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GAPCON-THERMAL-1: A COMPUTER PROGRAM
FOR CALCULATING THE GAP CONDUCTANCE
IN OXIDE FUEL PINS

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GAPCON-THERMAL-1: A Computer Program
for Calculating the Gap Conductance in Oxide
Fuel Pins

C. R. Hann
C. E. Beyer
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Prepared for
Directorate of Licensing
US Atomic Energy Commission

September 1973

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PREFACE

This report is one of a series of interim reports that will be issued on the computer code GAPCON. The name of the modified code was changed to GAPCON-THERMAL-1 to differentiate between the fast reactor code used by Hanford Engineering Development Laboratory and this code which was prepared by Battelle-Pacific Northwest Laboratories and is used by the Regulatory Staff as a calculational tool. This preliminary version of the code is being published primarily to consolidate the changes in the code into one package for the Regulatory Staff. The code should not be used as a fuel design code, but as one of several calculational tools available for accident analyses. The numerous models in the code are based on a best estimate of the data; no effort was expended to artificially force the code to agree with data.

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SECTION 1.
INTRODUCTION

GAPCON-THERMAL-1: A COMPUTER PROGRAM FOR CALCULATING
THE GAP CONDUCTANCE IN OXIDE FUEL PINS

C. R. Hann
C. E. Beyer
L. J. Parchen

1. INTRODUCTION

This report describes modifications to the GAPCON⁽¹⁾ computer code that have evolved as a result of the Regulatory Staff adapting the code as a tool for use in estimating fuel-cladding gap conductances and fuel stored energy. The code, in its current status, is not intended to be used as a fuel design code. A number of options that have been added to the code have proven useful for simulating fuel performance.

A related report by Hann, et al.⁽²⁾ discussed a preliminary evaluation of an unpublished version of the code.⁽¹⁾ The original version of GAPCON was developed by the Hanford Engineering Development Laboratory primarily for use in calculating fast reactor fuel gap conductances at beginning-of-life. The GAPCON⁽¹⁾ code was released for general use in September, 1972. It was recognized at the time of its release that the code contained limitations with regard to its applicability to thermal reactor fuels and in some of the relationships used in modeling fuel performance. Work is underway at the Pacific Northwest Laboratory to revise the GAPCON code to provide a calculational tool which more realistically computes gap conductance values for thermal reactor fuel. Interim results of this work have been incorporated in a modified version of GAPCON entitled GAPCON-THERMAL-1. This report describes the GAPCON-THERMAL code and presents comparisons of values predicted by the code with those measured or calculated from experimental data.

Prior to the fuel densification reported at the R. E. GINNA Plant, fuel temperatures at startup were considered to be most limiting, because

peaking factors were generally higher early in life and the diametral gap was thought to close sufficiently with burnup to offset the degrading effects of fission product gas. One of the postulated effects of fuel densification is an increase in the diametral gap between the fuel and cladding. Densification probably occurs over a period of time early in the life of the fuel although current evaluation models typically assume instantaneous densification. Thus, plant operating history became important in the determination of maximum stored energy in the fuel. Such calculations require the modeling of inter-related time dependent phenomena.

Some of the modifications discussed in this report reflect data or correlations that are more applicable to thermal reactor fuel. Other modifications were made as more recent data became available or as required to provide options for conservative safety evaluations. Our efforts have concentrated on models associated with large diametral gaps because these situations have been most limiting to date.

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SECTION 2.
SUMMARY AND CONCLUSIONS

2. SUMMARY AND CONCLUSIONS

GAPCON-THERMAL-1, a modification of GAPCON,⁽¹⁾ can be used to calculate the gap conductance and fuel temperatures in oxide fuel pins. The code in its current form was developed for the Regulatory Staff who use the code as a tool to independently calculate gap conductances for understanding various thermal performance models supplied by fuel vendors. The code is capable of calculating fuel temperatures for several coolant, cladding, and fuel material combinations. Changes in the diametral gap width are modeled. The source of these changes include differential thermal expansion of pellet and cladding, elastic and creep deformation of cladding, fission product expansion of the pellet, and fuel expansion induced by cracks and subsequent thermal ratcheting. In addition to the gap changes, the code simulates a variety of fill gas compositions and changes to the gas composition caused by the release of fission gas and volatile impurities.

Gap conductances are calculated with a slight modification of the Ross and Stoute model.⁽³⁾

Comparisons of calculations and experimental data indicate fuel temperatures are predicted reasonably well for short term irradiations and small gaps. The disagreement between predictions and experimental data is roughly proportional to the gap width and the calculated values are typically higher than the experimental values. Fuel temperature calculations for extended periods of irradiation become more uncertain because of inadequacies in the code and the dearth of well characterized data. These inadequacies are related principally to the kinetics of gap closure and fission gas release. On-going work is focused on reducing the uncertainty in these two areas of the code and in other areas of somewhat lesser significance. The affects of these uncertainties on the fuel stored energy are offset somewhat by the reduction in rod powers with burnup.

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SECTION 3.
DESCRIPTION OF CODE

3. DESCRIPTION OF CODE

The original GAPCON⁽¹⁾ code has been revised to emphasize water reactor fuel and to improve the flexibility required for safety analysis. We have designated the modified version of the code GAPCON-THERMAL-1 to eliminate possible confusion with subsequent versions of the fast reactor oriented version of GAPCON.⁽¹⁾ Additional versions of the code will be issued as models are improved or added. Details of the modifications and additions to the code are included in the discussion section. The essentially unaltered portions of the code are described in Appendix A and represent almost a direct copy of the original descriptions. Input instructions for the code are discussed in Appendix B. A listing is contained in Appendix C, and Appendix D contains a sample problem.

A number of input options are available to keep the code user-oriented. Various material and gap closure phenomena can be simulated with appropriate input signals. Output can be also controlled with a number of options. The user can control power shape and axial nodes to model short experimental pins or 12-foot long commercial fuel rods. A simplified flow sheet for GAPCON-THERMAL-1 is depicted in Figure 1.

FIGURE 1. Simplified Flow Chart for GAPCON-THERMAL-1

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SECTION 4.
DISCUSSION

4. DISCUSSION

ELEMENTS OF A THERMAL PERFORMANCE CODE

An analytical model for calculating the heat transfer coefficient (gap conductance) between the fuel and cladding eventually evolves into a series of complex, interacting models which cannot be treated separately. Physical phenomena must be adequately modeled mathematically to simulate the dynamic situation in a fuel rod. Inability to accurately model some phenomena can have relatively large effects on the calculation while relatively large errors in other models may have a relatively small effect.

The complexity of the physical processes that occur in an operating fuel rod and their interactions with each other requires a self consistent approach to even crudely predict actual performance. An analytical model for simulating fuel thermal performance should consider the following:

- fuel thermal conductivity
- fuel thermal expansion
- fuel cracking and radial relocation
- fuel restructuring kinetics
- fuel swelling
- fuel creep
- gas generation and release
- cladding thermal expansion
- cladding thermal conductivity
- cladding elastic deformation
- cladding creep

The high fuel temperatures calculated as a result of assuming instantaneous densification and isotropic shrinkage of the pellet also produce high fission gas release fractions. The released fission gases change the gas composition thereby reducing the conductivity of the gas. Two factors offsetting the rapidly changing gas compositions are gap closure mechanisms and the gradual decline in rod power associated with fuel depletion. The gap closure mechanisms that have the most pronounced effects are those associated with fuel swelling, cladding creepdown, and radial relocation

of the fuel via cracking. All three phenomena are difficult to describe quantitatively. A large number of qualitative observations on fuel cracking and fuel swelling have been made but very little success has been achieved in quantifying these two phenomena.

The computed results from an analytical model should relate to the observations made during the irradiation or the results of postirradiation examinations. Comparison of the analytical results with experimental observations is an essential test of both the computer code and the mathematical models of the phenomena being simulated. Discrepancies between computed results and observations can be attributed to either uncertainties in the models or poorly characterized experiments. Many computer codes developed to simulate fuel performance are adjusted to agree with specific observations. Such codes should be checked against independent data that were not used in the development of the models comprising the code.

Models for calculating gap conductance are often compared with reported values calculated from experimental data. A number of assumptions usually have to be made by the experimenter to calculate a gap conductance from the data. These assumptions lead to accumulation of all the error in the estimated fuel surface temperature from which the temperature difference and thus the gap conductance is calculated. Most of the reported gap conductance values are based on interpretation of microstructural features observed in the fuel after completion of the irradiation. These microstructural boundaries include the once molten fuel radius, the columnar grain growth radius, and the equiaxed grain growth region. These features represent isotherms that existed in the fuel during operation. Disagreement still exists as to the temperatures associated with the above boundaries. The various experimenters also disagreed as to what features defined the boundaries, and on the thermal conductivity of UO_2 . Accordingly, the gap conductances reported by any one experimenter may be internally consistent for his particular test but should not be compared directly with the gap conductances calculated from other experiments. The comparison of predicted values with various reported values is not entirely valid, unless the gap conductances are calculated in a consistent manner for all the experiments.

A more consistent method of comparing an analytical model with experimental data is to compare the model with the variable that was measured in the experiment. These variables usually include fission gas release fractions, microstructural boundaries, and the output of thermocouples located in the fuel. These comparisons are also somewhat limited because very few well characterized experiments have been published for thermal reactor fuels. Evaluation of the report on the experiment usually reveals relatively large uncertainties in heat ratings, dimensional tolerances, physical characteristics of the fuel, and flux depressions.

MODIFICATIONS TO GAPCON

A number of modifications and additions have been made to the original GAPCON⁽¹⁾ code primarily to reflect data that are more applicable to thermal reactor fuel and to improve the flexibility of the code for use as a calculational tool. A number of models in the code have been reviewed to determine potential inadequacies, and to assure that the best available data was being used. The following areas were revised or reviewed to determine which models required additional development.

- UO_2 thermal conductivity equation
- porosity correction factor
- UO_2 thermal expansion equation
- zircaloy thermal conductivity values
- volatile impurities
- fission gas release model
- fission gas production model
- gas pressure model

Additions were made to the code in the following areas:

- cladding elastic deflection
- cladding creep
- stored energy
- power and coolant temperature profile
- axial segments for analyzing power profiles
- short-term gap closure

UO₂ Thermal Conductivity Equation

The current version of the code utilizes the thermal conductivity equation derived by Lyons, et al.^(4,5) for 95% TD UO₂

$$K = \frac{38.24}{402.4 + T} + 6.1256 \times 10^{-13} (T + 273)^3 \quad (1)$$

K = Thermal conductivity (W/cm-°C)

T = Temperature (°C)

Equation 1 yields an integral-to-melt value of 93 W/cm, is a best estimate of the data, and replaces Equation 2 below which is based on extrapolation of Godfreys, et al.⁽⁶⁾ data from 1100°C to the melting point

$$K = \frac{45.1}{135 + T} + 4.79 \times 10^{-13} T^3 \quad (2)$$

K = Thermal conductivity (W/cm-°C)

T = Temperature (°K)

Porosity Correction Factor for UO₂ Thermal Conductivity

The Maxwell-Eucken^(7,8) relationship, Equation 3, is used to account for effects of porosity on UO₂ thermal conductivity

$$K_p = k_{100} \frac{(1 - P)}{(1 + \beta P)} \quad (3)$$

K_p = thermal conductivity of UO₂ with porosity, P

k₁₀₀ = thermal conductivity of 100% dense UO₂

P = volume fraction of porosity

β = porosity coefficient (β = 0.5 is used for fuel densities greater than 90% TD)

The value of 0.5 for beta is based on recommendations of Belle, et al.⁽⁹⁾

Equation 3 is used as a multiplier (Equation 4 below) to the UO_2 thermal conductivity equation.

$$\frac{1.025}{0.95} \left[\frac{F}{1 + (1 - F) 0.5} \right] \quad (4)$$

F = fraction of theoretical density

The Maxwell-Eucken relationship replaces the Loeb⁽¹⁰⁾ correction (Equation 5) used originally in GAPCON

$$K_p = k_{100} \left(1 - \alpha \right) \left(\frac{\rho_{100} - \rho}{\rho_{100}} \right) = k_{100} (1 - \alpha P) \quad (5)$$

ρ = density

P = volume fraction of porosity

α = porosity coefficient ($\alpha = 2.5$ in GAPCON)

The Loeb equation was a recommendation of the IAEA Panel on Thermal Conductivity⁽¹¹⁾ wherein the value of alpha ranged from 1 to 4. The use of the Maxwell-Eucken relationship reduces some of the conservatism in fuel temperatures for low density fuel.

Thermal Expansion of UO_2

The coefficient of linear expansion, alpha, in the original version of GAPCON⁽¹⁾ was based on data of Roth and Halteman.⁽¹²⁾ The equation for alpha (Equation 6) allowed Horn and Panisko to include the effects of various PuO_2 additions to UO_2 .

$$\alpha = [9.45 \exp(-0.0034C) + (0.0012 + 8.66 \times 10^{-5} C) T] 1.15 \times 10^{-6} \quad (6)$$

T = Temperature ($^{\circ}C$)

C = PuO_2 content (%)

The alpha for UO_2 was determined for using C = 0.0 in Equation 6. A review of Roth and Halteman's⁽¹²⁾ paper indicates Equation 6 is the instantaneous alpha (i.e. $\frac{d(\Delta L/L)}{dT}$) rather than an average alpha (i.e.,

$\frac{(\Delta L/L)}{\Delta T}$). The equation for an average alpha based on Roth and Halteman data at zero PuO_2 content is given below:

$$\alpha = 9.45(T - 25) + 0.0006(T^2 - 625)10^{-6} \frac{1}{(T - 25)} \quad (7)$$

The 1.15 multiplier in Equation 7 was used to get better agreement between GAPCON predictions and experimental results.

We have used an equation developed by Conway, Finkel, and Hein⁽¹³⁾ for UO_2 . It is the best available for UO_2 while the Roth and Halteman data are primarily for mixed oxides.

$$\frac{\Delta L}{L} = 2.896 \times 10^{-9} T^2 + 6.797 \times 10^{-6} T - 1.723 \times 10^{-4} \quad (8)$$

Note: The equation often appears with a positive 1.723×10^{-4} which is a typographical error⁽¹⁴⁾

An average alpha as calculated with Equation 9 is currently used in GAPCON-THERMAL

$$\alpha = \frac{\Delta L/L}{\Delta T} = (T^2 - 625)2.896 \times 10^{-9} + (T - 25)6.797 \times 10^{-6} \frac{1}{(T - 25)} \quad (9)$$

Average alpha values from Equation 7 are larger than those from Equation 9 below temperatures of approximately 1100°C . For temperatures above 1100°C Equation 9 gives the larger values. Nutt and Tokar^(15,16) suggest that the alpha values for PuO_2 do not vary significantly from UO_2 , and are essentially identical to the Conway, et al.⁽¹³⁾ UO_2 data over the temperature range 1000 - 1400°C . The discrepancy between the Nutt and Tokar data and the Roth and Halteman data may possibly be due to variations in O/M or impurity content. Roth, et al.⁽¹⁷⁾ report a 34% increase in alpha for a 3.6% decrease in O/M for 20 wt% PuO_2 - UO_2 . Consequently, we believe the Conway, Finkel, and Hein equation is more applicable to UO_2 than the Roth and Halteman equation.

Thermal Conductivity of Zircaloy

The thermal conductivity values used by the original version of GAPCON⁽¹⁾ were modified to those data reported by Scott⁽¹⁸⁾ (Table 1). The higher values provide a more realistic basis for computing fuel temperatures.

TABLE 1
THERMAL CONDUCTIVITY OF ZIRCALLOY-2 AND -4
(Btu/hr-ft-°F)

Temperature (°F)	Original GAPCON		GAPCON-THERMAL	
	Zr-2	Zr-4	Zr-2	Zr-4
75	6.94	--	--	--
212	6.94	--	7.74	7.86
392	7.40	--	8.38	8.27
572	7.40	--	9.02	8.79
752	7.52	--	9.83	9.48
932	7.81	--	10.64	10.40

Cladding Elastic Deflection

Since the wall thickness for most commercial fuel cladding is greater than one-tenth the radius,⁽¹⁹⁾ we used the thick-wall vessel formulas in an elastic deflection option for GAPCON-THERMAL. The option should not be used if the cladding diameters are obtained from a creep collapse code because a double correction may be inadvertently provided.

The general tangential and radial stress relations (Lame equations) are:⁽²⁰⁾

$$S_t = \frac{[(r_1^2 p_1 - r_2^2 p_2) + (p_1 - p_2) r_1^2 r_2^2 / r^2]}{(r_2^2 - r_1^2)} \quad (10)$$

$$S_r = \frac{[(r_1^2 p_1 - r_2^2 p_1) - (p_1 - p_2) r_1^2 r_2^2 / r^2]}{(r_2^2 - r_1^2)} \quad (11)$$

where S_t = tangential stress, (psi)
 S_r = radial stress, (psi)
 p_1 = uniform internal pressure, (psi)
 p_2 = uniform external pressure, (psi)
 r_1 = cladding inner radius, (in.)
 r_2 = cladding outer radius, (in.)
 $r_2 > r > r_1$

Now at the inner boundary (i.e., $r = r_1$), the tangential elongation is: ⁽¹⁹⁾

$$\epsilon_t = (S_t - \mu S_r) / E \quad (12)$$

where ϵ_t = tangential elongation, (in./in.)
 μ = Poisson's Ratio
 E = Young's Modulus, (psi)

As a result, the change in cladding inner radius, Δr_1 , due to internal and external pressure is:

$$(E)(\epsilon_t) = S_t - \mu S_r \quad (13)$$

$$(E) \left(\frac{2\pi \Delta r_1}{2\pi r_1} \right) = S_t - \mu S_r \quad (14)$$

$$\Delta r_1 = \frac{r_1}{E(r_2^2 - r_1^2)} \left[(r_1^2 p_1 - r_2^2 p_2)(1 - \mu) + (p_1 - p_2)(r_2^2)(1 + \mu) \right] \quad (15)$$

where =

Δr_1 = change in cladding inner radius, (in.)

Substituting values for PWR cladding data into Equation 15 and using $\mu = 0.492$ and $E = 11.1 \times 10^6$ psi, we obtained these values:

Case 1

With $P_1 = 0$ and $P_2 = 2250$ psi, $\Delta r_1 = -0.000349$ in.

Case 2

With $P_1 = 600$ psi and $p_2 = 2250$ psi, $\Delta r_1 = -0.000261$ in.

Cladding Creep

Creep of the cladding will contribute to gap closure and thus lower fuel temperatures. Creepdown is currently a user option (see section on input instructions) in that a table of cladding diameters as a function of time must be supplied. The option has been used to simulate various gap closure data. Cladding diameters can also be obtained from the BUCKLE⁽²⁰⁾ code output which contains uniform creepdown rates.

Volatile Impurities

Release of volatile impurities from the fuel can affect calculated fuel temperatures by a rather large amount. Often the initial gas content and composition are not known nor are the release rates of the various species of gas. In addition to these unknowns, the disposition of the gases once they are released is poorly understood. The principal constituents of the gas released to the gap include H_2 , Ar, O_2 , N_2 , CH_4 , CO, CO_2 , and H_2O vapor. The primary source of most of the gas is the sintering atmosphere and impurities in the fuel, but CO and CO_2 can sometimes be attributed to atmospheric contamination. Impurities in the fuel that can result in degradation of gas thermal conductivity are largely dependent on

sintering atmosphere and can vary from vendor to vendor. Table 2 summarizes the possible contribution of each impurity (in cm^3/g of UO_2) for a hypothetical specification. A specification for total volatile content is often used in addition to limits on fuel impurities.

Carlson⁽²¹⁾ reported sorbed gas contents of 0.01 to 0.5 cm^3/g for mixed oxide fuel in the 91 to 95% TD range. Vacuum outgassing reduced the gas content to levels of 0.02-0.04 cm^3/g for pellets of ~90% TD. Vance, et al.⁽²²⁾ reported volatile releases of 0.02 cm^3/g - 0.059 cm^3/g exclusive of water. Fuel densities were not reported but probably were ~90% TD. Large amounts of gas were evolved at 500°C and above and the release of CO increased dramatically above 1300°C. Commercial fuel pellet densities range from 90 to 95% TD and reported gas contents prior to loading are typically lower than Carlson's data.

TABLE 2
POTENTIAL GAS VOLUMES FROM FUEL IMPURITIES

<u>Impurity</u>	<u>Concentration (ppm)</u>	<u>Gas Volume $\text{cm}^3/\text{gm}-\text{UO}_2$</u>
H_2O	20	0.025
H_2		0.025
O_2		0.0124
N_2	75	0.06
H_2 (without H_2O)	5	0.055
C	100	
CO		0.187
CO_2		0.187

The hydrogen, oxygen, water vapor, CO, and CO₂ probably react quite rapidly with the cladding or fuel.⁽²³⁻²⁵⁾ Nitrogen, argon, and some hydrogen are probably the biggest contributors to degradation of the fill gas thermal conductivity.

Hydrogen can currently be handled in several ways with the code. The fraction of sorbed gas which is hydrogen can be specified and the user can assume all hydrogen remains in the fuel pin or is consumed (i.e., reacts with the cladding). If the above options are used, the release fraction of hydrogen is assumed to be the same as the fission gas.

Another option available is to specify the fraction of the initial fill gas that is hydrogen. This approach obviously assumes instantaneous release. Preliminary efforts indicate instantaneous release of hydrogen is a reasonable approximation. Diffusion data of Wheeler⁽²⁶⁾ provide diffusion coefficients for hydrogen in UO₂. Using an approach suggested by Darken and Gurry⁽²⁷⁾ to estimate the diffusion of hydrogen out of the fuel indicates 100% release between 10 and 100 hours at 500°C. Most of the hydrogen from the sintering atmosphere should be released before rod loading if the fuel is off-gassed at 500°C. Wheeler⁽²⁶⁾ estimates approximately 20% may be retained for release during irradiation.

Nitrogen impurities in the fuel are probably present as uranium nitrides. Nitrogen gas is released by decomposition of the uranium nitrides, diffusion of nitrogen to the fuel surface, and formation of nitrogen molecules at the fuel surface. Ferrari^(28,29) has reported values for the diffusion coefficients of nitrogen in UO₂. Diffusion is sufficiently slow that a time- and temperature-dependent release fraction should be used. A diffusion model such as one proposed by Booth^(30,31) could be used, but the Booth model depends upon defining the radius of an equivalent hypothetical sphere which in turn is a function of pellet density and surface area. A time-dependent release fraction is under consideration for a future version of GAPCON-THERMAL; the present version assumes only a temperature dependent release which is the same as the current fission gas release model. This approach is obviously conservative for beginning-of-life calculations.

The effects of argon are modeled by including the argon content in the initial fill gas.

Fission Gas Production

An error in the FISGAS subroutine associated with fission yields was corrected to yield lower fission gas production. A more exhaustive evaluation of the fission yields and the FISGAS subroutine will be made to obtain the best available yield data and to establish the limitation of the subroutine.

Fission Gas Release

The original version of GAPCON⁽¹⁾ contained a gas release fraction based on the Dutt, et al.⁽³²⁾ correlation for fast reactor fuel. The Dutt model released 100% of the gas above 1350°C. For temperatures below 1350°C the release fraction was a function of rod linear power and burnup. The release fraction in the original version of GAPCON was never less than 2%.

Fission gas release is a function of fuel temperature. Consequently, a release correlation based on a fast reactor linear power cannot be used with a thermal reactor linear power. Fuel surface temperature in a fast reactor pin will be higher than for the same thermal rod power (assuming equal gap conductance) because coolant temperatures and heat fluxes are much higher in the fast reactor. Fuel surface temperatures in a fast reactor pin are typically around 1000°C while fuel surface temperatures for thermal reactor fuel are closer to 500°C. Thus for the same linear heat rating, the volumetric average fuel temperature will be considerably higher in a fast reactor fuel pin.

The bulk of the data for thermal reactor fuel suggests that 100% release occurs above 1600-1700°C and that there is no discernible effect of burnup below about 15000 MWD/MTM. Therefore, a gas release model for thermal reactor fuel should be used if GAPCON is to be applied to thermal reactor fuel. There are several thermal fuel gas release models available for engineering application. These models include ones proposed by Hoffman-Coplin,⁽³³⁾ Booth,⁽³¹⁾ Lewis,⁽³⁴⁾ and Baston.⁽³⁵⁾ We selected the

Hoffman-Coplin correlation for the first version of GAPCON-THERMAL in order to simulate thermal fuel behavior. However, other correlations are under consideration. The Hoffman-Coplin model was also more compatible with an earlier version of the code that used one axial node.

The Hoffman-Coplin correlation is an empirical model that relates the release fraction to the fuel rod volumetric average temperature. The fuel rod volumetric average temperatures in the Hoffman-Coplin work were calculated by dividing the average temperature at the peak node by the peak-to-average flux profile. The data used in the correlation were obtained from rods about 3 feet long with peak-to-average values of 1.2 to 1.6, fuel densities of 94 to 97% TD and % g/d (gap/fuel diameter) ranging from 1.41 to 1.95%. Although Hoffman and Coplin used Lyons, et al. thermal conductivity relationship to calculate fuel temperatures we do not know what microstructural features in the fuel they used for an index or the value of gap conductance needed to calculate fuel surface temperature. Therefore, systematic errors in addition to analytical errors may exist in the data. To be consistent with the Hoffman-Coplin correlation, the code uses the volume average temperature of the fuel rod (i.e., the radial volume average temperatures of all axial fuel segments are summed and divided by the total number of axial segments) to calculate the release fraction and thus the amount of fission gas released in the rod. The axial segments are discussed in more detail in the following sections.

There is some doubt as to the validity of applying release fractions and volume average temperatures from the short 3 foot experimental rods to the larger rods used in modern commercial reactors. Also, the release rate in a fuel rod is based on the local conditions along that rod so that a more physically correct correlation would be to assign a release fraction to the local fuel temperatures and burnup. More work should be done to develop such a correlation from well characterized data. If the data used by Hoffman-Coplin had had very low peak-to-average ratios (i.e., ~ 1.0) their correlation could have been used to predict release fractions from local fuel temperatures.

Power and Coolant Temperature Profile

A power profile which is normalized to average pin power can be input to the code as described in the Table of Input Variables. The normalized power profile when plotted versus X/L must integrate to 1.0 with the peak of the profile being equal to the peak power/average power ratio for that pin. The profile has to contain values which bound each axial segment along the pin since power is linearly interpolated from the points that bound each axial segment. Thus the number of input values for the power profile has to be equal to $N + 1$, N being number of segments. For example, if the first two values entered for the normalized power profile were 0.2 and 0.5, 0.35 would be used for the first segment.

The axial temperature profile of the coolant is calculated from the power profile, the temperature gradient of the coolant across the core, and the inlet coolant temperature. A reasonable approximation of the coolant temperature profile can be made by assuming a direct correlation between integrated fraction of power along the pin to the coolant temperature gradient. A power fraction is calculated for each axial segment by integrating the power from the bottom of the pin to each axial segment and dividing that power by the total power of the pin (i.e., the integrated power fraction for the axial segment at the top edge of the fuel is 1.0). Thus, if 70% of the power of a pin was located in the lower half of the pin, the axial segment at the middle of the pin would have a coolant temperature equal to $T_{\text{inlet}} + 0.7 \Delta T_{\text{core}}$. Considering the intended use of the code and its accuracy (which is limited by other areas of the code), the additional computer time required to perform a more extensive hydraulics calculation is not justified.

Axial Segments

GAPCON-THERMAL uses the same one dimensional (radial) type of heat transfer calculations as the original version of GAPCON⁽¹⁾ but considers a specified number of axial segments. Each equal length axial segment has its own fuel, fission gas inventory, heat rating, coolant temperature and pellet-to-clad gap. Since only radial heat flow is considered, the

temperature profile of each axial segment is calculated at the center of the segment using the heat rating and coolant temperature associated with the mid-point of the axial segment (see section on the power and coolant temperature profile). One radial temperature profile describes the thermal conditions of the entire axial segment. Thus, a more accurate axial temperature profile is obtained the greater the number of segments, but ten axial segments are usually sufficient.

As in the original version of GAPCON, an iteration is performed with a convergence on gap conductance to obtain the radial temperature profile. In addition, the axial version requires a second iteration scheme which converges on the axial temperature profile. The iteration is complicated by the fact that the gas release fraction of the fuel is dependent on the fuel temperature and in turn the fuel temperatures are affected by the composition of gas in the gap. Radial convergence is required on all axial segments before a new axial iteration is performed. The axial iteration scheme is based on the volume average temperature of the fuel rod. The code calculates the fuel rod VAT by summing radial volume average temperatures of all axial segments and then dividing by the total numbers of axial segments. The iteration scheme is also based on the gas release fraction (although no convergence criteria is required for the release fraction) since the code correlates the fuel rod VAT to the gas release fraction with the Hoffman and Coplin⁽³³⁾ model. The Hoffman and Coplin gas release model is an empirical correlation which is discussed in further detail in the section on gas release.

The axial iteration is initiated by a first approximation of the VAT of the fuel rod. This is accomplished by calculating the radial temperature profile of each axial segment with no communication of released fission gas between segments (the gas release fraction is calculated from the VAT of each segment). This usually gives a VAT value within 15% or less of the converged answer. This first approximation of the VAT of the rod is then used to determine a release fraction for the entire fuel rod based on the Hoffman-Coplin model. The fission product generated from each axial

segment is summed and multiplied by this newly acquired gas release fraction to determine the amount of fission gas to be released to the rod in the second axial iteration. After the radial temperatures at all axial segments have been calculated in the second axial iteration, a new VAT of the fuel rod is calculated and compared to the previously calculated VAT and if the VAT's don't agree to within 0.5%, a new release fraction is determined from the new VAT and a third axial iteration is performed. The iterative process continues until convergence is attained to within 0.5% on the VAT. The first estimate of the VAT is usually fairly close. Consequently between 3 to 5 iterations are required before the criteria for convergence are met.

We recognize that the Hoffman-Coplin gas release model may not be consistent with gas release in long fuel pins. The temperature dependence of gas release results in a wide variation in the amount of gas released due to the significant temperature gradients, radial and axial, in the fuel. However, the VAT or Hoffman-Coplin model compares reasonably well with release fractions obtained from Yankee fuels.⁽³⁶⁾ (Table 3). The agreement is good for the high burnup pins but rather poor for low burnup. The disparity is probably caused by the lack of a "memory" or path dependence, and the absence of a well characterized, short-term gap closure model in GAPCON-THERMAL.

A second method for calculating the release fraction of the fuel, using the Hoffman-Coplin model, has been tried in GAPCON-THERMAL. This method allows each axial segment to release its own amount of gas based on the radial VAT of that segment. The initial axial iteration on temperatures is performed the same as in the first method but the gas released from each segment is summed and divided by the number of axial segments (N) to obtain a value of n_N moles of gas which is the new estimate of gas in each segment for the next iteration on temperatures. In other words, the gas released in the first iteration is equally distributed over the fuel rod to calculate new temperatures in the second iteration. The new VAT temperatures for each segment, calculated in the second iteration, are used

TABLE 3
A COMPARISON OF GAS RELEASE PREDICTED BY THE HOFFMAN-COPLIN
MODEL AND REPORTED FROM YANKEE FUEL (37)

Rod Number	Rod Volume Average Power*	Burnup (MWd/MTM)	Volumetric Average Fuel Temperature Reported/Prediction (°F)	Gap Conductance Reported/Prediction (Btu/hr-ft ² -°F)	Gas Release Reported/Prediction (%)
E6-SE-F5	6.27	35,000	1880/1841	410/445	7/8
E6-NW-A/L	6.65	35,000	1822/1786	497/549	9.5/6
E6-SE-E4	6.92	35,000	1907/1724	481/736	7.5/4
G4-SE-F5	5.41	15,000	1624/2554	438/163	7.5/36
H5/NW-A/L	5.44	15,000	1415/2556	686/165	7.5/36

* Maximum power during the life of the rod

to calculate a new release rate for each segment and thus a new estimate of released gas which is again equally distributed over the pin. This iterative process continues until the VAT of the pin has converged with the same criteria for convergence as in the first approach. An initial comparison of temperatures predicted by the two methods agree within 1 to 3% but a more complete comparison (at several heat ratings and gap sizes) has to be made in order to draw any firm conclusions. The second method (based on the VAT and release rates of short segments of the fuel which have essentially a flat power profile) is not consistent with the VAT and release rates from fuel rods with significant axial power profiles used to develop the Hoffman-Coplin model. However, the second method will be more compatible with a gas release model based on localized fuel temperatures. A new gas release model which is under development will be included as it becomes available.

Gas Pressures

Fuel rod gas pressures are calculated in the code with the following relationship:

$$P = \frac{M^T}{\frac{V^P}{T^P} + \sum_{i=1}^{i=N} \left(\frac{V_i^V}{T_i^V} + \frac{V_i^G}{T_i^G} \right)}$$

where N = number of axial segments

M^T = total moles of gas in the free volume of the fuel rod

V_i^V = volume of center void of segment i

T_i^V = temperature of the center void of segment i

V^P = plenum volume of the fuel rod

T^P = temperature of the plenum, assumed to be equal to the coolant temperature $+10^\circ\text{F}$

V_i^G = volume of the pellet-to-clad gap of segment i

T_i^G = the average temperature between the fuel surface temperature and inside clad temperature at segment i .

Stored Energy

An option for calculating stored energy of the fuel was added to GAPCON-THERMAL because stored energy is the main parameter in a safety evaluation of the fuel system. Some accident codes use steady-state codes to initialize temperature profiles; some index on a volumetric average temperature; others may use the stored energy per unit volume or mass of fuel. All of the above parameters are included as output of the code.

Two methods are available for calculating stored energy for each axial segment from the heat capacity and temperature of the fuel. One method approach approximates the stored energy by using the volume average temperature of an axial segment multiplied by the enthalpy for that temperature. However, due to the nonlinearity of heat capacity in certain temperature regimes this approximation can be off as much as 20%. The second method is more exact in that the pellet is divided into 50 concentric annular rings of unit length and the stored energy contribution of each ring is summed.

$$E \text{ (cal/g - UO}_2\text{)} = \left[\frac{\sum_{i=1}^N m_i \int_{298}^{T_i} c_p(t) dT}{m} \right] \frac{1}{270 \text{ g/mole - UO}_2}$$

m_i = mass of segment (i), grams
 T_i = temperature of segment (i),
 $c_p(t)$ = heat capacity, cal/mole-°k
 E = stored energy

$$\bar{E} \text{ (cal/g - UO}_2\text{)} = \left[\int_{298}^{\bar{T}} c_p(t) dT \right] \frac{1}{270 \text{ g/mole - UO}_2}$$

$\bar{E}$ = stored energy at volumetric average
 temperature $\bar{T}$

The relationship used in the code to describe heat capacity of UO_2 as a function of temperature was taken from Kerrisk and Clifton.⁽³⁷⁾

Gap Closure

Almost all computer codes that attempt to simulate fuel thermal behavior contain adjustable constants to force predicted values to agree with experimental observations. Such computer codes could probably be placed in one of two categories. The first category of codes use an assumed value for the gap conductance to force the code to agree with experimental data. This is probably a reasonable approach as long as the calculations are limited to fuel operating within the experimental data matrix. The second broad category of computer codes attempts to calculate a gap conductance based on gap widths, gas conductivity, etc. Formulation of the equations for calculation of the temperature drop between fuel and cladding can be obtained from either first principles or empirical correlations. The second category of codes rely for the most part on adjusting the gap width to force the predicted values to agree with the experimental observations, because the calculated thermal expansion of the pellet does not sufficiently close the gap. The original version of GAPCON⁽¹⁾ contained such a correction in that the thermal expansion coefficient was modified to give better agreement with experimental values. The original version of GAPCON was a code that had been correlated or indexed against certain data with the emphasis on fast reactor fuel. Changing portions of the codes, such as thermal expansion, can lead to disagreement between experimental and predicted values because the code may contain compensating errors in other models.

Many instances of complete or partial gap closure early in life have been reported in the literature.⁽³⁸⁻⁴²⁾ Bellamy and Rich⁽⁴³⁾ as well as Mikailoff, et al.⁽⁴⁴⁾ have reported instances of gap opening followed by gap closure. The observations of Bellamy and Rich⁽⁴³⁾ have been attributed to irradiation induced densification; a more plausible explanation involves cladding strain caused by differential thermal expansion. The residual gap is observed until the fuel becomes somewhat bonded to the cladding

whereupon the thermal contraction appears as circumferential cracks in the fuel. The work of Mekailoff, et al.⁽⁴⁴⁾ suggests that low density (probably <90% TD) fuel contracts during operation and the gap is not recovered for several thousand MWD/MTM.

A few irradiation tests⁽⁴⁵⁻⁴⁸⁾ with thermocouples in the fuel have indicated temperatures initially rise and then decay to some equilibrium value. The initial rise could be attributed to densification or release of volatile impurities from the fuel. The decay to an equilibrium value is probably associated with a gap closure phenomena. We believe that gap closure associated with fuel cracking is the dominant factor. There is little evidence that irradiation induced densification actually produces a larger diametral gap. Examination of almost any metallographic cross-section of irradiated fuel reveals that the initial cold gap has been closed somewhat by some irreversible fuel relocation. Unfortunately, the phenomena is poorly understood and is not currently amenable to a rigorous analytical solution. The experiments wherein a fuel temperature rise was detected are discussed in the subsequent paragraphs.

An experiment described by Kjaerheim and Rolstad⁽⁴⁵⁾ indicated an approximate 100°C increase in fuel centerline temperature measurements after about 4300 MWd/T burnup. Apparently no measurements were made between the startup measurements and the mid-life measurements. Consequently, it is difficult to determine whether the fuel temperature gradually increased with exposure because of gap enlargement or whether the power cycling associated with the final temperature measurements caused a rapid degradation of the gap conductance via release of gas to the pellet-cladding gap. The exposure may also have been obtained at sufficiently low fuel temperatures to induce a degradation of the UO₂ thermal conductivity.

Asamoto, et al.⁽⁴⁶⁾ reported an increase in fuel temperatures in approximately 100°C over about 120 hours for fuel operated at temperatures less than 1650°C. The apparent degradation of the fuel rod conductance disappeared once the fuel rod powers were raised to cause significant restructuring of the fuel. A gradual increase in temperature of 100-200°C

was detected for fuel rod powers above 15 kW/ft and fuel temperatures to 2100°C. We would tentatively interpret the causes of the initial temperature increase as degradation of the gap conductances by the release of sorbed gas and fission gas. Figure 3-5a of the Asamoto report shows a gradual increase in fuel temperatures followed by a gradual decrease. We suspect the decrease may have been caused by gap closure associated with fuel cracking and rapid fuel swelling.

Fitts, et al.⁽⁴⁷⁾ reported a 250°C increase in central temperature after a return to power. The effect could possibly be associated with gas released as a result of fuel cracking. Gap closure via a fuel cracking mechanism could possibly account for the disappearance of the temperature increase within a few hours of operation.

Panisko, et al.⁽⁴⁸⁾ also report initial increases in fuel temperature (~100°C) that gradually decay with time. The authors did not discuss possible mechanisms. We suggest that the initial increase can be attributed to degradation of the gap conductance caused by (1) release of either sorbed gases or fission gases or (2) fuel densification. The gradual decay is probably caused by gap closure associated with fuel crack ratcheting and rapid fuel swelling.

The amount of gap closure that occurs in short-term irradiations is often approximately equal to the amount calculated by assuming irreversible thermal expansion. The postulate that thermal expansion of the fuel cannot be fully recovered is supported somewhat by the observation that the fuel is extensively cracked from thermal stresses. These cracks occupy a finite volume and therefore the pellet cannot return to its original dimensions. A ratchet mechanism associated with cracking requires a temperature or power change. Little is known about the magnitude of the power change required or the effects of the rate of power change. The fuel tends to behave in a more plastic mode under steady state or slow power changes. Consequently, the amount of gap closure may be higher in a rabbit type irradiation as compared to the rather slow rate of power increases in a commercial plant.

We have calculated the thermal expansion of a fuel pellet as a function of gap/pellet diameter ratio, with heat rating as a parameter. If the thermal expansion is assumed to be completely irreversible, the residual expansion (thermal expansion/pellet diameter) can be plotted as a function of gap/pellet diameter ratio (Figure 2). The feedback from a variable gap conductance is clearly illustrated by the upward trend at constant heat rating. All calculated values, with the exception of the one case at 24 kW/ft, were based on helium as an initial fill gas.

The data reported by Bain⁽³⁸⁾ and plotted in Figure 2 were short-term (minutes) tests and represent the residual expansion measured after one thermal cycle. Because Bain's test utilized argon as the initial fill gas, the residual expansion may be biased as compared to helium filled pins. The high heat rating data also reflect the volume expansion contribution of fuel melting which GAPCON does not consider. The calculated residual expansion values for the low heat ratings (~15 kW/ft) are typically larger than Bain's experimental points.

A cursory review of Janviers, et al.⁽⁴⁰⁾ work produced the other set of data points in Figure 2. These data range from 12 to 17 kW/ft and include the effects of a number of thermal cycles required to reach several thousand MWd/MTM burnup. The calculated values, assuming irreversible thermal expansion, are typically higher than the experimental points.

We also modeled a thermal ratchet by assuming thermal expansion was not recovered after a thermal cycle to calculate the number of cycles required to close the gap at power. Three cycles were sufficient to close the gap in a BWR pin operating at 16 kW/ft with an initial gap of about 0.019 inches.

Mechanisms other than a thermal ratchet induced by a power or temperature change of undefined magnitude may contribute to gap closure early in the life of the fuel. A possible additional source of short term gap closure could be high, unrestrained swelling of the fuel.

We are pursuing a concept for a gap closure mechanism based on the premise that unrestrained fuel expands rapidly due to the large volumetric

FIGURE 2. Residual Pellet Expansion as a Function of Cold Gap/Pellet Diameter and Linear Heat Rating

swelling rates of fuel above 1300°C. Dimensional changes of unrestrained fuel operating at high temperatures are quite high⁽⁴⁹⁻⁵⁵⁾ and in some instances appear to saturate with exposure.⁽⁴⁹⁾ We have not been able to obtain true swelling rates based on pre- and postirradiation density measurements, because most of the reported volume increases are inferred from dimensional measurements. Consequently, the data include the effects of thermal cycling and some irreversible thermal expansion. We are in the process of evaluating the data further in an attempt to segregate the effects of thermal cycling from the unrestrained swelling.

We have modeled the concept of gap closure via unrestrained swelling via the following generalized equations:

$$S = CB^x$$

where

S = volume change, $\% \Delta V/V$

C = constant for a specific temperature regime

B = burnup, (fissions/cm³ x 10²⁰)

x = an exponent ≤ 1

We have assumed for the preliminary model that the fuel can be divided into four temperature zones:

- (1) fuel below 1300°C
- (2) fuel between 1300 and 1500°
- (3) fuel between 1500 and 1700°C
- (4) fuel greater than 1700°C

The unrestrained swelling for each zone is calculated from the following equations:

Zone 1 $S = 0.4B$

Zone 2 $S = 2B^{0.611}$

Zone 3 $S = 5B^{0.611}$

Zone 4 $S = 14B^{0.611}$

The volume changes from each temperature zone are accumulated to obtain the pellet dimensions as a function of time. We have assumed isotropic expansion of the fuel and that the outer, cold region of the fuel is cracked and provides no restraint until the fuel contacts the cladding. Actual fuel density changes are probably much less than those calculated with above equations because the data represent dimensional rather than density measurements.

The swelling in Zone 1 is effectively the contribution of solid fission products. The exponent for the swelling equation for Zones 2, 3 and 4 is based on a small data set and could vary with additional analysis. For example, the swelling in Zone 2 perhaps does not saturate as rapidly as the model indicates. The restraint that may be supplied by the outer regions of fuel is also difficult to assess and may in reality reduce the apparent swelling calculated from the above relationships as the apparent volume change is accommodated in internal porosity.

The volume expansion predicted by the above equations is plotted as a function of burnup in Figure 3. A limited amount of data obtained by the Battelle-Columbus Laboratories⁽⁴⁹⁻⁵³⁾ and Gulf United Nuclear⁽⁵⁴⁻⁵⁵⁾ on USAEC programs are presented on the same plot for comparison.

The gap closure model is contained in the subroutine SWELL which is programmed as a user option. (See input instructions). We view the model as speculative at this time. We currently limit the swelling in Zones 3 and 4 to the amount calculated at about 8000 MWd/MTM. Because of the sparsity of data, we further assume that cladding strain can only be caused by differential thermal expansion or swelling calculated from the Geithoff model.⁽⁵⁶⁾ If the gap closes due to the "unrestrained swelling" model, the heat transfer distance remains fixed at the sum of the surface roughness of the fuel and cladding until the Geithoff swelling model overtakes the unrestrained swelling model, closes the gap, and causes cladding strain. The Geithoff⁽⁵⁶⁾ model as used in GAPCON-THERMAL does not result in pellet dimensional changes until about 20,000 MWd/MTM burnup is reached. The combination of the unrestrained swelling model and the Geithoff model

FIGURE 3. A Comparison of the Swelling Rates from Subroutine SWELL with Experimental Data

is an attempt to simulate (1) early-in-life pellet dimensional changes, and (2) the swelling rates inferred from cladding diameter changes or measurements of fuel density changes after a relatively large exposure.

Preliminary results of these models show that gap closure occurs rather rapidly at powers above 10 kW/ft for a typical PWR pin (Figure 4). At powers of 15 kW/ft the gap is closed at approximately 5000 MWD/MTM.

The true situation for rapid gap closure is probably a combination of unrestrained swelling and irreversible pellet expansion. We are examining additional "unrestrained swelling" data in an attempt to more adequately justify the model. The model has not yet been compared with extensive experimental data and should be treated as a speculative concept.

LIMITATIONS OF THE CODE

As previously indicated the original version of GAPCON was modified to provide a more appropriate calculational tool for computing gap conductance values in thermal reactor fuels. This revised version of the code, GAPCON-THERMAL, still contains certain limitations to its application. These limitations stem principally from the sparsity of well characterized data for establishing performance models and for checking the calculational models. Since the code is based on empirical models as well as first principles, the lack of well characterized data can result in a conservative calculation. We have been unable to locate much well characterized data for thermal reactor fuel, with large diametral gaps, especially in the 10 to 15 kW/ft range. Most of the data contain enough experimental uncertainties to preclude anything but a best estimate calculation. Furthermore, some information concerning initial conditions or operating history is usually either completely lacking or is inconsistent with other information in the report. We are continuing our evaluation of data reported in the open literature, but a definite need exists for good data applicable to commercial fuel in the operating range of interest.

To further improve the thermal performance modeling capability of the code, efforts are being applied to better delineate the following perform-

FIGURE 4. Calculated Gap Closure as a Function of Burnup and Heat Rating

ance and operational characteristics of the fuel. In addition, revision and validation of the code will be made as additional data becomes available.

- gap closure
- fuel melting
- restructuring
- volatile impurities
- fission gas
- power history
- contact conductance
- effects of xenon and krypton
- symmetric heat transfer

Gap Closure

The area of gap closure is currently the most limiting aspect of the GAPCON-THERMAL code because of the data concerning the kinetics and magnitude of gap closure. A number of options in the code allow the user to simulate gap closure data.

Sources of gap closure include cladding elastic deflection, thermal expansion, and creep; and fuel thermal expansion, swelling and cracking. Fuel swelling and radial relocation caused by fuel cracking typically provide the most gap closures. Unfortunately, very little well characterized, quantitative data have been published to model early-in-life gap closure caused by a combination of fuel swelling and fuel cracking. The phenomena are currently poorly understood and are not currently amenable to a rigorous analytical solution. We are currently involved in developing semi-empirical models for swelling and thermal ratchetting based on open literature data.

Fuel Melting

Much short-term data on thermal performance contains the effects of molten fuel. Fuel melting produces approximately a 9.6%⁽⁵⁷⁾ increase in volume. Some of the volume increase is accommodated in the residual

fabrication porosity, pellet dishes, and pellet cracks. The balance of the volume increase will be translated into dimensional changes of the pellet. Because GAPCON-THERMAL does not presently model the volume changes associated with melting, melt radii calculated with the code are typically larger than the experimental values. Often thermal performance computer codes are correlated with data via some adjustable constants. Applying a correlation based on molten fuel data to fuel operating below melting may inadvertently introduce a large error in calculated results for moderate power (12 to 15 kW/ft) rods with large diametral gaps. The postulated gaps associated with densified fuel place commercial fuel in just such an operating regime. Consequently, the volume expansion associated with fuel melting must be correctly modeled to avoid overpredicting the pellet diameter at lower powers.

Restructuring

Restructuring or grain growth is an important factor in oxide fuel temperature calculations because the formation of the central void reduces the heat flow path while the densification improves the thermal conductivity of the fuel. Calculated effects depend on the amount of sintering, the temperature at which sintering begins, and how sintering varies with time. The void distribution will affect other calculations such as fuel dimensional changes. Restructuring should be treated as a continuous time-dependent process. GAPCON-THERMAL contains a time-dependent relationship for columnar grain growth,⁽⁵⁸⁾ but we have not compared the model with others available. Some controversy exists as to the temperatures associated with the microstructural changes and the postulated densities in the restructured regions. For example, reported equiaxed grain growth temperatures vary from 1300 to 1700°C, and columnar grain growth temperatures range from 1600 to 2200°C. Restructured fuel densities vary from 92% TD to 100% TD. Some of the scatter can be attributed to the use of different assumptions for calculating the fuel temperatures from an experiment, and the difficulty of measuring residual porosity. Temperature gradients and pore morphology would also influence the results. Although

commercial fuel does not typically operate at powers sufficiently high to produce restructuring, the availability of a restructuring option will provide capability to model overpower conditions and additional experimental data.

Volatile Impurities

Comparison of calculated values with experimental data can be influenced by the assumptions made about volatile impurities in the fuel. Often the initial gas content and composition are not known. The release kinetics of most of the gases are poorly understood. In addition, the reaction kinetics of the released gases with the cladding and fuel are not well characterized. Efforts at PNL are being focused on the release kinetics and disposition of the gases in commercial fuel rods.

Fission Gas

The inventory of fission product atoms for fuel in a commercial plant will probably vary from the inventory calculated with GAPCON-THERMAL and also vary from plant to plant. We have not compared the fission product inventory calculated by GAPCON-THERMAL with the results of a more rigorous physics code.

The release of fission gas is primarily a function of fuel temperature. A burnup dependence exists but has not been resolved below about 15,000 MWD/MTM. A number of engineering models have been developed with the incentive of designing fission gas plenums to prevent overstressing the cladding. We have not evaluated the large amount of gas release data using a consistent set of assumptions nor have we established how well characterized the various experiments were. Often various investigators correlate gas release versus fuel temperature, but fail to list their assumptions required to arrive at the fuel temperature. In addition, determining the amount of gas released can be the source of considerable error. We are currently adapting a gas release model to replace the Hoffman-Coplin model. The replacement model will be correlated against data reduced with a consistent set of assumptions.

Power History

Changes in power as a function of time (e.g., reactor shutdown and subsequent startup) cannot currently be modeled with the code. The calculations at a specific power and time are independent of any previous history. In other words, the code returns to a zero time base for each calculation. Consequently, it is difficult to index certain calculations against experimental data. The calculation of fission gas release fractions with the code present such a problem because the inventory of gas in the fuel and the gap depend on the previous power history. An algorithm is being developed that will provide some path-dependent capability in the code.

Contact Conductance

We have not placed a high priority on evaluation of the contact conductance models because the postulated effects of fuel densification have forced the most limiting conditions to be a gas filled gap. A power history capability probably should be added to correctly model the contact conductance because fuel cladding mechanical interactions are obviously going to strongly influence the calculation. Fuel creep is currently not considered in the code. More appropriate structural mechanics formulations should be introduced to reduce the relative error in contact conductances. However, the stored energy is usually reduced sufficiently when fuel-cladding contact occurs to perhaps preclude a more complex structural mechanics approach.

We have occasionally encountered nonconvergence problems with the code. The nonconvergence typically occurs with low gap conductance and with very small hot radial gaps. The nonconvergence is probably associated with an incompatibility between the gap conductance model for a physical gap and the contact model. Small changes in gap width near fuel-cladding contact change the conductance considerably and the calculated values tended to oscillate unless the calculation was damped. We have tried a number of convergence schemes including a convergence on hot gap size. The hot gap convergence approach typically converged faster than the onvergence

approach based on gap conductance, but the gap width approach failed sometimes in the regime of low gap conductances and small hot gaps. The code currently uses a convergence criteria based on gap conductance. We expect that an evaluation of the heat transfer formulations may reduce the potential for nonconvergence.

Effects of Xenon and Krypton on Gap Conductance

Additional work is needed to resolve the discrepancies between experimental observations for xenon filled pins and the calculated results. Three experiments indicate xenon and krypton do not degrade the gap conductance in direct proportion to their relative low conductivity as compared to helium. Cohen, et al.^(59,60) reported no apparent effect of the gas atmosphere within the rods. Rods having diametral gaps of about 0.003 inches showed no apparent difference between helium and a 25% Kr- 75% Xe mixture. Horn⁽⁶¹⁾ indicated mixtures of helium-38% xenon, and helium-60% xenon, resulted in about the same gap conductance as 100% helium. Horn's⁽⁶¹⁾ tests were conducted at high heat ratings with initial diametral gaps of about 0.006 inches. Lawrence, et al. reported a helium-41% xenon mixture had no apparent effect (relative to 100% helium) on the calculated gap conductance. The tests reported by Lawrence, et al.⁽⁴¹⁾ consisted of irradiating at about 25 kW/ft UO_2 - 25 wt% PuO_2 rods that had diametral gaps of about 0.011 inches.

We postulate that either volatile impurities degraded the helium fill gas in the above tests to yield relative low thermal conductivities or the data for xenon and krypton are not applicable to in-reactor conditions. We are currently involving on resolving this anomaly by obtaining other xenon and krypton data and by additional analyses of the above experiments.

Symmetric Heat Transfer

Only heat transfer in the radial direction and a concentric pellet position within the cladding are considered. The conditions in an operating fuel pin typically are asymmetric and, the concentric case has been shown⁽⁶²⁾ to be the most conservative heat transfer situation. The concentric heat transfer in GAPCON-THERMAL contributes to the higher

temperature predicted by the code for large hot gaps. Consequently, comparisons of the code with experimental results become more conservative as the hot gap increases. However, other phenomena such as gap closure caused by thermally induced cracking probably are the largest sources of disparity between calculated and experimental values for large hot gaps.

COMPARISON OF CALCULATIONS WITH EXPERIMENTAL DATA

We have simulated the behavior of a number of experimental fuel rods and fuel contained in irradiation capsules. A number of assumptions were required to model the tests. The assumptions varied, but included uncertainties in dimensions, heat ratings, power history, grain growth characteristics, fuel and cladding surface roughness, sorbed gas contents, plenum volumes, and flux depression. We assumed a fuel and cladding surface roughness of 100 μ in. where the experimenter failed to report these values. Because gas contents were rarely specified, we assumed 0.0 cm³/gm unless otherwise noted. Flux depressions could have some error because these were calculated with the subroutine DEPRES rather than a physics code. The HPR-80 data was modeled with flux depressions obtained from a physics code.

Data from the sources listed below were selected for comparison.

- AE-411 (Reference 63)
- AECL-2588 (Reference 38)
- CEA-R-3358 (Reference 40)
- CVNA-142 (Reference 67)
- HPR-80 (Reference 45)
- NEDM-10735 (Reference 68)
- RISO-269 (Reference 69)
- WAPD-228 (Reference 59)
- WCAP-2923 (Reference 70)

AE-411 Data

The rig for the AE-411⁽⁶³⁾ experiment was too complicated to be modeled with GAPCON-THERMAL, but the experiment included temperature measurements at the fuel center and at two different radii within the fuel. These temperature measurements provided a check of measured versus calculated thermal conductivity from the following considerations:

Since the temperature within the fuel should follow the relation.

$$T_i - T_j = \frac{Q}{2K_{(t)}} \left[\frac{r_j^2 - r_i^2}{2} - \frac{\ln \left(\frac{r_j}{r_i} \right)}{r_i^2} \right]$$

where r_i = inner radius

r_j = any particular radius in the fuel

T_i = temperature at the inner radius

then a plot of T_j versus radius from GAPCON-THERMAL should be matched by the radial points from AE-411 providing the form of $K_{(t)}$ is the same, and providing Q and T_i match. The latter assumption was satisfied as nearly as possible by repeated GAPCON-THERMAL runs at varying input gaps until the situation shown in Figure 5 was attained. Figure 6 shows the temperature as a function of radius for the three check points noted in Figure 5. The error bars and boxes were estimated from the author's quoted uncertainty of about 7% in the thermal conductivity and its corresponding effect on the centerline temperature.

The agreement is actually better than indicated by Figures 5 and 6. If the temperatures from GAPCON-THERMAL are altered by simply adding or subtracting the ΔT required to make the centerline temperatures match, the comparison in Table 4 can be made.

FIGURE 5. A Comparison of Predicted and Measured Fuel Centerline Temperatures from AE-411

FIGURE 6. A Comparison of GAPCON-THERMAL UO_2 Thermal Conductivity with Data from AE-411

TABLE 4
COMPARISON OF GAPCON-THERMAL CALCULATIONS
WITH TEMPERATURES FROM AE-411

<u>Linear Heat rating kW/ft</u>	<u>Temperature radius = 3.0mm (0.118 in.) °C</u>		<u>Temperature at 4.25mm (0.167 in.) °C</u>	
	<u>GAPCON</u>	<u>AE-411</u>	<u>GAPCON</u>	<u>AE-411</u>
4.7	697	695	653	657
6.7	1073	1083	1083	1004
10.9	1615	1592	1460	1430

These results show good agreement between predicted fuel temperature and measured fuel temperatures in the range of about 600 to 1800°C.

AECL-2588 Data

Bain⁽³⁸⁾ has reported on a relatively large amount of gap conductance data for UO_2 fuel elements. We have compared some of his data with GAPCON-THERMAL predictions. We selected rods with reported evidence of fuel melting for the primary comparison because reported gap conductances are often valid only as a relative comparison for data in a particular experiment. The rods had diametral gaps ranging from 0.006 to 0.033 inches and were filled with either argon or helium. All the irradiations were very short. Rod powers covered the range from 15 kW/ft to 36 kW/ft. A comparison of predicted and reported melt radii (Figure 7) indicates GAPCON-THERMAL overpredicts the melt radii. Two rods, E-49 and E-53, had reported melt radii that were larger than predicted values. These two rods operated at 33.6 and 35.8 kW/ft. A small uncertainty in rod power could account for the difference. The bulk of the discrepancies between calculated melt radii and reported melt radii probably are associated with (1) uncertainties in rod power, (2) uncertainties in microstructural features defining melting, and (3) the lack of a molten fuel volume expansion model in GAPCON-THERMAL. We have compared predicted and reported

FIGURE 7. A Comparison of Predicted Melt Radii and Reported Melt Radii from AECL-2588

gap conductances (subject to the reservations above) in Figure 8. With three exceptions, GAPCON-THERMAL predicts lower values than the reported gap conductances. The comparisons in Figure 7 and Figure 8 are summarized in more detail in Table 5 and 6. Reported grain growth radii and gap conductances are compared with predicted values in Table 6 for a number of helium filled pins. The predicted grain growth radii are all larger than the experimental values. The temperature we selected for equiaxed grain growth was 1400°C while Bain used 1650 to 1700°C. We have not completed an estimate of the uncertainty in these data primarily because the code does not adequately model fuel melting.

CEA-R-3358 Data

The data reported by Janvier, et al.⁽⁴⁹⁾ consisted of grain growth measurements obtained from rods irradiated for two or four reactor cycles. Pellet diameters were a nominal 0.510 inches and diametral gaps ranged from 0.004 to 0.012 inches. Nominal burnups achieved for the two series of lists were 3000 and 6000 MWd/MTM. Rod powers varied considerably during the irradiation with peak powers occurring at the first startup and the last startup. The power history makes it difficult to determine the operating condition that controlled grain growth. Initial power conditions may have established the microstructure observed during the postirradiation examination, but the high powers towards the end of life could have controlled the grain growth. Gap conductance could have improved via radial fuel relocation to offset the higher powers at the end of life. Furthermore, the fission products are impurity atoms that could possibly inhibit grain growth towards end-of-life.

A number of observations have been reported that make it difficult to relate the structure observed in a postirradiation examination with the structure that may have existed at some time before the final stages of irradiation.

Bain⁽⁶⁴⁾ reported that two weeks operation at about 2000°C eliminated any evidence of a molten zone. Similar restructuring of the columnar grain growth region and the equiaxed grain growth region could perhaps

FIGURE 8. A Comparison of Predicted and Reported Gap Conductance from AECL-2588 Data

TABLE 5

CALCULATED AND REPORTED GAP CONDUCTANCES FOR AECL-2588
PHASE 13 HYDRAULIC RABBIT SPECIMENS AT ZERO DAYS

Rod #	Pellet Diameter (in.)	Initial Diametral Gap (in.)	Pellet Density (%TD)	Rod Power (kW/ft)	Hgap Reported/Predicted (Btu/hr-ft ² -°F)	Melt Radius Reported/Predicted (%)
E-4	0.6362	0.0331	97.7	15.4	125/109	13/53
E-12	0.6354	0.0331	97.7	14.9	118/108	20/50
E-17	0.6492	0.0201	97.7	21.5	248/232	26/41
E-18	0.6433	0.0260	97.7	21.2	236/172	28/62
E-20	0.6362	0.0331	97.7	19.7	185/134	37/70
E-34	0.6433	0.0260	97.3	25.0	336/184	38/72
E-36	0.6362	0.0331	97.3	26.5	308/178	52/82
E-37	0.6492	0.0201	97.3	26.0	444/323	32/43
E-43	0.6555	0.0130	97.3	27.1	748/859	27/30
E-46*	0.6433	0.0260	97.3	25.3	486/398	19/48
E-48*	0.6433	0.0260	97.3	25.4	486/440	20/45
E-49	0.6634	0.0059	97.1	35.8	2325/838	67/62
E-53	0.6492	0.0201	97.1	33.6	1075/785	73/60

* Helium Fillgas, Balance of Pins Contained Argon

TABLE 6

CALCULATED AND REPORTED GAP CONDUCTANCES FOR AECL-2588, X-23301
AND X-23303 TESTS

<u>Rod #</u>	<u>Pellet Diameter (in.)</u>	<u>Initial Diametral Gap (in.)</u>	<u>Pellet Density (%TD)</u>	<u>Rod Power (kW/ft)</u>	<u>Hgap Reported/Predicted (Btu/hr-ft²-°F)</u>	<u>Equiaxed Grain* Growth Radius Reported/Predicted (%)</u>
FAN	0.7047	0.0142	95.8	21.46	528/757	72/79
FAO	0.7047	0.0142	95.7	16.86	352/303	67/76
FAP	0.7047	0.0142	95.5	19.92	480/494	70/76
FAT	0.6902	0.0291	95.9	18.01	234/151	84/100
FAW	0.6902	0.0291	95.5	19.92	276/167	83/100
FAZ	0.6902	0.0291	96.1	21.46	317/181	82/100

* Equiaxed grain growth assumed to occur at 1400°C

also occur. An irradiation test by MacDonald⁽⁶⁵⁾ suggests that equiaxed grain growth was retarded by previous irradiation history. The test consisted of reirradiating a rod that had achieved 484 full power days at 50% higher power. MacDonald's calculations suggested the diameter of grain growth should have increased about 0.050 inches for an additional 22 full power days whereas the measured amount was as low as 0.010 inches. MacEwan and Hajaski⁽⁶⁶⁾ (as reported by MacDonald) showed that grain growth was inhibited for samples irradiated below 1500°C and subsequently raised to 1500-1750°C for an additional 290 hours. Thus, the magnitude and deviation of power changes during irradiation could have a pronounced effect on grain growth because of the time-temperature relationship and the effect of fission induced impurities.

We were not able to determine which power conditions established the extent of grain growth observed in the CEA-R-3358 tests. We attempted to simulate the thermal behavior by comparing GAPCON-THERMAL predictions based on (1) maximum beginning-of-life powers, (2) maximum end-of-life powers and (3) time-averaged end-of-life powers. The beginning-of-life (BOL) conditions were simulated by running GAPCON-THERMAL at $\pm 10\%$ of the BOL heat ratings to establish an uncertainty band for the reported powers. The fuel temperatures were plotted as a function of fuel radius for the power range of interest. We superimposed the grain growth measurements obtained from the postirradiation examination and delineated the uncertainty rectangle by using the authors reported grain growth dimensional uncertainty and our estimate of $\pm 100^\circ\text{C}$ on the grain growth temperature. We assumed a columnar grain growth temperature of 1700°C and an equiaxed grain growth temperature of 1400°C . All of the sorbed gas was assumed to have reacted with the cladding and fuel. With the exception of the 4112 samples, the predicted values for BOL conditions agree with the experimental data (Figure 9 to 24).

The predictions for maximum EOL rod powers typically resulted in higher values than the experimental values. We attempted to simulate the effects of burnup by running the code at the time averaged rod power in the last cycle because GAPCON-THERMAL cannot simulate power cycling. The

FIGURE 9. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4110-AE1

FIGURE 10. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4110-AE2

FIGURE 11. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4110-BE1

FIGURE 12. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4110-BE2

FIGURE 13. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4111-AE1

FIGURE 14. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4111-AE2

FIGURE 15. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4111-BE1

FIGURE 16. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4111-BE2

FIGURE 17. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4112-AE1

FIGURE 18. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4112-AE2

FIGURE 19. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4112-BE1

FIGURE 20. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4112-BE2

FIGURE 21. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4113-AE1

FIGURE 22. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4113-AE2

FIGURE 23. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4113-BE1

FIGURE 24. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4113-BE2

results (Figure 25 through 28) indicate that (1) the code overpredicts the effects of fission gas degradation of the fill gas, or (2) the hot gap is not modeled correctly, or (3) grain growth is not established by time-averaged EOL conditions.

Our estimates for grain growth temperature are reasonable, yet conservative. Higher grain growth temperatures (e.g., 1700°C rather than 1400°C for equiaxed grain growth) would of course provide a better fit to the data.

CVNA-142 Data

Duncan⁽⁶⁷⁾ has reported the results of short-term irradiations (~40 hours) wherein diametral gaps and rod powers ranged from 0.006 to 0.025 inches and 11 to 24 kW/ft, respectively. We selected 7 rods out of the 18 rods that were irradiated. Our emphasis was toward helium filled rods that operated at powers sufficiently high to cause fuel melting. Some low power rods were included for a comparison of predicted and reported gas conductances. The results summarized in Table 7 indicate GAPCON-THERMAL predicts a larger melt radius and lower gap conductances (Figure 29).

Columnar and equiaxed grain growth radii were reported for three samples. Comparisons (Figures 30, 31 and 32) indicate GAPCON-THERMAL overpredicts the grain growth in these samples. Our uncertainty estimate for the extent of grain growth was ± 0.010 inches and $\pm 100^\circ\text{C}$. We did not complete an uncertainty analyses on reported rod powers or sample dimensions. The predicted values were obtained at $\pm 10\%$ of reported rod powers. The uncertainty estimates suggest the data fall within the range of calculated values for BOL conditions.

The calculations for EOL conditions in Figures 29, 30, 31, show a rather large effect of fill gas degradation for a 40-hour irradiation which suggests the code definitely provides conservative results for fuel that has achieved some burnup. Radial fuel relocation would offset the calculated effects of fission gas degradation of gap conductance.

FIGURE 25. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4110-AE1 (EOL Conditions)

FIGURE 26. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4111-AE2 (EOL Conditions)

FIGURE 27. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4112-AE1 (EOL Conditions)

FIGURE 28. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CEA-R-3358, Sample 4112-AE2 (EOL Conditions)

FIGURE 29. A Comparison of Predicted Gap Conductances with Reported Values From CVNA-142

FIGURE 30. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CVNA-142, Sample 11-1

FIGURE 31. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CVNA-142, Sample 11-2

FIGURE 32. A Comparison of GAPCON-THERMAL Predictions with Grain Growth Measurements from CVNA-142, Sample 11-3

TABLE 7

CALCULATED AND REPORTED GAP CONDUCTANCES FOR CVNA-142
DATA AT ZERO DAYS (HELIUM FILL GAS)

Rod No.	Pellet Diameter (in.)	Initial Diametral Gap (in.)	Rod Power (kW/ft)	H _{gap}	Melt Radius
				Reported/Predicted (Btu/hr-ft ² -°F)	Reported/Predicted %
4-2	0.4301	0.0125	16	630/580	0/0
6-1	0.4299	0.0064	18	30,000/2,175	0/0
6-2	0.4300	0.0126	18	1,970/740	0/0
6-3	0.4299	0.0256	18	570/340	0/10
11-1	0.4299	0.0064	24	13,300/10,600	0/0
11-2	0.4301	0.0125	24	2,640/1,300	0/28
11-3	0.4300	0.0252	24	520/450	21/67

HPR-80 Data

These data consisted of centerline temperature determined by thermocouples located in the fuel. Fuel densities were 96% TD and 98% TD, and pellet diameters were about 0.440 inches. We assumed all the sorbed gas reacted with the fuel or cladding. The predicted values for the rods with 0.002 initial gaps agree quite well with the experimental values (Figures 33 through 38). The predicted values are somewhat higher than the data for rods with a 0.006 inch gap (Figure 35 and 38). The experimental uncertainties in power and thermocouple readings were obtained from Kjaerheim and Rolstads⁽⁴⁵⁾ reported estimates. The authors reported an increase in fuel temperatures of about 60 to 80°C after burnups of 4200 to 4300 MWd/MT UO₂. GAPCON-THERMAL predictions indicate about 10°C increase in centerline temperature at 12 kW/ft for the same burnup. The only contribution to the simulated temperature rise is fission gas degradation of the fill gas because the effects of irradiation on UO₂ thermal conductivity are not considered in the code.

FIGURE 33. A Comparison of GAPCON-THERMAL Predictions with Fuel Center-line Temperatures from HPR-80, Sample HBA

FIGURE 34. A Comparison of GAPCON-THERMAL Predictions with Fuel Centerline Temperatures from HPR-80, Sample HBB

FIGURE 35. A Comparison of GAPCON-THERMAL Predictions with Fuel Centerline Temperatures from HPR-80, Sample HBC

FIGURE 36. A Comparison of GAPCON-THERMAL Predictions with Fuel Centerline Temperatures from HPR-80, Sample HCA

FIGURE 37. A Comparison of GAPCON-THERMAL Predictions with Fuel Centerline Temperatures from HPR-80, Sample HCD

FIGURE 38. A Comparison of GAPCON-THERMAL Predictions with Fuel Centerline Temperatures from HPR-80, Sample HCC

NEDM-10735 Data

Gap conductances for three fuel rods were reported by Ditmore and Elkins.⁽⁶⁸⁾ The AEG rod was at power a very short time while the DP-4 rod operated to approximately 8000 to 10,000 MWd/MTM burnup. Both rods had diametral gaps of about 0.016 inches. The reported gap conductances were apparently calculated from fuel microstructures obtained from axial segments of the pin. The third rod that we simulated was designated HP (from page 26, Table 8 of NEDM-10735). These data consisted of a series of rods with 0.006 inch gaps that operated at rod powers of 26 to 46 kW/ft. Fuel burnups ranged from 1300 MWd/MTM to 2000 MWd/MTM. The authors did not report their assumptions required to calculate a gap conductance nor did they provide an estimate of the uncertainty. Therefore, any comparison of a computer code with these data is almost an exercise in futility. GAPCON-THERMAL predictions are compared with reported gap conductances for rod AEG in Figure 39. The predicted values are within the data scatter for this short-term test. However, different assumptions for grain growth temperatures could change the reported gap conductances to higher values. The DP-4 and HP rods (Figures 40 and 41) were modeled by assuming zero burnup and irradiation time corresponding to the reported burnups at 20 and 26 kW/ft, respectively. The zero day case for DP-4 was slightly conservative relative to the reported gap conductances. The effect of burnup was to lower the zero day gap conductance by about $200 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$. The calculations for the zero day case for rod HP show reasonably good agreement with the data while the simulated burnup case is definitely conservative.

RISO-269 Data

The data in this report⁽⁶⁹⁾ were presented as curves of cladding and fuel temperatures as a function of linear heat rating which ranged from 1 to 13 kW/ft. As Figure 42 indicates, agreement of GAPCON-THERMAL with the measured center fuel temperatures is within 5% over the full range of linear powers. We could not determine the size of the uncertainty band from the data. Fayl and Hansen⁽⁶⁹⁾ suggested that the scatter in the data

FIGURE 39. A Comparison of Predicted and Reported Gap Conductances From NEDM-10735, Sample AE6

FIGURE 40. A Comparison of Predicted and Reported Gap Conductances From NEDM-10735, Sample DP4

FIGURE 41. A Comparison of Predicted and Reported Gap Conductances From NEDM-10735, Sample HP

FIGURE 42. Comparison of GAPCON-THERMAL Predictions and Data From RISO Report No. 269

leads to a 7% uncertainty in the thermal conductivity of UO_2 . An overall uncertainty of at least $\pm 10\%$ in centerline temperatures seems reasonable and was used in Figure 42.

WAPD-228 Data

The experiments described by Cohen, et al.⁽⁵⁹⁾ in WAPD-228 involved in-reactor measurements of fuel centerline and cladding temperatures. The heat rating was inferred from thermocouple readings in the cladding and the conductivity of UO_2 was inferred from this heat rating, the measured centerline temperature in WAPD-228, and the calculated gap conductances.

Not all the experiments were compared with GAPCON-THERMAL. All the experiments are listed in Table 8, with a brief explanation as to why they were or were not included in this comparison.

The results of comparison with experiments involving helium-filled gaps (22-5, 1 and 3) are presented in Figures 43 and 44. In Figure 43 uncertainty boxes are placed around the specific test points. In Figure 44, uncertainty bands are placed about the centerline temperatures. The 22-5 experiment was one of two for which the authors presented variation between sets of thermocouples. Two sets of the thermocouples in the clad were used, and predicted heat ratings were presented for 11 data points, ranging from 1 to 6.3 kW/ft. The deviation from the mean was consistently $\pm 5\%$, so that a confidence band on linear power can be estimated as $5\% \times 2.5 = 12.5\%$. In addition there is a variation in centerline temperature of $\pm 3\%$ at the same predicted heat rating. Assuming $\pm 6\%$ for an error band, this translates directly to a $\pm 6\%$ error band in K_{UO_2} , which affects the predicted heat rating. Combining the two effects, $(\sqrt{12.5^2 + 6^2} = 14\%)$ results in the total uncertainty band in predicted power. The temperature deviations in Figure 43 and 44 were calculated from the data using the 14% variation in heat rating. In Figure 44 the uncertainty band on experiment 22-3 is nearly doubled because of an indicated $\pm 100\%$ variation in calculated gap conductance at the same heat rating.

FIGURE 43. Effect of Linear Heat Rating - GAPCON-THERMAL Predictions vs WAPD-228 Data

FIGURE 44. Effect of Initial Cold Gap - GAPCON-THERMAL Predictions vs WAPD-228 Data

TABLE 8

EXPERIMENTS IN WAPD-228 INVOLVING IN-REACTOR MEASUREMENTS
OF FUEL CENTERLINE AND CLADDING TEMPERATURES

<u>Experiment Number</u>	<u>Cold Diametral Gap, Mils</u>	<u>Heat Ratings Attained kW/ft</u>	<u>Fill Gas</u>	<u>Comments</u>
22-1	3.5	2	He	Included
22-2	8.0	3	Vac.	Not included - no practical interest
22-3	8.0	2	He	Included
22-4	1.5	5	He	Not included. Essen- tially duplicated by 22-5
22-5	1.5	6.3	He	Included
22-6	0.0	--	He	Not included. No practical interest
22-7	13.0	5	3 Xe + 1 Kr	Included
22-9	8.0	--	3 Xe + 1 Kr	Not included
22-11	0.0	--	3 Xe + 1 Kr	Not included
22-14	2.5	--	3 Xe + 1 Kr	Not included. Dupli- cated by 22-15
22-15	3.5	7.2	3 Xe + 1 Kr	Included

The comparison of GAPCON-THERMAL with experiments involving xenon-krypton filled gaps is presented below in Table 9. As noted, most of the temperature difference is caused by a difference in gap conductance. The uncertainty band on the centerline temperature was calculated assuming a 14% uncertainty in linear heat rating.

TABLE 9

A COMPARISON OF GAPCON WITH WAPD-228 DATA FOR XENON-KRYPTON FILLED GAPS

Experiment Number	Cold Gap Mils	Heat Rate kW/ft	Fuel Centerline Temperature °C		GAP ΔT °C	
			WAPD-228, Measured	GAPCON	WAPD-228	GAPCON
22-7	13.0	5.47	987 $\pm$ 100	2097	284	1193
22-15	3.5	7.13	1144 $\pm$ 300	2334	252	1201

Cohen, et al.⁽⁵⁹⁾ note that their gap conductances for xenon-krypton gaps contradict theory in that gap conductances are nearly the same as for equivalent helium-filled gaps. The authors propose that cracking and rearrangement of the fuel brings it in contact with the cladding which may explain the anomaly. Assuming the pellet in experiment 22-7 was tangent to the clad, we calculated a weighted "effective" gap conductance based on GAPCON-THERMAL results for smaller clearances. The result yields a gap ΔT of

$$\frac{\text{GAPCON conductance}}{\text{effective conductance}} \times \text{GAPCON } \Delta T = \frac{97}{151} \times 1193 = 800^\circ\text{C}$$

This calculated ΔT would lower the centerline temperature considerably due to the enhanced UO_2 conductivity; the result would be approximately 1200°C which is considerably closer to the measured value. Thus, the concentric fuel-cladding gap model used in GAPCON-THERMAL may be unreasonably conservative for large diametral gaps.

WCAP-2923 Data

The results of capsule irradiations with thermocouples located in the fuel were used by Balfour, et al.⁽⁷⁰⁾ to measure the conductivity of UO_2 . Seven thermocouples, consisting of two concentric rings of three thermocouples and one centerline thermocouple, were placed in each of three capsules. Heat ratings as high as 25 kW/ft were achieved. The fuel rods contained 1.250 inch diameter pellets and a nominal 0.0245 inch gap. Fuel densities were 95% TD. We simulated two of the three capsules by running the code at heat ratings that varied $\pm 10\%$ from the reported values. The uncertainty associated with the position of the thermocouple was estimated from the reported dimensions. Measured temperature uncertainties were estimated by using the maximum deviation from the average of three values or 2% of the reported values. The fuel was modeled with zero sorbed gas and $0.05 \text{ cm}^3/\text{g}$ sorbed gas of which 75% was hydrogen. The results for Capsule I (Figure 45 to 49) show poor agreement between the predicted centerline temperatures and the reported values. The calculated temperatures in the inner regions of the fuel show an upward bias relative to the experimental points. The $0.05 \text{ cm}^3/\text{g}$ sorbed gas contents had little effect on the comparison. Capsule II fuel was supposedly identical to Capsule I, but GAPCON-THERMAL predictions (Figure 50 to 54) are closer to the experimental value at heat ratings of about 13 kW/ft.

The comparisons of predicted and measured centerline temperatures for the two capsules are depicted in Figures 45 and 49. Capsule I agreement is poor while the predicted values for Capsule II are somewhat better. Comparison of reported centerline temperature for the two capsules at the same heat rating indicates Capsule II operated about 200°C higher (at 20 kW/ft) than Capsule I. Reported powers could be in error, but it is our opinion that the thermocouples near the center of Capsule II may have failed to operate as intended.

Some of the disagreements could be associated with the perturbation created by the presence of a thermocouple. Gnecco and Michel⁽⁷¹⁾ calculated a 200 to 400°C error in the fuel temperature distribution caused by

FIGURE 45. A Comparison of GAPCON-THERMAL Predictions with Reported Centerline Temperatures from WCAP-2923, Capsule 1

FIGURE 46. A Comparison of GAPCON-THERMAL Predictions with Fuel Temperature Measurements from WCAP-2923, Capsule I, at 21.2 kW/ft

FIGURE 47. A Comparison of GAPCON-THERMAL Predictions with Fuel Temperature Measurements from WCAP-2923, Capsule I, at 21.75 kW/ft

FIGURE 48. A Comparison of GAPCON-THERMAL Predictions with Fuel Temperature Measurements from WCAP-2923, Capsule I, at 22.96 kW/ft

FIGURE 49. A Comparison of GAPCON-THERMAL Predictions with Fuel Temperature Measurements from WCAP-2923, Capsule I, at 22.96 kW/ft (0.05 cm³/gm Sorbed Gas)

FIGURE 50. A Comparison of GAPCON-THERMAL Predictions with Reported Centerline Temperatures from WCAP-2923, Capsule II

FIGURE 51. A Comparison of GAPCON-THERMAL Predictions with Fuel Temperature Measurements from WCAP-2923, Capsule II, at 13.36 kW/ft

FIGURE 52. A Comparison of GAPCON-THERMAL Predictions with Fuel Temperature Measurements from WCAP-2923, Capsule II, at 18.97 kW/ft

FIGURE 53. A Comparison of GAPCON-THERMAL Predictions with Fuel Temperature Measurements from WCAP-2923, Capsule II, at 21.81 kW/ft

FIGURE 54. A Comparison of GAPCON-THERMAL Predictions with Fuel Temperature Measurements from WCAP-2923, Capsule II, at 23.72 kW/ft

the introduction of a thermocouple. The temperature of the thermocouple hot junction was calculated at 1870°C for a fuel centerline temperature of 2135°C. Although we have not verified the calculations of Gnecco and Michel, the error introduced by the presence of a thermocouple may be significant in a comparison of a computer code with experimental results.

SENSITIVITY STUDY

A limited parametric study was done to establish the relative sensitivity of the calculations to initial gap size, volatile impurities, and axial power shape. The effects of these parameters were considered over a range of heat ratings and burnups.

Effect of Initial Cold Gap

A BWR pin was modeled with g/D (initial gap/pellet diameter) ratios ranging from 0.01 to 0.05. Rod powers were varied from 10 to 16 kW/ft. A g/D of about 0.03 is a typical postulated gap for densified fuel and the heat ratings selected are in the range of the peak rod powers for a modern BWR. Calculated gap conductances are shown in Figure 55. The effects of operating for 100 full power days are also shown in Figure 55. The results show little effect of fission gas degradation at these exposures for the low g/D ratios. Calculated fuel temperatures are sufficiently high for pins with large gaps so as to result in large calculated gas releases. A similar plot for the volumetric average temperature of the hot node is shown in Figure 56. These comparisons do not include the effects of gap closure by means other than differential thermal expansion. Consequently, the calculated gap conductances are lower than values that might exist in fuel operating under these conditions.

Effect of Volatile Impurities (Sorbed Gas)

As discussed earlier in the report, assumptions about the content, composition, and disposition of volatile impurities can affect the calculated results considerably. We modeled a BWR rod with two gap sizes: 0.010 inches and 0.016 inches. The 0.010 inch gap is in the range of gaps for commercial fuel while the 0.016 inch gap is representative of the

FIGURE 55. The Effects of Initial Cold Gap, Burnup, and Heat Rating on the Gap Conductance of a BWR Rod

FIGURE 56. The Effects of Initial Cold Gap, Burnup, and Heat Rating on the Volumetric Average Temperature of a BWR Rod

postulated gaps associated with densification. We considered three levels (0.0, 0.02, and 0.05 cm³/g) of gas content and three gas compositions (100% nitrogen, 25% nitrogen and 100% hydrogen). We also considered one case where the hydrogen was released from the cladding. Calculated gap conductances and volumetric average temperature of the hot node are depicted in Figures 57 and 58. These calculations assume the total inventory of gas is released in the same manner as the fission gas. Mixtures of hydrogen and helium (Case 6) result in a better calculated gap conductance relative to 100% helium. The relatively large effects of nitrogen in the fill gas suggest that nitrogen release must be considered as a time-temperature release process rather than solely a temperature dependent release. Similar trends were obtained for the 0.016 inch gap case (Figure 59 and 60) but the relative effects were larger.

Effects of Axial Power Shape

A PWR pin was used to illustrate the sensitivity of fuel temperature to power shapes and peak-to-average ratios. The axial power profiles used are shown in Figure 61. The axial temperature profiles of a fuel rod corresponding to these power shapes are shown in Figure 62.

Power Profiles I and II have the same peak-to-average ratio (~ 1.2) but different shapes (i.e., Profile I peaks in the center and Profile II peaks at the top of the rod). The effects these two power profiles have on the volumetric average fuel temperature of the rod and the volumetric average temperature of the hot node at various peak powers are shown in Figures 63 and 64. Changing the shape of the power profile without changing the peak-to-average ratio has little effect on the fuel temperature at the hot node or the rod. Power Profiles III and IV have peak-to-average ratios of 1.0 and 1.6, respectively, and were used to determine the maximum possible difference in fuel temperatures that could result for a typical range of peak-to-average ratio. The results (Figures 63 and 64) show that the difference between the volumetric average fuel temperatures of the rod for Profiles III and IV can be significant (~ 800 - 1100°F) even though the same peak powers were issued. The difference in volumetric average temperatures of the hot node can also be significant (400 - 600°F)

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APPENDIX C
LISTING OF GAPCON

FIGURE 57. The Effects of Sorbed Gas Release on the Gap Conductance of a BWR Rod (0.010 Gap)

FIGURE 58. The Effects of Sorbed Gas Release on the Volumetric Average Temperature of a BWR Rod (0.010 Gap)

FIGURE 59. The Effects of Sorbed Gas Release on the Gap Conductance of a BWR Rod (0.016 Gap)

FIGURE 60. The Effects of Sorbed Gas Release on the Volumetric Average Temperature of a BWR Rod (0.016 Gap)

FIGURE 61. Axial Power Profiles for GAPCON-THERMAL Sensitivity Study

FIGURE 62. Volumetric Average fuel Temperatures vs Axial Length for different Power Profiles at 12.0 kW/ft and 200 days

FIGURE 63. The Effect Different Power Profiles with the Same Peak Heat Ratings Have on Volumetric Average Fuel Temperatures of the Rod

FIGURE 64. The Effects of Power Shapes on Fuel Rod Hot Node Temperatures

at peak powers between 10 and 14 kW/ft. Higher powers (>14 kW/ft) yielded a difference of 200-300°F. From these results the following conclusions can be made:

- Varying the shape of a power profile with a constant peak-to-average ratio has little effect (10-20°F) on the volumetric average fuel temperatures of the entire rod nor the temperatures of the hot node.
- Varying the peak-to-average profile with a constant peak power has a very significant effect on the volumetric average fuel temperature of the rod with the effect being larger at lower powers. The effect on the hot node temperatures is not as great.

COMPARISON OF GAPCON-THERMAL-1, TO OTHER VERSIONS OF GAPCON

GAPCON-THERMAL-1 is compared against the original fast reactor version of GAPCON⁽¹⁾ and an earlier version of the original GAPCON which included correlations that were more applicable to thermal reactor fuel but, as in the original GAPCON, only had the capability of performing calculations at one axial node (at the point of peak power) for a fuel rod.

The internal rod pressures and fuel temperatures predicted by these codes are given in Figure 65-68 at two heat ratings 10 and 14 kW/ft. The results show that all three codes predict similar internal pressures and temperatures at zero burnup, but then differ as burnup progresses. The two earlier versions of the code predict internal pressures which are considerably higher than GAPCON-THERMAL with the original version showing the largest differences (between a factor of 2 to 3 higher) at 30,000 MWD/MTM. The revised one node version is higher by 20 and 60% for the two heat ratings at 30,000 MWD/MTM. The decrease in pressures between the original version and the revised one node version can be attributed to a key punch error on a fission gas yield in the original code. The pressure decrease from the revised one node version to the present multi node version can be attributed to the revised pressure calculator which uses a $\frac{V}{t}$ relationship for each axial node as explained in a previous section of this document, as shown in Figures 67 and 68 the original version of GAPCON predicts

FIGURE 65. Comparison of Pressures as Predicted by GAPCON-THERMAL-1 to Other Versions of GAPCON at 10.0 kW/ft

FIGURE 66. Comparison of Pressures as Predicted by GAPCON-THERMAL-1 to Other Versions of GAPCON at 14 kW/ft

FIGURE 67. Comparison of Temperatures as Predicted by GAPCON-THERMAL-1 to Other Versions of GAPCON at 10 kw/ft

FIGURE 68. Comparison of Temperatures as Predicted by GAPCON-THERMAL-1 to Other Versions of GAPCON at 14. kW/ft

250-500°F (depending on heat rating and burnup) higher volume average temperatures. However, the revised one node version predicts volume average temperatures which are slightly lower 25-110°F than GAPCON-THERMAL.

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SECTION 5.
ACKNOWLEDGMENTS

5. ACKNOWLEDGMENTS

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SECTION 6.
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APPENDIX A
DESCRIPTION OF UNALTERED PORTIONS OF GAPCON

APPENDIX ADESCRIPTION OF UNALTERED PORTIONS OF GAPCONFUNCTION TERP

TERP is a linear interpolation function which is called frequently to interpolate the many tables of values that are used throughout the program.

SUBROUTINE HTCW

HTCW is a subroutine used to calculate the cladding-to-coolant heat transfer coefficient if the coolant is water (if SIGHF is less than zero). The calculation is based on the Dittus-Boelter⁽⁷²⁾ equation:

$$h_f = .023 \frac{k}{D_e} \left(\frac{D_e V \rho}{\mu} \right)^{0.8} (Pr)^{0.4}$$

where h_f = cladding-to-coolant heat transfer coefficient
 k = thermal conductivity of coolant (Btu/hr ft °F)
 D_e = equivalent diameter of coolant passage (in)
 V = coolant velocity (ft/sec)
 ρ = coolant density (lbs/ft³)
 μ = coolant viscosity (lb/ft-sec)
 Pr = Prandtl number = $C_p \mu / k$

All coolant properties are evaluated at the mean temperature of the coolant film. The properties of water as a function of temperature are included in the subroutine. The values used are those tabulated in Krieth.⁽⁷³⁾

SUBROUTINE HTCLM

HTCLM is a subroutine used to calculate the cladding-to-coolant heat transfer coefficient if the coolant is liquid sodium (if SIGHF equals zero). The calculation is based on:

$$h_f = \frac{k}{D_e} \left[7.0 + 0.025 \left(\frac{D_e V \rho C_p}{k} \right)^{0.8} \right]$$

where h_f = cladding-to-coolant heat transfer coefficient,
 k = thermal conductivity of sodium,
 D_e = coolant passage equivalent diameter,
 V = coolant velocity,
 ρ = density of sodium,
 C_p = heat capacity of sodium.

The temperature dependent properties of liquid sodium included as part of this subroutine are those presented in Reference 74.

$$\begin{aligned} k_{Na} &= 54.306 - 1.878 \times 10^{-2} T (^{\circ}\text{F}) + 2.0914 \times 10^{-6} T^2 (^{\circ}\text{F}) \\ \rho_{Na} &= 59.566 - 7.9504 \times 10^{-3} T (^{\circ}\text{F}) - 0.2872 \times 10^{-6} T^2 (^{\circ}\text{F}) + \\ &\quad 0.06035 \times 10^{-9} T^3 (^{\circ}\text{F}) \\ (C_p)_{Na} &= 0.34574 - 0.79226 \times 10^{-4} T (^{\circ}\text{F}) + 0.34086 \times 10^{-7} T^2 (^{\circ}\text{F}) \end{aligned}$$

SUBROUTINE FISGAS

FISGAS is a subroutine used to estimate the fission gas inventory of an irradiated fuel pin. Fission yields for those isotopes that contribute to the gas inventory are those reported by Meek and Rider⁽⁷⁵⁾ and are summarized in Talbes A-1 (fast fission yields) and A-2 (thermal fission yields). The fission cross sections used for various heavy metal atoms are summarized in Tables A-3 (fast fission cross sections) and A-4 (thermal fission cross sections).

SUBROUTINE DEPRES

DEPRES is a subroutine which estimates the radial flux depression profile for irradiations conducted in a thermal flux. These calculations are

TABLE A-1

FISSION YIELDS USED FOR FAST FLUX IRRADIATION⁽⁷⁵⁾

Isotope	Yields (%) From Fission of:			
	<u>U²³⁵</u>	<u>U²³⁸</u>	<u>Pu²³⁹</u>	<u>Pu²⁴¹</u>
Kr ⁸³	0.77	0.40	0.38	--
K ⁴⁸⁴	0.92	0.85	0.52	--
Kr ^{85I}	1.22	0.73	0.69	--
Kr ⁸⁵	0.0	0.0	0.0	--
Kr ⁸⁶	1.70	1.38	0.90	--
Te ^{131I}	0.52	0.0	0.0	--
Te ¹³¹	3.11	3.2	3.3	--
I ¹³¹	0.0	0.0	0.10	--
Xe ¹³¹	0.0	0.0	0.0	--
Te ¹³²	5.5	4.4	3.5	--
I ¹³²	0.2	0.3	0.26	--
Xe ¹³²	0.0	0.0	0.0	--
I ¹³³	5.50	5.5	5.7	--
Xe ¹³³	0.0	0.0	0.0	--
Xe ¹³⁴	5.9	6.6	6.4	--
I ¹³⁵	5.6	5.9	6.3	--
Xe ^{135I}	0.0	0.0	0.0	--
Xe ¹³⁵	0.5	0.1	0.5	--
Xe ¹³⁶	6.0	5.9	6.9	--

TABLE A-2

FISSION YIELDS USED FOR THERMAL FLUX IRRADIATION⁽⁷⁵⁾

Isotope	Yields (%) From Fission of:			
	U^{235}	U^{238}	Pu^{239}	Pu^{241}
Kr ⁸³	0.52	--	0.29	0.208
Kr ⁸⁴	0.97	--	0.47	0.341
Kr ⁸⁵ I	1.30	--	0.535	0.30
Kr ⁸⁵	0.0	--	0.0	0.0
Kr ⁸⁶	1.93	--	0.75	0.40
Te ¹³¹ I	0.44	--	0.0	0.0
Te ¹³¹	2.52	--	3.7	3.01
I ¹³¹	0.0	--	0.09	0.0
Xe ¹³¹	0.0	--	0.0	0.0
Te ¹³²	4.33	--	5.2	4.44
I ¹³²	0.0	--	0.15	0.03
Xe ¹³²	0.0	--	0.0	0.0
I ¹³³	6.69	--	5.3	6.54
Xe ¹³³	0.0	--	1.2	0.0
Xe ¹³⁴	7.92	--	7.47	7.81
I ¹³⁵	6.17	--	5.7	7.23
Xe ¹³⁵ I	0.0	--	0.0	0.0
Xe ¹³⁵	0.13	--	1.51	0.07
Xe ¹³⁶	6.46	--	6.66	7.04

TABLE A-3

FAST FISSION CROSS-SECTIONS USED FOR THE HEAVY METAL ATOMS

<u>Isotope</u>	<u>Fission Cross Sections (barns)</u>
U^{235}	1.4
U^{238}	0.1
Pu^{239}	1.6
Pu^{241}	1.6

TABLE A-4

THERMAL FISSION CROSS-SECTIONS USED FOR THE HEAVY METAL ATOMS

<u>Isotope</u>	<u>Fission Cross Section (barns)</u>
U^{235}	535.
U^{238}	0.
Pu^{239}	740.
Pu^{241}	0.
Pu^{241}	950.

at best rough approximations and this subroutine should be called only when no other flux depression information is available. The calculations become increasingly inaccurate as the magnitude of the flux depression increases. Therefore, this subroutine should not be called when the fuel pin for which calculations are being made contains PuO_2 or when ^{235}U enrichment is greater than 4%.

SUBROUTINE EXPAND

EXPAND calculates the increase in fuel radius caused by thermal expansion of the fuel as follows:

The fuel pellet is divided into 50 equally spaced radial increments. Each annular ring formed is assumed to be a free body at its average temperature T . The increase in radius of each ring due to thermal expansion in the circumferential direction is calculated from:

$$\Delta R_c = \alpha R_{avg} (T - T_r)$$

where ΔR_c = increase in radius due to expansion in the circumferential direction

α = linear coefficient of thermal expansion

R_{avg} = average radius of the increment

T = average temperature of the increment

T_r = room temperature (25°C).

The code then finds that node in which the maximum increase in radius occurs, and it is assumed that all the thermal expansion that occurs inside that increment is accounted for by the radius increase of that increment. EXPAND then calculates the increase in thickness of each node outside the node of maximum circumferential expansion from

$$\Delta t_i = \alpha t (T - T_r)$$

where Δt_i = increase in thickness of increment i due to thermal expansion in the radial direction.

t = initial thickness of node i .

The total increase in fuel radius due to thermal expansion is then assumed to be:

$$\Delta R = (\Delta R_c)_{max} + \left(\sum_{i=1}^L \Delta t_i \right) - \frac{\Delta t_i}{2}$$

where ΔR = total increase in fuel radius due to thermal expansion

L = the number of the increment immediately outside that increment in which $(\Delta R_c)_{\max}$ occurs (numbering starts with the outermost increment being 1).

Main Program

Calculations performed in the main body of the program. If NCON equals zero, the code will calculate fuel thermal conductivities from the WARD design equations for UO_2 - PuO_2 :⁽⁷⁶⁾ For fuel less than 95% dense, $k = -(1 - 2.1\rho + \rho^2) [(.288 + .00252T)^{-1} + 5.83 \times 10^{-12}T^3]$. For fuel equal to or greater than 95% dense, or for all restructured fuel: $k = (3\rho - 1) [(5.75 + .0503T)^{-1} + 2.91 \times 10^{-13}T^3]$.

If NCON is less than zero, GAPCON-THERMAL calculates fuel thermal conductivity from an equation derived from the data of Lyons et. al.^(4,5)

If NCON is greater than zero, the user must input a table of thermal conductivity values (see input instructions).

The user must specify an initial time in reactor, a time increment, and a final time. The program then makes a complete calculation at each time increment. Burnups are calculated by assuming power generation remains constant over the life of the fuel element.

The temperature drop through the fuel is calculated by dividing the fuel region into 50 radial increments, then calculating the temperature drop across each increment assuming that thermal conductivity and volumetric heat generation rate are constant within each increment. The calculation proceeds as follows: the heat generated within an increment is determined from the total heat generation rate, increment volume, and the flux depression table provided previously; an average temperature of the increment is assumed; and appropriate thermal conductivity value is assigned; temperature drop across the increment and, therefore, average temperature is calculated; and the calculated average temperature is compared to the assumed value. If the assumed and calculated values do not agree, a new value is assumed and the process is repeated. The temperature drop across each increment is calculated from:

$$\Delta T_i = \frac{q'''_i}{2\pi k} \left[\frac{1}{2} - \left(\frac{\gamma_i^2}{\gamma_o^2 - \gamma_i^2} - \frac{q_i}{q'''_i} \right) \ln \frac{\gamma_o}{\gamma_i} \right]$$

where ΔT_i = temperature drop across increment i

q'''_i = heat generated in increment i

k = fuel thermal conductivity

γ_i = inside radius of increment i

γ_o = outside radius of increment i

q_i = heat transferred into increment i .

Expansion due to fuel swelling is calculated from the relationship proposed by Geithoff,⁽⁵⁶⁾ et. al:

$$\Delta V_B = [(h_f)(V_f)(f) + (h_c)(V_c)] \frac{BU}{10,000} - (1-f)(0.8V_h + 0.5V_v + 0.3V_\ell)$$

where ΔV_B = change in volume due to burnup (fission product swelling)

f = fractional density

h_f = swelling rate for entire fuel rod, presumed to be 1.6% $\Delta V/V$ per 10,000 MWd/MTM

V_f = volume of fuel per unit length

h_c = additional swelling in fuel between 1300 and 1700°C, presumed to be 0.4% $\Delta V/V$ per 10,000 MWd/MTM

V_c = volume of fuel between 1300 and 1700°C

BU = Burnup, MWd/MTM

V_h = volume of fuel, above 1700°C

V_ℓ = volume of fuel below 1300°C.

It is assumed that 1/3 of the volume increase is longitudinal; therefore;

$$\Delta r_b = \frac{2/3 (\Delta V_B)}{2\pi r}.$$

The thermal conductivity of a mixture of gases at low density is calculated from:⁽⁷⁷⁾

$$k_{mix} = \sum_{i=1}^n \frac{X_i k_i}{\sum_{j=1}^n X_j \Phi_{ij}}$$

where the X_i and X_j are mole fractions, and the k_i is the thermal conductivity of the pure components. The coefficients Φ_{ij} are computed from:⁽⁷⁷⁾

$$\Phi_{ij} = \frac{1}{\sqrt{8}} \left(1 + \frac{M_i}{M_j} \right)^{-1/2} \left[1 + \left(\frac{\mu_i}{\mu_j} \right)^{1/2} \left(\frac{M_j}{M_i} \right)^{1/4} \right]^2$$

where the M_i and M_j are molecular weights of the pure components, and the μ_i and μ_j are viscosities of the pure components. Viscosities of the pure gases are estimated from:⁽⁷⁷⁾

$$\mu_i = 2.67 \times 10^{-5} \frac{(M_i T)^{1/2}}{\sigma_i^2 \Omega_i}$$

where T is temperature in $^{\circ}\text{K}$, σ_i is the characteristic diameter of the molecule and Ω_i is a function of $(\kappa/\epsilon)T$ (κ is the Boltzman constant and ϵ is a characteristic energy of interaction between molecules of a pure gas). Values of σ and (ϵ/κ) for various gases and a table of Ω as a function of $(\kappa/\epsilon)T$ are tabulated in Reference 77.

For monatomic gases, thermal conductivity of the pure gas is calculated from: (77)

$$k_i = 1.989 \times 10^{-4} \frac{(T/M_i)^{1/2}}{\sigma_i^2 \Omega_i} \quad (\text{cal/cm-sec-}^{\circ}\text{C}).$$

For nitrogen and hydrogen, thermal conductivity is estimated from: (77)

$$k_i = (C_p + \frac{5}{4} R) \frac{\mu_i}{M_i}$$

where C_p is heat capacity at constant pressure, and R is the gas constant (1.987 cal/gmole/ $^{\circ}\text{K}$).

This calculational technique was checked against gas-mixture thermal conductivity data reported by von Ubisch. (78) For ternary mixtures of helium, kryton, and xenon covering extremes of composition and temperatures from 29 to 520 $^{\circ}\text{C}$, calculated gas thermal conductivities were in all cases within 10% of the values reported by von Ubisch and in most cases were within 5% of the reported value.

Gap conductances are calculated by using a slight modification of a method proposed by Ross & Stoute: (3)

$$h_g = \frac{k_m(P_i)}{a_o R^{0.5} H} + \frac{k_g}{c(R_1 + R_2) + (g_1 + g_2)} + h_r^*$$

* Strictly speaking, the term $(g_1 + g_2)$ in the denominator of the second term should be replaced (for concentric cylinders) with $\ln(\frac{r_2}{r_1}) + \frac{g_1}{g_2} + \frac{q_2}{r_2}$. However, the error introduced is extremely small (<1/2%) and was therefor ignored.

where $k_m = \frac{2k_1k_2}{k_1+k_2}$,

k_1 = thermal conductivity of the cladding at $T = T_{ci}$

k_2 = thermal conductivity of the fuel at $T = T_s$

P_i = interfacial pressure

a_0 = a constant - $0.5 \text{ cm}^{1/2}$

$$R = \left(\frac{R_1^2 + R_2^2}{2} \right)^{1/2}$$

R_1 = arithmetic mean roughness height of the cladding

R_2 = arithmetic mean roughness height of the fuel

H = Meyer-Hardness of the cladding

k_g = thermal conductivity of the interfacial gas

c = a coefficient dependent on P_i

g_1 and g_2 = "temperature jump distances" at cladding inside
and pellet outside surfaces

h_r = Radiant heat transfer conductance.

Relationships to calculate the coefficient c and the temperature jump distances (g_1+g_2) were determined empirically from data presented by Ross & Stoute. The coefficient c is assumed to depend exponentially on interfacial pressure and to be independent of interfacial gas or temperature. Accordingly, the following relationship was derived to fit the Ross & Stoute data:

$$c = 1.98e^{-.00125 P_i} .$$

As discussed in detail in Reference 79, the "temperature jump distances," g_1 and g_2 , represent the temperature discontinuities that occur at the cladding and fuel surfaces as a result of incomplete energy interchange between the surfaces and the gas. A theoretical analysis shows that the value of g for a particular solid surface is proportional to the molecular mean free path of the gas in contact with that surface⁽⁸⁰⁾ and

$$(g_1 + g_2) \propto L.$$

Also, from Reference 79.

$$L \propto \left[\frac{\mu}{P} \left(\frac{T}{M} \right)^{1/2} \right]$$

where L = mean free path
 μ = viscosity of the gas
 P = pressure of the gas
 T = temperature of the gas
 M = molecular weight of the gas.

From the data presented by Ross & Stoute, and values of c as determined above, the following relationship was derived empirically for UO_2 - Zircaloy-2 interfaces.

$$(g_1 + g_2) = 5.448 \left[\frac{\mu}{P} \left(\frac{T}{M} \right)^{1/2} \right]$$

where $g_1 + g_2$ is in cm, μ is in grams/cm-sec and P is in lbs/in².

The temperature jump distance for a particular solid surface is also a function of the molecular weight of the material comprising that surface; therefore, values of $(g_1 + g_2)$ obtained for a UO_2 - Zircaloy-2 interface should not be applied to other systems such as (U, Pu) O_2 - stainless steel

interfaces without some correction. However, calculations showed that the magnitude of such a correction is extremely small; it is, therefore, not considered in GAPCON.

The radiant heat transfer coefficient, h_r , is determined from:

$$h_r = \frac{(q_r/A_1)}{(T_1 - T_2)}$$

but,

$$(q_r/A_1) = \sigma_{SB} \left[\frac{1}{\epsilon_1} + \frac{A_1}{A_2} \left(\frac{1}{\epsilon_2} - 1 \right) \right]^{-1} [T_1^4 - T_2^4]$$

therefore,

$$h_r = \sigma_{SB} \left[\frac{1}{\epsilon_1} + \frac{A_1}{A_2} \left(\frac{1}{\epsilon_2} - 1 \right) \right]^{-1} [T_1^2 + T_2^2] [T_1 + T_2]$$

where σ_{SB} is the Steffan-Boltzman constant, ϵ_1 and ϵ_2 are emmisitivities of the fuel surface and cladding surface respectively, A_1 and A_2 are the fuel and cladding surface areas, respectively, and T_1 and T_2 are temperatures of the fuel and cladding surfaces, respectively.

If the gap does not close due to thermal expansion and/or fuel swelling (i.e., $t_H \geq c(R_1 + R_2)$), then h_g is calculated from:

$$h_g = \frac{k_g}{t_H + (g_1 + g_2)} + h_r$$

where t_H = radial thickness of the fuel to cladding gap.

In the event that the gap closes,[†] fuel-to-cladding interfacial pressures are calculated from the following expression, which was derived from elastic deformation theory for a thick walled cylinder subjected to a thermal gradient:

$$P_i = \left[\frac{\Delta r}{r_1} E_c + \frac{2 P_2 r_2^2}{r_2^2 - r_1^2} \right] \left[\frac{r_2^2 + r_1^2}{r_2^2 - r_1^2} + \mu_c + \frac{E_c}{E_f} (1 - \mu_f) \right]^{-1}$$

It is assumed that P_i can never exceed that pressure that will cause yielding of the cladding; therefore:

$$(P_i)_{\max} = \frac{[\sigma_y - (\sigma_t)_t] [r_2^2 - r_1^2] + 2 P_2 r_2^2}{r_1^2 + r_2^2}$$

where P_i = interfacial pressure

P_2 = external pressure on cladding

Δr = calculated fuel-clad interference

r_1 = cladding inside radius

r_2 = cladding outside radius

E_c = modules of elasticity for cladding

E_f = modules of elasticity for fuel

μ_c = Poission's ratio for cladding

μ_f = Poission's ratio for fuel

$(\sigma_t)_t$ = thermal stress in cladding

σ_y = yield stress of cladding.

Fuel restructuring is assumed to occur to some temperature that is dependent on time at power. The relationship used in GAPCON was derived from data presented by Christensen:⁽⁵⁸⁾

[†] Contact conductance is currently under review.

* This term is not used if the option for cladding elastic deformation is used since the ICDF option has taken this term into account in the Δr term.

$$1/T_{RS} = 0.00001367 \log_{10} (t) + 0.000480$$

where T_{RS} = temperature to which restructuring occurs ($^{\circ}\text{K}$)
 t = time at power (hr).

As Christensen indicated, a unique restructuring temperature-time relationship should be used for each combination of burnup (xenon content of the pores) and thermal gradient. The above relationship was derived to represent an average over the life of a fuel pin.

A restructured fuel radius and center hole radius are calculated based on the above restructuring temperature and the (input) density of restructured fuel. The temperature distribution calculations are then repeated for the restructured fuel pin.

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APPENDIX B
INPUT INSTRUCTIONS FOR GAPCON-THERMAL

APPENDIX BINPUT INSTRUCTIONS FOR GAPCON-THERMAL

GAPCON-THERMAL uses a combination of formatted and non-formatted (NAMELIST) input. This minimizes errors in input data and simplifies running a number of consecutive cases in which the values of only a few variables change from one case to the next. The following steps are required to input data to GAPCON-THERMAL.

- The first card for each case contains the title (in columns 2-80) which will be printed at the beginning of the output. If no title is desired a blank card must be inserted.
- The next group of cards contains input data in NAMELIST form. Those variables that may be input in this manner are listed in Table B-1. The first of these cards must have a dollar sign (\$) in column 2 and the name INPUT in columns 3 through 7. Values for the variables are then entered as simple algebraic statements separated by commas; e.g., $FRDEN = .92$, $FRSIN = .98$, etc. As many cards as required may be used but a variable name and its value must be on the same card (e.g., $FRDEN =$ on one card followed by $.92$ on the next card is not allowed). Only columns 2 through 72 may be used.
- A dollar sign (\$) must appear somewhere in column 2 through 72 after the last NAMELIST variable entered for each case.
- The next group of cards, which is optional, contains formatted input for fuel thermal conductivity values. The number of cards in this group is equal to NCON (see Table B-1). On each card, columns 1-10 contain a temperature ($^{\circ}\text{C}$), columns 11-20 contain the thermal conductivity values (watts/cm $^{\circ}\text{C}$) for as-fabricated fuel associated with that temperature, and columns 21-30 contain the thermal conductivity values (watts/cm $^{\circ}\text{C}$) for restructured fuel. These data can be input in either exponential or decimal format. The cards in this group must be arranged so that temperatures are in either ascending or descending order.

- The next group of cards, which is optional, contains formatted input for cladding properties. The number of cards in this group is equal to NCLAD (see Table B-1). On each card, columns 1-10 contain a temperature ($^{\circ}\text{F}$), columns 11-20 contain the thermal conductivity value ($\text{Btu/hr ft } ^{\circ}\text{F}$), columns 21-30 contain the yield strength value (lbs/in^2), columns 31-40 contain the modulus of elasticity value (lb/in^2), columns 41-50 contain the Poission's ratio value, columns 51-60 contain the linear coefficient of thermal expansion value ($\text{in/in } ^{\circ}\text{F}$), and columns 61-70 contain the Meyer hardness number (kg/cm^2) associated with that temperature. These data can be input in either exponential or decimal format. The cards in this group must be arranged so that temperatures are in either ascending or descending order.
- The next group of cards, which is optional, contains formatted input for flux depression values. The number of cards in this group is equal to NFLX (see Table B-1). On each card, columns 1-10 contain a diameter (inches) and columns 11-20 contain the relative neutron flux at that diameter. These data can be input in either exponential or decimal dormat. The cards in this group must be arranged so that the radii are in either ascending or descending order.
- The final group of cards, which is also optional, contains formatted input for clad creep down values. The number of cards in this group is equal to ICREP (see Table B-1). On each card columns 1-10 contain the time in days and columns 11-20 the diametral change (inches) at this time. At time zero a diametral change due to elastic deflection of the clad, from the pressure differential, should be input. Also if a creep down table is input the option for calculating the elastic clad deflection (see ICDF in Table B-1) should not be used.

An example of input to GAPCON is shown in Figure B-1. The NAMELIST variables need not be input in any particular order and, in fact, it is not necessary to input values for all the variables. If a variable is omitted, the program will use the previous value entered for that variable (this would be zero for the first case in any particular run).

TABLE B-1

NAMELIST VARIABLES THAT MAY BE INPUT TO GAPCON-THERMAL

Variable Name	Definition and Comments
FRPU02	The weight fraction of the fuel which is PuO_2 (the reminder is assumed to be UO_2).
FR35	The weight fraction of the U which is ^{235}U (the remainder is assumed to be ^{238}U).
FR40	The weight fraction of the Pu which is ^{240}Pu .
FR41	The weight fraction of the Pu which is ^{241}Pu .
FRDEN	Fractional density of the fuel pellet.
FRSIN	Fractional density of restructured fuel.
DFS	Pellet diameter (inches).
DCI	Cladding inside diameter (inches).
DC0	Cladding outside diameter (inches).
DB0	Outside diameter of a secondary cladding or basket (inches). If DB0 is omitted, no secondary cladding is assumed to exist.
KB	Thermal conductivity of the secondary cladding or basket ($\text{Btu/hr-ft}^{\circ}\text{F}$).
HBC	Heat transfer coefficient between basket and cladding ($\text{Btu/hr-ft}^2\text{F}$).
DV0IDZ	Diameter of initial central void in the fuel pellets (inches).
LV0IDZ	Length of initial central void in the fuel pellets (inches).

TABLE B-1 (Continued)

Variable Name	Definition and Comments
DSINZ	Initial diameter of restructured fuel (normally equals 0.) (inches).
LFUEL	Length of fuel column (inches).
VPLENZ	Volume of gas plenum included in the fuel pin (cubic inches).
ATMOS	Initial fill gas pressure (atmospheres).
FRACHE	Fraction of initial fill gas which is helium.
FRACAR	Fraction of initial fill gas which is argon.
FRACH	Fraction of initial fill gas which is hydrogen.
FRACN	Fraction of initial fill gas which is nitrogen.
FRACXE	Fraction of initial fill gas which is xenon.
FRACKR	Fraction of initial fill gas which is krypton.
S	Fuel sorbed gas content (cc/g of fuel).
XX	Fraction of sorbed gas which is hydrogen (remainder is assumed to be nitrogen).
NOH	An integer signal to specify disposition of the hydrogen present in the sorbed gas. If NOH = 1, the hydrogen is assumed to react with the cladding. If NOH = 0, the hydrogen is assumed to remain in the fuel pin. If NOH is omitted, the code sets NOH = 1.
R0UF	Arithmetic mean fuel surface roughness (inches).

TABLE B-1 (Continued)

<u>Variable Name</u>	<u>Definition and Comments</u>
RØUC	Arithmetic mean cladding ID surface roughness (inches).
EXTP	Coolant pressure (psi)
TINLET	Inlet coolant temperature (°F)
KØØL	If a value (integer) greater than zero is assigned to KØØL, the coolant temperature is the same temperature of the cladding ID.
DTEMP	The axial ΔT across the core, (i.e. T inlet- T outlet.)
TDAYS	Time in-reactor (days) for the first case.
DELT	Time increment. Time in-reactor can be incremented in the same manner that it increments heat rating.
TMAX	Maximum time in-reactor (days).
TM	Melting temperature of the fuel (°C).
SIGHF	A signal to specify the type of coolant If SIGHF < 0, coolant is water, a film coefficient will be calculated. If SIGHF = 0, coolant is sodium, a film coefficient will be calculated. If SIGHG > 0, coolant is unspecified and the film coefficient will be set to SIGHF.
DE	Equivalent diameter of the coolant passage (inches). May be omitted if SIGHF is greater than zero.
V	Coolant velocity (ft/sec). May be omitted if SIGHF is greater than zero.

TABLE B-1 (Continued)

Variable Name	Definition and Comments
IFLUX	<p>An integer signal to specify whether this is a fast or thermal flux irradiation.</p> <p>If IFLUX = 0, flux is fast If IFLUX > 0, flux is thermal</p>
NFLX	<p>An integer signal to specify flux depression values used.</p> <p>If NFLX < 0, flux depression values will be estimated in Subroutine DEPRES. NFLX should not be set to less than zero for fuel pins containing PuO₂ or for pins in which ²³⁵U enrichment is greater than 4%.</p> <p>If NFLX = 0, it is assumed there is no flux depression.</p> <p>If NFLX > 0, a table of relative flux versus diameter is input as described previously with the number of points (diameters) equal to NFLX.</p>
NEWFLX	<p>An integer signal (any number greater than zero) to indicate that new flux depression data are to be input. If NFLX is greater than zero, NEWFLX must be greater than zero for that case.</p>
NEWK	<p>An integer signal (any number greater than zero) to indicate that new fuel thermal conductivity values are to be input. If NCON is greater than zero, NEWK must be greater than zero for that case.</p>
NCON	<p>An integer signal to specify fuel thermal conductivity</p> <p>If NCON < 0, thermal conductivity equation for UO₂ is used If NCON = 0, thermal conductivity equation for UO₂-PuO₂ is used If NCON > 0, a table of thermal conductivity value must be input</p>

TABLE B-1 (Continued)

Variable Name	Definition and Comments
NCLAD	<p>An integer signal to specify type of cladding</p> <p>If NCLAD < 0, cladding is Zircaloy If NCLAD = 0, cladding is 20% cold worked 316 SS If NCLAD > 0, cladding properties are input as described previously with the number of points (temperatures) input equal to NCLAD.</p>
ZCLAD	<p>An integer signal to specify Zr-2 or Zr-4 cladding. Material properties.</p> <p>If ZCLAD > 0, cladding is Zr-4 If ZCLAD < 0, cladding is Zr-2</p>
	<p>NOTE: NCLAD must have a value of <0 to use ZCLAD.</p>
NEWCL	<p>An integer signal (any number greater than zero) to indicate that new cladding property data to be input. If NCLAD is greater than zero NEWCL must be greater than zero for that case.</p>
ICREP	<p>An integer signal to specify cladding creep down values.</p> <p>If ICREP < 0 it is assumed there is no cladding deformation. If ICREP > 0 a table of time versus cladding creep down values must be used. ICREP must equal the number of time values used in the table. Input format F10.0 and E10.0 (one set of values per card). (limit of 20 values.)</p>
ICDF	<p>An integer signal that allows the user to include the elastic deflection of the clad due to differential internal and external pressures in the closure of the pellet to clad gap. If ICDF < 0 elastic clad deflection taken into account. If ICDF > 0 the option is not used. If a table of creep down values (see ICREP) is input this option should not be used.</p>

TABLE B-1 (Continued)

<u>Variable Name</u>	<u>Definition and Comments</u>
DELP	Linear power increment (kW/ft). Allows a number of consecutive cases to be run incrementing power. The code will increment either the peak power (PKPOWER) or average power (PAVRG) whichever is input, by DELP until the maximum power (PMAX) is reached.
PMAX	Maximum linear power (kW/ft).
IPEAK	An integer to specify whether an average or peak power is to be input. If >0 an average power needs to be input, if ≤ 0 a peak power needs to be input.
PAVRG	Average power of pin. If an average power is input then PKPOWER should be left blank or zero and IPEAK set equal to 1. (kW/ft)
PKPOWER	Peak power of pin. If a peak power is inputted then PAVRG (kW/ft) should be left blank or zero and IPEAK ≤ 0 .
NPOW	Number of axial segments. (Limit of 20.)
POWER	A table that is used to input a normalized axial power profile for the pin. NPOW + 1 values for the profile need to be entered with the first and last corresponding to the bottom and top of the fuel respectively. If a power profile is not input a standard one in the code will be used.
MINI	An integer signal to specify the output wanted. If MINI = 0 a complete summary is given for each axial segment. If MINI = 1 a complete summary is listed for the hottest segment of the pin and a short summary given for all the axial segments. MINI = -1 only a short summary is given for the axial segments..

TABLE B-1 (Continued)

<u>Variable Name</u>	<u>Definition and Comments</u>
ISWELL	A signal that allows the user to use the revised gap closure model. If ISWELL <0 the code uses the revised closure model. If ISWELL ≥0 the code uses the Geithoff, et al. model.
ISTOR	An integer to specify the calculation of stored energy in the fuel. If ISTOR <0 no calculation is performed. If ISTOR ≥0 the calculation is performed.

NEWFLX=-1,NFLX=-1,DFS=.362,\$
 \$INPUT
 TEST CASE (EXAMPLE INPUT) NO. 2

.356	1.060
.341	1.042
.292	1.0116
.256	.9917
.195	.9777
.1462	.9662
.0975	.9593
.0487	.9556
0.	.9547

TDAYS=0.0, DELT=100., TMAX=100., PKPDUR=10., DELP=4.0, PMAX=14.0, \$
 DTEMP=100., MINI=1, ISHELL=1, IPEAK=1, ICDF=-1,
 NPQW=10, POWER(1)=.35, .86, 1.08, 1.175, 1.19, 1.19, 1.19, 1.17, 1.12, .78, .37,
 VPLENZ=0.5, TINLET=570., EXTP=2250., ATMDS=20.0, FRACHE=1.0,
 NEWK=-1, NEWFLX=1, NCON=-1, TW=2790., LFUEL=132., HG=1000., PEKAVG=1.0,
 SIGHF=25000., ROUF=.000039, ROUC=.00002, IFLUX=1, NCLAD=-1, NFLX=9,
 FRDEN=.935, FR35=.965, FR35=.0254, DFS=.3650, DC1=.3735, DCD=.422,
 \$INPUT
 TEST CASE (EXAMPLE INPUT) NO. 1

.356	1.060
.341	1.042
.292	1.0116
.256	.9917
.195	.9777
.1462	.9662
.0975	.9593
.0487	.9556
0.	.9547

TDAYS=0.0, DELT=100., TMAX=100., PKPDUR=10., DELP=4.0, PMAX=14.0, \$
 DTEMP=100., MINI=1, ISHELL=1, IPEAK=1, ICDF=-1,
 NPQW=10, POWER(1)=.35, .86, 1.08, 1.175, 1.19, 1.19, 1.19, 1.17, 1.12, .78, .37,
 VPLENZ=0.5, TINLET=570., EXTP=2250., ATMDS=20.0, FRACHE=1.0,
 NEWK=-1, NEWFLX=1, NCON=-1, TW=2790., LFUEL=132., HG=1000., PEKAVG=1.0,
 SIGHF=25000., ROUF=.000039, ROUC=.00002, IFLUX=1, NCLAD=-1, NFLX=9,
 FRDEN=.935, FR35=.965, FR35=.0254, DFS=.3650, DC1=.3735, DCD=.422,
 \$INPUT
 TEST CASE (EXAMPLE INPUT) NO. 1

FIGURE B-1. Example input to GAPCON-THERMAL.

ELT HTCW,1,730803, 47820

APPENDIX C

```

1.      SUBROUTINE HTCW (T,FLUX,V,D,H,TW)
2.      DIMENSION TITB(3,100)
3.      DATA((TITB(I,J),I=1,2),J=1,12)/32.,203.6,100.,320.6,150.,392.7,
4.      X200.,453.4,250.,497.0,300.,536.0,350.,565.3,400.,577.3,450.,584.6,
5.      X500.,585.3,550.,577.2,600.,561.1/
6.      C    T = COOLANT TEMPERATURE, F
7.      C    FLUX = HEAT FLUX, BTU/HR/FT2/F
8.      C    TW = TEMP AT CLAD (OR BASKET) OR
9.      ITRY = 0
10.     TF1 = T
11.     C=V**.2/D**.2
12.     6 B=TERP(TF1,TITB,2,12)
13.     H=B*C
14.     TW = T + FLUX/H
15.     TF = (TW + T)/2.
16.     DIFF = ABS(TF - TF1)
17.     IF ( DIFF - 2. ) 1,1,2
18.     2 ITRY = ITRY + 1
19.     IF ( ITRY - 50 ) 3,3,4
20.     3 TF1 = (TF + TF1)/2.
21.     GO TO 6
22.     4 WRITE (6, 5)
23.     5 FORMAT (10X,'NO CONVERGENCE IN CHEAT ITRY=')
24.     1 RETURN
25.     END

```

1. ELT HTCLM,1,730803, 47819

```
1. SUBROUTINE HTCLM(HF,TCOOL,DE,V)
2. REAL KNA
3. KNA=54.306-1.878E-2*TCOOL+2.0914E-6*TCOOL**2.
4. RHONA=59.566-7.9504E-3*TCOOL-.2872E-6*TCOOL**2.+.06035E-9*TCOOL**3
5. CPNA=.34574-.79226E-4*TCOOL+.34086E-7*TCOOL**2
6. DEF = DE/12.
7. VF = V*3600.
8. HF = KNA/DEF*(7.+.025*(DEF*VF*RHONA*CPNA/KNA)**(.8))
9. RETURN
10. END
```

* ELT TERP,1,730803, 47822

```
1.      FUNCTION TERP(TT, TABLE, L, N)
2.      C      L = THE INDEX TO THE TABLE
3.      DIMENSION TABLE(8,100)
4.      I=1
5.      IF (TABLE(I,1).GT.TABLE(I,N)) GO TO 110
6.      IF ( TT.LE.TABLE(I,1)) GO TO 104
7.      IF ( TT.GE.TABLE(I,N)) GO TO 106
8.      DO 100 J=1,N
9.      IF (TT-TABLE(I,J)) 101,102,100
10.     100 CONTINUE
11.     104 TERP = TABLE(L,1)
12.     RETURN
13.     106 TERP = TABLE(L,N)
14.     RETURN
15.     102 TERP = TABLE(L,J)
16.     RETURN
17.     101 TERP=TABLE(L,J-1)+(TABLE(L,J)-TABLE(L,J-1))*(TT-TABLE(I,J-1))/
18.     x(TABLE(I,J)-TABLE(I,J-1))
19.     RETURN
20.     110 IF (TT.GE.TABLE(1,1)) GO TO 104
21.     IF (TT.LE.TABLE(1,N)) GO TO 106
22.     DO 120 J=1,N
23.     IF (TT-TABLE(1,J)) 120,102,101
24.     120 CONTINUE
25.     END
```


* ELT HCAP,1,730803, 47823

```

1.      SUBROUTINE HCAP(TEMP,CPNOM,CPMIN,CPMAX)
2.      DIMENSION TTK(10),CLMIN(10),CLMAX(10)
3.      REAL K1,K2,K3
4.      DATA (TTK(I),I=1,10)/0.0,298.,500.,1000.,1500.,2000.,2500.,3000.,3
5.      x100.,6000./
6.      DATA (CLMIN(I),I=1,10)/0.,0.,.02,.02,.02,.02,.03,.06,.10,.10/
7.      x/
8.      DATA (CLMAX(I),I=1,10)/1.0,1.0,1.02,1.02,1.02,1.02,1.03,1.06,1.1,1
9.      x.1/
10.     150 TKEL=535.285
11.     EL=37.6946
12.     K1=19.1450
13.     K2=.000784733
14.     K3=5643730.0
15.     R=.001986
16.     C  TEMP= AVERAGE VOLUMETRIC FUEL TEMPERATURE
17.     TEMPK=TEMP + 273.0
18.     CL=1.0
19.     CPNOM=CL*(((K1*TKEL**2*EXP(TKEL/TEMPK))/(TEMPK**2*(EXP(TKEL/TEMPK)
20.     x-1)**2))+((2*K2*TEMPK)+((K3*ED)/(R*TEMPK**2))*EXP(-ED/(R*TEMPK))))
21.     CLN=TEPP(TEMPK,CLMIN,TTK,10)
22.     C1=1.0-CLN
23.     CPMIN=C1*(((K1*TKEL**2*EXP(TKEL/TEMPK))/(TEMPK**2*(EXP(TKEL/TEMPK)
24.     x-1)**2))+((2*K2*TEMPK)+((K3*ED)/(R*TEMPK**2))*EXP(-ED/(R*TEMPK))))
25.     C2=TEPP(TEMPK,CLMAX,TTK,10)
26.     CPMAX=C2*(((K1*TKEL**2*EXP(TKEL/TEMPK))/(TEMPK**2*(EXP(TKEL/TEMPK)
27.     x-1)**2))+((2*K2*TEMPK)+((K3*ED)/(R*TEMPK**2))*EXP(-ED/(R*TEMPK))))
28.     RETURN
29.     END

```

' EL1 DEPRES,1,730303, 47824

```

1. SUBROUTINE DEPRES (DENSIT,FR10,FR1,DFS,RV)
2. DIMENSION RV(8,100)
3. DATA SIGAS,SIGAE,SIGAO,SIG15,SIGT8,SIG10/578.,2.33,0.,566.5,10.8,
4. 4.2/
5. EL5=DENSIT*FR10*.00225927
6. EN8=DENSIT*FR1*.00223079
7. ENO=(EN5+EN8)*2.
8. SGA=(EN5*SIGAS+EN8*SIGAE+ENO*SIGAO)
9. SGT=(EN5*SIG15+EN8*SIGT8+ENO*SIG10)
10. CAPSQ=3.*SGA*SGT/(1.-.8*SGA/SGT)
11. CAPPA=SGT(CAPSQ)
12. RV(1,1)=0.
13. RV(2,1)=1.
14. DO 10 I=2,11
15. 10 RV(1,I)=RV(1,I-1)+DFS/10.
16. DO 20 I=2,11
17. 20 RV(2,I)=1.+R**2.+R**4./4.+R**6./36.+R**8./576.
18. RETURN
19. END
20.

```

' ELT EXPAND,1,730,03, 47830

```

1.      SUBROUTINE EXPAND (RMELT,RFS,RD,FRDEN,TT,TMF,TFS,FRPU02,DELRT,
2.      XDELCT,DELL,DELM,DFLN,RVOIDZ,VOL,VCRAK,L,LLM)
3.      DIMENSION TT(100),DELCT(50),DELL(50)
4.      TA(T1,T2)=((T1+T2)/2.-32.)/1.8
5.      DELRT=0.
6.      FR=FRPU02*100.
7.      DO 6 I=1,50
8.        DELL(I)=0.
9.        6 DELCT(I)=0.
10.       DO 1 I=1,50
11.        RIN=RFS-RD*I
12.        RON=RIN+RD
13.        2 IF(I.GT.1)GO TO 4
14.        TAC=TA(TFS,TT(1))
15.        GO TO 16
16.       4 TAC=TA(TT(I-1),TT(I))
17.       16 CONTINUE
18.       17 CONTINUE
19.       CST=2.896E-9*(TAC**2-25.**2) + 6.797E-6*(TAC-25.)
20.       RAVG=(RIN+RON)*.5
21.       DELCT(I)=CST*RAVG
22.       DELL(I)=CST*RD
23.       1 CONTINUE
24.       3 BIG=ABS(DELCT(1))
25.       L=1
26.       DO 11 I=2,50
27.        AB=ABS(DELCT(I))
28.        IF(AB-BIG)11,11,12
29.       12 BIG=ABS(DELCT(I))
30.       L=I
31.       11 CONTINUE
32.       21 DO 13 I=1,L
33.       13 DELRT=DELRT+DELL(I)
34.       DELRT=DELRT-DELL(L)/2.+DELCT(L)
35.       RETURN
36.       END

```

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' ELT TEPP,1,730803, 47831

```

1.      C      FUNCTION TEPP(TC,CRF,CRFT,N)
2.      C      TEPP IS A LINEAR INTERPOLATION FUNCTION WHOSE VALUE IS EQUAL TO THE
3.      C      INTERPOLATED VALUE.
4.      C      TC-IS THE VALUE OF THE INDEPENDENT VARIABLE
5.      C      CRF-DEPENDENT VARIABLE ARRAY
6.      C      CRFT-INDEPENDENT VARIABLE ARRAY
7.      C      N-NUMBER OF POINTS IN VARIABLE ARRAYS
8.      C      DIMENSION CRF(N),CRFT(N)
9.      C      I=1
10.     IF(TC,LI,CRFT(1)) GO TO 104
11.     DO 100 I=1,N
12.     J=1
13.     IF(TC-CRFT(I)) 101,102,100
14.     100 CONTINUE
15.     104 TEPP=CRF(I)
16.     RETURN
17.     102 TEPP=CRF(I)
18.     RETURN
19.     101 TEPP=CRF(I-1)+(CRF(I)-CRF(I-1))*(TC-CRFT(I-1))/(CRFT(I)-CRFT(I-1))
20.     RETURN
21.     END

```

' ELT SWELL,1,730803, 47833

```
1. SUBROUTINE SWELL(R1300,R1500,R1700,RFS,RVOID,PI,BURNUP,TH,GAP,DELR
2. XT,DELRCD,DELRBH)
3.   BFCC=BURNUP/3560.
4.   S1700=14.*BFCC**611/100.
5.   S1500=5.0*BFCC**611/100.
6.   S1300=2.0*BFCC**611/100.
7.   STMP=0.4*BFCC/100.
8.   S17MAX=.2138
9.   S15MAX=.0764
10.  IF(S1500.GE.S15MAX) S1500=S15MAX
11.  IF(S1700.GE.S17MAX) S1700=S17MAX
12.  DELVBT=PI*(STMP*(RFS**2-R1300**2)+S1500*(R1300**2-R1500**2)+S1500
13.  *(R1500**2-R1700**2)+S1700*(R1700**2-RVOID**2))
14.  DELRBH=DELVBT/(3.*PI*RFS)
15.  TH=GAP/2-(DELRCD+DELRBH)+DELRCD
16.  RETURN
17.  END
```

1. ELT MOVEKA,1,730303, 47834

```
1. SUBROUTINE MOVEKA(K,I,J,H)  
2. DIMENSION IA(N)  
3. DO 100 I=1,N  
4.   IA(I)=K  
5. CONTINUE  
6. RETURN  
7. END
```

' ELT POWDIS,1,730P03, 47835

```

1. SUBROUTINE POWDIS
2. COMMON /PO,RAY/ PAVRG,LFUEL,LF,POWER(21),AI(21),NPOW,PTOT,LPMAX
3. * ,PKPOW,IPEAK,DELP,PMAX
4. REAL LF,LFUEL
5.
6. C
7. C INTEGRATE THE LOCAL POWER DISTRIBUTION AND NORMALIZE
8. C THE RESULT TO 1.0. THIS AINCR REPRESENTS THE .5 OF THE
9. C AVERAGING TIMES THE X INCREMENT WHICH IS 1.0/NPOW. NPOW IS
10. C THE NUMBER OF REGIONS.
11. C
12. C AINCR=.5/FLOAT(NPOW)
13. C NPOW1 = NPOW+1
14. C AI(1) = (POWER(1)+POWER(2))*AINCR
15. C LPMAX=1
16. C POLD=(POWER(1)+POWER(2))*0.5
17. C IF (NPOW.LE.1) GO TO 101
18. C DO 100 I=2,NPOW
19. C P = (POWER(I)+POWER(I+1))*0.5
20. C AI(I) = AI(I-1) + (POWER(I)+POWER(I+1))*AINCR
21. C IF (P.LT.POLD) GO TO 100
22. C LPMAX = I
23. C POLD=P
24. C CONTINUE
25. C AITOT = AI(NPOW)
26. C IF (AITOT.LE.0.) RETURN 0
27. C
28. C RENORMALIZE THE POWER AND AI SUCH THAT AI(1)=1.0.
29. C
30. C IF (IPEAK.NE.0) GO TO 300
31. C DO 200 I=1,NPOW
32. C POWER(I) = POWER(I)*PAVRG/AITOT
33. C AI(I)=AI(I)/AITOT
34. C CONTINUE
35. C POWER(NPOW+1)=POWER(NPOW+1)*PAVRG/AITOT
36. C
37. C GO TO 400
38. C
39. C CALCULATE POWER DISTRIBUTION BASED ON PEAK POWER (KW/FT)
40. C
41. C CONTINUE
42. C PEAK = POWER(1)
43. C DO 310 I=2,NPOW1
44. C PEAK = AMAX1(PEAK,POWER(I))
45. C CONTINUE

```

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46.	C			05/23/73
47.	C		NORMALIZE THE POWER DISTRIBUTION TO PKPOWER	05/23/73
48.	C			05/23/73
49.		DO 320 1=1,UPQ/1		05/23/73
50.		POWER(I) = POWER(I)*PKPOWER/PEAK		05/23/73
51.		AI(I)=AI(I)/AITOT		05/23/73
52.	320	CONTINUE		05/23/73
53.		PAVRG=AITOT*PKPOWER/(PFAK)		05/23/73
54.	900	CONTINUE		05/23/73
55.		PTOT = LFUEL*PAVRG/12.		05/23/73
56.	C			05/23/73
57.	C	TEST TO SEE IF TOTAL POWER IS ZERO. IF ZERO EPR OFF		05/23/73
58.	C			05/23/73
59.		IF (PTOT.LE.0.) RETURN		05/23/73
60.		RETURN		
61.		END		

' EL1 CARL,1,730803, 47836

```

1. SUBROUTINE CARL(TSS,TFS,TT,N,PI,DFS,STORE)
2. DIMENSION AREA(50),TVOL(50),HCAT(50)
3. DIMENSION TSS(50),TT(50)
4. REAL K1,K2,K3
5. DO 10 I=1,N
6. 10 AREA(I)=((TSS(I)**2-TSS(I+1)**2)*PI)
7. TVOL(I)=(((TFS+TT(1))*5)-32.)/(1.8)+273.
8. DO 20 I=2,N
9. 20 TVOL(I)=(((TT(I)+TT(I-1))*5)-32.)/(1.8)+273.
10. TKEL=535.285
11. ED=37.6946
12. K1=19.1450
13. K2=.000784733
14. K3=5643730.0
15. R=.001986
16. CL=1.0
17. STORE = 0.
18. DO 40 I=1,4
19. TEMPK=TVOL(I)
20. HCAT(I)=CL*(K2*(TEMPK**2-298.**2)+K3*EXP(-ED/P/TEMPK)
21. * +K1*TKEL*(1./(EXP(TKEL/TEMPK)-1.))-1./(EXP(TKEL/298.))-1.))
22. STORE = STORE+HCAT(I)*AREA(I)
23. CONTINUE
24. STORE = STORE*4./(PI*DFS**2)
25. C
26. C WE NOW HAVE STORE IN CAL/MOLE OF U O2.
27. C NOW CONVERT IT TO CAL./GRAM OF U.O2
28. C
29. STORE=STORE/270.
30. RETURN
31. END

```

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• ELI MOVEAA,1,730003, 47857

```
1. SUBROUTINE MOVEA(A,B,N)
2. DIMENSION A(N),R(N)
3. DO 100 I=1,N
4.   B(I)=A(I)
5. CONTINUE
6. RETURN
7. END
```

' ELT FISSAS,1,730828, 55090

```

1.      SUBROUTINE FISSAS(TIN,PHI,P,CONEN,IFLUX,MTIME,NKR,NXE)
2.      C
3.      C      SUBROUTINE FISSAS IS USED TO CALCULATE THE AMOUNT
4.      C      OF FISSION GAS PRODUCED FOR A GIVEN TIME AND POWER.
5.      C      CALCULATIONS ARE BASED ON TWO MODELS. THE FIRST ASSUMES
6.      C      A PRIMARILY FAST SPECTRUM. AND THE SECOND ASSUMES A
7.      C      THERMAL SPECTRUM.
8.      C
9.      COMMON /BRNRAY/VOLCC,N1Z,N7Z,N8Z,N9Z,N10Z
10.     DOUBLE PRECISION X1,X2,X3,X4,X5,X6,X7,X8,X9,X10,X11,X12,X13,X14,
11.     X15,X16,X17,X18,X19,X20,X21,X22,X23,X24,X25,X26,X27,X28,X29,
12.     X30,X31,X32,X33,X34,X35,X36,X37,X38,X39,X40,X41,X42,X43,X44,
13.     X45,X46,X47,X48,X49,X50,X51,X52,X53,X54,X55,X56,X57,X58,X59,
14.     X60,X61,X62,X63,X64,X65,X66,X67,X68,X69,X70,X71,X72,X73,X74,
15.     X75,X76,X77,X78,X79,X80,X81,X82,X83,X84,X85,X86,X87,X88,X89,
16.     X90,X91,X92,X93,X94,X95,X96,X97,X98,X99,X100,X101,X102,X103,
17.     X104,X105,X106,X107,X108,X109,X110,X111,X112,X113,X114,X115,
18.     X116,X117,X118,X119,X120,X121,X122,X123,X124,X125,X126,X127,
19.     X128,X129,X130,X131,X132,X133,X134,X135,X136,X137,X138,X139,
20.     X140,X141,X142,X143,X144,X145,X146,X147,X148,X149,X150,X151,
21.     X152,X153,X154,X155,X156,X157,X158,X159,X160,X161,X162,X163,
22.     X164,X165,X166,X167,X168,X169,X170,X171,X172,X173,X174,X175,
23.     X176,X177,X178,X179,X180,X181,X182,X183,X184,X185,X186,X187,
24.     X188,X189,X190,X191,X192,X193,X194,X195,X196,X197,X198,X199,
25.     X200,X201,X202,X203,X204,X205,X206,X207,X208,X209,X210,X211,
26.     X212,X213,X214,X215,X216,X217,X218,X219,X220,X221,X222,X223,
27.     X224,X225,X226,X227,X228,X229,X230,X231,X232,X233,X234,X235,
28.     X236,X237,X238,X239,X240,X241,X242,X243,X244,X245,X246,X247,
29.     X248,X249,X250,X251,X252,X253,X254,X255,X256,X257,X258,X259,
30.     X260,X261,X262,X263,X264,X265,X266,X267,X268,X269,X270,X271,
31.     X272,X273,X274,X275,X276,X277,X278,X279,X280,X281,X282,X283,
32.     X284,X285,X286,X287,X288,X289,X290,X291,X292,X293,X294,X295,
33.     X296,X297,X298,X299,X300,X301,X302,X303,X304,X305,X306,X307,
34.     X308,X309,X310,X311,X312,X313,X314,X315,X316,X317,X318,X319,
35.     X320,X321,X322,X323,X324,X325,X326,X327,X328,X329,X330,X331,
36.     X332,X333,X334,X335,X336,X337,X338,X339,X340,X341,X342,X343,
37.     X344,X345,X346,X347,X348,X349,X350,X351,X352,X353,X354,X355,
38.     X356,X357,X358,X359,X360,X361,X362,X363,X364,X365,X366,X367,
39.     X368,X369,X370,X371,X372,X373,X374,X375,X376,X377,X378,X379,
40.     X380,X381,X382,X383,X384,X385,X386,X387,X388,X389,X390,X391,
41.     X392,X393,X394,X395,X396,X397,X398,X399,X400,X401,X402,X403,
42.     X404,X405,X406,X407,X408,X409,X410,X411,X412,X413,X414,X415,
43.     X416,X417,X418,X419,X420,X421,X422,X423,X424,X425,X426,X427,
44.     X428,X429,X430,X431,X432,X433,X434,X435,X436,X437,X438,X439,
45.     X440,X441,X442,X443,X444,X445,X446,X447,X448,X449,X450,X451,

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95. N6=0.
96. N7=0.
97. N8=0.
98. N9=0.
99. N10=0.
100. N11=0.
101. N12=0.
102. N13=0.
103. N14=0.
104. N15=0.
105. N101=0.
106. N102=0.
107. N103=0.
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109. N105=0.
110. N106=0.
111. N107=0.
112. N108=0.
113. N109=0.
114. N110=0.
115. N111=0.
116. N112=0.
117. N113=0.
118. N114=0.
119. N115=0.
120. N116=0.
121. N117=0.
122. N118=0.
123. N119=0.
124. N1=12
125. N7=N72
126. N8=N82
127. N9=N92
128. N10=N102
129. 4 CONTINUE
130. IF (IFLUX.NE.0) 30 TO 10
131. DO 5 I=1,25
132. CX(I)=FCX(I)
133. 5 FX(I)=FFX(I)
134. GO TO 20
135. 10 DO 15 I=1,25
136. CX(I)=TCX(I)
137. 15 FX(I)=TFX(I)
138. 20 CONTINUE
139. DO 25 I=1,15
140. 25 AX(I)=CX(I)-FX(I)
141. IF (IFLUX.NE.0) GO TO 35
142. DO 30 I=1,4
143. 30 J=1,19

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144. 30 Y(I,J)=FY(I,J)
145. 60 TO 45
146. 35 DO 40 I=1,4
147. DO 40 J=1,19
148. 40 Y(I,J)=TY(I,J)
149. 45 CONTINUE
150. T = TJ-JPREV
151.
152. C CONVERT POWER FROM KW/FT TO KW/INCH
153. C
154. C
155. PFORIN = P/12.
156. PHI=PFORIN/(COHEN*(N17*FX(1)+N72*FX(7)+N82*FX(8)+N92*FX(9)
157. A +N102*FX(10)))
158. DO 50 I=1,19
159. F(I)=PHI*(FX(10)+H10*Y(1,1)+FX(1)*N1*Y(2,1)+FX(7)*N7*Y(3,1)+FX(9)*
160. ANQ*Y(4,1))
161. 50 CONTINUE
162. 9996 FORMAT (6,N INPUT TERMS @/(1X,1P6E12.6))
163. X1=PHI*CX(1)
164. X2=PHI*CX(2)+DC2
165. X3=PHI*CX(3)+DC3
166. X4=DC4
167. X5=DC5
168. X6=DC6
169. X7=PHI*CX(7)
170. X8=PHI*CX(8)
171. X9=PHI*CX(9)
172. X10=PHI*CX(10)
173. X11=PHI*CX(11)
174. X12=DC12
175. X13=PHI*CX(13)
176. X14=PHI*CX(14)+JC14
177. X15=PHI*CX(15)+JC15
178. N1=EN1(N1,X1,T)
179. N2=EN1(N2,X2,T)+EN2(PHI,AX(1),N1,X2,T)
180. N3=EN1(N3,X3,T)+EN3(DC2,N2,X3,T)
181. N4=EN1(N4,X4,T)+EN2(PHI,AX(2),N2,X4,T)
182. N5=EN1(N5,X5,T)+EN2(PHI,AX(3),N3,X5,T)+EN3(DC4,N4,X5,T)
183. N6=EN1(N6,X6,T)+EN3(DC5,N5,X6,T)
184. N10=EN1(N10,X10,T)
185. N11=EN1(N11,X11,T)+EN2(PHI,AX(10),N10,X11,T)
186. N12=EN1(N12,X12,T)+EN2(PHI,AX(11),N11,X12,T)
187. N13=EN1(N13,X13,T)+EN3(DC12,N12,X13,T)
188. N14=EN1(N14,X14,T)+EN2(PHI,AX(13),N13,X14,T)
189. N15=EN1(N15,X15,T)+EN3(DC14,N14,X15,T)
190. N7=EN1(N7,X7,T)+EN2(PHI,AX(15),N15,X7,T)+EN3(DC3,N3,X7,T)
191. N8=EN1(N8,X8,T)+EN2(PHI,AX(7),N7,X8,T)+EN3(DC6,N6,X8,T)
192. N9=EN1(N9,X9,T)+EN2(PHI,AX(8),N8,X9,T)

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193. X101=PHI*CX(20)
194. X103=DC65I
195. X104=PHI*CX(21)+DC85
196. X106=DC21
197. X107=DC22
198. X108=DC23
199. X109=PHI*CX(22)
200. X110=DC25
201. X111=DC31
202. X112=PHI*CX(23)
203. X113=DC26
204. X114=PHI*CX(24)+DC33
205. X116=DC28
206. X117=DC34
207. X118=PHI*CX(25)+DC35
208. IF(CX(20).LE.1.E-30) GO TO 100
209. N101=EM1(N101,X101,T)+F(1)*FAC(X101,T)
210. GO TO 101
211. 100 N101=N101+F(1)*T
212. 101 N102=N102+(F(2)+PHI*CX(20)*N101)*T
213. N103=EM1(N103,X103,T)+F(3)*FAC(X103,T)
214. N104=EM1(N104,X104,T)+(F(4)+.21*X103*N103)*FAC(X104,T)
215. N105=N105+(F(5)+PHI*CX(21)*N104)*T
216. N106=EM1(N106,X106,T)+F(6)*FAC(X106,T)
217. N107=EM1(N107,X107,T)+(F(7)+.18*X106*N106)*FAC(X107,T)
218. N108=EM1(N108,X108,T)+(.82*X106*N106+X107*N107)*FAC(X108,T)
219. IF(CX(22).LE.1.E-30) GO TO 102
220. N109=EM1(N109,X109,T)+X106*N108*FAC(X109,T)
221. GO TO 103
222. 102 N109=N109+X108*N108*T
223. 103 N110=EM1(N110,X110,T)+F(10)*FAC(X110,T)
224. N111=EM1(N111,X111,T)+X110*N110*FAC(X111,T)
225. IF(CX(23).LE.1.E-30) GO TO 104
226. N112=EM1(N112,X112,T)+(X111*N111+X109*N109)*FAC(X112,T)
227. GO TO 105
228. 104 N112=N112+(X111*N111+X109*N109)*T
229. 105 N113=EM1(N113,X113,T)+F(13)*FAC(X113,T)
230. N114=EM1(N114,X114,T)+X113*N113*FAC(X114,T)
231. N115=N115+(F(15)+PHI*CX(24)*N114)*T
232. N116=EM1(N116,X116,T)+F(16)*FAC(X116,T)
233. N117=EM1(N117,X117,T)+.3*X116*N116*FAC(X117,T)
234. N118=EM1(N118,X118,T)+(F(18)+.7*X116*N116+X117*N117)*FAC(X118,T)
235. N119=EM1(N119,X119,T)+PHI*CX(25)*N118)*T
236. N120=N101+N102+N103+N104+N105
237. N121=N109+N112+N114+N115+N117+N118+N119
238. RETURN
239. END

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KR 83
KR 85I
KR 85
TE 131
TE 131
I 131
XE 131
TE 132
I 132
XE 132
I 133
XE 133
I 135
XE 135I
XE 135
KR 83
KR 83
KR 84
KR 85I
KR 85
KR 86
TE 131
TE 131
I 131
XE 131
TE 132
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I 133
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XE 134
I 135
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XE 136

' ELT GAPAXL,1,730931, 51999

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1. C GAPVAT IS THE MATR PROGRAM BASED ON GAPCON TO PERFORM AXIAL
2. C VOLUME TEMPERATURE AVERAGED GAS MIXING.
3. C
4. C COMMON /POWRAY/ PAVRG,LFUEL,LF,POWER(21),AI(21),NPOW,PTOT,LPMAX
5. C 1,PKPOWR,IPEAK,DELFP,PMAX
6. C COMMON /PRNRAY/ VOLCC,N1Z,N7Z,N8Z,N9Z,N10Z
7. C COMMON /BRNGAS/ NKRR(20),NXE(20),PHI(20),ENXE(20),ENKR(20)
8. C COMMON /AXIAL/ VOLTX(20),TBAR(20),TCLINE(20),HGX(20),PRESX(20)
9. C 1,TAVGXX(20),RDOT(20),RGAPX(20),ROP(20),HFLUX(20)
10. C 2,XMOLS(21),FXMOL(6,21),PRESTO(20)
11. C 3,SUMOLS(6),FRACTN(6)
12. C DIMENSION TSR(100),VOLAT(28),FISGR(28)
13. C 1,CLCRP(6,20),ZR(7,6),ZR4(7,6)
14. C DIMENSION TITLE(20),AA(8,100),BR(8,100),CF(8,100),
15. C 1RV(3,100),ST(8,100),TABLE(8,100),PHICAP(6,6),CSUBP(6),
16. C 2CGN(10),CUM(50),DDUM(50),EKLJ(6),GMWT(6),DELCT(50),DELL(50),
17. C 3OMEGA(6),PCFR(50),J(60),G1N(60),SIGLJ(6),TS(100),TT(100),VISCOS(6)
18. C REAL N1,N1Z,N7,N7Z,N8,N3Z,N9,N9Z,N10,N10Z,KM,LF,MUF,MTONFT,MTM,KB,GAP
19. C 1,NKRXE,MOL(6)
20. C 2,MOLTOT,MOLGAP,MOLEFR(6),MLFR(6),LVOIDZ
21. C 3,LFUEL
22. C EQUIVALENCE (MOLEFR(1),MLFR(1)),(FRACHE,FRACTN(1))
23. C 1,(FRACAR,FRACTN(2)),(FRACH,FRACTN(3)),(FRACN,FRACTN(4))
24. C 2,(FRACKP,FRACTN(5)),(FRACXE,FRACTN(6))
25. C DATA PI,CCPIN3,SECDAY,AVGGAD,PR,CONEN/3,14159,16.367,6400.,9/
26. C 16.023E3,22400.,3.2F-14/
27. C DATA SDOT,SDOTT,EF,MUF,EPSIC/.016,.004,22.E6,.30,.8,.9/
28. C DATA ISTPLM/5/
29. C DATA WORD1/6HSTOP /
30. C DATA VOLAT/0.0,745.,755.,760.,785.,800.,810.,820.,825.
31. C 1,830.,840.,850.,855.,890.,920.,940.,955.,975.,985.,1000.,1015.,103GAP
32. C 20.,1100.,1160.,1300.,1470.,1690.,2000./
33. C DATA FISGR/0.,0006,.0008,.001,.002,.003,.004,.005,.006,.007,.008
34. C 1,.009,.01,.02,.03,.04,.05,.06,.07,.08,.09,.1,.16,.2,.3,.4
35. C 2,.5,.52/
36. C DATA {(ZR(I,J),I=1,7),J=1,6)/
37. C 1 75., 7.30, 4.48E4, 1.38E7, .370, 3.24E-6, 9470.,
38. C 2 212., 7.74, 3.48E4, 1.30E7, .400, 3.47E-6, 7360.,
39. C 3 392., 8.38, 2.39E4, 1.21E7, .446, 3.70E-6, 5030.,
40. C 4 572., 9.02, 1.58E4, 1.11E7, .492, 3.87E-6, 3340.,
41. C 5 752., 9.83, 1.21E4, 1.31E7, .492, 3.99E-6, 2560.,
42. C 6 932., 10.64, 1.00E4, 9.09E6, .492, 4.08E-6, 2110./
43. C
44. C ZIRC-4 DATA BY D.R. SCOTT (%CAP-3629-41) PAGE 8
45. C

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95.      60.,.6335,70.,.6194,80.,.6076,.90.,.5973,200.,.5882/
96.      DATA (SM/T(I),I=1,6)/4.003,39.944,2.016,28.02,83.8,131.3/
97.      DATA (SIGLJ(I),I=1,6)/2.576,3.418,2.915,3.681,3.498,4.055/
98.      DATA (SKLJ(I),I=1,6)/10.2,124.38,.915,225.229,./
99.      NAMELIST/INPUT/ NPOW,FRDEN,FRSIN,DSINZ,FRPU02,FR35,FR40,FR41,
100.      1DFS,DV0IDZ,DCI,DCO,VPLENZ,ATMOS,LFUEL,S'XX,ROUF,ROUC,EXTP,TINLET
101.      2,DE,V,PAVRG,POWER,TDAYS,DELT,TMAX,TFR,TM,DBO,KR,HBC,SIGHF,
102.      3IFLUX, NCLAD,NGCON,NFLY,KOOL,FRACHE,FRACAR,EPACH,FRACN,FRACKR,
103.      4FRACXE,NEWK,NEWCL,NEWFLX,LVOIDZ,NOH,HGACEL,ZCLAD,MINI
104.      5,ZCLAD,ICDF,ISTOR,ICREP,ISWELL
105.      6,PKPOWR,IPEAK,DELP,PVAX
106.      DATA ISTOR,PVAX,DELP,FRDEN,FRSIN,DSINZ,FRPU02,FR35,FR40,FR41,
107.      1DFS,DV0IDZ,DCI,DCO,VPLENZ,ATMOS,LFUEL,S'XX,ROUF,ROUC,EXTP,TINLET
108.      2,DE,V,PAVRG,ICREP,TDAYS,DELT,TMAX,TFR,TM,DBO,KR,HBC,SIGHF,
109.      3IFLUX, NCLAD,NGCON,NFLY,KOOL,FRACHE,FRACAR,FRACH,FRACN,FRACKR,
110.      4FRACXE,NEWK,NEWCL,NEWFLX,LVOIDZ,NOH,HGACEL,ZCLAD,MINI
111.      5,ICLF,ISWELL,PKPOWR,HG,PEKAVG/60*0/
112.      DATA DTEMP/100./,TPEAK/0/,NPOW/10/
113.      DATA POWER/.23,.63,.96,1.21,1.35,1.4,1.35,1.21,.96,.63,.23
114.      1,.10*0/
115.      TCW1(D,T)=(1.-2.*D+D**2)*(-1./(.288+.00252*T)-5.83E-12*T**3)
116.      TCW2(D,T)=(3.*D-1.)*(1./(.5.75+.0503*T)+2.91E-13*T**3)
117.      TCOR(D,T)=(.1,025/.95)*(D/(1.+(1.-D)*.5))*((38.24/(402.4+T))+(6.1GAP 117
118.      1256E-13*(T+273.))**3)))
119.
120.      C INITIALIZE AND THE BEGIN CALCULATIONS.
121.      C
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144.	NPOW1=NPOW+1	GAP 144
145.	FNPOW=FNPOW	GAP 145
146.	LF=LFUEL/FNPOW	GAP 146
147.	TPLENA=(TINLET+DTFMP-22.)/1.8+273.	GAP 147
148.	PEKAV6=1.0	GAP 148
149.	HG=1000.	GAP 149
150.	ITIME=0	GAP 150
151.	NF=NFLEX	GAP 151
152.	FR38=1.-FR35	GAP 152
153.	RSINZ=DSINZ/2.	GAP 153
154.	RVOIDZ=DVOIDZ/2.	GAP 154
155.	VVOIDZ=PI*RVOIDZ**2*LVOIDZ/FNPOW	GAP 155
156.	FRU02=1.-FRPU02	GAP 156
157.	DENSIT=FRPU02*11.46+FRU02*10.97	GAP 157
158.	FR39=1.-FR40-FR41	GAP 158
159.	IF (FRU02.LE11.E-10) FR39=0.	GAP 159
160.	GAP=DCI-DFS	GAP 160
161.	KFS=DFS/2.	GAP 161
162.	RCI=DCI/2.	GAP 162
163.	RCO=DCO/2.	GAP 163
164.	VULGAS=PI/4.*(DCI**2-DFS**2)*LF+VVOIDZ	GAP 164
165.	IF (NFLX) 160,150,170	GAP 165
166.	RV(1,1)=0.	GAP 166
167.	RV(1,2)=1.	GAP 167
168.	RV(2,1)=1.	GAP 168
169.	RV(2,2)=1.	GAP 169
170.	NF=2	GAP 170
171.	GO TO 170	GAP 171
172.	CALL DEPRES (DENSIT,FR35,FR38,DFS,RV)	GAP 172
173.	NF=11	GAP 173
174.	CONTINUE	GAP 174
175.	WRITE (6,1530)	GAP 175
176.	WRITE (6,1540) TITLE	GAP 176
177.	WRITE (6,1550)	GAP 177
178.	WRITE (6,1560) FRPU02,FR39,FR40,FR41,FRU02,FR35,FR38,FRDEN,FRSIN,DGAP	GAP 178
179.	IFS,DSINZ,DVOIDZ	GAP 179
180.	WRITE (6,1570) GAP,DCI,LCU,LFUEL,S,XX	GAP 180
181.	WRITE (6,1580) VPLENZ,TINLET,DTEMP,DEV,EXTP,PEKAVG,ROUF,ROUC	GAP 181
182.	WRITE (6,1590) PAVRG,PKPOWER,DELP,PMAX	GAP 182
183.	WRITE (6,1600) TDAYS,DELT,TMAX,DBO,KB,HBC	GAP 183
184.	WRITE (6,1610) ATMOS	GAP 184
185.	WRITE (6,1630) FRACHE,FRACAK,FRACH,FRACN,FRACKR,FRACXE	GAP 185
186.	WRITE (6,2090)	GAP 186
187.	IF (SIGMF) 180,190,200	GAP 187
188.	WRITE (6,1960)	GAP 188
189.	GO TO 210	GAP 189
190.	WRITE (6,1970)	GAP 190
191.	GO TO 210	GAP 191
192.	WRITE (6,1980) SIGHF	GAP 192

193.	210	WRITE (6,2090)	GAP 193
194.		IF (IFLUX) 220,220,230	GAP 194
195.	220	WRITE (6,1990)	GAP 195
196.		GO TO 240	GAP 196
197.	230	WRITE (6,2000)	GAP 197
198.	240	WRITE (6,2090)	GAP 198
199.		IF (NCLAU) 250,270,280	GAP 199
200.	250	CONTINUE	GAP 200
201.		IF (ZCLAD,31.0.) GO TO 260	GAP 201
202.		WRITE (6,2010)	GAP 202
203.		GO TO 290	GAP 203
204.	260	CONTINUE	GAP 204
205.		WRITE (6,2020)	GAP 205
206.		GO TO 290	GAP 206
207.	270	WRITE (6,2030)	GAP 207
208.		GO TO 290	GAP 208
209.	280	WRITE (6,2040)	GAP 209
210.	290	WRITE (6,2090)	GAP 210
211.		IF (NCON) 300,310,320	GAP 211
212.	300	WRITE (6,2050)	GAP 212
213.		GO TO 330	GAP 213
214.	310	WRITE (6,2060)	GAP 214
215.		GO TO 330	GAP 215
216.	320	WRITE (6,2070)	GAP 216
217.	330	WRITE (6,2090)	GAP 217
218.	C		GAP 218
219.	C	COMPLETE MIXING OF GASES IS ASSUMED.	GAP 219
220.	C		GAP 220
221.		WRITE (6,2080)	GAP 221
222.		WRITE (6,2090)	GAP 222
223.		WRITE (6,1620)	GAP 223
224.		RHO=DEVSIT*FRDEH	GAP 224
225.		RHOS=DENSIT*FRSIN	GAP 225
226.		VOLUME=PI/4.*(IDS**2-DVOIDZ**2)	GAP 226
227.		VOLCC=VOLUME*CCPIN3	GAP 227
228.		WERHO*VOLCC	GAP 228
229.		GRPUCC=FRPU02*RHO	GAP 229
230.		GRUCC=ERHO-GRPUCC	GAP 230
231.		UATWT=235.*FR35+238.*FR38	GAP 231
232.		FRUU=UATWT/(UATWT+32.)	GAP 232
233.		PUATWT=239.*FR39+240.*FR40+241.*FR41	GAP 233
234.		FRPUPU=PUATWT/(PUATWT+32.0)	GAP 234
235.		N1Z=FR38*FRUU*AVOGAD/238.*VOLCC*GRUCC	GAP 235
236.		N7Z=FR39*FRPUPU*AVOGAD/239.*VOLCC*GRPUCC	GAP 236
237.		N3Z=FR40*FRPUPU*AVOGAD/240.*VOLCC*GRPUCC	GAP 237
238.		N9Z=FR41*FRPUPU*AVOGAD/241.*VOLCC*GRPUCC	GAP 238
239.		N10Z=FR35*FRUU*AVOGAD/235.*VOLCC*GRPUCC	GAP 239
240.		N1=N1Z	GAP 240
241.		N7=N7Z	GAP 241

242.	NI0=NI0Z		GAP 242
243.	NN=NBZ		GAP 243
244.	NN=NBZ		GAP 244
245.	IF (NCON) 370,340,350		GAP 245
246.	DO 360 J=1,10		GAP 246
247.	TEMP=260.+277.777R*(J-1)+273.		GAP 247
248.	CF(1,J)=(TEMP-273.)*1.8+32.		GAP 248
249.	CF(3,J)=57.8*TCW2(FRSIN,TEMP)		GAP 249
250.	IF (FRDEN*GE..95) GO TO 350		GAP 250
251.	CF(2,J)=57.8*TCW1(FRDEN,TEMP)		GAP 251
252.	GO TO 360		GAP 252
253.	CF(2,J)=57.8*TCW2(FRDEN,TEMP)		GAP 253
254.	CONTINUE		GAP 254
255.	NN=10		GAP 255
256.	GO TO 400		GAP 256
257.	DO 380 J=1,10		GAP 257
258.	TEMP=260.+277.777R*(J-1)		GAP 258
259.	CF(1,J)=TEMP*1.8+32.		GAP 259
260.	CF(2,J)=57.8*TCOR(FRDEN,TEMP)		GAP 260
261.	CF(3,J)=57.8*TCOR(FRSIN,TEMP)		GAP 261
262.	CONTINUE		GAP 262
263.	NN=10		GAP 263
264.	GO TO 400		GAP 264
265.	NN=NCON		GAP 265
266.	WRITE (6,1640) ((CF(I,J),I=1,3),J=1,NN)		GAP 266
267.	WRITE (6,1650)		GAP 267
268.	WRITE (6,1660) (RV(1,J),RV(2,J),J=1,NF)		GAP 268
269.	WRITE (6,1690)		GAP 269
270.	WRITE (6,1700) NPOW,MINI,ICDF,ISTOP,ICREP,ISWELL,IPEAK		GAP 270
271.	WRITE (6,1670)		GAP 271
272.	IF (NCLAD) 410,430,450		GAP 272
273.	DO 420 I=1,7		GAP 273
274.	DO 420 J=1,6		GAP 274
275.	AA(I,J)=ZR(I,J)		GAP 275
276.	IF (ZCLAG*GT.0) AA(I,J)=ZR4(I,J)		GAP 276
277.	CONTINUE		GAP 277
278.	NN=6		GAP 278
279.	GO TO 460		GAP 279
280.	DO 440 I=1,7		GAP 280
281.	DO 440 J=1,23		GAP 281
282.	AA(I,J)=ST(I,J)		GAP 282
283.	CONTINUE		GAP 283
284.	NN=23		GAP 284
285.	GO TO 460		GAP 285
286.	NN=NCLAD		GAP 286
287.	CONTINUE		GAP 287
288.	PC=P		GAP 288
289.	JCASE=1		GAP 289
290.	CONTINUE		GAP 290
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291.	CALL POWDIS	GAP 291
292.	T=IDAYS*SECCAY	GAP 292
293.	ANKR=0.	GAP 293
294.	ANXE=0.	GAP 294
295.	DO 480 IPOW=1,NPOW	GAP 295
296.	P=0.5*(POWER(IPOW+1)+POWER(IPOW))	GAP 296
297.	WTIME=0	GAP 297
298.	CALL FISGAS (T,PHI(IPOW),P,CONEN,IFLUX,WTIME,ANKR(IPOW),NXE(IPOW))	GAP 298
299.	ANKR=ANKR+ANKR(IPOW)	GAP 299
300.	ANXE=ANXE+NXE(IPOW)	GAP 300
301.	CONTINUE	GAP 301
302.		GAP 302
303.	SETUP PLENUM MOLE CONTENT.	GAP 303
304.		GAP 304
305.	XMOLS(NPOW1)=VPLENZ*CCPIN3*ATMOS/RR	GAP 305
306.	CALL MOVEAA (FFACTN,FXMOL(1,NPOW1),6)	GAP 306
307.		GAP 307
308.	BEGIN AXIAL CALCULATIONS	GAP 308
309.		GAP 309
310.	ISTOP=ISTPLM	GAP 310
311.	DO 1410 ISTEP=1,ISTPLM	GAP 311
312.	TAVGX=0.	GAP 312
313.	VCLIXS=0.	GAP 313
314.	HGACEL=0.8	GAP 314
315.	DO 490 I=1,6	GAP 315
316.	SUMOLS(I)=FXMOL(I,NPOW1)*XMOLS(NPOW1)	GAP 316
317.	CONTINUE	GAP 317
318.	DO 1370 IPOW=1,NPOW	GAP 318
319.		GAP 319
320.	CALCULATE THE POWER, TCOOL, AND THE NEW NUMBER OF XE AND KR	GAP 320
321.	ATOMS IN EACH SEGMENT.	GAP 321
322.		GAP 322
323.	NKR(IPOW)=ANKR/FNPOW	GAP 323
324.	NXE(IPOW)=ANXE/FNPOW	GAP 324
325.	P=0.5*(POWER(IPOW+1)+POWER(IPOW))	GAP 325
326.	TCOOL=TIMLET+DTEMP*AI(IPOW)	GAP 326
327.	TCOCLC=(TCOOL-32.)/1.8	GAP 327
328.	IF (RSIN2*GT.0.) GO TO 500	GAP 328
329.	WGT=RHC*(RFS**2-RVOIDZ**2)*PI	GAP 329
330.	WGT=0.	GAP 330
331.	GO TO 510	GAP 331
332.	WGT=RHC*(RFS**2-RSINZ**2)*PI	GAP 332
333.	WGT=RHOS*(RSINZ**2-RVOIDZ**2)*PI	GAP 333
334.	WGT=100 GRAMS PER FOOT	GAP 334
335.	WGT=(WGT+WGT)*196.64477	GAP 335
336.	PKWPIN=P/12.	GAP 336
337.	RSINERSINZ	GAP 337
338.	DSIN=CSINZ	GAP 338
339.	RVOID=RVOIDZ	GAP 339

340.	DVOID=DVOIDZ	GAP 340
341.	VVOID=VVOIDZ	GAP 341
342.	GTOT=P*3413.	GAP 342
343.	GRAM IS IN BTU/HP/GRAM OF FUEL	GAP 343
344.	GRAM=GTOT/WGT	GAP 344
345.	QU IS IN BTU/HP/FT3	GAP 345
346.	QU=GRAM*RHO*28316.8466	GAP 346
347.	QS IS IN BTU/HP/FT3	GAP 347
348.	QS=GRAM*RHO*28316.8466	GAP 348
349.	RSIN=RSIN/12.	GAP 349
350.	MTONFT=RHO*VOLCC*12./1.E6	GAP 350
351.	MIN=MTONFT*(FRUO*FRUO2+FRPI*PU*FRPUO2)	GAP 351
352.	BURNUP=P*.001*TDAYS/MTM	GAP 352
353.		GAP 353
354.	ITER=0	GAP 354
355.	DELR=0	GAP 355
356.	DELRCC=0.	GAP 356
357.	DELRCC=0.	GAP 357
358.	DELRCC=0.	GAP 358
359.	CONTINUE	GAP 359
360.	ITER=ITER+1	GAP 360
361.	GOVRAC=P*3413./(PI*(DCO+2.*DELRCC))*12.	GAP 361
362.	HFLUX(IPOW)=GOVRAC	GAP 362
363.	GOVHAI=P*3413./(PI*(DCI+2.*DELRCC))*12.	GAP 363
364.	GOVRAS=P*3413./(PI*(DFS+2.*DELR))*12.	GAP 364
365.	IF (KQOL.GT.0) GO TO 680	GAP 365
366.	IF (DBO) 580,580,530	GAP 366
367.	GOVRAB=P*3413./(PI*DBO)*12.	GAP 367
368.	IF (SIGHF) 540,550,560	GAP 368
369.	CALL HTCM (TCOOL,GOVRAB,V,DE,HF,TBSKS)	GAP 369
370.	GO TO 570	GAP 370
371.	CALL HTCLM (HF,TCOOL,DE,V)	GAP 371
372.	GO TO 570	GAP 372
373.	HF=SIGHF	GAP 373
374.	CONTINUE	GAP 374
375.	TBO=TCOOL+GOVRAB/HF	GAP 375
376.	GABLM=(GOVRAC-GOVRAB)/ALOG(GOVRAC/GOVRAB)	GAP 376
377.	DELTB=GABLM*(DBO-PCO)/(24.*KB)	GAP 377
378.	TBI=TBO+DELTB	GAP 378
379.	TCO=GOVRAC/HBC+TBI	GAP 379
380.	GO TO 630	GAP 380
381.	IF (SIGHF) 590,600,610	GAP 381
382.	CALL HTCM (TCOOL,GOVRAC,V,DE,HF,TCO)	GAP 382
383.	GO TO 620	GAP 383
384.	CALL HTCLM (HF,TCOOL,DE,V)	GAP 384
385.	GO TO 620	GAP 385
386.	HF=SIGHF	GAP 386
387.	CONTINUE	GAP 387
388.	TCO=TCOOL+GOVRAC/HF	GAP 388

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389. CONTINUE
390. TAVGC=TCO+20.
391. QOVRAA=(QOVRAAC+QOVRAI)/2.
392. IITRY=1
393. TCC=TEP(TAVGC,AA,2,NIN)
394. IITRY=IITRY+1
395. DELTC=QOVRAA*(DCO+2.*DELRCO-DCI-2.*DELRC)/(2.*TCC)
396. TCI=TCO+DELTC
397. TAVGC=(TCO+TCI)/2.
398. DEL=ABS(TAVGC1-TAVGC)
399. IF (DEL-1.) 670,670,650
400. TAVGC=TAVGC1
401. IF (IITRY-50) 640,640,660
402. WRITE (6,1470)
403. CONTINUE
404. GO TO 630
405. TCI=TCOOL
406. TCO=TCI-.5*(QOVRAAC+QOVRAI)*(DCO+2.*DELRCO-DCI-2.*DELRC)/144.
407. CONTINUE
408. QOVRAE=(QOVRAAS+QOVRAI)/2.
409.
410. C
411. C
412. SET UP SYSTEM OF N NODES OF EQUAL THICKNESS, RADII IN FEET
413. TFS=TCI+QOVRAE/HG
414. N=50
415. DR=(RFS+DELR-RVOID)/FLOAT(N)/12.
416. R0=(RFS+DELR)/12.
417. DO 700 I=1,N
418. R IS IN FEET
419. R=R0-Q*(I-1)
420. KRR=(2.*R-DR)*12.
421. RATIO=TEP(RRR,RV,2,NF)
422. RDR=R-DR
423. IF (RDR-GE,RSINF) Q(I)=PI*(R**2-RDR**2)*RATIO*QOU
424. IF (RDR-LT,RSINF.AND.P.GT,RSINF) Q(I)=(R**2-RSINF**2)*QOU+(RSINF*GAP
425. 1*2-RDR**2)*QOS)*PI*RATIO
426. IF (RDR-LT,RSINF.AND.R.LE,RSINF) Q(I)=PI*(R**2-RDR**2)*RATIO*QOS
427. CONTINUE
428. CORRECT FOR ACCUMULATION OF ERROR IN HEAT GENERATION
429. SUMQ=0.
430. DO 710 I=1,N
431. SUMQ=SUMQ+Q(I)
432. CORRTOT=SUMQ
433. DO 720 I=1,N
434. Q(I)=CORRTOT/I
435. ACC=1.
436. WIN(1)=GTOT-Q(1)
437. DO 730 I=2,N
438. WIN(I)=GTN(I-1)-Q(I)
439. IPE=0

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438.	DO 860 I=1,N		GAP 438
439.	R=(RFS+DELR)/12.-DR*FLOAT(I-1)		GAP 439
440.	RDR=DR		GAP 440
441.	IF (I.GT.1) GO TO 740		GAP 441
442.	TAV=TFS		GAP 442
443.	TZ=TFS		GAP 443
444.	GO TO 750		GAP 444
445.	TAV=TT(I-1)		GAP 445
446.	TZ=TT(I-1)		GAP 446
447.	CONTINUE		GAP 447
448.	DEN=FRDEN		GAP 448
449.	IF (R.LE.RSINF) DEN=FRSIN		GAP 449
450.	TAVC=(TAV-32.)/1.8		GAP 450
451.	TAVK=TAVC+273.		GAP 451
452.	IF (NCON) 770,780,800		GAP 452
453.	C=57.8*TCOR(DEN,TAVC)		GAP 453
454.	GO TO 810		GAP 454
455.	IF (FRDEN.GE..95.OR.R.LE.RSINF) GO TO 790		GAP 455
456.	C=57.8*ICW1(DEN,TAVK)		GAP 456
457.	GO TO 810		GAP 457
458.	C=57.8*ICW2(DEN,TAVK)		GAP 458
459.	GO TO 810		GAP 459
460.	KK=2		GAP 460
461.	IF (R.LE.RSINF) KK=3		GAP 461
462.	C=TERP(TAV,CF,KK,NIN)		GAP 462
463.	CONTINUE		GAP 463
464.	IF (RDR.LT.1.E-20) GO TO 820		GAP 464
465.	TERM=(RDR**2/IR**2-RDP**2)-GIN(I)/Q(I))*ALOG(R/RDR)		GAP 465
466.	GO TO 830		GAP 466
467.	TERM=0.		GAP 467
468.	TT(I)=(TZ+Q(I))/(2.*PI*C)*(.5-TERM)		GAP 468
469.	TAV1=(TZ+TT(I))/2.		GAP 469
470.	TTAV=TAV		GAP 470
471.	DIFF=ABS(TAV-TAV1)		GAP 471
472.	IF (DIFF-ACC) 860,860,840		GAP 472
473.	TAV=TAV1		GAP 473
474.	IME=IME+1		GAP 474
475.	IF (IME-10) 760,850,850		GAP 475
476.	WRITE (6,1920) TTAV,TAV1		GAP 476
477.	IME=0		GAP 477
478.	DO 870 I=1,N		GAP 478
479.	TS(I)=(RFS+DELR)-(RFS+DELR-PVOID)*FLOAT(I)/FLOAT(N)		GAP 479
480.	CONTINUE		GAP 480
481.	DO 880 I=1,N		GAP 481
482.	BB(1,I)=TT(I)		GAP 482
483.	BB(2,I)=TS(I)		GAP 483
484.	IF (KOUNT.EQ.0) GO TO 900		GAP 484
485.	IF (FRDEN.GE.FRSIN) FRDEN=FRDEN		GAP 485
486.	TSINC=1350.		GAP 486

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487. IF (T,LE,0.) GO TO 890
488. RETEM=.00001367*ALOG10(1/3600.)*.000480
489. TSINC=1./RETEM-273.
490. CONTINUE
491. TSIN=1.8*TSINC+32.
492. RSIN=TERP(TSIN,RR,2,N)
493. IF (RSIN,LE,RSIN2) RSIN=RSIN2
494. DSIN=2.*PSIN
495. RSINF=RSIN/12.
496. RVOID=RVOID
497. RVOID=SQRT((PSIN**2)*(RSIN-FRDN)/FRSIN+(RVOIDZ**2)*FRDN/FRSIN)
498. IF (RVOID,LE,RVOIDZ) RVOID=RVOIDZ
499. DVOID=2.*RVOID
500. ELTC=LF-LVOIDZ/FRPOW
501. VTC=PI*ELTC*RVOIDZ**2
502. VVOID=(FI*LF*RVOIDZ**2-VTC)
503. CONTINUE
504.
505. C
506. C
507. C
508. C
509. C
510. C
511. C
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527. C
528. C
529. C
530. C
531. C
532. C
533. C
534. C
535. C

IF (T,LE,0.) GO TO 890
RETEM=.00001367*ALOG10(1/3600.)*.000480
TSINC=1./RETEM-273.
CONTINUE
TSIN=1.8*TSINC+32.
RSIN=TERP(TSIN,RR,2,N)
IF (RSIN,LE,RSIN2) RSIN=RSIN2
DSIN=2.*PSIN
RSINF=RSIN/12.
RVOID=RVOID
RVOID=SQRT((PSIN**2)*(RSIN-FRDN)/FRSIN+(RVOIDZ**2)*FRDN/FRSIN)
IF (RVOID,LE,RVOIDZ) RVOID=RVOIDZ
DVOID=2.*RVOID
ELTC=LF-LVOIDZ/FRPOW
VTC=PI*ELTC*RVOIDZ**2
VVOID=(FI*LF*RVOIDZ**2-VTC)
CONTINUE

VOLUME AVERAGE THE TEMPERATURE.
TSR(N+1)=RVOID
DO 910 I=1,N
BI=1
TSR(I)=(RFS+DELR)-(((RFS+DELR)-RVOID)/FLOAT(N))*(BI-1.0)
VAFR=(TSR(1)**2-TSR(2)**2)*PI*((TFS+TT(1))*5)
DO 920 I=2,N
VAFR=VAFR+(TSR(I)**2-TSR(I+1)**2)*PI*((TT(I)+TT(I+1))*5)
CONTINUE
VAVGT=VAFR/(((RFS+DELR)**2-RVOID**2)*PI)
VAVGTC=(VAVGT-32.)/1.8
IF (KOUNT.EQ.0) TRAP(TPOW)=VAVGT
C
CALCULATE RADIUS AVERAGED FUEL TEMPERATURE
TEMP=C
DO 930 I=1,50
TEMP=TEMP+BB(1,I)*(RFS+DELR+RVOID)/50.
CONTINUE
TAVGF=TEMP/(RFS+DELR-RVOID)
TAVGTC=(TAVGF-32.)/1.8
RQ=(RFS-RVOIDZ)/N
TMF=TM*1.8+32
RMELT=TERP(TM,RR,2,N)
CALL EXPAND(RMELT,RFS,RR,FRDN,TT,TMF,FRPU02,DELR,DELCT,DELL)
1,DELM,DELN,RVOIDZ,VOL,VCRAK,L,LLM)
T1300=2372.
R1300=TERP(T1300,RR,2,N)
R1700=TERP(3092.,RR,2,N)
R1500=TERP(2732.,RR,2,N)
IF (KOUNT.GT.0) R1700=RSIN
R1350=TERP(2462.,RR,2,N)

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536.	VH=PI*(R1700**2	GAP 536
537.	VL=PI*(RFS**2-R1350**2)	GAP 537
538.	VC=PI*(R1350**2-R1700**2)	GAP 538
539.	DELVB=(SDOT*VOLUME*FRDEN+SDOTT*VC)*BURNUP/1.E4-(1.--FRDEN)*(1.8*VH+.	GAP 539
540.	15*VC+.3*VL)	GAP 540
541.	IF (DELVB) 940,940,950	GAP 541
542.	DELVB=0.	GAP 542
543.	CONTINUE	GAP 543
544.	DELRB=DELVB/(3.*PI*RFS)	GAP 544
545.	TAVGC=(TCI+TCO)/2.	GAP 545
546.	ALPHAC=TERP(TAVGC,AA,6,NN)	GAP 546
547.	DELRG=RCI*ALPHAC*(TAVGC-77.)	GAP 547
548.	DELRG=DELRG	GAP 548
549.	DELRG=RCO*ALPHAC*(TAVGC-77.)	GAP 549
550.	DELRCC=0.	GAP 550
551.	PRESI=ATMOS*14.696*(((TCI+TFS)/2.)-32.)/1.9+273.)/298.	GAP 551
552.	IF (ISTEP.EG.1.AND.ITER.EG.1) PRESTO(1)=PRESI	GAP 552
553.	PRESGN=2.0*(EXTP*(RCO+DELRCCO)**2-PRESTO(ISTEP)*(RCI+DELRG)**2)	GAP 553
554.	IF (ICPRE.LE.0) GO TO 960	GAP 554
555.	DELRCC=TERP(TDAYS,CLCPP,2,NCR)	GAP 555
556.	DELRCC=DELRCC-DELRCC	GAP 556
557.	DELRCC=DELRCC-DELRCC	GAP 557
558.	DELRP=0.	GAP 558
559.	PRESGN=0.	GAP 559
560.	GO TO 970	GAP 560
561.	CONTINUE	GAP 561
562.	IF (ICDF.GE.0.0) GO TO 970	GAP 562
563.	EC=TERP(TAVGC,AA,4,NN)	GAP 563
564.	CMU=TERP(TAVGC,AA,5,NN)	GAP 564
565.	DELRP=(RCI+DELRG)/(EC*(RCO+DELRCCO)**2-(RCI+DELRG)**2))*((PRESTO(IGAP 565	
566.	1STEP)*(RCI+DELRG)**2-EXTP*(RCO+DELRCCO)**2)*(1.-CMU)+(PRESTO(ISTEP)GAP 566	
567.	2-EXTP)*(RCO+DELRCCO)**2)*(1.+CMU))	GAP 567
568.	DELRCC=DELRCC+DELRP	GAP 568
569.	DELRCC=DELRCC+DELRP	GAP 569
570.	PRESGN=0.	GAP 570
571.	CONTINUE	GAP 571
572.	DELR=DELR+DELRB	GAP 572
573.	THC=TH	GAP 573
574.	TH=GAP/2.+DELRCC-DELR	GAP 574
575.	IF (ISWELL) 980,1000,1000	GAP 575
576.	CONTINUE	GAP 576
577.	IF (TH.LE.0) GO TO 990	GAP 577
578.	CALL SWELL (R1300,R1500,R1700,RFS,RVOID,PI,BURNUP,TH,GAP,DELR,DEL	
579.	RC,DELRBH)	GAP 579
580.	IF (TH.GT.0) GO TO 990	GAP 580
581.	TH=1.9*(ROUF+K0UC)+1.0E-0	GAP 581
582.	CONTINUE	GAP 582
583.	IF (DELRB.LT.DELRBH.AND.TH.GT.0) DELRB=DELRBH	GAP 583
584.	CONTINUE	GAP 584

585.	DELRT=DELRT+DELRT	GAP 585
586.	THR=TH-1.98*(ROUF+ROUC)	GAP 586
587.	VOLGAP=I/4.*((JCT+2.*DELRK)**2-(DFS+2.*DELR)**2)*LF	GAP 587
588.	CRUF=1.980*(ROUF+ROUC)	GAP 588
589.	VRUF=PI*DFS*CRUF*LF	GAP 589
590.	IF (VOLGAP.LE.VRUF) VOLGAP=VRUF	GAP 590
591.	VOLGP=VOLGAP+VVGIN	GAP 591
592.	VCOLD=PI*((RFS+2.*DELR)**2-R1350**2)	GAP 592
593.	VCOOL=PI*(R1350**2-R1700**2)	GAP 593
594.	VHOT=PI*(R1700**2-RVOID**2)	GAP 594
595.	VTOT=VCOLD+VCOOL+VHOT	GAP 595
596.		GAP 596
597.	INTERPOLATE FISSION GAS RELEASE TABLE ON VOL. AVG. TEMP	GAP 597
598.		GAP 598
599.	TVOLAVE=VAVGIC	GAP 599
600.	IF (ISTEP.GT.1) GO TO 1030	GAP 600
601.	F=TEPP(TVOLAV,FISGR,VOLAT,28)	GAP 601
602.	ROOT(IPOW)=F	GAP 602
603.		GAP 603
604.	CALCULATE GAS COMPOSITION	GAP 604
605.		GAP 605
606.	FILMOL=STP*VOLGAS*CCPIN3*ATMOS/FR	GAP 606
607.	MOL(1)=FILMOL*FRACHE	GAP 607
608.	MOL(2)=FILMOL*FRACAP	GAP 608
609.	MOL(3)=FILMOL*FRACH+WS*XX*LF/RR*ROOT(IPOW)	GAP 609
610.	IF (NOH.GT.0) MOL(3)=0.	GAP 610
611.	MOL(4)=FILMOL*FRACH+WS*(1.-XX)*LF/RR*ROOT(IPOW)	GAP 611
612.	MOL(5)=FILMOL*FRACH+NH*(IPOW)/AVOGAD*LF*ROOT(IPOW)	GAP 612
613.	MOL(6)=FILMOL*FRACH+NXE(IPOW)/AVOGAD*LF*ROOT(IPOW)	GAP 613
614.		GAP 614
615.	CALCULATE MOLE FRACTIONS OF GAS IN THE FUEL PIN.	GAP 615
616.	XMOLS(IPOW)=0.0	GAP 616
617.	DO 1010 I=1,6	GAP 617
618.	XMOLS(IPOW)=XMOLS(IPOW)+MOL(I)	GAP 618
619.	CONTINUE	GAP 619
620.	DO 1020 I=1,6	GAP 620
621.	FXMOL(I,IPOW)=MOL(I)/XMOLS(IPOW)	GAP 621
622.	MOLFR(I)=FXMOL(I,IPOW)	GAP 622
623.	CONTINUE	GAP 623
624.	CONTINUE	GAP 624
625.	MOLTOT=XMOLS(IPOW)	GAP 625
626.	MOLGAP=MOLTOT*VOLGAP/VOLGP	GAP 626
627.	TGAS=(TCI+TFS)/2.	GAP 627
628.	ASTGAS=(TGAS-32.)/1.8+273.	GAP 628
629.		GAP 629
630.	CALCULATE THERMAL CONDUCTIVITY AND VISCOSITY OF THE GAS	GAP 630
631.		GAP 631
632.	DO 1040 I=1,6	GAP 632
633.		GAP 633

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634. TKE=ARTGAS/EKLJ(I)
635. OMEGA(I)=TERP(TKE, TABLE, 2, 80)
636. CONTINUE
637. DO 1050 I=1,6
638. VISCOS(I)=2.67E-5*SQRT(ABIGAS*GMWT(I))/(OMEGA(I)*SIGLJ(I)**2)
639. CONTINUE
640. DO 1060 I=1,6
641. DO 1060 J=1,6
642. PHICAP(I,J)=1./SQRT(8.)/(SQRT(1.+GMWT(I)/GMWT(J)))*(1.+SQRT(VISCOS(I)*VISCOS(J)))
643. 1(I)/VISCOS(J))*((GMWT(J)/GMWT(I))**.25)**2
644. CONTINUE
645. DO 1070 I=1,6
646. IF (I.EQ.3) GO TO 1070
647. IF (I.EQ.4) GO TO 1070
648. CON(I)=1.9891E-4*(SQRT(ARTGAS/GMWT(I)))/(SIGLJ(I)**2*OMEGA(I))
649. CONTINUE
650. CSUBP(3)=6.947-0.20E-3*ABTGAS+4.808E-7*ABTGAS**2
651. CSUBP(4)=6.524+1.25E-3*ABTGAS-1.E-9*ABTGAS**2
652. DO 1080 I=3,4
653. CON(I)=(CSUBP(I)+1.25*1.987)*VISCOS(I)/GMWT(I)
654. CONTINUE
655. GASKON=0.
656. VISMIX=0.
657. DO 1100 I=1,6
658. DENOM=0.
659. DO 1090 J=1,6
660. DENOM=DENOM+MOLEFR(J)*PHICAP(I,J)
661. CONTINUE
662. GASKON=GASKON+MOLEFR(I)*CON(I)/DENOM
663. VISMIX=VISMIX+MOLEFR(I)*VISCOS(I)/DENOM
664. CONTINUE
665. GK=GASKON*.241.9
666. CALCULATE GAS PRESX(IPOW) SURE IN THE PIN
667. ARTCV=(TT(N)-32.)/1.8+273.
668. V2=VVOID
669. V1=PI*((RCI+DELR)**2-(RFS+DELR)**2)*LF
670. IF (V1.LE.VRUF) V1=VRUF
671. VCLOVT=V1/ABTGAS+V2/ARTCV
672. PRESX(IPOW)=73.604*MOLTOT/VOLOVT
673. IF (ISTEP.EQ.1) PRESTO(1)=PRESX(IPOW)
674. EMMIX=VOLEFR(1)*4.0+MOLEFR(2)*39.94+MOLEFR(3)*2.016+MOLEFR(4)*28.06
675. 12*MOLEFR(5)*83.80+MOLEFR(6)*131.3
676. ELL=VISMIX/PRESTO(ISTEP)*SQRT(ABTGAS/EMMIX)
677. GIPG2=2.1448*ELL
678. IF=TH-1.98*(ROUF+ROUC)
679. IF (THR) 1120, 1120, 1110
680. HGAS=GK/(TH+GIPG2)*12.
681. HSOLID=0.
682. GO TO 1180

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683.	1120	CONTINUE		GAP 683
684.		TR=ABS(THR)		GAP 684
685.		EC=TERP(TAVGC,AA,4,NN)		GAP 685
686.		CMU=TERP(TAVGC,AA,5,NN)		GAP 686
687.		YDSTR=TERP(TAVGC,AA,3,NN)		GAP 687
688.		RCI=DCI/2.		GAP 688
689.		RCO=DCO/2.		GAP 689
690.		RSQRC=(RCO+DELRCO)**2-(RCI+DELRFC)**2		GAP 690
691.		RSQRPC=(RCO+DELRCO)**2+(RCI+DELRFC)**2		GAP 691
692.		ALOGC=ALOG((RCO+DELRCO)/(RCI+DELRFC))		GAP 692
693.		STREST=ALPHAC*EC*(TCI-TCO)/(2.*(1.-CMU)*ALOGC)*(1.-(2.*(RCO+DELRCO)GAP 693		
694.		1)**2/RSQRC*ALOGC)		GAP 694
695.		PFACE=(TR*EC/(RCI+DELRFC)+PRESCN/RSQRC)/(RSQRPC/RSQRC+CMU+EC*(1.-GAP 695		
696.		1MU)/EF)		GAP 696
697.		PF=PFACE		GAP 697
698.		PFMAX=((YDSTR-STREST)*RSQRC+PRESCN)/RSQRPC		GAP 698
699.		IF (PFACE.GT.PFMAX) PFACE=PFMAX		GAP 699
700.		IF (PFACE.LT.0.0) PFACE=0.0		GAP 700
701.		TFSC=(TFS-32.)/1.8		GAP 701
702.		TFSK=TFSC+273.		GAP 702
703.		IF (NCON) 1160,1140,1130		GAP 703
704.		FK=TERP(TFS,CF,2,NCON)		GAP 704
705.		GO TO 1170		GAP 705
706.	1140	IF (FRDEN.GE.195) GO TO 1150		GAP 706
707.		FK=57.8*TCW1(FRDEN,TFSK)		GAP 707
708.		GO TO 1170		GAP 708
709.	1150	FK=57.3*TCW2(FRDEN,TFSK)		GAP 709
710.		GO TO 1170		GAP 710
711.	1160	FK=57.8*TCOR(FRDEN,TFSK)		GAP 711
712.	1170	CONTINUE		GAP 712
713.		CK=TERP(TCI,AA,2,NN)		GAP 713
714.		K**2=FK*CK/(FK+CK)		GAP 714
715.		CKM=KM/57.8		GAP 715
716.		CPFACE=PFACE/14.194		GAP 716
717.		CEE=1.980*EXP(-.00125*CPFACE)		GAP 717
718.		ROUGH=SQRT((ROUF**2+ROUC**2)/2.)		GAP 718
719.		GROUGH=ROUGH*2.54		GAP 719
720.		HMEYER=TERP(TCI,AA,7,NN)		GAP 720
721.		CZZ=SQRT(CROUGH)		GAP 721
722.		AO=140.*CZZ-.103		GAP 722
723.		HSOL=CKN*CPFACE/(AO+CZZ*HMEYER)		GAP 723
724.		HSOLIN=HSOL*1761.7		GAP 724
725.		HGAS=GF/(CEE*(ROUF+ROUC)+G1PG2)*12.		GAP 725
726.		CONTINUE		GAP 726
727.		TFSR=TFS+460.		GAP 727
728.		TCISR=TCI+460.		GAP 728
729.		AF=RF5+DELR		GAP 729
730.		AC=RCI+DELR		GAP 730
731.		HFAU=.1713E-8/(1./EPSIF+AF/AC*(1./EPSIC-1.))*(TFSR**2+TCISR**2)*(TGAP 731		

732.	1FSR+TCISR)	GAP 732
733.	HGC=HSOLID+HGAS+HRAD	GAP 733
734.		GAP 734
735.	BEGIN CONVERGENCE OF HG NOW.	GAP 735
736.		GAP 736
737.	DELTA=HGC-HG	GAP 737
738.	DELHG=HG-HGOLD	GAP 738
739.	HGOLD=HG	GAP 739
740.	IF (ABS(DELTA/HG).LT.0.01) GO TO 1230	GAP 740
741.	IF (ITER.GT.35) GO TO 1220	GAP 741
742.		GAP 742
743.	TEST FOR SIMILAR SLOPES IN THE CONVERGENCE APPROACH AND	GAP 743
744.	IF THE LAST TWO ITERATIONS HAVE HAD SIMILAR VALUES, USE	GAP 744
745.	A DIFFERENT ITERATION SCHEME. GAPAXL CAN ENCOUNTER	GAP 745
746.	TWO BASIC TYPES AND THEY ARE: (1) OSCILLATING (UNDERDAMPED),	GAP 746
747.	OR (2) OVERDAMPED.	GAP 747
748.		GAP 748
749.	IF (IOSC.EQ.1) GO TO 1190	GAP 749
750.	IF (DELTA*DELTAQ.LT.0.) IOSC=1	GAP 750
751.	IF (DELTA*DELTAQ.LE.0.) GO TO 1190	GAP 751
752.		GAP 752
753.	SINCE THE LAST TWO ITERATIONS HAVE HAD SIMILAR SLOPES,	GAP 753
754.	I.E., BOTH POSITIVE OR NEGATIVE, USE AN EFFECTIVE ACCELERATION	GAP 754
755.	PARAMETER OF 1.4.	GAP 755
756.		GAP 756
757.	HG=HGC+0.4*DELTA	GAP 757
758.	IF (HG.GT.0.) GO TO 1210	GAP 758
759.	IOSC=1	GAP 759
760.	HG=HGOLD	GAP 760
761.		GAP 761
762.	THE SOLUTION IS OSCILLATING ABOUT WHAT SHOULD BECOME THE	GAP 762
763.	CONVERGED SOLUTION AND THE CONVERGENCE MUST BE CONSTRAINED	GAP 763
764.	TO FORCE A FASTER SOLUTION. THE EFFECTIVE ACCELERATION	GAP 764
765.	PARAMETER USED IS REDUCED TO HALF OF ITS ORIGINAL	GAP 765
766.	VALUE TO DAMPEN THE OSCILLATION.	GAP 766
767.		GAP 767
768.	CONTINUE	GAP 768
769.	IF (ITER.LE.5) GO TO 1200	GAP 769
770.	IF (ABS(DELHG/DELHG).LT.1.2) HGACEL=0.5*HGACEL	GAP 770
771.	IF (HGACEL.LT.0.1) HGACEL=0.1	GAP 771
772.	CONTINUE	GAP 772
773.	HG=HG+HGACEL*DELTA	GAP 773
774.	IF ((HG+HGC).LT.1000.AND.ITER.LE.5) HGACEL=0.5	GAP 774
775.	CONTINUE	GAP 775
776.	DELTAQ=DELTA	GAP 776
777.	DELHG=DELHG	GAP 777
778.	GO TO 520	GAP 778
779.	CONTINUE	GAP 779
780.	IF (ISTEP.LE.1) GO TO 1230	GAP 780

781.		WRITE (6,1680) HG,HGC,ISTEP,IPOW,NPOW	GAP 781
782.	1230	CONTINUE	GAP 782
783.	C		GAP 783
784.		HGACEL=0.8	GAP 784
785.		IF (THR.GT.0) PRACE=0.	GAP 785
786.		IF (KOUNT.EQ.0) ICASE=ICASE+1	GAP 786
787.	C	ICASE=ICASE+1	GAP 787
788.		TROC=(TBO-32.)/1.8	GAP 788
789.		TBIC=(TBI-32.)/1.8	GAP 789
790.		TCOC=(TCO-32.)/1.8	GAP 790
791.		TCIC=(TCI-32.)/1.8	GAP 791
792.		TFSC=(TFS-32.)/1.8	GAP 792
793.		IF (KOUNT.NE.0) GO TO 1240	GAP 793
794.		VOLTIX(IPOW)=VOLGVT	GAP 794
795.		HGX(IPOW)=HG	GAP 795
796.		TCLINE(IPOW)=TT(N)	GAP 796
797.		ROP(IPOW)=RFS+DELR	GAP 797
798.		RGAPX(IPOW)=TH	GAP 798
799.	1240	CONTINUE	GAP 799
800.		IF (ISTEP.LT.ISTOP) GO TO 1360	GAP 800
801.		IF (MINI.LT.0) GO TO 1320	GAP 801
802.		IF (MINI.NE.0.AND.LPMAX.NE.IPOW) GO TO 1320	GAP 802
803.		IF (ISTEP.LT.ISTOP) GO TO 1320	GAP 803
804.		WRITE (6,1710) ICASE,IPOW,NPOW	GAP 804
805.		IF (KOUNT.GT.0) WRITE (6,1890)	GAP 805
806.		WRITE (6,1540) TITLE	GAP 806
807.		PEAK=AMAX1(POWER(IPOW),POWER(IPOW+1))	GAP 807
808.		WRITE (6,1720) P,PEAK,TDAYS,BURNUP,PHI(IPOW)	GAP 808
809.		IF (DBO.LT..001) GO TO 1250	GAP 809
810.		WRITE (6,1730) GOVRAB	GAP 810
811.	1250	WRITE (6,1740) GOVRAC,GOVRAS,TCOOL,TCOOLC	GAP 811
812.		IF (DBO.LT..001) GO TO 1260	GAP 812
813.		WRITE (6,1750) TBO,TBOC,TBI,TBIC	GAP 813
814.	1260	WRITE (6,1760) HF,TCC,TCO,TCOC,TCI,TCIC,TFS,TFSC	GAP 814
815.		IF (TT(N).LT.TMF) RMELT=0.	GAP 815
816.		DO 1270 I=1,N	GAP 816
817.		DUM(I)=(TT(I)-32.)/1.8	GAP 817
818.		DDUM(I)=TS(I)*2.54	GAP 818
819.	1270	CONTINUE	GAP 819
820.		DO 1290 I=1,N	GAP 820
821.		PCFR(I)=TS(I)*100./(RFS+DELR)	GAP 821
822.	1290	CONTINUE	GAP 822
823.		WRITE (6,1770) (TS(I),TT(I),DDUM(I),DUM(I),PCFR(I),I=5,N,5)	GAP 823
824.		WRITE (6,1780) TMF,TM	GAP 824
825.		PCMELT=100.*RMELT/(RFS+DELR)	GAP 825
826.		WRITE (6,1790) RMELT,PCMELT	GAP 826
827.		IF (KOUNT.GT.0) GO TO 1290	GAP 827
828.		WRITE (6,1800) FDOT(IPOW)	GAP 828
829.		WRITE (6,1810) TAVGF,TAVGFC	GAP 829

830.		WRITE (6,1820) DELRT,DELRB,DELR,DELRCl,DELRP,RGAPX(IPOW),PFACE	GAP 830
831.		PSOLID=100.*HSOLID/HG	GAP 831
832.		PGAS=100.*HGAS/HG	GAP 832
833.		PRAD=100.*HRAD/HG	GAP 833
834.	1290	CONTINUE	GAP 834
835.		WRITE (6,1830) HG	GAP 835
836.		WRITE (6,1840) HSOLID,PSOLID,HGAS,PGAS,HRAD,PRAD	GAP 836
837.		IF (KOUNT.EQ.0) GO TO 1300	GAP 837
838.		PCSIN=FRSIN*100.	GAP 838
839.		PDSIN=RSIN/RFS*100.	GAP 839
840.		PVOID=RVOID/RFS*100.	GAP 840
841.		WRITE (6,1900) TSIN,TSINC,PCSIN	GAP 841
842.		WRITE (6,1910) DSIN,PDSIN,DVOID,PVOID,VAVGTC,VAVGTC	GAP 842
843.		IF (KOUNT.GT.0) GO TO 1350	GAP 843
844.	1300	CONTINUE	GAP 844
845.		WRITE (6,1850) (MLFR(I),MOLEFR(I),I=1*6)	GAP 845
846.		WRITE (6,2100) XMOTCT,MOLTOT	GAP 846
847.		WRITE (6,1860) GASKON,GK	GAP 847
848.		WRITE (6,1870) G1PG2	GAP 848
849.		WRITE (6,1880) PRFSX(IPOW),VAVGTC,VAVGTC	GAP 849
850.		IF (ISTOR.GT.0) GO TO 1310	GAP 850
851.		CALL HCAP (VAVGTC,CPNOM,CPMIN,CPMAX)	GAP 851
852.		CALL CARL (TSR,TFS,TT,N,PI,DFS,STORE)	GAP 852
853.		TEMPK=VAVGTC+273.	GAP 853
854.		C1=7.84733E-4*(TEMPK**2-298**2)+5643730.*EXP(-37.6946/TEMPK/0.0019	GAP 854
855.		186)	GAP 855
856.		C2=535.285*(1.0/(EXP(535.285/TEMPK)-1.))-1./(EXP(535.285/298.))-1.))	GAP 856
857.		STOR=(C1+19.145*C2)/270.	GAP 857
858.		STORB=STOR*1.8	GAP 858
859.		STOREB=STORE*1.8	GAP 859
860.		STOREC=STORE*RHC*(DFS**2/4)*PI*2.54**2	GAP 860
861.		STOREF=STOREC*12.*2.54/252.	GAP 861
862.	C		GAP 862
863.	C	CONVERT CPNOM TO UNITS OF BTU/(LB-DEG F)	GAP 863
864.	C		GAP 864
865.		CPNOMF=CPNOM*270.	GAP 865
866.		WRITE (6,2120) CPNOM,CPNOMF	GAP 866
867.		WRITE (6,2130) STOR,STORB,STORE,STOREB,STOREC,STOREF	GAP 867
868.	1310	CONTINUE	GAP 868
869.	1320	CONTINUE	GAP 869
870.		IF (KOUNT.GT.0) GO TO 1350	GAP 870
871.		IF (T.LE..001.OR.FRDEN.EQ.FRSIN) GO TO 1350	GAP 871
872.		KOUNT=1	GAP 872
873.		IF (FRDEN.GE.FRSIN) FRSIN=FRDEN	GAP 873
874.		IF (T.LE..0) GO TO 1330	GAP 874
875.		RETEM=.00001367*ALOG10(T/3600.))+.000480	GAP 875
876.		TSINC=1./RETEM-273.	GAP 876
877.		TSIN=1.8*TSINC+32.	GAP 877
878.		RRSIN=RSIN	GAP 878

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879.      GO TO 1340
880.      TSIN=1.E10
881.      ITER=0
882.      GO TO 520
883.      RSIN=TERP(TSIN,35,2,N)
884.      IF (RSIN.LE.RRSIN) FRSIN=RSIN
885.      DSIN=2.*RSIN
886.      RRV=RRVOID
887.      RVOID=SQRT((RSIN**2)*(FRS,N-FRDN)/FRSIN+(RVOIDZ**2)*FRDN/FRSIN)
888.      IF (RVOID.LE.RRV) PVOID=RRVOID
889.      DVOID=2.*RVOID
890.      ELTC=LF-LVOIDZ/FNPOW
891.      VTC=PI*ELTC*RVOIDZ**2
892.      VVOID=(PI*LF*RVOID**2-VTC)
893.      ITER=0
894.      GO TO 520
895.      KOUNT=0
896.      CONTINUE
897.      TAVGX=TAVGX+TRAR(IPOW)
898.      VOLTXS=VOLTXS+VOLTX(IPOW)
899.      CONTINUE
900.      TAVGX(I,STEP+1)=TAVGX/FNPOW
901.      VOLTXS=VOLTXS+VPLFNZ/TPLENA
902.      TVOLAVE=(TAVGX(I,STEP+1)-32.)/1.8
903.      F=TEPP(TVOLAVE,FISGR,VOLAT,28)
904.
905.      C
906.      C
907.      FILMOL=STP*(FNPOW*VOLGAS+VPLENZ)*CCPIN3*ATMOS/RR
908.      MOL(1)=FILMOL*FRACHE
909.      MOL(2)=FILMOL*FRACAF
910.      MOL(3)=FILMOL*FRACH+W*S*XA*(FUEL/RR)*F
911.      IF (NOH.GT.0) MOL(3)=0.
912.      MOL(4)=FILMOL*FRACN+W*S*(1.-XX)*LFUEL/RR*F
913.      MOL(5)=FILMOL*FRACKR+NKR(IPOW)/AVOGAD*LFUEL*F
914.      MOL(6)=FILMOL*FRACXE+NXE(IPOW)/AVOGAD*LFUEL*F
915.
916.      C
917.      C
918.      C
919.      C
920.      C
921.      C
922.      C
923.      C
924.      C
925.      C
926.      C
927.      C

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928.	C		GAP 928
929.		PRESTO(ISTEP+1)=73.604*XMOTOT/VOLTXS	GAP 929
930.		XMOLS(NPOW1)=PRESTO(ISTEP+1)*VPLENZ/(73.604*TPLENA)	GAP 930
931.		DO 1400 I=1,NPOW	GAP 931
932.		CALL MOVEAA (FXMOL(1,I),FXMOL(1,I),6)	GAP 932
933.		RDOT(I)=F	GAP 933
934.		XMOLS(I)=PRESTO(ISTEP+1)*VOLTXS(I)/73.604	GAP 934
935.	1400	CONTINUE	GAP 935
936.		IF (ISTOP.LE.ISTEP) GO TO 1420	GAP 936
937.		IF (ISTEP.LT.2) GO TO 1410	GAP 937
938.		DELTX=TAvgXX(ISTEP+1)-TAvgXX(ISTEP)	GAP 938
939.		IF (ABS(DELTX)/TAvgXX(ISTEP+1).LT.0.005) ISTOP=1+ISTEP	GAP 939
940.	1410	CONTINUE	GAP 940
941.	C		GAP 941
942.	C	BEGIN AXIAL PRINTOUT.	GAP 942
943.	C		GAP 943
944.	1420	CONTINUE	GAP 944
945.		WRITE (6,1530)	GAP 945
946.		WRITE (6,1480) JCASE,TDAYS	GAP 946
947.		WRITE (6,1540) TITLE	GAP 947
948.		XL0=-LF*0.5	GAP 948
949.		WRITE (6,1490)	GAP 949
950.		DO 1430 I=1,NPOW	GAP 950
951.		P=(POWER(I)+POWER(I+1))*0.5	GAP 951
952.		XL=XL0+FLOAT(I)*LF	GAP 952
953.		WRITE (6,1500) XL,P,HFLUX(I),TCLINE(I),TBAR(I),HGX(I),RGAPx(I),RDOGAP	GAP 953
954.		IT(I),FXMOL(1,I)	GAP 954
955.	1430	CONTINUE	GAP 955
956.	C		GAP 956
957.	C	PRINT SUMMARY OF AVERAGED TEMP AND PRESSURE.	GAP 957
958.	C		GAP 958
959.		WRITE (6,1510) (I,TAvgXX(I+1),PRESTO(I+1),I=1,ISTOP)	GAP 959
960.	C		GAP 960
961.	C	CHECK TO SEE IF THERE IS ANOTHER TIME STEP TO BE EXECUTED.	GAP 961
962.	C		GAP 962
963.		IF (ABS(TDAYS-TMAX)/TMAX.LE.1.0E-4) GO TO 1440	GAP 963
964.		TDAYS=TDAYS+DELT	GAP 964
965.		JCASE=JCASE+1	GAP 965
966.		GO TO 470	GAP 966
967.	1440	CONTINUE	GAP 967
968.		TDAYS=0.0	GAP 968
969.		IF (IPEAK.NE.0) GO TO 1450	GAP 969
970.		PAVRG=PAVRG+DELP	GAP 970
971.		IF (PAVRG.LE.PMAX) GO TO 470	GAP 971
972.		GO TO 100	GAP 972
973.	1450	CONTINUE	GAP 973
974.		PKPOWER=PKPOWER+DELP	GAP 974
975.		IF (PKPOWER.LE.PMAX) GO TO 470	GAP 975
976.		GO TO 100	GAP 976

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977. 1460 CONTINUE GAP 977
978. STOP GAP 978
979. C GAP 979
980. 1470 FORMAT (10X, @NO CONVERGENCE IN TCC@) GAP 980
981. 1480 FORMAT (6 CASE =@, I2, 10X, @AXIAL SUMMARY@/1H0, 10X, @TIME AT POWER IN@ GAP 981
982. 1 DAYS @, F10.1) GAP 982
983. 1490 FORMAT (1H0, 35X, @CLAD@, 6X, @CENTER@, 7X, @AVERAGE@, 8X, @GAP@, 8X, @RADI@ GAP 983
984. 1L@, /, 10X, @AXIAL@, 6X, @HEAT@, 9X, @SURFACE@, 6X, @LINE@, 10X, @VOL.@, 5X, @CGAP 984
985. 2ONDUCTANCE@, 5X, @HOT@, 12X, @GAS@, 9X, @MOLE@, /, 8X, @DISTANCE@, 5X, @RATING@ GAP 985
986. 3G@, 6X, @HEAT FLUX@, 6X, @TEMP.@, 6X, @FUEL TEMP.@, 4X, @BTU/HR=@, 7X, @GAP@ GAP 986
987. 4, 10X, @RELEASE@, 6X, @FRACTION@, /, 8X, @ (INCHES) @, 4X, @ (KW/FT) @, 6X, @BTU/GAP 987
988. 5HR-FT@, 5X, @DEG F@, 8X, @DEG F@, 6X, @FT2-DEG F@, 4X, @ (INCHES) @, 9X, @RATE@ GAP 988
989. 6@, 8X, @HELIUM@ /) GAP 989
990. 1500 FORMAT (3X, 10 (3X, 1PE10.3)) GAP 990
991. 1510 FORMAT (@0 AXIAL, VOLUME-TEMPERATURE @, @AVERAGED@/10X, @TEMP@ GAP 991
992. 1PERATURE@, 5X, @PRESSURE@/5X, @I@, 10X, @DEG. F@, 10X, @PSI@ / (1X, 1S, 1P2E@ GAP 992
993. 215.4)) GAP 993
994. 1520 FORMAT (20A4) GAP 994
995. 1530 FORMAT (1H1) GAP 995
996. 1540 FORMAT (1H0, 20A4) GAP 996
997. 1550 FORMAT (58X, @*****@, /, 58X, @* INPUT VALUES *@, /, 20X, @ GAP 997
998. 1@*****@ GAP 998
999. 2*****@/20X, @*@, 91X, @*) GAP 999
1000. 1560 FORMAT (20X, @*@, 8Y, @FUEL COMPOSITION@, 67X, @*@/20X, @*@, 10X, F5.4, @ GAP 1000
1001. 1WIGHT FRACTION PU02@, 27X, @FRPU02@, 21X, @*@/20X, @*@, 13X, F5.4, @ WEIGH@ GAP 1001
1002. 2GHT FRACTION PU23@, 23X, @FR3@ @, 21X, @*@/20X, @*@, 13X, F5.4, @ WEIGH@ GAP 1002
1003. 3T FRACTION PU24@, 23X, @FR4@ @, 21X, @*@/20X, @*@, 13X, F5.4, @ WEIGHT@ GAP 1003
1004. 4FRACTION PU241@, 23X, @FR41 @, 21X, @*@/20X, @*@, 9X, F6.4, @ WEIGHT FR@ GAP 1004
1005. 5ACTION U02@, 28X, @FRU02 @, 21X, @*@/20X, @*@, 13X, F5.4, @ WEIGHT FRACTI@ GAP 1005
1006. 6ON U235@, 24X, @FR35 @, 21X, @*@/20X, @*@, 13X, F5.4, @ WEIGHT FRACTION@ GAP 1006
1007. 7U238@, 24X, @FR38 @, 21X, @*@/20X, @*@, 91X, @*@/20X, @*@, 8X, @FUEL DENSIT@ GAP 1007
1008. 8Y@, 28X, @ (FRACTION TD) FRD@, 7X, F4.3, 11X, @*@/20X, @*@, 8X, @RESTRUC@ GAP 1008
1009. 9TURED FUEL DENSITY@, 15X, @ (FRACTION TD) FRSING@, 7X, F4.3, 11X, @*@/20@ GAP 1009
1010. 9X, @*@, 8X, @PELLET DIAMETER@, 25X, @ (INCHES) @, 8X, @DFS@, 8X, F6.4, 10X, @*@ GAP 1010
1011. 9/20X, @*@, 8X, @INITIAL RESTRUCTURED FUEL DIAM.@, 9X, @ (INCHES) @, 8X, @DS@ GAP 1011
1012. 9ING@, 8X, F5.4, 10X, @*@/20X, @*@, 8X, @INITIAL CENTER HOLE DIAMETER@, 12X, @ GAP 1012
1013. 9@ (INCHES) @, 8X, @VOID@, 7X, F5.4, 10X, @*@) GAP 1013
1014. 1570 FORMAT (20X, @*@, 8Y, @PELLET-TO-CLAD GAP@, 22X, @ (INCHES) @, 8X, @GAP@, 9X@ GAP 1014
1015. 1F5.4, 10X, @*@/20X, @*@, 8X, @CLAD INSIDE DIAMETER@, 20X, @ (INCHES) @, 8X, @ GAP 1015
1016. 2@DCI@, 8X, F6.4, 10X, @*@/20X, @*@, 8X, @CLAD OUTSIDE DIAMETER@, 19X, @ (IN@ GAP 1016
1017. 3HES) @, 8X, @DCO@, 8X, F6.4, 10X, @*@/20X, @*@, 8X, @FUEL LENGTH@, 29X, @ (IN@ GAP 1017
1018. 4ES) @, 8X, @LFUEL@, 4X, F6.2, 12X, @*@/20X, @*@, 8X, @SORBED GAS CONTENT@, 22@ GAP 1018
1019. 5X, @ (CC/GRAM) @, 7X, @SD@, 11X, F5.4, 10X, @*@/20X, @*@, 8X, @FRACTION OF SOR@ GAP 1019
1020. 6EU GAS WHICH IS H2@, 22X, @XX@, 9X, F6.4, 10X, @*@) GAP 1020
1021. 1580 FORMAT (20X, @*@, 8X, @PLENUM VOLUME@, 27X, @ (CU. IN.) @, 7X, @VPLEN@, 4X, @ GAP 1021
1022. 1F5.2, 12X, @*@/20X, @*@, 8X, @COOLANT TEMPERATURE@, 21X, @ (DEG F) @, 9X, @TIG@ GAP 1022
1023. 2NLET@, 2X, F6.1, 13X, @*@/20X, @*@, 8X, @AXIAL TEMPERATURE GRADIENT ACROSS@ GAP 1023
1024. 3 CORE (DEG F) @, 9X, @TEMP@, 3X, F6.1, 13X, @*@/20X, @*@, 8X, @COOLANT P@ GAP 1024
1025. 4SSAGE EQUIVALENT DIAMETER@, 5X, @ (INCHES) @, 8X, @DE@, 8X, F7.4, 10X, @*@/2@ GAP 1025

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1075. 1710 FORMAT (1H1,2X,1CASE @,I3,5X,AXIAL SEGMENT @,I2,2X,@OF @,I2) GAP1075
 1076. 1720 FORMAT (1H0,9X,ELINEAR HEAT RATING (AVG) @,5X,F12.4,@ KW/FT@,5GAP1076
 1077. 1X,@(PEAK =@,F6.2,2X,@KW/FT)@/10X,@TIME IN=REACTOR @,5XGAP1077
 1078. 2,F12.4,2X,@DAYS1/10X,@BURNUP @,7X,F10.2,2X,@MGAP1078
 1079. 3WD/MTMG/20X,@AVERAGE FLUX IN FUCL @,5X,1PE10.4,2X,@NVD) GAP1079
 1080. 1730 FORMAT (20X,@BASKET SURFACE HEAT FLUX@,9X,1PE10.4,2X,@BTU/HR-FT2@)GAP1080
 1081. 1740 FORMAT (20X,@CLAD OD SURFACE HEAT FLUX @,5X,1PE10.4,2X,@BTU/HR-FT2@)GAP1081
 1082. 1T2@/20X,@FUEL SURFACE HEAT FLUX @,5X,1PE10.4,2X,@BTU/HR-FT2@/GAP1082
 1083. 220X,@COOLANT TEMPERATURE@,14X,0FF10.2,2X,@DEG F (@,F7.2,@ DEG C)GAP1083
 1084. 3@) GAP1084
 1085. 1750 FORMAT (20X,@BASKET OD TEMPERATURE@,12X,F10.2,2X,@DEG F (@,F7.2,GAP1085
 1086. 1@ DEG C)@/20X,@BASKET ID TEMPERATURE@,12X,F10.2,2X,@DEG F (@,F7.GAP1086
 1087. 22,@ DEG C)@) GAP1087
 1088. 1760 FORMAT (20X,@FILM COEFFICIENT@,17X,F10.2,2X,@BTU/HR-FT2-DEG F@/20XGAP1088
 1089. 1,@CLAD THERMAL CONDUCTIVITY@,8X,F10.2,2X,@BTU/HR-FT-DEG F@/20X,@CLGAP1089
 1090. 2AD OD TEMPERATURE@,14X,F10.2,2X,@DEG F (@,F7.2,@ DEG C)@/20X,@CLGAP1090
 1091. 3AD ID TEMPERATURE@,14X,F10.2,2X,@DEG F (@,F7.2,@ DEG C)@/20X,@FUGAP1091
 1092. 4EL SURFACE TEMPERATURE@,9X,F10.2,2X,@DEG F (@,F7.2,@ DEG C)@) GAP1092
 1093. 1770 FORMAT (1H0,24X,@RADIUS@,10X,@TEMPERATURE@,15X,@RADIUS@,12X,@TEMPEGAP1093
 1094. 1RATURE@,10X,@PERCENT OF@,/,24X,@(INCHES)@,11X,@(DEG F)@,18X,@(CM)@GAP1094
 1095. 2,15X,@(DEG C)@,12X,@FUEL RADIUS@,/(24X,F6.4,9X,F10.0,17X,F6.4,13XGAP1095
 1096. 3,F8.0,10X,F10.2)) GAP1096
 1097. 1780 FORMAT (1H0,19X,@MELT TEMPERATURE@,16X,F10.0,2X,@DEG F (@,F7.0,@GAP1097
 1098. 1 DEG C)@,) GAP1098
 1099. 1790 FORMAT (20X,@MELT RADIUS @,5X,F10.4,2X,@INCH (@,GAP1099
 1100. 1F6.2,@ PERCENT FUEL RADIUS)@) GAP1100
 1101. 1800 FORMAT (1H0,19X,@GAS RELEASE RATE@,36X,F10.4) GAP1101
 1102. 1810 FORMAT (20X,@RADIUS AVERAGED FUEL TEMPERATURE @GAP1102
 1103. 1,3X,F10.1,2X,@DEG F (@,F6.1,@ DEG C)@,) GAP1103
 1104. 1820 FORMAT (20X,@INCREASE IN FUEL RADIUS DUE TO THERMAL EXPANSION @GAP1104
 1105. 1,3X,F10.6,2X,@INCH@,/20X,@INCREASE IN FUEL RADIUS DUE TO SWELLING GAP1105
 1106. 2 @,3X,F10.6,2X,@INCH@,/20X,@TOTAL INCREASE IN FUEL RADIGAP1106
 1107. 3US @,3X,F10.6,2X,@INCH@,/20X,@CHANGE IN CLADGAP1107
 1108. 4 RADIUS DUE TO THERMAL EXP. AND CREEP @,3X,F10.6,2X,@INCH@,/20X,@CGAP1108
 1109. 5HANGE IN CLAD RADIUS(PRESSURE) @,3X,F10.6,2X,@GAP1109
 1110. 6INCH@,/20X,@HOT GAP (RADIAL) @,GAP1110
 1111. 73X,F10.6,2X,@INCH@,/20X,@FUEL-CLAD INTERFACIAL PRESSURE GAP1111
 1112. 8 @,3X,F10.2,2X,@PSI@) GAP1112
 1113. 1830 FORMAT (1H0,19X,@FUEL-TO-CLAD GAP CONDUCTANCE @,20X,F10.0,2XGAP1113
 1114. 1,@BTU/HR-FT2-F@,/) GAP1114
 1115. 1840 FORMAT (30X,@COMPONENT DUE TO SOLID-SOLID CONTACT @,5X,F10.1,GAP1115
 1116. 1,2X,@BTU/HR-FT2-F (@,F5.2,1X,@PERCENT)@,/30X,@COMPONENT DUE TO CGAP1116
 1117. 2NDUCTION THROUGH THE GAS@,5X,F10.1,2X,@BTU/HR-FT2-F (@,F5.2,1X,@PGAP1117
 1118. 3PERCENT)@,/30X,@COMPONENT DUE TO RADIANT HEAT TRANSFER @,5X,F10GAP1118
 1119. 4,1,2X,@BTU/HR-FT2-F (@,F5.2,1X,@PERCENT)@,/) GAP1119
 1120. 1850 FORMAT (20X,@COMPOSITION OF PIN GAS@,30X,@COMPOSITION OF GAS@,@ LOGAP1120
 1121. 1CALLY@/1H0,26X,F10.6,2X,@MOLE FRACTION HELIUM@,21X,F10.6,@ MOLE FGAP1121
 1122. 2RATIO HELIUM@/27X,F10.6,2X,@MOLE FRACTION ARGON@,22X,F10.6,@ MOGAP1122
 1123. 3LE FRACTION ARGON@/27X,F10.6,2X,@MOLE FRACTION HYDROGEN@,19X,F10.6GAP1123

APPENDIX D

A sample problem and output from GAPCON-THERMAL is shown on the following pages. The data input to execute this sample problem is shown in Figure D-1.

SAMPLE PROBLEM

GLOBE 7100

STANDARD FORM

1
2
3
4
5
6
7

2	9
3	1
4	2

BNWL-1778

SAMPLE PROBLEM

* INPUT VALUES *

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*****
*
* FUEL COMPOSITION
* .0000 WEIGHT FRACTION PU02 FRPU02
* .0000 WEIGHT FRACTION PU239 FR39
* .0000 WEIGHT FRACTION PU240 FR40
* .0000 WEIGHT FRACTION PU241 FR41
* 1.0000 WEIGHT FRACTION UO2 FRUO2
* .0254 WEIGHT FRACTION U235 FR35
* .9746 WEIGHT FRACTION U238 FR38
*
* FUEL DENSITY (FRACTION TD) FRDEN .935
* RESTRUCTURED FUEL DENSITY (FRACTION TD) FRSDN .935
* PELLET DIAMETER (INCHES) DFS .3650
* INITIAL RESTRUCTURED FUEL DIAM. (INCHES) DSIN .0000
* INITIAL CENTER HOLE DIAMETER (INCHES) DVOID .0000
* PELLET-TO-CLAD GAP (INCHES) GAP .0085
* CLAD INSIDE DIAMETER (INCHES) DCI .3735
* CLAD OUTSIDE DIAMETER (INCHES) DCO .4220
* FUEL LENGTH (INCHES) LFUEL 132.00
* SORBED GAS CONTENT (CC/GRAM) S .0000
* FRACTION OF SORBED GAS WHICH IS H2 XX .0000
* PLENUM VOLUME (CU. IN.) VPLENZ .50
* COOLANT TEMPERATURE (DEG F) TINLET 570.0
* AXIAL TEMPERATURE GRADIENT ACROSS CORE (DEG F) DTEMP 100.0
* COOLANT PASSAGE EQUIVALENT DIAMETER (INCHES) DE .0000
* COOLANT VELOCITY (FT/SEC) V .000
* PRESSURE ON CLAD OD (PSI) EXTP 2250.0
* LONG. PEAK/AVG FLUX RATIO PEKAVG 1.000
* FUEL SURFACE ROUGHNESS, ARITH. MEAN (INCH) ROUF .000039
* CLAD ID SURFACE ROUGHNESS, ARITH. MEAN (INCH) ROUC .000020
* AVERAGE POWER GENERATION (KW/FT) PAVRG 8.50
* INITIAL PEAK POWER GENERATION (KW/FT) PKPOWR 10.00
* POWER INCREMENTS (KW/FT) DELP 4.00
* MAXIMUM POWER GENERATION (KW/FT) PMAX 14.00
* MINIMUM TIME AT POWER (DAYS) TDAYS .00
* TIME INCREMENTS (DAYS) DELT 100.00
* MAXIMUM TIME AT POWER (DAYS) TMAX 100.00
* DIAMETER OF AUXILIARY BASKET (INCHES) DBO .0000
* BASKET THERMAL CONDUCTIVITY (BTU/HR-FT-F) KB .00
* BASKET-TO-CLAD HEAT TRANSFER COEFF. (BTU/HR-FT2-F) HBC .0
* FILL GAS PRESSURE (ATMOSPHERES) ATMOS 20.0
* FILL GAS COMPOSITION
* 1.00000 MOLE FRACTION HELIUM

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*      .00000 MOLE FRACTION ARGON
*      .00000 MOLE FRACTION HYDROGEN
*      .00000 MOLE FRACTION NITROGEN
*      .00000 MOLE FRACTION KRYPTON
*      .00000 MOLE FRACTION XENON
*
* COOLANT NOT SPECIFIED, FILM COEFFICIENT IS 25000.
*
* THERMAL FLUX IRRADIATION
*
* CLADDING IS ZIRCALOY-2
*
* FUEL THERMAL CONDUCTIVITY VALUES DETERMINED FROM DATA OF LYONS, ET AL
* THIS CALCULATION ASSUMES COMPLETE MIXING OF GASES
*
* FUEL THERMAL CONDUCTIVITY VALUES USED
*
*      TEMPERATURE      THERMAL CONDUCTIVITY
*      (DEG F)          (BTU/HR-FT-DEG F)
*
*      -----      UNRESTRICTED FUEL      RESTRICTED FUEL
*
*      500.      3.265      3.265
*      1000.     2.315      2.315
*      1500.     1.818      1.818
*      2000.     1.532      1.532
*      2500.     1.371      1.371
*      3000.     1.298      1.298
*      3500.     1.295      1.295
*      4000.     1.354      1.354
*      4500.     1.472      1.472
*      5000.     1.648      1.648
*
* FLUX DEPRESSION VALUES USED
*
*      DIAMETER (IN)      FLUX RATIO
*
*      .0000      1.0000
*      .0365      1.0009
*      .0730      1.0038
*      .1095      1.0085
*      .1460      1.0151
*      .1825      1.0237
*      .2190      1.0342
*      .2555      1.0467
*      .2920      1.0612

```


CASE 1 AXIAL SEGMENT 6 OF 10

SAMPLE PROBLEM

LINEAR HEAT RATING (AVG)	10.0000	KW/FT	(PEAK = 10.00	KW/FT)	
TIME IN-REACTOR	.0000	DAYS			
BURNUP	.00	MWD/MTM			
AVERAGE FLUX IN FUEL	4.6663+13	NV			
CLAD OD SURFACE HEAT FLUX	3.0893+05	BTU/HR-FT2			
FUEL SURFACE HEAT FLUX	3.5717+05	BTU/HR-FT2			
COOLANT TEMPERATURE	631.84	DEG F	(333.30	DEG C)	
FILM COEFFICIENT	25000.00	BTU/HR-FT2-DEG F			
CLAD THERMAL CONDUCTIVITY	9.50	BTU/HR-FT-DEG F			
CLAD OD TEMPERATURE	644.29	DEG F	(345.16	DEG C)	
CLAD ID TEMPERATURE	714.25	DEG F	(379.03	DEG C)	
FUEL SURFACE TEMPERATURE	1179.41	DEG F	(637.45	DEG C)	
RADIUS (INCHES)	TEMPERATURE (DEG F)	RADIUS (CM)	TEMPERATURE (DEG C)	PERCENT OF FUEL RADIUS	
.1643	1439.	.4172	782.	89.10	
.1460	1696.	.3708	925.	79.20	
.1278	1943.	.3245	1062.	69.30	
.1095	2171.	.2781	1188.	59.40	
.0913	2373.	.2318	1300.	49.50	
.0730	2543.	.1854	1395.	39.60	
.0548	2678.	.1391	1470.	29.70	
.0365	2776.	.0927	1525.	19.80	
.0183	2835.	.0484	1557.	9.90	
.0000	2855.	.0000	1568.	.00	
MELT TEMPERATURE	5054.	DEG F	(2790.	DEG C)	
MELT RADIUS	.0000	INCH	(.00	PERCENT FUEL RADIUS)	
GAS RELEASE RATE	.0525				
RADIUS AVERAGED FUEL TEMPERATURE	2266.1	DEG F	(1241.2	DEG C)	
INCREASE IN FUEL RADIUS DUE TO THERMAL EXPANSION	.001847	INCH			
INCREASE IN FUEL RADIUS DUE TO SWELLING	.000000	INCH			
TOTAL INCREASE IN FUEL RADIUS	.001847	INCH			
CHANGE IN CLAD RADIUS DUE TO THERMAL EXP. AND CREEP	.000443	INCH			
CHANGE IN CLAD RADIUS (PRESSURE)	-.000207	INCH			
HOT GAP (RADIAL)	.002639	INCH			
FUEL-CLAD INTERFACIAL PRESSURE	.00	PSI			
FUEL-TO-CLAD GAP CONDUCTANCE	759.	BTU/HR-FT2-F			
COMPONENT DUE TO SOLID-SOLID CONTACT	.0	BTU/HR-FT2-F	(.00	PERCENT)	
COMPONENT DUE TO CONDUCTION THROUGH THE GAS	749.4	BTU/HR-FT2-F	(98.72	PERCENT)	
COMPONENT DUE TO RADIANT HEAT TRANSFER	14.4	BTU/HR-FT2-F	(1.90	PERCENT)	

COMPOSITION OF PIN GAS

1.000000 MOLE FRACTION HELIUM
 .000000 MOLE FRACTION ARGON
 .000000 MOLE FRACTION HYDROGEN
 .000000 MOLE FRACTION NITROGEN
 .000000 MOLE FRACTION KRYPTON
 .000000 MOLE FRACTION XENON

 G/MOLES TOTAL 1.542-02 IN PIN

THERMAL CONDUCTIVITY OF FILL GAS

.0006847 CAL/SEC-CM-DEG C (.16562 BTU/HR-FT-DEG F)

TEMPERATURE JUMP DISTANCE

.0000134 INCH

INTERNAL GAS PRESSURE

821.2 PSI

AVERAGE VOLUMETRIC FUEL TEMP.

1957.28 (DEG F)

(1069.60 DEG. CENTIGRADE)

NOMINAL HEAT CAPACITY CPNOM= 2.104+01 CAL/(DEG K-MOLE)

(5.682+03 BTU/(LB-DEG F)

STORED ENERGY AT TBAR

EBAR= 74.93 CAL/GRAM (134.87 BTU/LB)

VOLUME AVERAGE STORED ENERGY

E= 75.27 CAL/GRAM (135.49 BTU/LB)

STORED ENERGY PER UNIT LENGTH

EPL= 521.21 CAL/CM (63.04 BTU/FOOT)

COMPOSITION OF GAS LOCALLY

1.000000 MOLE FRACTION HELIUM
 .000000 MOLE FRACTION ARGON
 .000000 MOLE FRACTION HYDROGEN
 .000000 MOLE FRACTION NITROGEN
 .000000 MOLE FRACTION KRYPTON
 .000000 MOLE FRACTION XENON

 5.803-04 LOCAL

CASE = 1

AXIAL SUMMARY

TIME AT POWER IN DAYS

.0

SAMPLE PROBLEM

AXIAL DISTANCE (INCHES)	HEAT RATING (KW/FT)	CLAD SURFACE HEAT FLUX BTU/HR-FT	CENTER LINE TEMP. DEG F	AVERAGE VOL. FUEL TEMP. DEG F	GAP CONDUCTANCE BTU/HR- FT ² -DEG F	RADIAL HOT GAP (INCHES)	GAS RELEASE RATE	MOLE FRACTION HELIUM
6.600+00	5.084+00	1.569+05	1.623+03	1.273+03	5.360+02	3.489-03	5.251-02	1.000+00
1.980+01	6.151+00	2.515+05	2.360+03	1.684+03	6.484+02	3.003-03	5.251-02	1.000+00
3.300+01	9.475+00	2.924+05	2.688+03	1.859+03	7.152+02	2.761-03	5.251-02	1.000+00
4.620+01	9.937+00	3.066+05	2.806+03	1.922+03	7.481+02	2.661-03	5.251-02	1.000+00
5.940+01	1.000+01	3.085+05	2.832+03	1.938+03	7.591+02	2.652-03	5.251-02	1.000+00
7.260+01	1.000+01	3.089+05	2.855+03	1.957+03	7.591+02	2.639-03	5.251-02	1.000+00
8.580+01	9.916+00	3.063+05	2.849+03	1.959+03	7.591+02	2.648-03	5.251-02	1.000+00
9.900+01	9.622+00	2.968+05	2.791+03	1.933+03	7.443+02	2.727-03	5.251-02	1.000+00
1.122+02	7.983+00	2.463+05	2.410+03	1.740+03	6.670+02	3.013-03	5.251-02	1.000+00
1.254+02	4.812+00	1.491+05	1.674+03	1.333+03	5.491+02	3.552-03	5.251-02	1.000+00

AXIAL, VOLUME-TEMPERATURE AVERAGED

	TEMPERATURE DEG. F	PRESSURE PSI
1		
1	1.7649+03	8.1885+02
2	1.7600+03	8.2125+02
3	1.7600+03	8.2122+02

CASE 2 AXIAL SEGMENT 6 OF 10

SAMPLE PROBLEM

LINEAR HEAT RATING (AVG) 10.0000 KW/FT (PEAK = 10.00 KW/FT)
 TIME IN-REACTOR 100.0000 DAYS
 BURNUP 5375.63 MWD/MTM
 AVERAGE FLUX IN FUEL 4.6663+13 NV
 CLAD OD SURFACE HEAT FLUX 3.0893+05 BTU/HR-FT2
 FUEL SURFACE HEAT FLUX 3.5717+05 BTU/HR-FT2
 COOLANT TEMPERATURE 631.94 DEG F (333.30 DEG C)
 FILM COEFFICIENT 25000.00 BTU/HR-FT2-DEG F
 CLAD THERMAL CONDUCTIVITY 9.50 BTU/HR-FT-DEG F
 CLAD OD TEMPERATURE 644.29 DEG F (340.16 DEG C)
 CLAD ID TEMPERATURE 714.25 DEG F (379.03 DEG C)
 FUEL SURFACE TEMPERATURE 1240.94 DEG F (671.63 DEG C)

RADIUS (INCHES)	TEMPERATURE (DEG F)	RADIUS (CM)	TEMPERATURE (DEG C)	PERCENT OF FUEL RADIUS
.1643	1509.	.4172	820.	89.05
.1460	1773.	.3708	967.	79.15
.1278	2026.	.3245	1108.	69.26
.1095	2259.	.2781	1237.	59.36
.0913	2464.	.2318	1351.	49.47
.0730	2637.	.1854	1447.	39.58
.0548	2774.	.1391	1524.	29.68
.0365	2873.	.0927	1578.	19.79
.0183	2933.	.0464	1611.	9.89
.0000	2953.	.0000	1623.	.00

MELT TEMPERATURE 5054. DEG F (2790. DEG C)
 MELT RADIUS .0000 INCH (.00 PERCENT FUEL RADIUS)

GAS RELEASE RATE .0845
 RADIUS AVERAGED FUEL TEMPERATURE 2353.7 DEG F (1289.8 DEG C)
 INCREASE IN FUEL RADIUS DUE TO THERMAL EXPANSION .001955 INCH
 INCREASE IN FUEL RADIUS DUE TO SWELLING .000000 INCH
 TOTAL INCREASE IN FUEL RADIUS .001955 INCH
 CHANGE IN CLAD RADIUS DUE TO THERMAL EXP. AND CREEP .000443 INCH
 CHANGE IN CLAD RADIUS(PRESSURE) -.000197 INCH
 HOT GAP (RADIAL) .002541 INCH
 FUEL-CLAD INTERFACIAL PRESSURE .00 PSI

FUEL-TO-CLAD GAP CONDUCTANCE 670. BTU/HR-FT2-F

COMPONENT DUE TO SOLID-SOLID CONTACT .0 BTU/HR-FT2-F (.00 PERCENT)
 COMPONENT DUE TO CONDUCTION THROUGH THE GAS 658.5 BTU/HR-FT2-F (98.23 PERCENT)
 COMPONENT DUE TO RADIANT HEAT TRANSFER 15.5 BTU/HR-FT2-F (2.31 PERCENT)

COMPOSITION OF PIN GAS

.933047 MOLE FRACTION HELIUM
 .000000 MOLE FRACTION ARGON
 .000000 MOLE FRACTION HYDROGEN
 .000000 MOLE FRACTION NITROGEN
 .007951 MOLE FRACTION KRYPTON
 .059002 MOLE FRACTION XENON

 G/MOLES TOTAL 1.653-02 IN PIN

THERMAL CONDUCTIVITY OF FILL GAS

.0005787 CAL/SEC-CM-DEG C (.13998 BTU/HR-FT-DEG F)

TEMPERATURE JUMP DISTANCE

.0000094 INCH

INTERNAL GAS PRESSURE

895.6 PSI

AVERAGE VOLUMETRIC FUEL TEMP.

2038.76 (DEG F)

(1114.87 DEG. CENTIGRADE)

NOMINAL HEAT CAPACITY CP(PIN) = 2.115+01 CAL/(DEG K-MOLE)

(5.711+03 BTU/(LB-DEG F)

STORED ENERGY AT TBAR

EBAR= 78.46 CAL/GRAM (141.23 BTU/LB)

VOLUME AVERAGE STORED ENERGY

E= 78.85 CAL/GRAM (141.93 BTU/LB)

STORED ENERGY PER UNIT LENGTH

EPL= 545.96 CAL/CM (66.03 BTU/FOOT)

COMPOSITION OF GAS LOCALLY

.933047 MOLE FRACTION HELIUM
 .000000 MOLE FRACTION ARGON
 .000000 MOLE FRACTION HYDROGEN
 .000000 MOLE FRACTION NITROGEN
 .007951 MOLE FRACTION KRYPTON
 .059002 MOLE FRACTION XENON

 5.966-04 LOCAL

CASE = 2

AXIAL SUMMARY

TIME AT POWER IN DAYS 100.0

SAMPLE PROBLEM

AXIAL DISTANCE (INCHES)	HEAT RATING (KW/FT)	CLAD SURFACE HEAT FLUX BTU/HR-FT	CENTER LINE TEMP. DEG F	AVERAGE VOL. FUEL TEMP. DEG F	GAP CONDUCTANCE BTU/HR- FT2-DEG F	RADIAL HOT GAP (INCHES)	GAS RELEASE RATE	MOLE FRACTION HELIUM
6.600+00	5.084+00	1.569+05	1.699+03	1.339+03	4.592+02	3.455-03	8.207-02	9.349-01
1.980+01	8.151+00	2.515+05	2.460+03	1.769+03	5.656+02	2.917-03	8.207-02	9.349-01
3.300+01	9.475+00	2.923+05	2.790+03	1.944+03	6.281+02	2.665-03	8.207-02	9.349-01
4.620+01	9.937+00	3.066+05	2.904+03	2.004+03	6.606+02	2.564-03	8.207-02	9.349-01
5.940+01	1.000+01	3.085+05	2.929+03	2.019+03	6.704+02	2.556-03	8.207-02	9.349-01
7.260+01	1.000+01	3.089+05	2.953+03	2.039+03	6.704+02	2.541-03	8.207-02	9.349-01
8.580+01	9.916+00	3.059+05	2.946+03	2.040+03	6.649+02	2.592-03	8.207-02	9.349-01
9.900+01	9.622+00	2.968+05	2.887+03	2.014+03	6.555+02	2.633-03	8.207-02	9.349-01
1.122+02	7.983+00	2.462+05	2.506+03	1.819+03	5.810+02	2.929-03	8.207-02	9.349-01
1.254+02	4.832+00	1.490+05	1.738+03	1.389+03	4.751+02	3.507-03	8.207-02	9.349-01

AXIAL, VOLUME-TEMPERATURE AVERAGED

I	TEMPERATURE DEG. F	PRESSURE PSI
1	2.0384+03	9.9430+02
2	1.9105+03	9.3355+02
3	1.8642+03	9.0901+02
4	1.8442+03	8.9994+02
5	1.8376+03	8.9662+02

CASE 2 AXIAL SEGMENT 6 OF 10

SAMPLE PROBLEM

LINEAR HEAT RATING (AVG) 14.0000 KW/FT (PEAK = 14.00 KW/FT)
 TIME IN-REACTOR .0000 DAYS
 BURNUP .00 MWD/MTM
 AVERAGE FLUX IN FUEL 6.5329+13 NV
 CLAD OD SURFACE HEAT FLUX 4.3183+05 BTU/HR-FT2
 FUEL SURFACE HEAT FLUX 4.9304+05 BTU/HR-FT2
 COOLANT TEMPERATURE 631.94 DEG F (333.30 DEG C)
 FILM COEFFICIENT 25000.00 BTU/HR-FT2-DEG F
 CLAD THERMAL CONDUCTIVITY 9.59 BTU/HR-FT-DEG F
 CLAD OD TEMPERATURE 649.21 DEG F (342.89 DEG C)
 CLAD ID TEMPERATURE 746.37 DEG F (398.87 DEG C)
 FUEL SURFACE TEMPERATURE 1210.29 DEG F (654.60 DEG C)

RADIUS (INCHES)	TEMPERATURE (DEG F)	RADIUS (CM)	TEMPERATURE (DEG C)	PERCENT OF FUEL RADIUS
.1666	1588.	.4231	865.	90.00
.1481	1477.	.3761	1081.	80.00
.1296	2357.	.3291	1292.	70.00
.1111	2709.	.2821	1487.	60.00
.0925	3018.	.2351	1659.	50.00
.0740	3273.	.1881	1800.	40.00
.0555	3471.	.1410	1910.	30.00
.0370	3611.	.0940	1988.	20.00
.0185	3694.	.0470	2034.	10.00
.0000	3721.	.0000	2050.	.00

MELT TEMPERATURE 5054. DEG F (2790. DEG C)
 MELT RADIUS .0000 INCH (.00 PERCENT FUEL RADIUS)

GAS RELEASE RATE .2082
 RADIUS AVERAGED FUEL TEMPERATURE 2844.4 DEG F (1562.4 DEG C)
 INCREASE IN FUEL RADIUS DUE TO THERMAL EXPANSION .002601 INCH
 INCREASE IN FUEL RADIUS DUE TO SWELLING .000000 INCH
 TOTAL INCREASE IN FUEL RADIUS .002601 INCH
 CHANGE IN CLAD RADIUS DUE TO THERMAL EXP. AND CREEP .000458 INCH
 CHANGE IN CLAD RADIUS(PRESSURE) -.000192 INCH
 HOT GAP (RADIAL) .001916 INCH
 FUEL-CLAD INTERFACIAL PRESSURE .00 PSI

FUEL-TO-CLAD GAP CONDUCTANCE 1057. BTU/HR-FT2-F

COMPONENT DUE TO SOLID-SOLID CONTACT .0 BTU/HR-FT2-F (.00 PERCENT)
 COMPONENT DUE TO CONDUCTION THROUGH THE GAS 1045.7 BTU/HR-FT2-F (98.90 PERCENT)
 COMPONENT DUE TO RADIANT HEAT TRANSFER 15.4 BTU/HR-FT2-F (1.45 PERCENT)

COMPOSITION OF PIN GAS		COMPOSITION OF GAS LOCALLY	
1.000000	MOLE FRACTION HELIUM	1.000000	MOLE FRACTION HELIUM
.000000	MOLE FRACTION ARGON	.000000	MOLE FRACTION ARGON
.000000	MOLE FRACTION HYDROGEN	.000000	MOLE FRACTION HYDROGEN
.000000	MOLE FRACTION NITROGEN	.000000	MOLE FRACTION NITROGEN
.000000	MOLE FRACTION KRYPTON	.000000	MOLE FRACTION KRYPTON
.000000	MOLE FRACTION XENON	.000000	MOLE FRACTION XENON
-----		-----	
G/MOLES TOTAL	1.542-02 IN PIN		4.583-04 LOCAL
THERMAL CONDUCTIVITY OF FILL GAS		.0006946	CAL/SEC-CM-DEG C (.16802 BTU/HR-FT-DEG F)
TEMPERATURE JUMP DISTANCE		.0000124	INCH
INTERNAL GAS PRESSURE		911.5	PSI
AVERAGE VOLUMETRIC FUEL TEMP.		2378.91	(DEG F) (1303.84 DEG. CENTIGRADE)
NOMINAL HEAT CAPACITY CPNOM=		2.169+01	CAL/(DEG K-MOLE) (5.857+03 BTU/(LB-DEG F)
STORED ENERGY AT TBAR	EBAR=	93.45	CAL/GRAM (168.20 BTU/LB)
VOLUME AVERAGE STORED ENERGY	E=	97.48	CAL/GRAM (175.47 BTU/LB)
STORED ENERGY PER UNIT LENGTH	EPL=	674.96	CAL/CM (81.64 BTU/FOOT)

CASE = 2

AXIAL SUMMARY

TIME AT POWER IN DAYS .0

SAMPLE PROBLEM

AXIAL DISTANCE (INCHES)	HEAT RATING (KW/FT)	CLAF SURFACE HEAT FLUX BTU/HR-FT	CENTER LINE TEMP. DEG F	AVERAGE VOL. FUEL TEMP. DEG F	GAP CONDUCTANCE BTU/HR- FT ² -DEG F	RADIAL HOT GAP (INCHES)	GAS RELEASE RATE	MOLE FRACTION HELIUM
6.600+00	7.113+00	2.136+05	2.098+03	1.542+03	6.059+02	3.173-03	2.082-01	1.000+00
1.980+01	1.141+01	3.521+05	3.121+03	2.070+03	8.249+02	2.425-03	2.082-01	1.000+00
3.300+01	1.326+01	4.092+05	3.126+03	2.267+03	9.793+02	2.055-03	2.082-01	1.000+00
4.620+01	1.391+01	4.292+05	3.675+03	2.345+03	1.039+03	1.945-03	2.082-01	1.000+00
5.940+01	1.400+01	4.319+05	3.709+03	2.368+03	1.049+03	1.921-03	2.082-01	1.000+00
7.260+01	1.400+01	4.318+05	3.721+03	2.379+03	1.057+03	1.916-03	2.082-01	1.000+00
8.580+01	1.388+01	4.289+05	3.715+03	2.382+03	1.057+03	1.923-03	2.082-01	1.000+00
9.900+01	1.347+01	4.155+05	3.637+03	2.347+03	1.025+03	1.989-03	2.082-01	1.000+00
1.122+02	1.118+01	3.447+05	3.156+03	2.118+03	8.470+02	2.433-03	2.082-01	1.000+00
1.254+02	6.763+00	2.097+05	2.126+03	1.589+03	6.162+02	3.230-03	2.032-01	1.000+00

AXIAL VOLUME-TEMPERATURE AVERAGE

TEMPERATURE DEG. F	PRESSURE PSI
-----------------------	-----------------

1

1

2

3

4

2.1541+03	9.0563+02
2.1406+03	9.1157+02
2.1403+03	9.1150+02
2.1404+03	9.1150+02

CASE 3 AXIAL SEGMENT 6 OF 10

SAMPLE PROBLEM

LINEAR HEAT RATING (AVG) 14.0000 KW/FT (PEAK = 14.00 KW/FT)
 TIME IN-REACTOR 100.0000 DAYS
 BURNUP 7525.88 MWD/MTM

AVERAGE FLUX IN FUEL 6.5329+13 NV
 CLAD OD SURFACE HEAT FLUX 4.3178+05 BTU/HR-FT2
 FUEL SURFACE HEAT FLUX 4.9179+05 BTU/HR-FT2
 COOLANT TEMPERATURE 631.94 DEG F (333.30 DEG C)
 FILM COEFFICIENT 25000.00 BTU/HR-FT2-DEG F
 CLAD THERMAL CONDUCTIVITY 9.59 BTU/HR-FT-DEG F
 CLAD OD TEMPERATURE 649.21 DEG F (342.89 DEG C)
 CLAD ID TEMPERATURE 746.33 DEG F (396.85 DEG C)
 FUEL SURFACE TEMPERATURE 1459.26 DEG F (792.92 DEG C)

RADIUS (INCHES)	TEMPERATURE (DEG F)	RADIUS (CM)	TEMPERATURE (DEG C)	PERCENT OF FUEL RADIUS
.1670	1880.	.4242	1027.	89.99
.1484	2306.	.3771	1264.	79.99
.1299	2714.	.3299	1490.	69.99
.1113	3081.	.2828	1694.	59.99
.0928	3395.	.2357	1868.	50.00
.0742	3648.	.1885	2009.	40.00
.0557	3842.	.1414	2117.	30.00
.0371	3978.	.0943	2192.	20.00
.0186	4058.	.0471	2237.	10.00
.0000	4084.	.0000	2251.	.00

MELT TEMPERATURE 5054. DEG F (2790. DEG C)
 MELT RADIUS .0000 INCH (.00 PERCENT FUEL RADIUS)

GAS RELEASE RATE .3390
 RADIUS AVERAGED FUEL TEMPERATURE 3196.9 DEG F (1758.3 DEG C)
 INCREASE IN FUEL RADIUS DUE TO THERMAL EXPANSION .003076 INCH
 INCREASE IN FUEL RADIUS DUE TO SWELLING .000000 INCH
 TOTAL INCREASE IN FUEL RADIUS .003076 INCH
 CHANGE IN CLAD RADIUS DUE TO THERMAL EXP. AND CREEP .000458 INCH
 CHANGE IN CLAD RADIUS(PRESSURE) -.000127 INCH
 HOT GAP (RADIAL) .001505 INCH
 FUEL-CLAD INTERFACIAL PRESSURE .00 PSI

FUEL-TO-CLAD GAP CONDUCTANCE 687. BTU/HR-FT2-F

COMPONENT DUE TO SOLID-SOLID CONTACT .0 BTU/HR-FT2-F (.00 PERCENT)
 COMPONENT DUE TO CONDUCTION THROUGH THE GAS 673.2 BTU/HR-FT2-F (97.99 PERCENT)
 COMPONENT DUE TO RADIANT HEAT TRANSFER 20.2 BTU/HR-FT2-F (2.94 PERCENT)

COMPOSITION OF FILL GAS		COMPOSITION OF GAS LOCALLY	
.710910	MOLE FRACTION HELIUM	.710910	MOLE FRACTION HELIUM
.000000	MOLE FRACTION ARGON	.000000	MOLE FRACTION ARGON
.000000	MOLE FRACTION HYDROGEN	.000000	MOLE FRACTION HYDROGEN
.000000	MOLE FRACTION NITROGEN	.000000	MOLE FRACTION NITROGEN
.034077	MOLE FRACTION KRYPTON	.034077	MOLE FRACTION KRYPTON
.255013	MOLE FRACTION XENON	.255013	MOLE FRACTION XENON
-----		-----	
G/MOLES TOTAL	2.170-02 IN. PIN	5.109-04	LOCAL
THERMAL CONDUCTIVITY OF FILL GAS .0003500 CAL/SEC-CM-DEG C (1.08466 BTU/HR-FT-DEG F)			
TEMPERATURE JUMP DISTANCE .0000043 INCH			
INTERNAL GAS PRESSURE 1403.6 PSI			
AVERAGE VOLUMETRIC FUEL TEMP. 2716.47 (DEG F) (1491.37 DEG. CENTIGRADE)			
NOMINAL HEAT CAPACITY	CPNOME 2.250+01	CAL/(DEG K-MOLE)	(6.075+03 BTU/(LB-DEG F)
STORED ENERGY AT T3AR	EBARE	108.77	CAL/GRAM (195.79 BTU/LR)
VOLUME AVERAGE STORED ENERGY	EE	114.68	CAL/GRAM (206.43 BTU/LR)
STORED ENERGY PER UNIT LENGTH	EPL	794.07	CAL/CM (96.04 BTU/FOOT)

CASE = 3

AXIAL SUMMARY

TIME AT POWER IN DAYS 100.0

SAMPLE PROBLEM

AXIAL DISTANCE (INCHES)	HEAT RATING (KW/FT)	CLAD SURFACE HEAT FLUX BTU/HR-FT	CENTER LINE TEMP. DEG F	AVERAGE VOL. FUEL TEMP. DEG F	GAP CONDUCTANCE BTU/HR- FT ² -DEG F	RADIAL HOT GAP (INCHES)	GAS RELEASE RATE	MOLE FRACTION HELIUM
6.600+00	7.118+00	2.199+05	2.531+03	1.907+03	3.552+02	2.852-03	3.384-01	7.113-01
1.980+01	1.141+01	3.520+05	3.555+03	2.447+03	5.199+02	2.004-03	3.384-01	7.113-01
3.300+01	1.326+01	4.091+05	3.920+03	2.624+03	6.296+02	1.626-03	3.384-01	7.113-01
4.620+01	1.391+01	4.290+05	4.050+03	2.691+03	6.729+02	1.526-03	3.384-01	7.113-01
5.940+01	1.400+01	4.317+05	4.068+03	2.700+03	6.880+02	1.521-03	3.384-01	7.113-01
7.260+01	1.400+01	4.317+05	4.084+03	2.716+03	6.870+02	1.505-03	3.384-01	7.113-01
8.580+01	1.388+01	4.280+05	4.063+03	2.706+03	6.898+02	1.532-03	3.384-01	7.113-01
9.900+01	1.347+01	4.153+05	4.003+03	2.685+03	6.626+02	1.579-03	3.384-01	7.113-01
1.122+02	1.118+01	3.446+05	3.573+03	2.484+03	5.280+02	2.018-03	3.384-01	7.113-01
1.254+02	6.765+00	2.086+05	2.530+03	1.934+03	3.563+02	2.927-03	3.384-01	7.113-01

AXIAL, VOLUME-TEMPERATURE AVERAGED

	TEMPERATURE DEG. F	PRESSURE PSI
1		
1	2.7464+03	1.5170+03
2	2.5423+03	1.4454+03
3	2.5006+03	1.4137+03
4	2.4912+03	1.4068+03
5	2.4895+03	1.4055+03

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