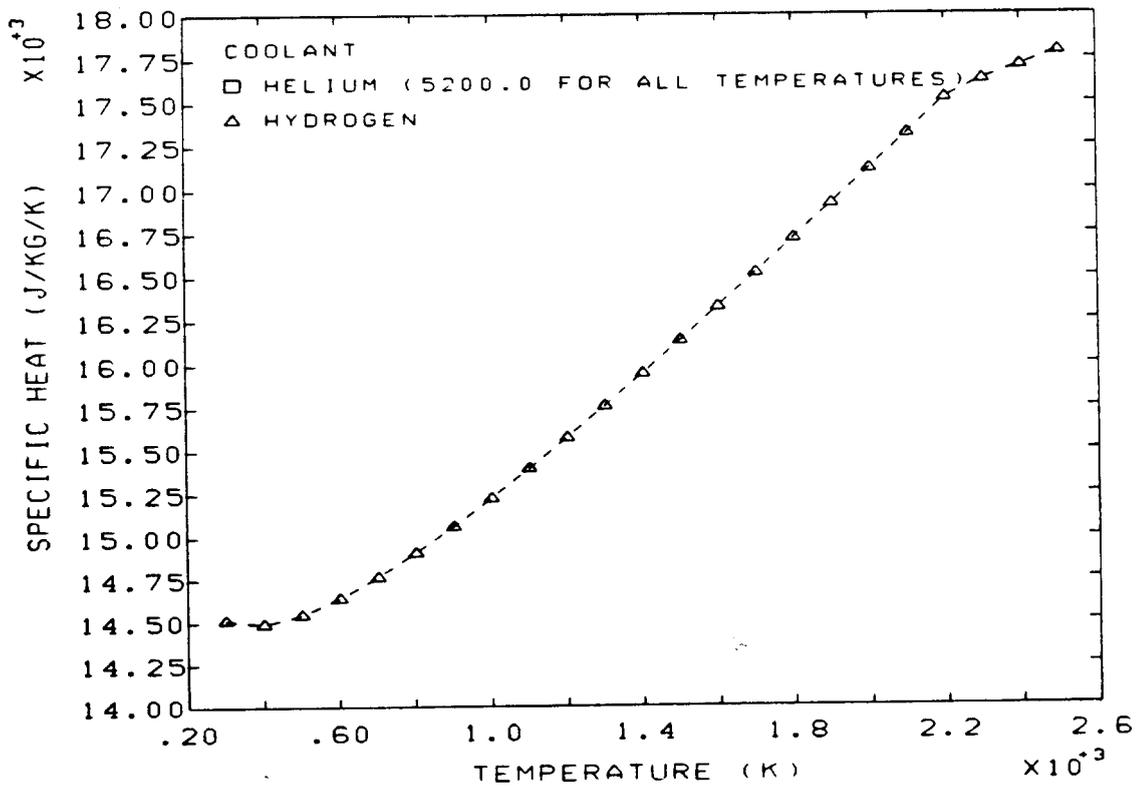


Figure 2.0.2 Coolant Specific Heat

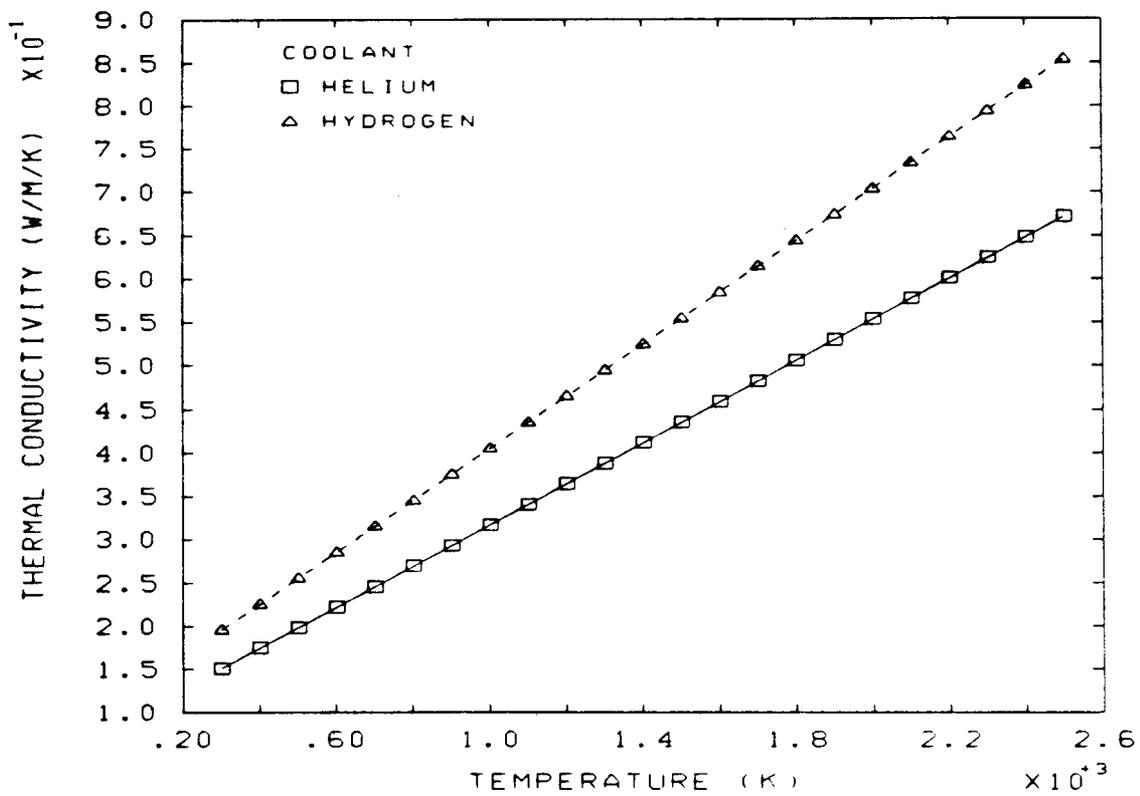


Figure 2.0.3 Coolant Thermal Conductivity

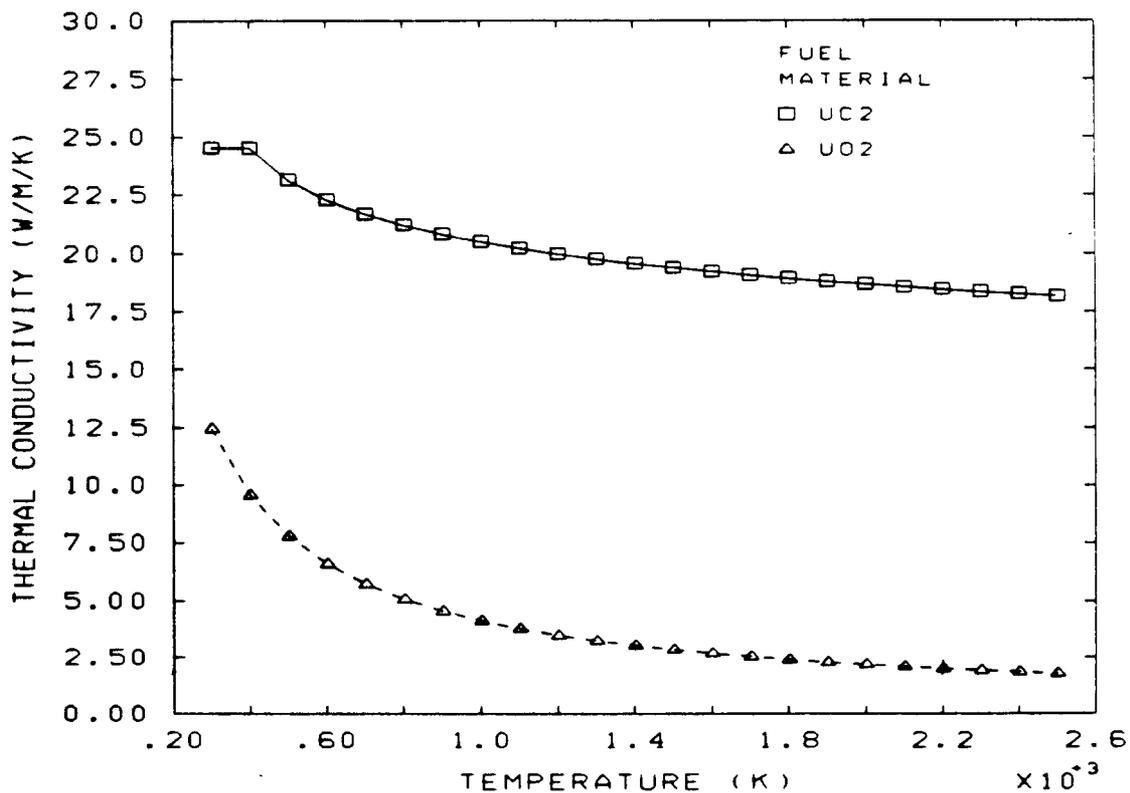


Figure 2.0.4 Fuel Thermal Conductivity

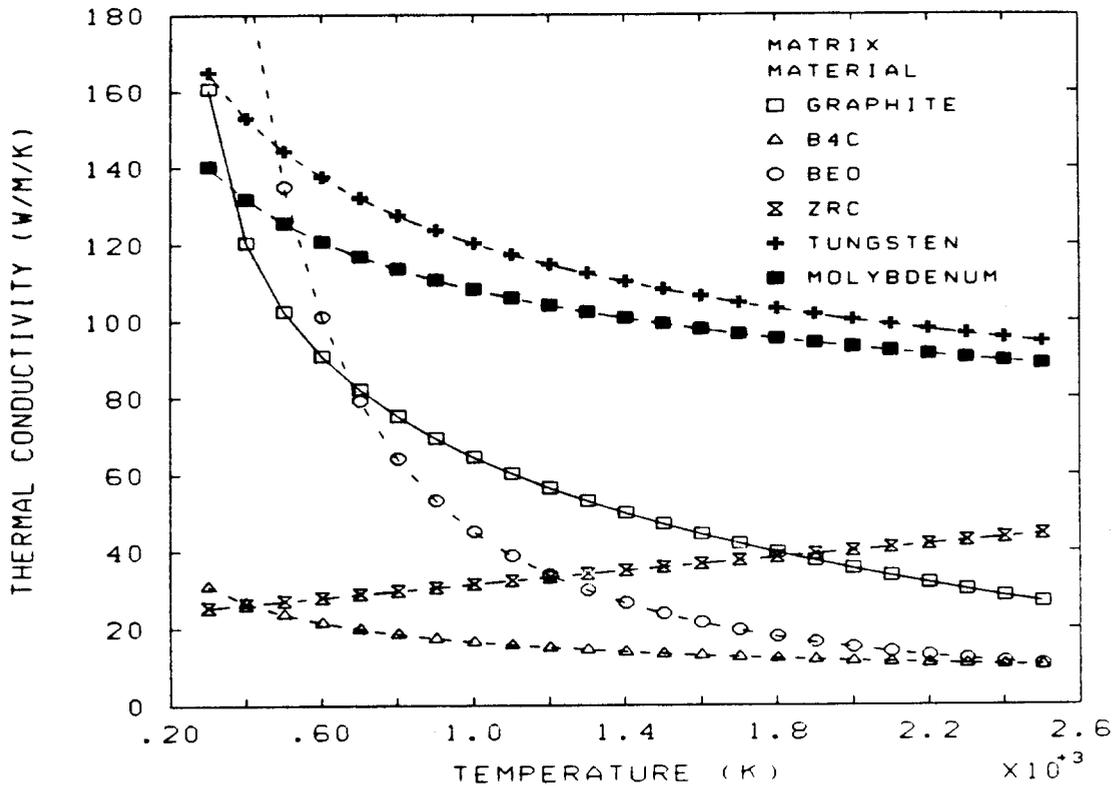


Figure 2.0.5 Matrix Thermal Conductivity

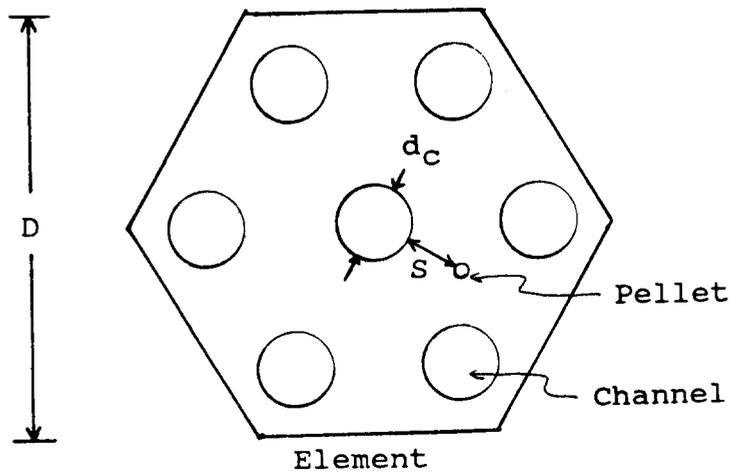


Figure 2.0.6 Fuel Element Cross-Sectional View

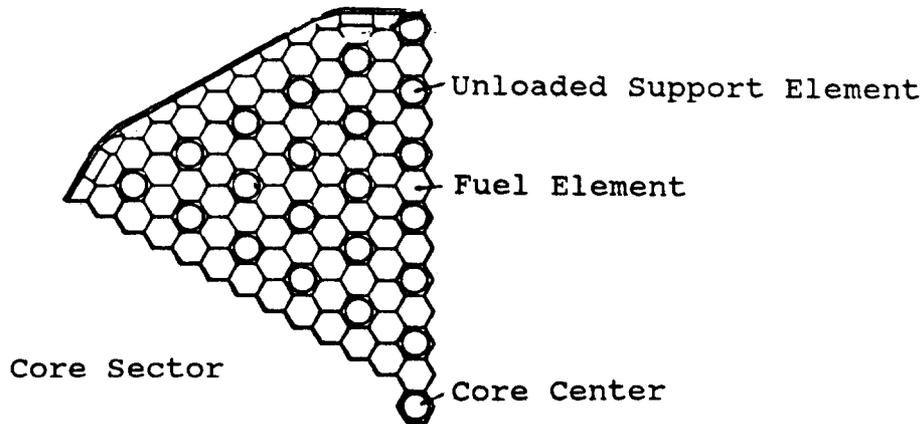
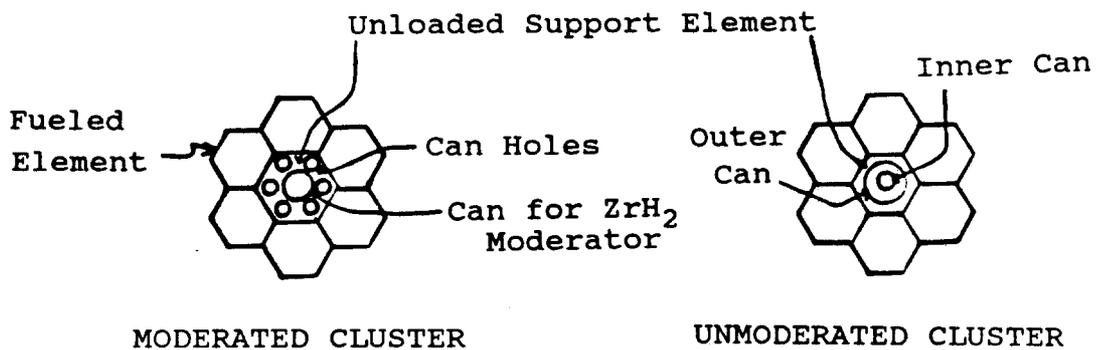


Figure 2.0.7 Cluster Configurations

3.0 COMPUTER PROGRAM USE

This section is included to provide an explanation of the use and interpretation of the program input and output. An annotated example input listing is included in Table 3.0.1; the annotations provide a concise description of the required input variables. The items marked with a "*" can be set to a value of one if the coolant makes only a single pass of the core and the total core power is not of interest. As mentioned in the previous section, the specific power is not affected by these variables.

Table 3.0.1 Example Input Listing

INPUT FOR NERVA-TYPE REACTOR POWER DENSITY CALCULATIONS	
2	COOLANT ID (1:HELIUM,2:HYDROGEN)
1	FUEL ID (1:UC,2:UO2,3:UB4)
4	MATRIX ID (4:C,5:B4C,6:BE0,7:ZRC,8:W,9:MO)
7	COATING ID (ANY OF 1 - 9)
1	NUMBER OF COOLANT PASSES
13.6E6	CORE INLET PRESSURE (PA)
400.0	CORE INLET TEMPERATURE (K)
1200.0	CORE OUTLET TEMPERATURE (K)
500.0	FUEL LOADING (KG/CUB.M)
1.0	RADIAL PEAK-TO-AVERAGE POWER RATIO
2.5	CORE HEIGHT (M) (MAX VALUE FOR HEIGHT OPTIMIZATION)
0.01	RELATIVE HEIGHT ERROR (ZERO FOR NO HEIGHT OPTIMIZATION)
0.60	MINIMUM ALLOWED HEIGHT FOR OPTIMIZATION (- FOR RANGE)
0.45	*CORE DIAMETER (M) (NEEDED IF NUMBER OF COOLANT PASSES > 1)
0.0191	HEXAGON FUELED ELEMENT FLAT-TO-FLAT WIDTH (M)
0.32727	*FRACTION OF TOTAL OF "UNMODERATED" CLUSTERS
7	TOTAL NUMBER OF ELEMENTS PER CLUSTER (CAN BE 1)
5.22	*AVG NUMBER OF FUELED ELEMENTS PER UNMODERATED CLUSTER
5.22	*AVG NUMBER OF FUELED ELEMENTS PER MODERATED CLUSTER
19	NUMBER OF CHANNELS PER UNMODERATED ELEMENT
12	NUMBER OF CHANNELS PER MODERATED ELEMENT
10	*NUMBER OF HOLES PER MODERATED ELEMENT
0.00254	DIAMETER OF COOLANT CHANNEL (M)
0.00468	*DIAMETER OF CAN HOLES (M)
0.001027	S, MAXIMUM MATRIX CONDUCTION LENGTH TO CHANNEL WALL (M)
0.00025	DIAMETER OF FUEL PELLETT (M) (- FOR COMPOSITE FUEL)
0.000125	THICKNESS OF PELLETT COATING (M)
0.0075	*DIAMETER OF INNER UNMODERATED CAN (M)
0.016	*DIAMETER OF OUTER UNMODERATED CAN (M)
0.00875	*DIAMETER OF INNER MODERATED CAN (M)
3000.0	MAXIMUM ALLOWED COATING TEMPERATURE (K)
5000.0	MAXIMUM ALLOWED MATRIX TEMPERATURE (K)
2300.0	MAXIMUM ALLOWED FUEL TEMPERATURE (K)
1.0	MAXIMUM ALLOWED PUMPING POWER FRACTION
0.1	MAXIMUM ALLOWED CORE PRESSURE DROP FRACTION
0.3	MAXIMUM ALLOWED COOLANT MACH NUMBER
31	NUMBER OF AXIAL CORE LEVELS (0 TO USE TOUT FOR HEAT TRANSFER)
0	0 - COSINE POWER SHAPE, 1 - FLAT, OR 2 - USER SPECIFIED SHAPE
0.05	EXTRAPOLATION LENGTH (M) (ONLY USED FOR COSINE POWER SHAPE)
	RELATIVE POWER FACTORS (FOR USER SPECIFIED SHAPE, ONE/LEVEL)

* PARAMETER CAN BE SET TO ONE IF NUMBER OF PASSES IS ONE

The specific power can be determined for any specified core height; or, if a nonzero value for the "relative height error" is entered, the program will automatically determine the core height that results in the maximum specific power. To use this option, a minimum and maximum core height must be entered to provide an interval in which the search for the maximum height is conducted. Also, if the minimum core height is entered as a negative number, the program will determine the specific power for a range (15 values) of core heights between the minimum and maximum height values.

As mentioned in Sections 1.0 and 2.0, the specific power is determined such that specified maximum core temperatures, pressure drop, and Mach number are not exceeded. The maximum core pressure drop is specified in the input as a maximum allowed core pressure drop fraction. This is defined as the maximum allowed core pressure drop divided by the core inlet pressure. Likewise, the maximum allowed coolant Mach number is defined as the maximum allowed coolant velocity divided by the coolant sonic velocity. Also, a maximum allowed pumping power can be imposed; this is defined as the maximum allowed pumping power for coolant flow through the core divided by the core power. (The core power is a function of the core diameter input variable.)

The number of axial core levels can be specified. If zero is chosen, the core is not subdivided and the heat transfer calculations are based on the coolant properties at the core outlet and the pressure drop calculation is based on the coolant properties evaluated at the coolant average temperature. Any power shape can be imposed on the core. If a cosine or flat power profile is desired, the program will automatically determine the relative power factors based on the number of axial levels selected. For the cosine profile, an axial extrapolation length can be specified. This is the distance outside the core where the neutron flux vanishes. If the diameter of the fuel pellet is specified as a negative number, the fuel is assumed to be in the form of a composite of the fuel and matrix materials. If this option is selected, the temperature drops across the pellet and the coating are not applicable. The maximum conduction length, S , can be determined using Equation (1) of Section 2.0.

Table 3.0.2 provides the final output of the program for the example input problem. For this problem, the optimum core height was found to be 0.63 m corresponding to a specific power of 32.6 MW/kg. Besides the specific power, other parameters of interest are included in the output such as pressure drops and pumping powers. The output also consists of the core temperatures as a function of axial position. This output is displayed graphically in Figure 3.0.1. This figure shows that the maximum fuel temperature (2300 K) occurs at a core elevation of about 0.35 m. This figure also shows that the largest temperature drops occur between the coolant and the channel wall and between the wall and the outside surface of the fuel coating.

Table 3.0.2 Example Program Output

```
CHANNEL VOLUME FRACTION = 0.30468
NUMBER OF FUEL PELLETS = 2.13640E+08
FUEL MASS (KG) = 19.23
NUMBER OF COOLANT CHANNELS = 5287
SONIC SPEED OF COOLANT (M/S) = 2608.74
CORE HEIGHT (M) = 0.629

CORE MASS FLOW RATE (KG/S) = 52.202
TOTAL CORE POWER (W) = 6.27717E+08

• POWER DENSITY (W/KG) = 3.26491E+07
• POWER DENSITY (W/CUB.M) = 1.63245E+10

CORE PRESSURE DROP (PA) = 1.14169E+06
CORE PUMPING POWER (W) = 1.74732E+07

CAN MASS FLOW RATE (KG/S) = 4.466
CAN PRESSURE DROP (PA) = 1.14169E+06
- TURNING PRESSURE DROP (PA) = 0.00000E+00
CAN PUMPING POWER (W) = 6.23422E+05

FRACTION OF SONIC SPEED IN CORE = 0.29773
FRACTION OF SONIC SPEED IN MODERATOR = 0.01951

TOTAL PRESSURE DROP (PA) = 1.1417E+06
FRACTION OF CORE PRESSURE = 0.08395
TOTAL PUMPING POWER (W) = 1.8097E+07
FRACTION OF CORE POWER = 0.02883
```

As an additional item of interest, the example problem was repeated using a flat axial power profile instead of a cosine profile. With the flat profile, the maximum specific power was found to be 37.9 MW/kg with an optimum core height of 0.54 m. This demonstrates the advantage that can be gained by flattening of the axial power profile. (The program also allows the specification of a radial peak-to-average power ratio as a simple means of accounting for the effect of a radial power distribution.)

As a final example of the program use, the example problem was repeated with the number of coolant core passes specified as two. This situation is representative of the original NERVA core. Table 3.0.3 shows the output for this case. Because two core passes are made, the core pressure drop is larger than for the single-pass case. The specific powers for the two cases are about the same, however. The reason for this is that the coolant velocity in the single-pass case was limited by the Mach number restriction; therefore, the advantage of the lower core pressure drop could not be realized.

Table 3.0.3 Output for Two-Pass Case

CHANNEL VOLUME FRACTION = 0.30468
NUMBER OF FUEL PELLETS = 2.10906E+08
FUEL MASS (KG) = 18.98
NUMBER OF COOLANT CHANNELS = 5287
SONIC SPEED OF COOLANT (M/S) = 2608.74
CORE HEIGHT (M) = 0.621

CORE MASS FLOW RATE (KG/S) = 50.648
TOTAL CORE POWER (W) = 6.09027E+08

- POWER DENSITY (W/KG) = 3.20875E+07
- POWER DENSITY (W/CUB.M) = 1.60438E+10

CORE PRESSURE DROP (PA) = 1.06567E+06
CORE PUMPING POWER (W) = 1.57627E+07

CAN MASS FLOW RATE (KG/S) = 50.648
CAN PRESSURE DROP (PA) = 2.54894E+05
- TURNING PRESSURE DROP (PA) = 1.38169E+05
CAN PUMPING POWER (W) = 1.57149E+06

FRACTION OF SONIC SPEED IN CORE = 0.28720
FRACTION OF SONIC SPEED IN MODERATOR = 0.25986

TOTAL PRESSURE DROP (PA) = 1.3206E+06
FRACTION OF CORE PRESSURE = 0.09710
TOTAL PUMPING POWER (W) = 1.7334E+07
FRACTION OF CORE POWER = 0.02846

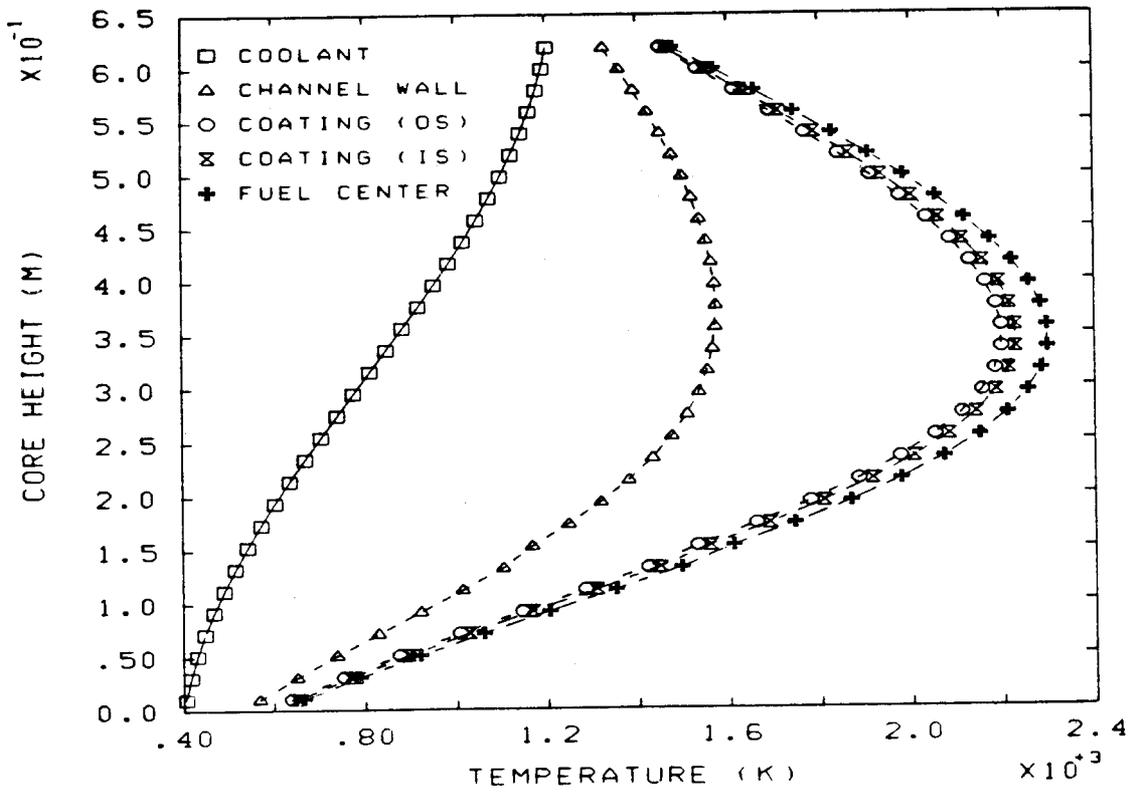


Figure 3.0.1 Core Temperatures

4.0 PARAMETRIC CALCULATIONS

To demonstrate the application of the specific power computer program, parametric calculations were performed for three different prismatic-core reactor concepts: (1) NERVA derivative, (2) PLUTO derivative, and (3) CERMET derivative. Three variations of the NERVA concept and three variations of the PLUTO concept were included in the parametric calculations. Table 4.0.1 lists the assumed criteria used for the specific power calculations for all concepts. The pressure drop for all calculations was based on a single pass of the hydrogen coolant. The effects of changing the maximum fuel temperature, pressure drop fraction, and Mach number were investigated and are discussed later in this section.

Table 4.0.1 Assumed Criteria

Power profile - flat
Outlet coolant temperature - 1200 K
Inlet coolant temperature - 400 K
Inlet pressure - 13.6 MPa
Maximum pressure drop fraction - 0.10
Maximum Mach number - 0.30
Maximum fuel temperatures -
NERVA (UC ₂ ,ZrC,C) - 2300 K
NERVA (UC ₂ -ZrC,C) - 2700 K
NERVA (UC ₂ ,ZrC) - 3000 K
PLUTO (UO ₂ ,BeO) - 2500 K
PLUTO (UC ₂ ,C) - 2700 K
PLUTO (UB ₄ ,B ₄ C) - 2300 K
CERMET (UO ₂ ,W,W) - 2400 K

The symbols in parentheses indicate the core materials. The first material listed is the fuel, the second material is the fuel coating, and the last material is the element or matrix material that the fuel is imbedded in. If the core is made of a composite of fuel and matrix material, no coating material is needed and only two materials are listed.

The specific power for a given concept was determined as a function of the fuel loading and the core height (length). The fuel loading is defined as the mass of fuel material per unit volume of solid element (i.e., the volume of the element minus the volume of the coolant channels). The fuel loading and core length are treated parametrically because their final values depend on reactor criticality considerations.

4.1 NERVA

Table 4.1.1 presents the pertinent geometric data that was used for the specific power calculations for the NERVA concepts. It is not necessary to specify a core diameter because specific power is independent of this parameter. (Recall that specific power is defined as the total power divided by the total fuel mass; both the total power and the total fuel mass are proportional to the square of the core diameter.)

Table 4.1.1 NERVA Geometric Data

Hexagon flat-to-flat width -	0.0191 m
Channel diameter -	0.00254 m
Number of channels/element -	19
Fuel pellet diameter -	0.00025 m
Coating thickness -	0.000125 m

Figure 4.1.1 shows the results of the NERVA specific power calculations for ZrC coated UC₂ pellet fuel in a graphite matrix. These curves show that a peak specific power occurs for a core length between about 0.55 and 0.65 m, depending on the fuel loading. To the left of the peak, the specific power is limited by the maximum fuel temperature limit (i.e., heat transfer limited); to the right of the peak, the specific power is limited by the pressure drop or Mach number limit (i.e., hydraulic limited). Therefore, to increase the specific power in the heat transfer limited region, it is necessary to improve the heat transfer characteristics of the core by increasing the channel wall area, by using materials with higher thermal conductivity, or by increasing the maximum allowed fuel temperature. To increase the specific power in the hydraulic-limited region, it is necessary to improve the flow characteristics of the core by increasing the channel hydraulic diameter, by increasing the maximum allowed Mach number, or by increasing the maximum allowed pressure drop.

Figure 4.1.2 illustrates the effect of increasing the maximum allowed fuel temperature. The peak is shifted to a smaller core length and the specific powers to the left of the peak are improved. Increasing the temperature limit, however, has no effect on the specific powers to the right of the peak because there, the specific powers are hydraulic limited.

Figure 4.1.3 shows the effect of changing the maximum allowed Mach number and pressure drop fraction. Increasing the Mach number to 0.4 without also increasing the pressure drop fraction has no effect on the specific power because the specific power is limited by the pressure drop restriction. Increasing only the pressure drop fraction without increasing the Mach number has a small effect over most of the hydraulic-limited region. However, further increase in the pressure drop limit would not change the specific power because of the Mach number restriction. To get any significant benefit in the hydraulic-limited region, it is necessary to increase both the Mach number and pressure drop limits. For example, increasing the pressure drop fraction to 0.5, with no Mach number restriction, results in a peak specific power of 54.0 MW/kg. This peak occurs at a core length of 0.86 m and an exit Mach number of 0.62.

Figure 4.1.4 shows the specific power for a variation of the NERVA concept. The core geometry information is the same as for the previous concept but the core is made from a composite of the UC₂-ZrC fuel and graphite matrix materials. Because the conduction resistances associated with a fuel pellet and coating are removed, the heat transfer characteristics of the composite core are improved. Also, the maximum allowed fuel temperature is higher for the composite, offering a further advantage over the pellet fuel. However, specific power is improved only in the heat transfer limited region. The specific power in the hydraulic-limited region remains the same as for the pellet fuel concept. Thus, the advantages of the composite core can be obtained only by using a very short core (for this particular core geometry).

Figure 4.1.5 shows the specific power for a third NERVA concept. The core for this concept is a UC₂ fuel, ZrC matrix composite. The higher maximum allowed temperature for this composite offers improved specific powers, but again, only for short cores. Pressure drop and Mach number constraints obviate any improvement for longer cores.

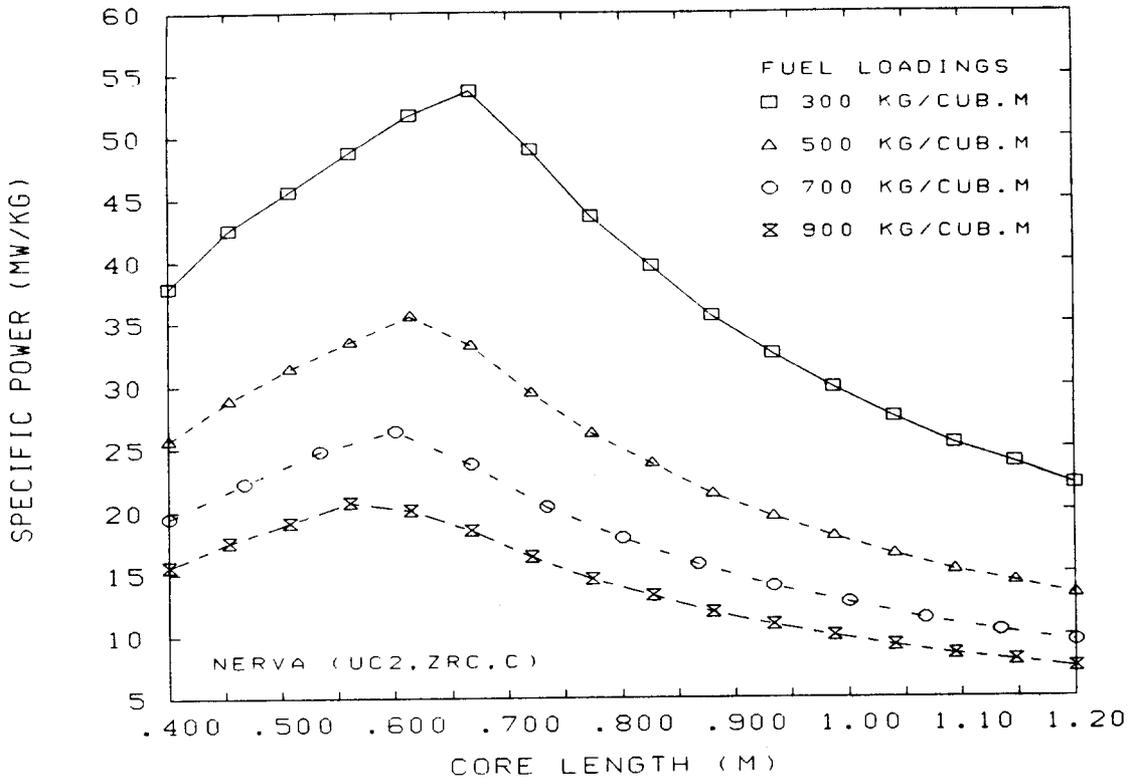


Figure 4.1.1 Specific Powers for NERVA Concept (Pellet Fuel)

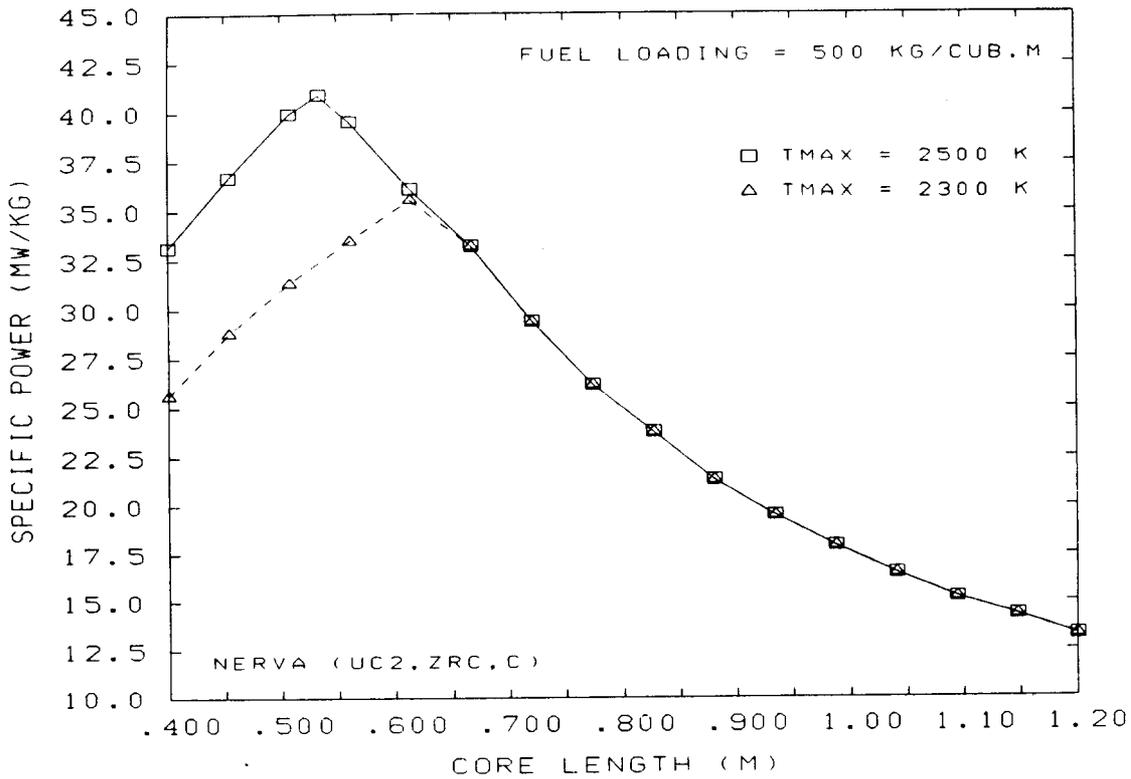


Figure 4.1.2 Effect of Maximum Fuel Temperature Limit on Specific Power (NERVA)

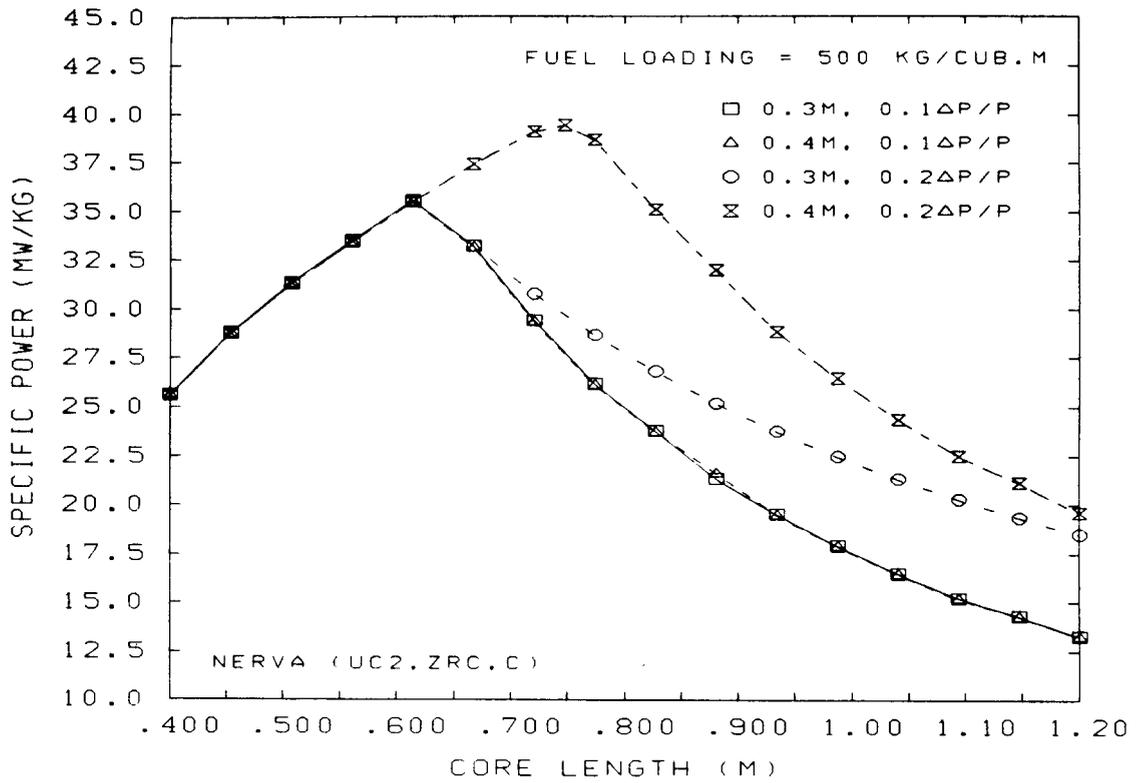


Figure 4.1.3 Effect of Mach Number and Pressure Drop Fraction on Specific Power (NERVA)

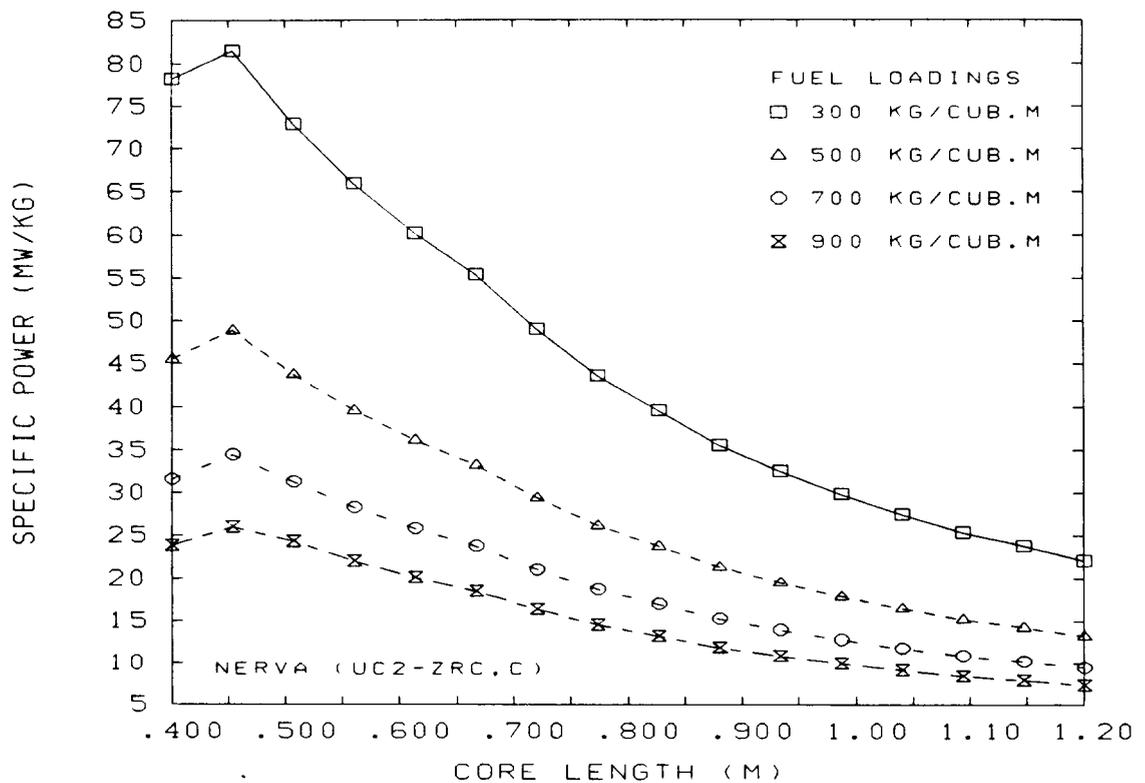


Figure 4.1.4 Specific Powers for NERVA Concept (UC₂-ZrC, C)

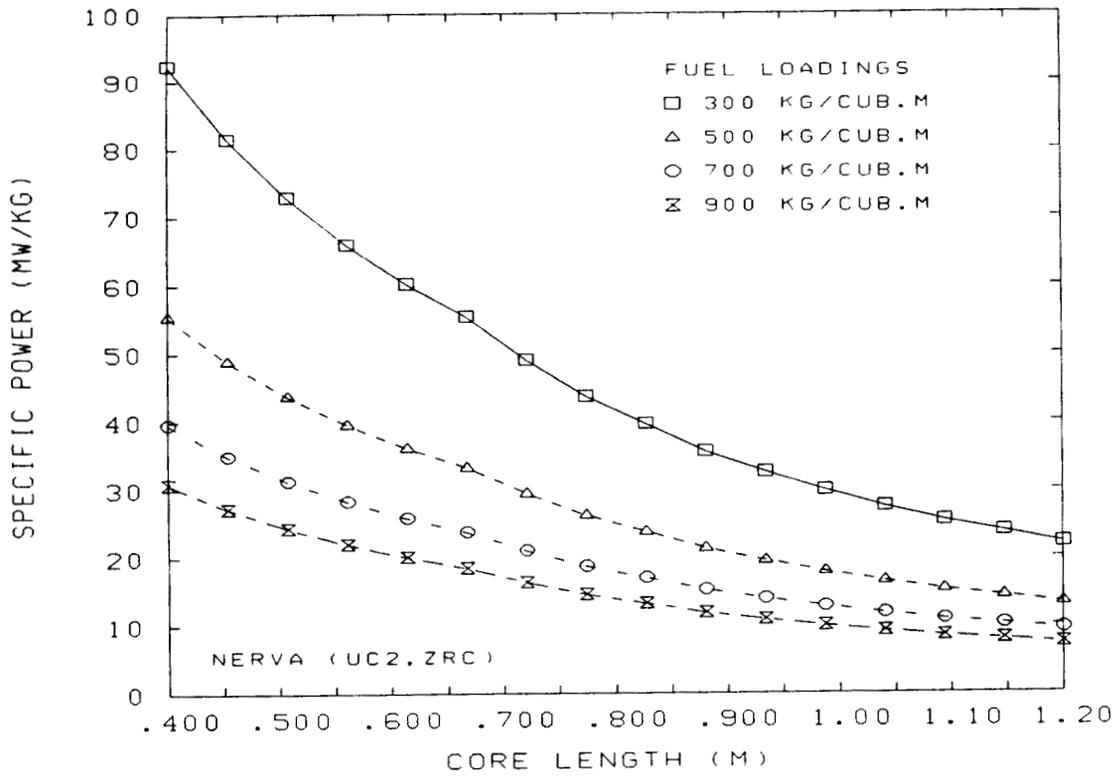


Figure 4.1.5 Specific Powers for NERVA Concept (UC₂, ZrC)

4.2 PLUTO

Three variations of the PLUTO concept [6] were investigated. The geometry for these concepts is given in Table 4.2.1. The major difference between this geometry and that used for the NERVA concepts is that only one cooling channel per element is used. However, the channel volume fraction, defined as the total channel volume divided by the total element volume, is about the same for both concepts (about 30%).

Table 4.2.1 PLUTO Geometric Data

Hexagon flat-to-flat width -	0.00683 m
Channel diameter -	0.004 m
Number of channels/element -	1

The first concept variation for PLUTO uses a UO_2 fuel, BeO matrix composite core. The specific power results are shown in Figure 4.2.1 for this concept. The effect of the PLUTO geometry on the specific power is that the peak occurs at a greater core length. Using one channel per element results in less wall area per channel compared to using 19 channels per element (as in NERVA). This reduces the specific power in the heat transfer limited region but increases it in the hydraulic-limited region for the concept. The effects of increasing the maximum allowed Mach number and pressure drop fraction are similar to that observed for NERVA and are shown in Figure 4.2.2.

An additional set of calculations was performed for this concept in which the channel diameter was varied. (The hexagon width was changed for each channel diameter to maintain the channel volume fraction equal to 0.30 to maintain structural integrity.) The results of these calculations are shown in Figure 4.2.3. Increasing the diameter reduces the specific power in the heat transfer limited region while decreasing the diameter reduces the specific power in the hydraulic-limited region. Obviously, choosing the optimum channel diameter depends on the core length, which can only be determined in conjunction with criticality and control considerations. However, with respect to heat removal, it is apparent that using many small diameter channels is better for shorter cores and that using a few large diameter channels is better for longer cores.

The second PLUTO concept variation uses a UC_2 fuel, graphite matrix composite core. This is essentially the same as the second NERVA concept except for the geometry. The specific power for this concept is shown in Figure 4.2.4. Because this concept is similar to NERVA, comparing this to Figure 4.1.4

shows the effect of changing the geometry from 19 small channels per element to one large channel per element. As expected, the effect is to increase the specific power for the larger values of core length.

The third PLUTO concept uses a core that is a composite of UB_4 fuel and B_4C matrix material. Because of the poor conductivity of this material, the specific powers are relatively low and are heat transfer limited over the core length of interest, as shown in Figure 4.2.5.

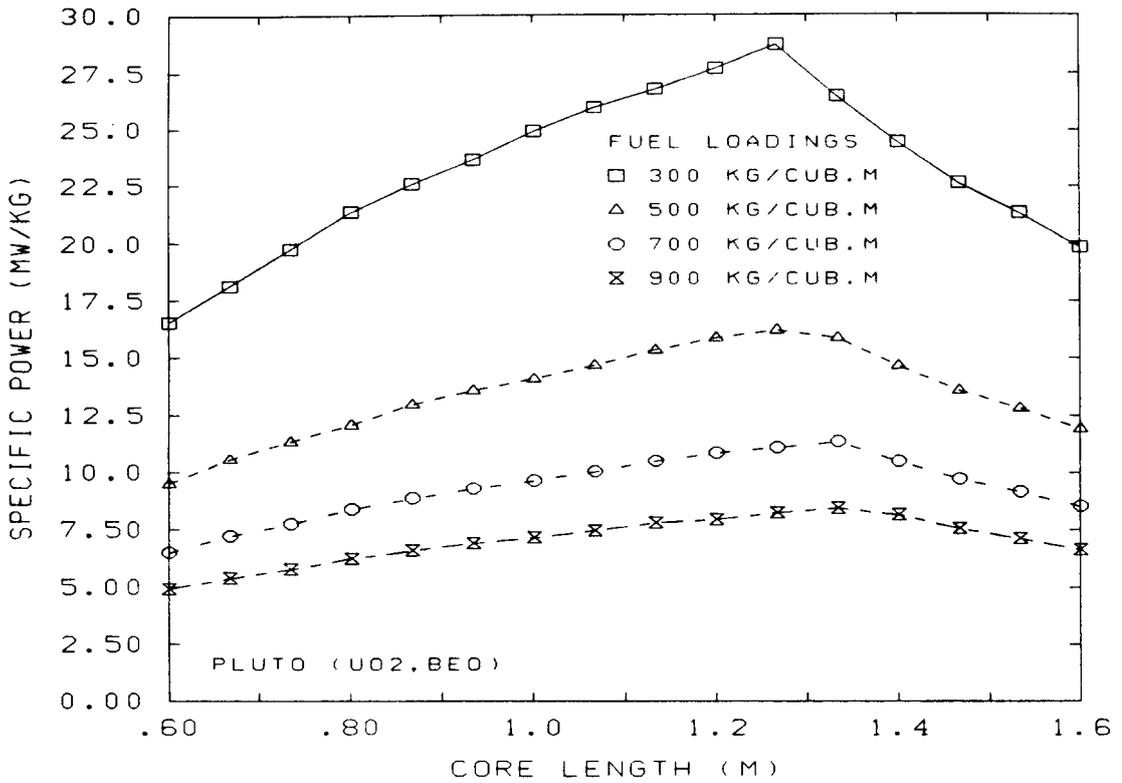


Figure 4.2.1 Specific Powers for PLUTO Concept (UO₂, BeO)

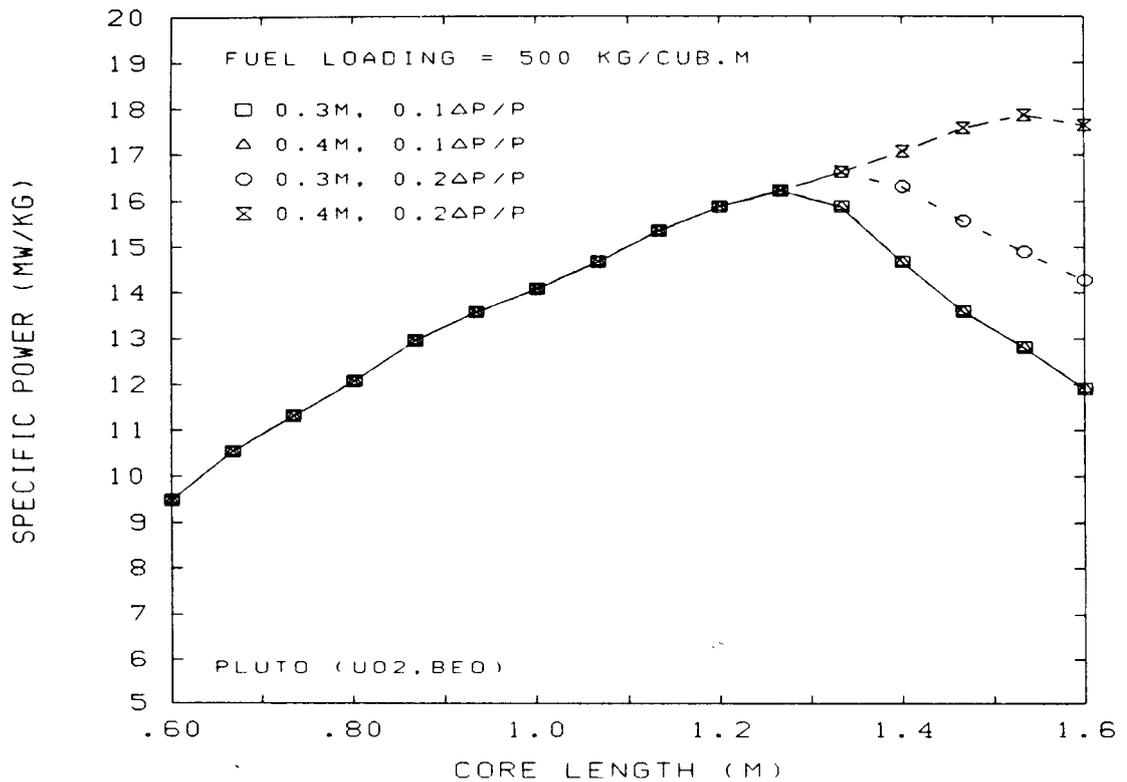


Figure 4.2.2 Effect of Mach Number and Pressure Drop Fraction on Specific Power (PLUTO)

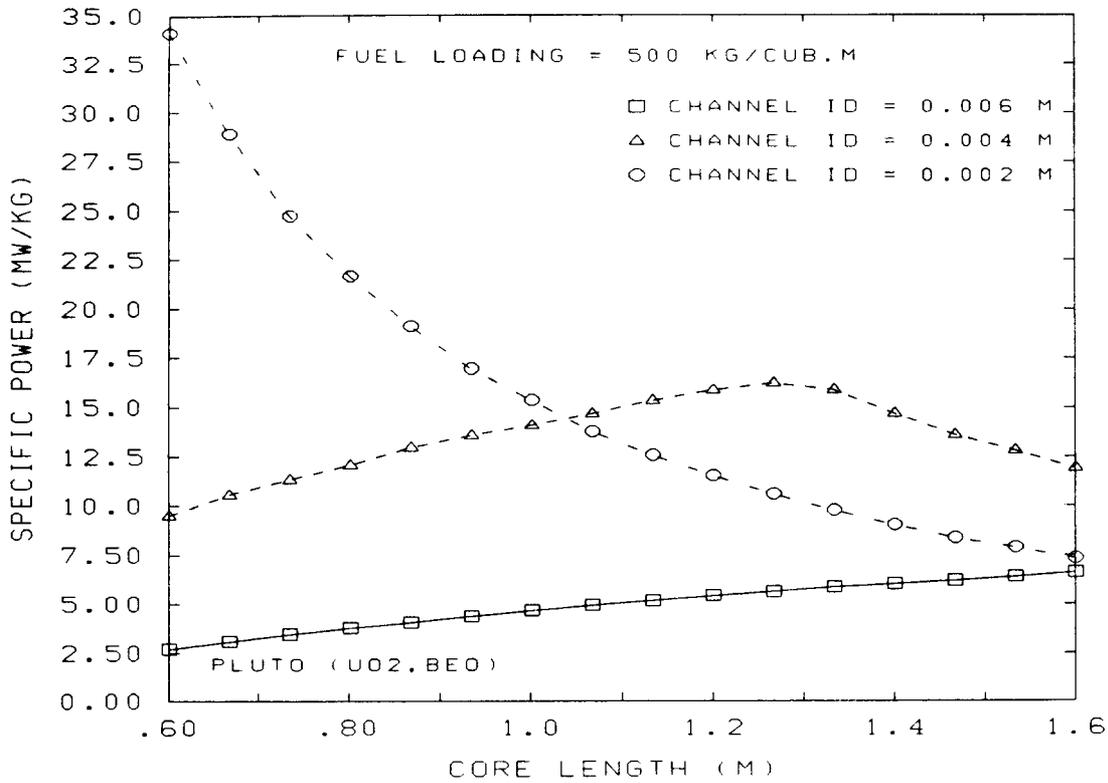


Figure 4.2.3 Effect of Channel Diameter (PLUTO)

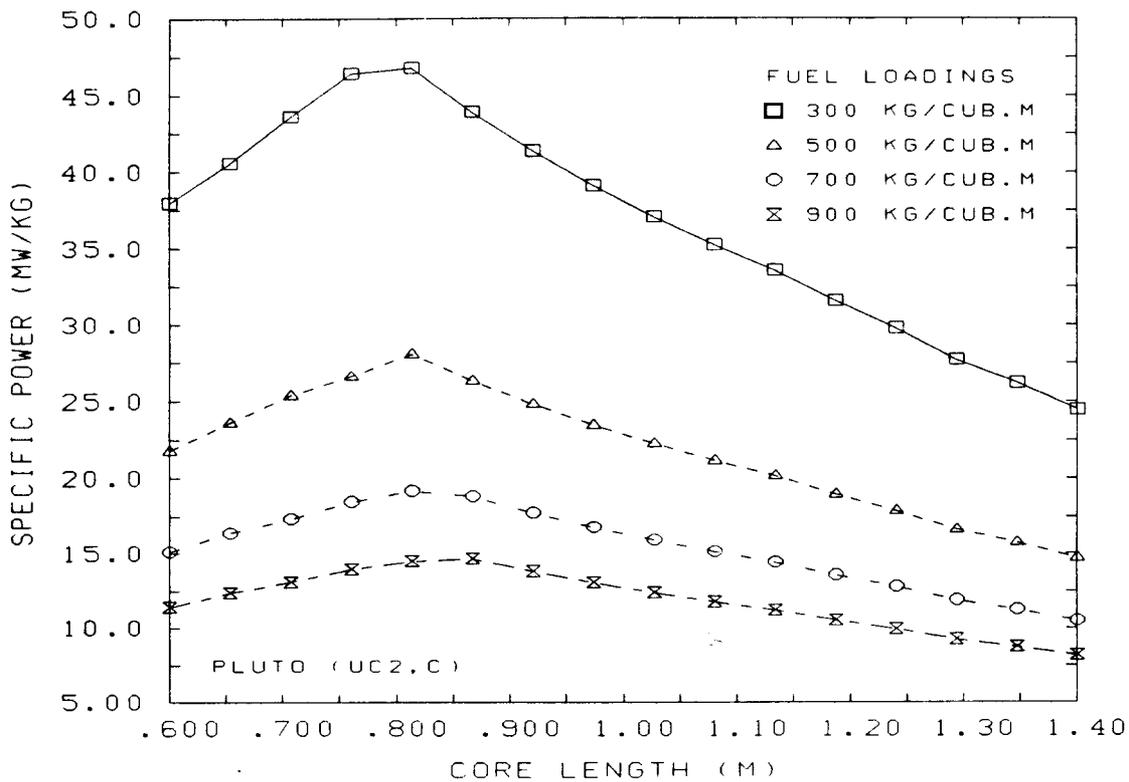


Figure 4.2.4 Specific Powers for PLUTO Concept (UC₂, C)

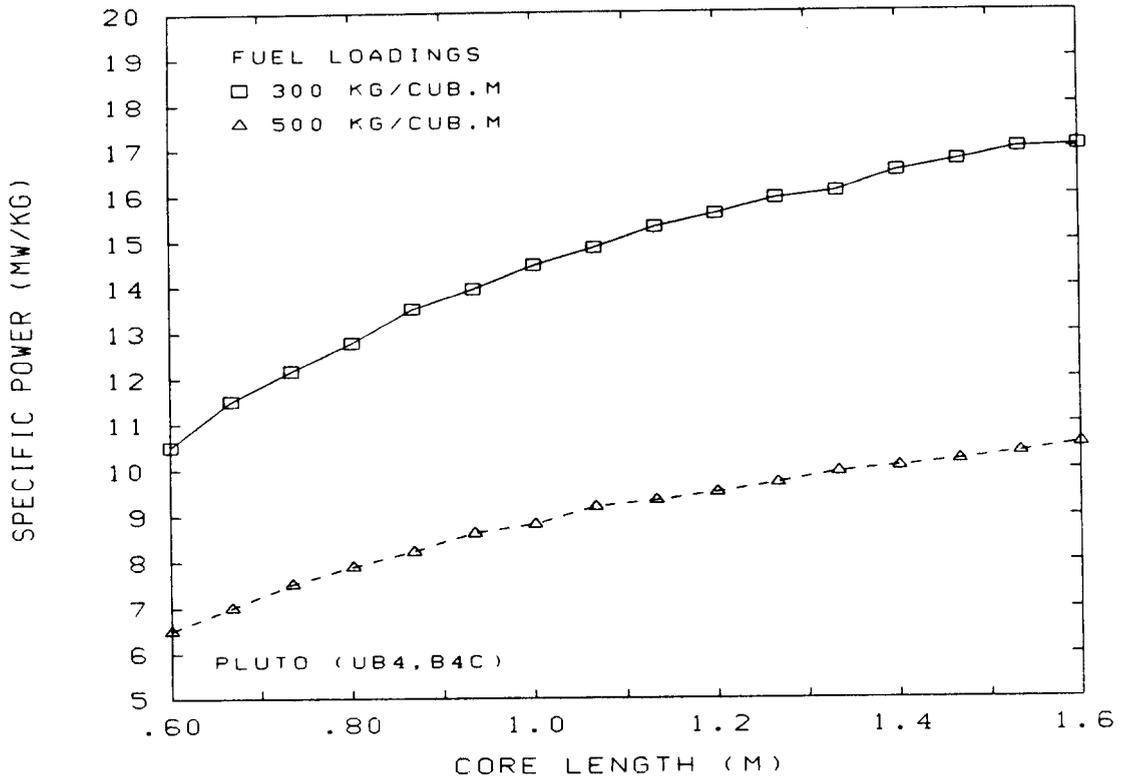


Figure 4.2.5 Specific Powers for PLUTO Concept (UB₄, B₄C)

4.3 CERMET

The final concept evaluated is a derivative of the 710 reactor [7] that used a core comprised of a ceramic fuel and a metal matrix material, referred to as a CERMET. The advantage of such a material is its very high thermal conductivity. The CERMET investigated is made of UO_2 fuel dispersed as coated pellets in a tungsten matrix. The coating is also tungsten. An alternative to tungsten is molybdenum, but, because its thermal conductivity is very similar to that of tungsten, specific power calculations were performed only for the tungsten CERMET concept.

The geometric data for the 710 CERMET core is given in Table 4.3.1. Based on this data, the channel volume fraction for the 710 core is only 0.154, compared to 0.30 for both NERVA and PLUTO. It is not known why such a low volume fraction was used; therefore, specific power calculations for both channel volume fractions were performed. (Also note that the pellet diameter is smaller than the pellet diameter used for NERVA.) The results are shown in Figure 4.3.1. (The fuel loadings used for these calculations are very high because, based on criticality calculations, the very high density of the matrix material results in an unacceptably low fuel-to-moderator ratio for lower fuel loadings.) As the figure shows, increasing the volume fraction to 0.30 appreciably increases the specific power. This same favorable increase can be realized for the other concepts provided structural integrity can be maintained at the higher volume fractions.

Table 4.3.1 CERMET Geometric Data

Hexagon flat-to-flat width -	0.03622 m
Channel diameter -	0.00343 m
Number of channels/element -	19
Fuel pellet diameter -	0.0001 m
Coating thickness -	0.00005 m

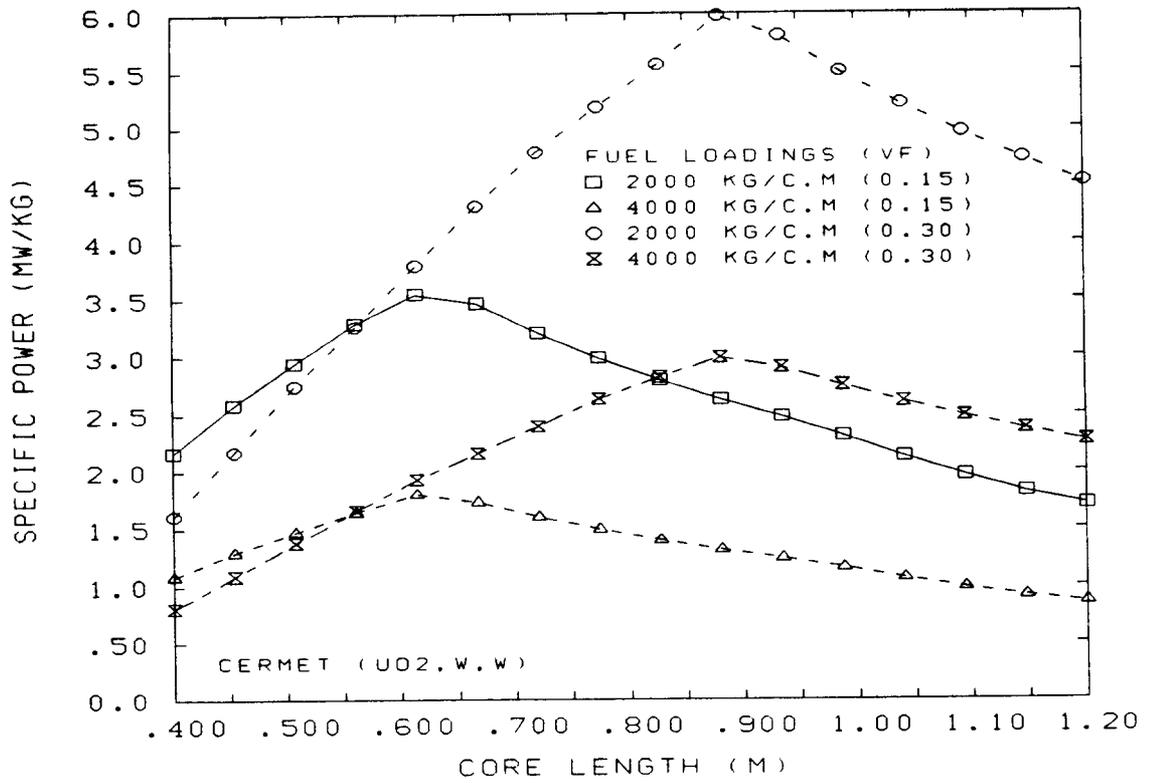


Figure 4.3.1 Specific Powers for CERMET Concept

4.4 SUMMARY OF PARAMETRIC CALCULATIONS

Figure 4.4.1 shows the specific power for the three different concepts and their variations (for a 500 kg/m^3 fuel loading). This set of curves can not really be used for comparing specific powers among the various concepts because they do not reflect the criticality aspects associated with the different fuel loadings, core lengths, and fuel and matrix materials. However, they do provide an indication of what geometric parameter would have to be changed to improve the specific power in either the heat transfer or hydraulic-limited regions. For example, The NERVA concepts offer very good heat transfer characteristics but poor hydraulic characteristics with respect to specific power. To improve the hydraulic characteristics (at the expense of the heat transfer characteristics) it would be necessary to use fewer channels of larger diameter. This would shift the specific power peak to the right. The PLUTO concept that uses UB_4 and B_4C would require the exact opposite change. That is, it would be necessary to use more channels of smaller diameter to increase the specific power in the heat transfer limited region.

All of the concepts analyzed had the same basic geometry; i.e., a group of hexagonal elements with a certain number of channels formed within each element for coolant flow. It would therefore be possible to "redesign" (without consideration for structural integrity) all of the concepts in order to optimize the specific power with respect to channel diameter and number. Thus, with respect to thermal hydraulic performance, the only parameters that distinguish one concept from another are the thermal conductivity and the maximum operating temperature. However, it may not be possible to take advantage of a materials higher conductivity or temperature capability due to the imposed hydraulic limits. Whether or not a higher conductivity or temperature will be of benefit can only be determined after considering the criticality and control aspects of the concept.

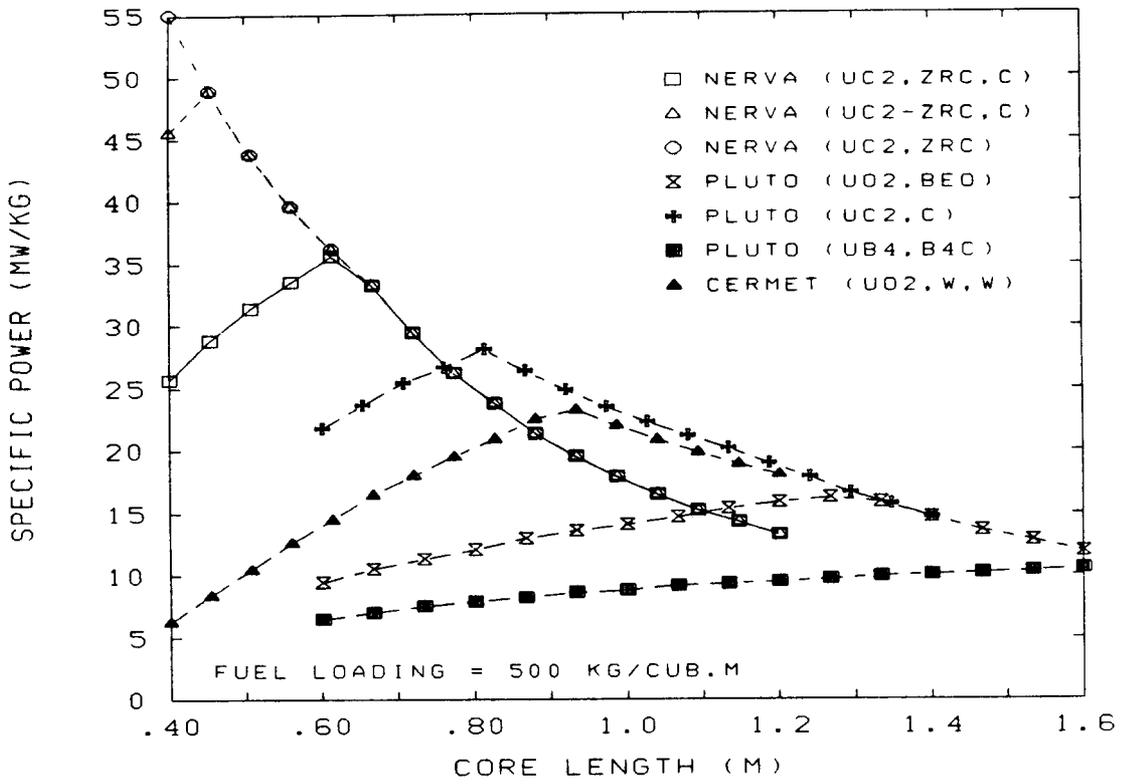


Figure 4.4.1 Specific Powers for All Concepts

5.0 SUMMARY AND CONCLUSIONS

A computer program has been written to determine the maximum specific power for prismatic-core reactors as a function of maximum allowable fuel temperature, core pressure drop, and coolant velocity. The prismatic-core reactors consist of hexagonally shaped fuel elements grouped together to form a cylindrically shaped core. A gas coolant (either helium or hydrogen) flows axially through circular channels within the elements and the fuel is dispersed within the solid element (matrix) material either as a composite or in the form of coated pellets. Different coolant, matrix, coating, and fuel materials can be selected to represent different prismatic-core concepts. The computer program allows the user to divide the core into any arbitrary number of axial levels to account for different axial power shapes. An option in the program allows the automatic determination of the core height that results in the maximum specific power.

This program provides a simple means for evaluating and comparing the specific power of various prismatic-core concepts. The program is written such that additional material properties can easily be added if desired. Various input parameters allow the program user to specify different heat transfer and hydraulic constraints along with different core geometries. Results from the program also provide information that can be useful in the redesign of the concept to take better advantage of the heat transfer characteristics of the various core materials.

6.0 REFERENCES

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2. Glasstone and Sesonske, NUCLEAR REACTOR ENGINEERING, Van Nostrand Reinhold, 1967.
3. Incropera and DeWitt, FUNDAMENTALS OF HEAT TRANSFER, 1981.
4. "Nuclear Engine Definition Study Preliminary Report," Volume II - Supporting Studies, LA-5044-MS, September, 1972.
5. "A Design Study of Low Power, Light Weight Rover Reactors," W. L. Kirk, Los Alamos National Laboratory, LA-3642-MS, August 1966.
6. "Tory IIC Reactor Test Report," edited by Harry L. Reynolds, October 12, 1964.
7. "710 High Temperature Gas Reactor Summary Report," GEMP-600, General Electric.

APPENDIX - COMPUTER PROGRAM LISTING

```

C
C PROGRAM TO DETERMINE MAXIMUM SPECIFIC POWER FOR A REACTOR
C COMPRISED OF HEXAGONAL FUEL ELEMENTS (SUCH AS NERVA)
C
C INPUT: UNIT 5
C OUTPUT: UNIT 6
C
COMMON/INPUT/IDCOOL,NPASS,PRES,TIN,TOUT,FLOAD,PTOAR,HERR,
1 HCOREMIN,DCORE,FTOF,FRACCLUSU,NECHANU,NECHANM,
2 NEHOLES,DCHANU,DHOLE,SCHAN,DFUEL,THCLAD,
3 DIU,DOU,DIM,TCLADMAX,TGMAX,TFUELMAX,FRACPPMAX,
4 FRACSPMAX,FRACSONIC,NAXIAL,ISHAPE,EXL,IFLAG,ICOMP,
5 NEPC,DFUEL,IDMOD,IDCLAD
COMMON/DIM/RELPOW(50),TCOOL(50),TWCHAN(50),POW(50),HTC(50)
1 ,TG(50),TCLAD(50),TFUEL(50),DELTAP(50),VEL(50)
2 ,PWORK(50)
COMMON/OUTPUT/VF,NCHAN,SONIC,POWTOTAL,DELPTOT1,POWDENV,
1 PWORKTOT1,DELTAPCAN,DPTURN,PWORKCAN,FSONIC,FSONICM,
2 DELPTOT2,FRACSP,PWORKTOT2,FRACPP
COMMON/REALS/MFUEL,NPELLET,MPELLET,MDOTMAX,MDOTCAN,
1 NPELAX,NCLUSPERA,NFEPCU,NFEPCM
REAL MFUEL,NPELLET,MPELLET,MDOTMAX,MDOTCAN,NPELAX,
1 NCLUSPERA,NFEPCU,NFEPCM
C
READ(5,1)NO
1 FORMAT(1)
READ(5,*)IDCOOL
READ(5,*)IDFUEL
READ(5,*)IDMOD
READ(5,*)IDCLAD
READ(5,*)NPASS
READ(5,*)PRES
READ(5,*)TIN
READ(5,*)TOUT
READ(5,*)FLOAD
READ(5,*)PTOAR
READ(5,*)HCORE
READ(5,*)HERR
READ(5,*)HCOREMIN
READ(5,*)DCORE
READ(5,*)FTOF
READ(5,*)FRACCLUSU
READ(5,*)NEPC
READ(5,*)NFEPCU
READ(5,*)NFEPCM
READ(5,*)NECHANU
READ(5,*)NECHANM
READ(5,*)NEHOLES
READ(5,*)DCHANU
READ(5,*)DHOLE
READ(5,*)SCHAN
READ(5,*)DFUEL

READ(5,*)THCLAD
READ(5,*)DIU
READ(5,*)DOU
READ(5,*)DIM
READ(5,*)TCLADMAX
READ(5,*)TGMAX
READ(5,*)TFUELMAX
READ(5,*)FRACPPMAX
READ(5,*)FRACSPMAX
READ(5,*)FRACSONIC

C
READ(5,*)NAXIAL
C IF NAXIAL = 0, THEN USE CORE EXIT TEMPERATURE TO DO HEAT TRANSFER
C CALCULATIONS BUT TAV TO DO DP CALCULATIONS
IF(NAXIAL.EQ.0)THEN
NAXIAL=1
IFLAG=1
ELSE
IFLAG=0
ENDIF
C ISHAPE = 0 COSINE POWER SHAPE IS USED
C ISHAPE = 1 FLAT AXIAL POWER SHAPE
C ISHAPE = 2 USER SPECIFIED POWER SHAPE
READ(5,*)ISHAPE
C EXL IS THE EXTRAPOLATION LENGTH
READ(5,*)EXL
IF(ISHAPE.GT.1)READ(5,*)(RELPOW(I),I=1,NAXIAL)
C FOR COMPOSITE FUEL INSTEAD OF PELLETS
ICOMP=0
IF(DFUEL.LT.0.0)ICOMP=1
DFUEL=ABS(DFUEL)
C
*****
C OPTIMIZE POWDENM WRT HCORE IF HERR GT 0.0
IF(HERR.GT.0.0)THEN
C FIND AN INTERVAL CONTAINING THE MAXIMUM
C (INPUT HCORE IS USED AS MAXIMUM ALLOWED HCORE)
CALL XINT(HCORE,HCOREMIN,H1,H2,FH1,FH2)
C USE MODIFIED REGULA-FALSI TO FIND HCORE AT WHICH MAX POWDENM OCCURS
C (IF NO MAX IS FOUND WITHIN ALLOWED HCOREMAX, SKIP OPTIMIZATION)
IF(H1.EQ.H2)GO TO 5
CALL MRF(H1,H2,FH1,FH2,HERR,HCORE)
CALL PDEN(HCORE,POWDENM)
ELSE
C NO OPTIMIZATION, JUST USE INPUT HCORE
5 CALL PDEN(HCORE,POWDENM)
ENDIF
C
*****
C WRITE OUT FINAL RESULTS

```

```

C
WRITE(6,2005)
DO 150 I=1,NAXIAL
TCOOLA=(TCOOL(IA)+TCOOL(IA+1))*0.5
150 WRITE(6,2030)IA,POW(IA),VEL(IA),HTC(IA),TCOOLA,TWCHAN(IA),
1TG(IA),TCLAD(IA),TFUEL(IA),DELTAP(IA)
WRITE(6,2000)VFNPELLET,MFUEL,NCHAN,SONIC,HCORE
WRITE(6,2010)MDOTMAX,POWTOTAL,POWDENM,POWDENV,
1DELPTOT1,PWORKTOT1
WRITE(6,2020)MDOTCAN,DELTAPCAN,DPTURN,PWORKCAN
WRITE(6,2040)FSONIC,FSONICM,DELPTOT2,FRACSP,PWORKTOT2,FRACPP
C
2000 FORMAT(' ',3X,'CHANNEL VOLUME FRACTION = ',F8.5,/,
13X,'NUMBER OF FUEL PELLETS = ',1PE11.5,/,
23X,'FUEL MASS (KG) = ',0PF8.2,/,
33X,'NUMBER OF COOLANT CHANNELS = ',110,/,
43X,'SONIC SPEED OF COOLANT (M/S) = ',F9.2,/,
53X,'CORE HEIGHT (M) = ',F8.3)
2005 FORMAT(' ',4X,'2',3X,' POWER (W) ',2X,'VELCTY (M/S)',
12X,'H (W/SO M/K)',3X,'TCOOL (K)',3X,'TWALL (K)',
23X,'TMOD (K)',4X,'TCLAD (K)',3X,'TFUEL (K)',
32X,'DELTA-P (PA)',/)
2010 FORMAT(' ',3X,'CORE MASS FLOW RATE (KG/S) = ',F9.3,/,
13X,'TOTAL CORE POWER (W) = ',1PE11.5,/,
25X,'SPECIFIC POWER (W/KG-U) = ',E11.5,/,
35X,'POWER DENSITY (W/CUB M-U) = ',E11.5,/,
43X,'CORE PRESSURE DROP (PA) = ',E11.5,/,
53X,'CORE PUMPING POWER (W) = ',E11.5)
2020 FORMAT(' ',3X,'CAN MASS FLOW RATE (KG/S) = ',F9.3,/,
13X,'CAN PRESSURE DROP (PA) = ',1PE11.5,/,
24X,'TURNING PRESSURE DROP (PA) = ',E11.5,/,
33X,'CAN PUMPING POWER (W) = ',E11.5)
2030 FORMAT(' ',2X,13,2X,9(1PE12.5,2X))
2040 FORMAT(' ',3X,'FRACTION OF SONIC SPEED IN CORE = ',F8.5,/,
13X,'FRACTION OF SONIC SPEED IN MODERATOR = ',F8.5,/,
13X,'TOTAL PRESSURE DROP (PA) = ',1PE11.4,/,
25X,'FRACTION OF CORE PRESSURE = ',0PF8.5,/,
33X,'TOTAL PUMPING POWER (W) = ',1PE11.4,/,
45X,'FRACTION OF CORE POWER = ',0PF8.5)
C
STOP
END
C
C----- SUBROUTINES -----
C
SUBROUTINE FUN(HC,DPDEN)
C FIND THE VALUE OF THE DERIVATIVE OF THE POWDEN FUNCTION
DEL=0.02
X1=AMAX1(HC-DEL,0.01)
X2=AMAX1(HC+DEL,X1+0.01)
CALL PDEN(X1,FX1)
CALL PDEN(X2,FX2)
C
DPDEN=(FX2-FX1)/2.0/DEL
CR
WRITE(6,4)X1,FX1,X2,FX2,HC,DPDEN
4 FORMAT(' ',2X,3(F7.4,2X,E12.4,3X))
RETURN
END
C
C
SUBROUTINE PDEN(HCORE,POWDENM)
COMMON/INPUT/IDCOOL,NPASS,PRES,TIN,TOUT,FLOAD,PTOAR,HERR,
1 HCOREMIN,DCORE,FTOF,FRACCLUSU,NECHANU,NECHANM,
2 NEHOLE,S,DCHANU,DHOLE,S,CHAN,DFUEL,THCLAD,
3 DIU,DOU,DIM,TCLADMAX,TGMAX,TFUELMAX,FRACPPMAX,
4 FRACSPMAX,FRACSONIC,NAXIAL,ISHAPE,EXL,IFLAG,ICOMP,
5 NEPC,IDFUEL,IDMOD,IDCLAD
COMMON/DIM/RELPOW(50),TCOOL(50),TWCHAN(50),POW(50),HTC(50)
1 TG(50),TCLAD(50),TFUEL(50),DELTAP(50),VEL(50)
2 PWORK(50)
COMMON/OUTPUT/VFNCHAN,SONIC,POWTOTAL,DELPTOT1,POWDENV,
1 PWORKTOT1,DELTAPCAN,DPTURN,PWORKCAN,FSONIC,FSONICM,
2 DELPTOT2,FRACSP,PWORKTOT2,FRACPP
COMMON/REALS/MFUEL,NPELLET,MPELLET,MDOTMAX,MDOTCAN,
1 NPELAX,NCLUSPERA,NFEPCU,NFEPCM
C
REAL MFUEL,NPELLET,MPELLET,MDOTMAX,MDOTCAN,NPELAX,
1 NCLUSPERA,NFEPCU,NFEPCM
C
C FRICTION FACTOR
FF(RE,PR)=0.184*RE**(-0.2)*PR**(-0.6)
C
PI=3.141592654
DCHANM=DCHANU
TERR=0.5
HE=HCORE+2.0*EXL
HS=-HCORE*0.5
DX=HCORE/NAXIAL
C
TOT=0.0
RMAX=0.0
DO 5 I=1,NAXIAL
IF(ISHAPE.EQ.1)RELPOW(I)=1.0
IF(ISHAPE.EQ.0)
1RELPOW(I)=SIN(PI/HE*(HS+I*DX))-SIN(PI/HE*(HS+(I-1)*DX))
RMAX=AMAX1(RMAX,RELPOW(I))
5 TOT=TOT+RELPOW(I)
C PEAK TO AVERAGE POWER FACTOR
PTOA2=RMAX/TOT*NAXIAL
C SCALE RELATIVE POWER SHAPE SO THE TOTAL POWER OF ALL
C AXIAL LEVELS ADDS TO THE CORRECT TOTAL CORE POWER
DO 7 I=1,NAXIAL
7 RELPOW(I)=RELPOW(I)/TOT
C

```

```

C CALCULATE CHANNEL FLOW AREA AND WALL AREA
  ACORE=PI*DCORE*DCORE*0.25
C AREA OF HEXAGON = FTOF**2 *1.5/TAN(60)
C NCLUSPERA - NUMBER OF CLUSTERS PER AREA OF CORE
  NCLUSPERA=1.0/(NEPC*0.866025*FTOF*FTOF)
  NCLUSTU=NCLUSPERA*FRACCLUSU*ACORE
  NCLUSTM=NCLUSPERA*(1.0-FRACCLUSU)*ACORE
C A CLUSTER CONTAINS A TOTAL OF NEPC ELEMENTS
C NFEPCLU IS NUMBER OF FUELED ELEMENTS/UNMOD CLUSTER
C NFEPCLM IS NUMBER OF FUELED ELEMENTS/MOD CLUSTER
  NCHANU=NCLUSTU*NECHANU*NFEPCLU
  NCHANM=NCLUSTM*NECHANM*NFEPCLM
  NCHAN=NCHANU+NCHANM
  ACHAN=PI*DCHANU*DCHANU*0.25+NCHANU*PI*DCHANM*DCHANM*0.25+NCHANM
  WACHAN=PI*DCHANU*HCORE*NCHANU+PI*DCHANM*HCORE*NCHANM
C
C SINGLE AND DOUBLE PASS
  ACANU=PI*DOU*DOU*0.25*NCLUSTU*(NEPC-NFEPCLU)
  ACANM=PI*DIM*DIM*0.25*NCLUSTM*(NEPC-NFEPCLM)
  AHOLE=PI*DHOLES*DHOLES*0.25*NCLUSTM*NEHOLES
C EFFECTIVE CHANNEL AND CAN HYDRAULIC DIAMETERS
  WPC=WACHAN/HCORE
  DCHAN=4.0*ACHAN/AMAX1(WPC,0.0001)
  WP=NCLUSTU*PI*(DOU+2.0*DIU)
  HDCANU=4.0*ACANU/AMAX1(WP,0.0001)
  IF(HDCANU.LT.1.0E-6)HDCANU=0.00001
C
C FOR THREE PASSES
  ACANU1=PI*DIU*DIU*0.25*NCLUSTU*(NEPC-NFEPCLU)
  ACANU2=ACANU-ACANU1
  WP2=NCLUSTU*PI*(DOU+DIU)
  HDCANU2=4.0*ACANU2/AMAX1(WP2,0.0001)
  IF(HDCANU2.LT.1.0E-6)HDCANU2=0.00001
C
C AREAS PER MOD AND UNMOD ELEMENTS (AREA OF MOD ELEMENT IS
C NECHANM/NECHANU OF UNMOD ELEMENT)
  APEU=1.0/(NEPC*NCLUSPERA)
  APEM=APEU*NECHANM/NECHANU
  AETOT=APEU*NCLUSTU*NFEPCLU+APEM*NCLUSTM*NFEPCLM
C TOTAL VOL OF ALL ELEMENTS AVAILABLE FOR FUEL LOADING
  VOLCORE=(AETOT-ACHAN)*HCORE
  VF=ACHAN/AETOT
  MFUEL=FLOAD*VOLCORE
  VOLPELLET=4.0/3.0*PI*(DFUEL*0.5)**3
C USE COLD (ROOM TEMPERATURE) DENSITY OF FUEL TO CALCULATE FUEL MASS
  CALL DENSITY(300.0,DFUEL,DENFUEL)
  MPELLET=VOLPELLET*DENFUEL
  NPELLET=MFUEL/MPELLET
  NPELAX=NPELLET/NAXIAL
C CALCULATE MASS OF MODERATOR IN FUELED ELEMENTS
  CALL DENSITY(300.0,DMOD,DENMOD)
  GMASS=DENMOD*(VOLCORE-MFUEL/DENFUEL)
C
C
C CALCULATE SONIC VELOCITY OF COOLANT AT CORE ENTRANCE AND EXIT
C (WM IS COOLANT MOLECULAR WEIGHT)
  WM=4.0
  IF(IDCOOL.EQ.2)WM=2.0
  CALL CSUBPCOOL(TIN,IDCOOL,CSUBPCI)
  CALL CSUBPCOOL(TOUT,IDCOOL,CSUBPCO)
  CALL DENCool(PRES,TIN,IDCOOL,DENCI)
  CALL DENCool(PRES,TOUT,IDCOOL,DENCO)
  GAMCOOL=CSUBPCI/(CSUBPCI-8314.5/WM)
  SONICI=(GAMCOOL/WM*8314.5*TIN)**0.5
  GAMCOO=CSUBPCO/(CSUBPCO-8314.5/WM)
  SONICO=(GAMCOO/WM*8314.5*TOUT)**0.5
C MAXIMUM SONIC VELOCITY IS AT CORE EXIT, BUT IF RESULTING CORE
C INLET VELOCITY IS GREATER THAN INLET SONIC VELOCITY, MUST USE
C INLET SONIC VELOCITY AS MAXIMUM ALLOWED
  IF(SONICO*DENCO/DENCI.GT.SONICI)THEN
    VELMAX=FRACSONIC*SONICI
    SONIC=SONICI
    G=VELMAX*DENCI
    ILOC=1
  ELSE
    VELMAX=FRACSONIC*SONICO
    SONIC=SONICO
    G=VELMAX*DENCO
    ILOC=NAXIAL
  ENDIF
C
C
C DO 1000 IV=1,300
C CORE FLOW RATE BASED ON MAXIMUM ALLOWED VELOCITY (G = VEL*DEN)
  MDOTMAX=G*ACHAN
  POWTOTAL=MDOTMAX*(CSUBPCO+CSUBPCI)*0.5*(TOUT-TIN)
  POWFUEL=POWTOTAL
  POWPELLET=POWFUEL/NPELLET
  POWDENM=POWTOTAL/MFUEL
  POWDENV=POWTOTAL/VOLCORE
C
C BEGIN STEPPING THROUGH EACH AXIAL ZONE TO DETERMINE COOLANT, CLAD,
C AND FUEL TEMPERATURES
  TCOOL(1)=TIN
C
C GUESS FOR AXIAL ZONE COOLANT TEMPERATURE INCREASE
  TI=(TOUT-TIN)/NAXIAL
  DXP=0.0
  PRESN=PRES
C
C
  TGC=0.0
  TCL=0.0
  TFU=0.0
  DELPTOT1=0.0
  PWORKTOT1=0.0

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C      DO 50 IA=1,NAXIAL
      DXP=DXP+DX
      POW(IA)=POWFUEL*RELPOW(IA)
C
      IF(IFLAG.EQ.1)THEN
      TAV=TOUT
      TCOOL(1)=TOUT
      TCOOL(2)=TOUT
      GO TO 65
      ELSE
      ENDIF
C
      TCOOL(IA+1)=TCOOL(IA)+T1
      CALL CSUBPCOOL(TCOOL(IA),IDCOOL,CSUBP1)
C      ITERATE TO DETERMINE ZONE EXIT TEMPERATURE
C      (ITERATION IS NECESSARY WHEN CSUBP IS NOT CONSTANT)
      DO 60 I2=1,50
      CALL CSUBPCOOL(TCOOL(IA+1),IDCOOL,CSUBP0)
      CPAVG=(CSUBP1+CSUBP0)*0.5
      TCNEW=POW(IA)*PTOAR/MDOTMAX/CPAVG+TCOOL(IA)
      IF(ABS(TCNEW-TCOOL(IA+1)).LT.TERR)GO TO 62
      60 TCOOL(IA+1)=TCNEW
      62 TCOOL(IA+1)=(TCOOL(IA+1)+TCNEW)*0.5
C
C      NOW DETERMINE ZONE PROPERTIES
      TAV=(TCOOL(IA)+TCOOL(IA+1))*0.5
      65 CONTINUE
      CALL DVISCOOL(PRESN,TAV,IDCOOL,DVIS)
      CALL DENCOOL(PRESN,TAV,IDCOOL,DEN)
      IF(PRESN.LE.0)DEN=1.0
      VEL(IA)=MDOTMAX/DEN/ACHAN
      VS=VEL(IA)
      RENUM=DEN*VEL(IA)*DCHAN/DVIS
      CALL CONDCOOL(TAV,IDCOOL,COND)
      CALL CSUBPCOOL(TCOOL(IA),IDCOOL,CSUBP1)
      CALL CSUBPCOOL(TCOOL(IA+1),IDCOOL,CSUBP2)
      CSUBP=(CSUBP1+CSUBP2)*0.5
      PRNUM=DVIS*CSUBP/COND
C
C      NOW CALCULATE CHANNEL WALL TEMPERATURE ITERATIVELY
      TW=TAV+50.0
      DO 70 I3=1,25
      CALL HTCC(TAV,DXP,COND,DCHAN,RENUM,PRNUM,TW,HTC(IA))
      TWN=TAV+POW(IA)*PTOAR/WACHAN*NAXIAL/HTC(IA)
      IF(ABS(TWN-TW).LT.TERR)GO TO 72
      70 TW=TWN
      72 TWCHAN(IA)=(TW+TWN)*0.5
C
C      CALCULATE MODERATOR DELTA T
      CALL CONDUCT(TWCHAN(IA),IDMOD,COND)
C      FOR COMPOSITE FUEL, CALCULATE AVERAGE CONDUCTIVITY OF FUEL/MODERATOR
      IF(ICOMP.NE.0)THEN
      CALL CONDUCT(TWCHAN(IA),IDFUEL,CONDFUEL)
      COND=(MFUEL/DENFUEL*CONDFUEL+GMASS/DENMOD*COND)
      1/(MFUEL/DENFUEL+GMASS/DENMOD)
      ELSE
      ENDIF
      DELTAT=POW(IA)/NCHAN*PTOAR*ALOG((SCHAN*2.0+DCHAN)/DCHAN)*0.5/PI
      1/DX/COND
      TG(IA)=TWCHAN(IA)+DELTAT
C      UPDATE THERMAL CONDUCTIVITY AND RE CALCULATE TG
      TNEW=(TWCHAN(IA)+TG(IA))/2.0
      CALL CONDUCT(TNEW,IDMOD,COND)
      IF(ICOMP.NE.0)THEN
      CALL CONDUCT(TNEW,IDFUEL,CONDFUEL)
      COND=(MFUEL/DENFUEL*CONDFUEL+GMASS/DENMOD*COND)
      1/(MFUEL/DENFUEL+GMASS/DENMOD)
      ELSE
      ENDIF
      DELTAT=POW(IA)/NCHAN*PTOAR*ALOG((SCHAN*2.0+DCHAN)/DCHAN)*0.5/PI
      1/DX/COND
      TG(IA)=TWCHAN(IA)+DELTAT
C
C      CALCULATE CLAD (OR COATING) DELTA T
      POWPEL=POW(IA)/NPELAX
      RFUEL=DFUEL*0.5
C
      DELTAT=0.0
      IF(ICOMP.EQ.0)THEN
      CALL CONDUCT(TG(IA),IDCLAD,CONDCLAD)
      DELTAT=POWPEL*PTOAR*THCLAD*0.25/PI/RFUEL/CONDCLAD/
      1(RFUEL+THCLAD)
      ELSE
      ENDIF
      TCLAD(IA)=TG(IA)+DELTAT
C
C      CALCULATE FUEL DELTA T
      DELTAT=0.0
      IF(ICOMP.EQ.0)THEN
      CALL CONDUCT(TCLAD(IA),IDFUEL,CONDFUEL)
      DELTAT=POWPEL*PTOAR/8.0/PI/RFUEL/CONDFUEL
      ELSE
      ENDIF
      TFUEL(IA)=TCLAD(IA)+DELTAT
C
      IF(IFLAG.EQ.0)GO TO 75
C      AVERAGE FOR CALCULATING DP
      TAV=(TIN+0.97*TOUT)*0.5
      CALL DVISCOOL(PRES,TAV,IDCOOL,DVIS)
      CALL DENCOOL(PRES,TAV,IDCOOL,DEN)
      VEL(IA)=MDOTMAX/DEN/ACHAN
      RENUM=DEN*VEL(IA)*DCHAN/DVIS
      CALL CONDCOOL(TAV,IDCOOL,COND)

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CALL CSUBPCOOL(TAV, IDCOOL, CSUBP)
PRNUM=DVIS*CSUBP/COND
C DETERMINE PRESSURE DROPS AND PUMP WORK
75 CONTINUE
F=FF(RENUM, PRNUM)
DELTAP(IA)=F*DX/DCHAN+DEN*0.5*VEL(IA)*VEL(IA)
PWORK(IA)=DELTAP(IA)*ACHAN*VEL(IA)
DELPOT1=DELPOT1+DELTAP(IA)
PWORKTOT1=PWORKTOT1+PWORK(IA)
C DETERMINE MAXIMUM TEMPERATURES CONSIDERING ALL ZONES
TGG=AMAX1(TGG, TG(IA))
TCL=AMAX1(TCL, TCLAD(IA))
TFU=AMAX1(TFU, TFUEL(IA))
C
PRESN=PRESN-DELTAP(IA)
50 CONTINUE
C
IF(NPASS.GT.1)GO TO 110
C
FOR SINGLE PASS FLOW
C FIRST CALCULATE PWORK FOR CANM
MDOTCAN=0.0
DELTAPCAN=0.0
DPTURN=0.0
PWORKCAN=0.0
CALL DVISCOOL(PRES, TIN, IDCOOL, DVIS)
CALL CONDCOOL(TIN, IDCOOL, COND)
CALL CSUBPCOOL(TIN, IDCOOL, CSUBP)
PRNUM=DVIS*CSUBP/COND
CALL DENCOOL(PRES, TIN, IDCOOL, DEN)
C MUST ITERATE TO DETERMINE VELOCITY IN CANS
VELMI=0.8*VELMAX
DO 80 I4=1, 15
RENUM=DEN+VELMI*DIM/DVIS
F=FF(RENUM, PRNUM)
VELMINEW=(2.0*DIM*DELPOT1/F/HCORE/DEN)**0.25
IF(ABS(VELMINEW-VELMI)/AMAX1(0.05, VELMI).LT.0.05)GO TO 82
80 VELMI=VELMINEW
82 VELMI=(VELMINEW+VELMI)*0.5
MDOTCAN=MDOTCAN+DEN*VELMI*ACANM
PWORKCAN=PWORKCAN+DELPOT1*ACANM*VELMI
C NOW REPEAT FOR HOLES
VELMH=VELMI
DO 90 I5=1, 15
RENUM=DEN+VELMH*DHOLES/DVIS
F=FF(RENUM, PRNUM)
VELMHNEW=(2.0*DHOLES*DELPOT1/F/HCORE/DEN)**0.25
IF(ABS(VELMHNEW-VELMH)/AMAX1(0.05, VELMH).LT.0.05)GO TO 92
90 VELMH=VELMHNEW
92 VELMH=(VELMHNEW+VELMH)*0.5
MDOTCAN=MDOTCAN+DEN*VELMH*AHOLE
PWORKCAN=PWORKCAN+DELPOT1*AHOLE*VELMH

C AND FINALLY FOR UNMODERATED CANS
VELU=VELMI
DO 100 I6=1, 15
RENUM=DEN+VELU*HDCANU/DVIS
F=FF(RENUM, PRNUM)
VELUNEW=(2.0*HDCANU*DELPOT1/F/HCORE/DEN)**0.25
IF(ABS(VELUNEW-VELU)/AMAX1(0.05, VELU).LT.0.05)GO TO 102
100 VELU=VELUNEW
102 VELU=(VELUNEW+VELU)*0.5
MDOTCAN=MDOTCAN+DEN*VELU*ACANU
PWORKCAN=PWORKCAN+DELPOT1*ACANU*VELU
VMAXM=AMAX1(VELMI, VELMH, VELU)
C
GO TO 140
110 CONTINUE
C FOR TWO PASSES
IF(NPASS.GT.2)GO TO 120
MDOTCAN=MDOTMAX
CALL DENCOOL(PRES, TIN, IDCOOL, DEN)
CALL DVISCOOL(PRES, TIN, IDCOOL, DVIS)
CALL CONDCOOL(TIN, IDCOOL, COND)
CALL CSUBPCOOL(TIN, IDCOOL, CSUBP)
PRNUM=DVIS*CSUBP/COND
DMU=(DIM/HDCANU)**0.5
DHU=(DHOLES/HDCANU)**0.5
C FIRST GUESS ASSUMING F'S ARE EQUAL
VU=MDOTMAX/DEN/(ACANU+ACANM*DMU+AHOLE*DHU)
VM=VU*DMU
VH=VU*DHU
REU=DEN+VU*HDCANU/DVIS
REM=DEN+VM*DIM/DVIS
REH=DEN+VH*DHOLES/DVIS
FU=FF(REU, PRNUM)
FM=FF(REM, PRNUM)
FH=FF(REH, PRNUM)
C CALCULATE NEW VELOCITY ESTIMATE
VU=MDOTMAX/DEN/(ACANU+ACANM*DMU*(FU/FM)**0.5+
1 AHOLE*DHU*(FU/FH)**0.5)
REU=DEN+VU*HDCANU/DVIS
REM=DEN+VM*DIM/DVIS
REH=DEN+VH*DHOLES/DVIS
FU=FF(REU, PRNUM)
FM=FF(REM, PRNUM)
FH=FF(REH, PRNUM)
VM=VU*DMU*(FU/FM)**0.5
VH=VU*DHU*(FU/FH)**0.5
DELTAPCAN=FU*HCORE/HDCANU+DEN*0.5*VU*VU
C ADD IN DP DUE TO TURNING LOSSES
DPTURN=FU*50.0*DEN*0.5*VU*VU
DELTAPCAN=DELTAPCAN+DPTURN
PWORKCAN=DELTAPCAN*(ACANU*VU+ACANM*VM+AHOLE*VH)
VMAXM=AMAX1(VU, VM, VH)

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C      GO TO 140
120 CONTINUE
C
C      FOR THREE PASSES
C
C      MDOTCAN=MDOTMAX
CALL DENCool(PRES,TIN,IDCOOL,DEN)
CALL DVISCool(PRES,TIN,IDCOOL,DVIS)
CALL CONDCool(TIN,IDCOOL,COND)
CALL CSUBPCool(TIN,IDCOOL,CSUBP)
PRNUM=DVIS*CSUBP/COND
FU1=1.0
FU2=1.0
FM=1.0
FH=1.0
DMU=((FU1/DIU+FU2/HDCANU2*(ACANU1/ACANU2)**2)/
1 (FM/DIM+FH/DHOLES*(ACANM/AHOLES)**2))**.5
VU1=MDOTMAX/DEN/(ACANU1+ACANM*DMU)
VM=VU1*DMU
VU2=VU1*ACANU1/ACANU2
VH=VM*ACANM/AHOLES
REU1=DEN*VU1*DIU/DVIS
REU2=DEN*VU2*HDCANU2/DVIS
REM=DEN*VM*DIM/DVIS
REH=DEN*VH*DHOLES/DVIS
FU1=FF(REU1,PRNUM)
FU2=FF(REU2,PRNUM)
FM=FF(REM,PRNUM)
FH=FF(REH,PRNUM)
DMU=((FU1/DIU+FU2/HDCANU2*(ACANU1/ACANU2)**2)/
1 (FM/DIM+FH/DHOLES*(ACANM/AHOLES)**2))**.5
VU1=MDOTMAX/DEN/(ACANU1+ACANM*DMU)
VM=VU1*DMU
VU2=VU1*ACANU1/ACANU2
VH=VM*ACANM/AHOLES
REU1=DEN*VU1*DIU/DVIS
REU2=DEN*VU2*HDCANU2/DVIS
REM=DEN*VM*DIM/DVIS
REH=DEN*VH*DHOLES/DVIS
FU1=FF(REU1,PRNUM)
FU2=FF(REU2,PRNUM)
FM=FF(REM,PRNUM)
FH=FF(REH,PRNUM)
DELTAPCAN1=FU1*HCORE/DIU*DEN*.5*VU1*VU1
DELTAPCAN2=FU2*HCORE/HDCANU2*DEN*.5*VU2*VU2
C ADD IN TURN DP'S
DPTURN1=FU1*50.0*DEN*.5*VU1*VU1
DPTURN2=FU2*50.0*DEN*.5*VU2*VU2
DPTURN=DPTURN1+DPTURN2
DELTAPCAN1=DELTAPCAN1+DPTURN1
DELTAPCAN2=DELTAPCAN2+DPTURN2

DELTAPCAN=DELTAPCAN1+DELTAPCAN2
PWORPCAN=DELTAPCAN1*ACANU1*VU1+
1 DELTAPCAN2*ACANU2*VU2+
2 DELTAPCAN1*ACANM*VM+
3 DELTAPCAN2*AHOLES*VH
VMAXM=AMAX1(VU1,VU2,VM,VH)
C
140 CONTINUE
C ADD IN CAN DELTA P AND PUMP WORK TO THOSE OF CHANNELS
DELTOT2=DELTOT1+DELTAPCAN
PWORKTOT2=PWORKTOT1+PWORPCAN
C
FRACPP=PWORKTOT2/POWTOTAL
FRACSP=DELTOT2/PRES
FSONICM=VMAXM/SONIC1
FSONIC=VEL(ILOC)/SONIC
IF(IFLAG.EQ.1)FSONIC=VS/SONIC
C
C NOW CHECK TO SEE IF ANY LIMITS ARE EXCEEDED: IF SO THEN REDUCE G
C AND REDO ALL CALCULATIONS
IF(TGG.LT.TGMAX.AND.TCL.LT.TCLADMAX.AND.TFU.LT.TFUELMAX.AND.
1FRACPP.LT.FRACPPMAX.AND.FRACSP.LT.FRACSPMAX.AND.FSONICM.LT.
2FRACSONIC.AND.FSONIC.LT.FRACSONIC)
3GO TO 1002
1000 G=0.985*G
1002 CONTINUE
C
RETURN
END
C
SUBROUTINE XINT(HCOREMAX,HCOREMIN,H1,H2,FH1,FH2)
SUBROUTINE TO FIND AN INTERVAL CONTAINING A ROOT
C
C IF HCOREMIN IS NEGATIVE, CALCULATE POWDEN FOR HCORE BETWEEN
C HCOREMIN AND HCOREMAX INCREMENTED BY DELX
C IF(HCOREMIN.LT.0.0)GO TO 10
C
DX=0.4
H1=HCOREMIN
H2=H1+DX
CALL FUN(H1,FH1)
I1=0
5 CALL FUN(H2,FH2)
I1=I1+1
IF(FH1*FH2.LE.0.0)RETURN
H1=H2
H2=H2+DX
H2=AMIN1(H2,HCOREMAX)
IF(H1.GE.H2)THEN
H1=H2
RETURN

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ELSE
ENDIF
FH1=FH2
IF (I1.GT.20) THEN
H1=H2
ELSE
GO TO 5
ENDIF
RETURN
10 HCOREMIN=ABS(HCOREMIN)
DELX=(HCOREMAX-HCOREMIN)/15.0
X=HCOREMIN
DO 15 J=1,15
CALL PDEN(X,FX)
WRITE(6,50)X,FX
C 50 FORMAT(' ',5X,'HCORE (M) = ',F8.4,4X,'SPECIFIC POWER (W/KG) = ',
C 11PE12.4)
50 FORMAT(' ',4X,F8.4,4X,1PE12.4)
15 X=X+DELX
H1=H2
RETURN
END

C
C SUBROUTINE MRF(H1,H2,F,G,HERR,ROOTN)
C USING MODIFIED REGULA FALSI METHOD TO GET ROOT
C
C ROOT0=H1
C
C NN=20
C DO 25 IM=1,NN
C GMF=G-F
C IF (ABS(GMF).LT.1.0E-15) GO TO 50
C FOR FUNCTIONS THAT DONT ALLOW NEG OR ZERO ARGUMENTS
C IF (ROOTN.LE.0.0) GO TO 60
C
C CHECK FOR ERROR
C IF (ABS((ROOTN-ROOT0)).GE.E) GO TO 6
C IF (ABS((ROOTN-ROOT0)/ROOTN).GE.HERR) GO TO 6
C CALL FUN(ROOTN,FN)
C IF (ABS(FN).GT.0.2) GO TO 70
C RETURN
C
C 6 CALL FUN(ROOTN,FROOT)
C IF (F.FROOT.GT.0.0) GO TO 10
C H2=ROOTN
C G=FROOT
C F=5*F
C GO TO 20
10 H1=ROOTN
C F=FROOT
C
C
C G=.5*G
20 CONTINUE
C ROOT0=ROOTN
25 CONTINUE
C IERR=2
C RETURN
50 IERR=12
C RETURN
60 IERR=22
C RETURN
70 IERR=32
C END

C
C SUBROUTINE HTCC(TA,XL,CON,HD,RE,PR,TW,HTC)
C TAYLOR EQUATION FOR HEAT TRANSFER
C CF=(TW/TA)**(1.59/XL+HD-0.57)
C HTC=0.023*CON/HD*RE**.8*PR**.4*CF
C RETURN
C END

C
C SUBROUTINE DENCOOL(P,T,ID,DEN)
C IDEAL GAS EQUATION OF STATE FOR HE AND H2
C WM=4.0
C IF (ID.EQ.2) WM=2.0
C DEN=P/T*WM/8314.5
C RETURN
C END

C
C SUBROUTINE CSUBPCOOL(T,ID,CP)
C COOLANT CSUBP
C ID=1 FOR HE AND ID=2 FOR H2
C CP=5200.0
C IF (ID.EQ.1) RETURN
C
C CP=5.76+5.78E-4*T+1.8+20.0/((1.8*T)**0.5)
C IF (T.GT.2222.2) CP=CP-3.3E-4*(T+1.8-4000.0)
C CP=0.5*CP/2.38846E-4
C RETURN
C END

C
C SUBROUTINE DVISCOOL(P,T,ID,DV)
C DYNAMIC VISCOSITY OF HE AND H2 AT 1 ATM
C IF (ID.EQ.1) THEN
C DV=1.4882E-5*(1.204+0.00132*(T+1.8-459.67))
C ELSE
C IF (T.LT.530.0) THEN
C DV=1.4882E-5*(0.5407+0.000764*(T+1.8-459.67))
C ELSE

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DV=1.4882E-5*(-2.22592+0.49798*ALOG(T*1.8-459.67))
ENDIF
ENDIF
RETURN
END
C
C
SUBROUTINE CONDCOOL(T, ID, CND)
C CONDUCTIVITY (W/M/K) OF HE AND H2 AT 1 ATM
CONDUCTIVITY (ID, EQ. 1) THEN
CND=1.7296*(0.08096+0.000076*(T*1.8-459.67))
ELSE
CND=1.7296*(0.105143+0.000096*(T*1.8-459.67))
ENDIF
RETURN
END
C
C
SUBROUTINE CONDUCT(T, ID, C)
C CONDUCTIVITY OF FUEL, MODERATOR, AND CLADDING MATERIALS
GO TO(1,2,3,4,5,6,7,8,9,10,11), ID
RETURN
C FUEL (UC) CONDUCTIVITY (W/M/K) P.104 OF NUCLEAR HEAT TRANSFER,
C EL WAKIL (POWER FIT OF DATA)
1 C=1.7307*26.0*(AMAX1(T*1.8-459.67,260.0))*(-0.1093)
RETURN
C UO2 FROM GLADSTONE AND SESONSKE
2 C=2308.5*T**(-0.916)
RETURN
C UB4 (JUST USE UC FOR NOW!!!)
3 CONTINUE
GO TO 1
RETURN
C TRANSVERSE GRAPHITE CONDUCTIVITY (W/M/K)
4 C=AMAX1(1.7307*(179.1-19.7*ALOG(1.8*T-459.67)),10.0)
RETURN
C B4C FROM LLL CONCEPT DOCUMENT
5 C=598.8*T**(-0.52)
RETURN
C BEO FROM P.767 IF INCROPERA AND DEWITT, FUND. OF HT
6 C=2.523E6*T**(-1.583)
RETURN
C ZRC CONDUCTIVITY (W/M/K) FROM P.131 OF LA-5044 VOL.2
7 C=22.67+0.00857*T
7 C=3.54+0.0022*T 40% POROUS ZRC
RETURN
C TUNGSTEN (INCROPERA AND DEWITT)
8 C=734.29*T**(-0.2621)
RETURN
C MOLY (INCROPERA AND DEWITT)
9 C=477.44*T**(-0.21506)

RETURN
C 60%UO2 - W
10 C=0.6*2308.5*T**(-0.916)+0.4*734.29*T**(-0.2621)
RETURN
C 60%UO2 - MO
11 C=0.6*2308.5*T**(-0.916)+0.4*477.44*T**(-0.21506)
RETURN
C
END
C
C
SUBROUTINE DENSITY(T, ID, D)
C DENSITY OF FUEL, MODERATOR, AND CLADDING MATERIALS
GO TO(1,2,3,4,5,6,7,8,9,10,11), ID
RETURN
C UC FUEL DENSITY (KG/CUB.M)
1 D=11000.0
OR D=13500.0
RETURN
C UO2
2 D=11000.0
RETURN
C UB4
3 D=12700.0
RETURN
C GRAPHITE DENSITY (KG/CUB.M)
4 D=1700.0
RETURN
C B4C (USE BEO FOR NOW!!!)
5 CONTINUE
GO TO 6
RETURN
C BEO
6 D=2803.0
RETURN
C ZRC
7 D=6570.0
RETURN
C TUNGSTEN (INCROPERA AND DEWITT)
8 D=19300.0
RETURN
C MOLY (INCROPERA AND DEWITT)
9 D=10240.0
RETURN
C 60%UO2 - W
10 D=0.6*11000.0+0.4*19300.0
RETURN
C 60%UO2 - MO
11 D=0.6*11000.0+0.4*10240.0
RETURN
C

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2560 J. Cutchen
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3154-1 C. H. Dalin (28) for DOE/DSTI
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6410 N. Ortiz
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6440 D. Dahlgren
6450 T. Schmidt
6500 A. W. Snyder
6510 W. Gauster
6511 L. Cropp (10)
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6511 S. Hudson
6511 A. Marshall (10)
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6511 F. Thome
6512 D. Ericson
8024 P. W. Dean
8400 R. Wayne
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9012 L. Connell
9012 R. Zazworski
9100 R. Clem
9110 P. Stokes
9140 D. Rigali