A CORRELATED CODE FOR THE PREDICTION OF LIQUID METAL FAST BREEDER REACTOR (LMFBR) FUEL THERMAL PERFORMANCE

BY

D. S. Dutta and R. B. Baker

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A CORRELATED CODE FOR THE PREDICTION OF
LIQUID METAL FAST BREEDER REACTOR (LMFBR) FUEL

THERMAL PERFORMANCE

D. S. Dutt and R. B. Baker

ABSTRACT

The SIEX computer program is a steady state heat transfer code developed to provide thermal performance calculations for a mixed-oxide fuel element in a fast neutron environment. Fuel restructuring, fuel-cladding heat conduction and fission gas release are modeled to provide assessment of the temperatures. Modeling emphasis has been placed on correlations to measurable quantities from EBR-II irradiation tests and the inclusion of these correlations in a physically based computational scheme.

SIEX is completely modular in construction allowing the user options for material properties and correlated models. Required code input is limited to geometric and environmental parameters, with a "consistent" set of material properties and correlated models provided by the code. The development of physically based correlations to model certain of the phenomena has resulted in a computer program which provides reliable estimates of thermal performance characteristics, yet requires a small amount of core storage and computer running time.
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FSINTR: FUEL TEMPERATURE CALCULATIONS

ROUTINES ASSOCIATED WITH THE FUEL THERMAL CONDUCTIVITY

CSINTR: CLADDING TEMPERATURE CALCULATIONS

CDELD: COMPUTATION OF DIMENSIONAL CHANGES OF THE CLADDING MATERIAL

FDELD: COMPUTATION OF FUEL DIMENSIONAL CHANGES

PPRES: COMPUTATION OF PLENUM PRESSURE

V. CORRELATED MODELS

FSWEL: RESIDUAL GAP CORRELATION

HGAP: FUEL-CLADDING CONDUCTANCE

RADIANT HEAT TRANSFER

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ACKNOWLEDGMENTS

A code strongly based on data is, of necessity, a result of the efforts of many disciplines and personnel. The authors wish to acknowledge the contribution of the Component Testing Section at HEDL who designed and executed the EBR-II tests and directed the postirradiation examinations from which the data were extracted. Their cooperation and assistance in data interpretation were necessary in all phases of the SIEX development. D. R. Wilson, R. J. Jackson, C. M. Cox, and R. D. Leggett were instrumental in the model development and checkout. Many of their ideas and procedures have been incorporated into SIEX.
I. INTRODUCTION

This documentation describes the SIEX computer program which is a fast running, steady state thermal performance code used to calculate coolant, cladding and fuel temperatures throughout the history of a fuel element. SIEX was developed by the Hanford Engineering Development Laboratory (HEDL) for performance analysis of mixed-oxide fuel pins irradiated under steady state fast flux conditions. Although versions of SIEX have existed at HEDL* since 1968, this is the first effort to place the current techniques used by the code at the disposal of a larger group of users.

It is necessary to have a method to accurately assess the thermal performance of a mixed-oxide fuel pin in a fast neutron environment. The resulting thermal analyses are the basis for:

1. subsequent steady state or transient stress analysis.
2. prediction of steady state or transient failure modes and times.
3. safety related accident analyses.

A code with short running times and relatively small storage requirements is needed in order to be routinely used as a test design/analysis tool or to define initial conditions for a more detailed subsequent analysis.

SIEX is constructed of a series of modules with a single set of dimensional units used throughout to provide flexibility in model usage and ease of upgrading as models developed from future tests are finalized. Radial steady state heat transfer can be computed for 21 axial segments. The code computes all major quantities which affect the thermal performance (restructuring, fission gas generation and release, etc.) Code running times are typically two to five seconds per case on the Control Data Corporation CYBER-74. The running time is dependent on the output refinement required by the user. The amount of core storage required is 50K octal (20K decimal) of 60 bit CYBER words. No peripheral storage is required, subject to the input/output devices selected by the user.

The documentation is also in modular form so that an update or modifica-

*Prior to 1970, the Pacific Northwest Laboratory, operated by Battelle Mem. Inst.
tion to any of the correlated (and if necessary, mathematical) models can be made without disturbing the rest of the document. The first section is a user's manual which describes the input/output subroutines and user options. Directions for the code usage in its present form and sample cases are given at the end of this section. The second and third sections, respectively, provide flow charts and descriptions or brief derivations of the mathematical and correlated models. Much of the code checkout and confirmation is contained in the last section where the correlations to observations are presented.
II. CODE DESCRIPTION

SIEX is a computer code which calculates the thermal performance characteristics and dimensional changes (swelling and thermal expansion) of mixed oxide fuel pins in a fast neutron environment. SIEX is comprised of a series of subroutines which model certain fast reactor fuels phenomena and is correlated to a significant amount of EBR-II irradiation test data. Program development and numerical techniques have been carried out in a way which provides a code with short running times and modular independence of models. The code satisfies the need for a data analysis and design tool in the LMFBR program.

The fuel pin is geometrically modeled as shown in Figure 1. The fuel column is divided axially into a user specified number of segments with equal height (equal fuel volume). One dimensional radial heat transfer is assumed at the axial center of each of these segments. The heat generated in each segment and released fission gas is accumulated over the segments for calculation of coolant temperatures and plenum pressure. For each segment, the following calculations are performed:

- Coolant temperature
- Cladding surface temperatures
- Fuel-cladding heat transfer coefficient
- Fuel temperatures
- Fuel restructuring radii
- Fuel and cladding displacements due to swelling and thermal expansion
- Fission gas generated and released.

The number of time (burnup) increments is left to the discretion of the code user. For each time increment, the fission gas release is updated, the plenum pressure is computed, and the fuel temperatures are adjusted to account for the changing gap conductance. SIEX results are independent of the step size.

The SIEX code consists of a "driving" routine, input/output routines, mathematical models, and physically-based correlated models. The mathematical models are heat transfer, gas pressure and, to a certain extent, dimensional
FIGURE 1. SIEX Fuel Pin Geometry.
changes of the fuel and cladding. A brief explanation or derivation of these models is included in this document for completeness. For the correlated models (gas release, restructuring, etc.), a summary is made of the data used in the correlation, a rationale for the models, and a model description. In most cases, these models can be updated or entirely replaced with little effect on the rest of the code mechanics. All internal coding is in cgs units. "Convenience unit" conversions are handled in the input and output subroutines.

The primary routines are listed in Table 1 along with a description of their usage. In those cases where auxiliary routines are used, they are listed. Figure 2 is a diagram of the routine call sequence. Figure 3 is a SIEX flow chart.

III. INPUT/OUTPUT

The Input/Output routines are a compromise between user convenience and code flexibility. "Overrides" to data values programmed into the code provide for new or extended applications of the code which necessitate modification. The first portion deals with those assumptions which may be considered input, but are programmed into SIEX for its use as an EBR-II test design/analysis code and an FFTF fuel pin performance analysis tool. The card input procedure will then be discussed with attention given to the options provided to the user.
## TABLE I
### PRIMARY ROUTINES IN SIEX

<table>
<thead>
<tr>
<th>ROUTINE NAME</th>
<th>DESCRIPTION</th>
<th>Routines Called</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAIN SIEX</strong></td>
<td><strong>ROUTINE NAME</strong></td>
<td><strong>DESCRIPTION</strong></td>
</tr>
<tr>
<td><strong>Physical Models</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FSINTR</td>
<td>Computes the radial temperature distribution across the fuel pellet using a two zone heat transfer model. The integral $kdt$ is computed by the function $S$, and fuel-cladding heat transfer coefficients have been computed by HGAP.</td>
<td>STRUCT, S, T RFIND</td>
</tr>
<tr>
<td>CSINTR</td>
<td>Computes the coolant axial temperature rise and the temperatures of the inner and outer cladding surfaces.</td>
<td>SINPUT</td>
</tr>
<tr>
<td>CDELD</td>
<td>Computes the cladding geometry during irradiation, considering deformations due to swelling and thermal expansion.</td>
<td></td>
</tr>
<tr>
<td>FDELD</td>
<td>Computes the fuel outer radius due to fuel thermal expansion and correlated permanent deformations as computed by FSWEL.</td>
<td>FSWEL</td>
</tr>
<tr>
<td>PPRES</td>
<td>Computes the plenum pressure based on the perfect gas law.</td>
<td></td>
</tr>
<tr>
<td><strong>Correlated Models</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HGAP</td>
<td>Computes fuel-cladding gap conductance based on a modified Ross-Stout model.</td>
<td>FSINTR, CONMIX, FDELD, PPRES, FISGAS</td>
</tr>
<tr>
<td>FISGAS</td>
<td>Computes fission gas generated and released.</td>
<td>FISGAS</td>
</tr>
<tr>
<td>STRUCT</td>
<td>Computes the restructuring radii of the fuel.</td>
<td>S, T, RFIND</td>
</tr>
<tr>
<td>FSWEL</td>
<td>Computes the permanent fuel deformations</td>
<td></td>
</tr>
<tr>
<td><strong>Input-Output</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INPUT</td>
<td>Reads input in &quot;engineering&quot; units converts to cgs.</td>
<td>SPAGE, FISGAS, FDELD</td>
</tr>
<tr>
<td>OUTPUT</td>
<td>Converts cgs units to &quot;engineering&quot; units and prints selected output tables.</td>
<td>SPAGE</td>
</tr>
</tbody>
</table>
FIGURE 2. Primary Routine Call Sequence of SIEX.
FIGURE 3. SIEX Flow Chart
VALUES WHICH CAN BE SUPPLIED BY THE CODE

Axial Power, Flux and Neutron Energy Profiles

The axial flux profile is supplied by the function AFP, the power profile by PMP, the average neutron energy by EBR, and the ratio of flux greater than 0.1 MeV to total neutron flux by FTX. In the cases of AFP and PMP, the profiles are normalized to the peak values. FTX and EBR return the actual values.

Four options are available to the user:

1. Axial power and flux profiles are identical "chopped" cosine curves with an extrapolation distance, E, specified by the user (Reference 1). The average neutron energy and the ratio of flux greater than 0.1 MeV to the total neutron flux are assigned the values consistent with EBR-II operation.

2. The values for the power and flux profiles are interpolated from a user-supplied table of data and assumed to have the same shape. The data table is programmed into the code as a data statement in BLKDAT. As in the first case, the average neutron energy and ratio of flux greater than 0.1 MeV to total flux are assigned constant values.

3. The user may specify a functional form to be evaluated for each of the functions. Examples of quadratics, which were obtained by analyzing certain EBR-II gamma scan data, are presently programmed. No significance should be attached to these correlations which serve as examples only.

4. All four values may be interpolated from tables of values supplied by the user through input. This will be explained in the section on card input.

Model Input Options

1. Fission gas release can be evaluated either by the fission gas release model discussed in Section III or a three region model in which the fraction released for each region is supplied by the user. The three regions of the user-supplied gas release fraction are assumed to be the fuel region characterized by columnar grain growth, the fuel region characterized by equiaxed grain growth, and the unrestructured fuel region. The fractional release for the user supplied case is assumed to be independent of burnup or in-reactor time.
2. The temperatures, in degrees Centigrade, which are used to predict the observed radial extent of columnar and equiaxed grain growth, may be taken as those presented in Section III or user-supplied values.

3. The fuel-cladding gap conductance model discussed in Section III may be replaced by a user-supplied constant.

In all of the above cases, the models were developed on a systematic basis, a user "override" should be used only after consideration of its effect on the other models, e.g., an "override" of the gas release model may be useful in determining maxima for pressure and temperatures, but an override on restructuring may give erroneous results for gas release and gap conductance.

Material Properties Options

Values for the material properties used in SIEX have been coded into the BLKDAT routine. However, these may be changed by the user through card input.

Those material properties which may be changed by the user are:

1. Cladding thermal expansion coefficient: The SIEX code assumes that the mean coefficient of thermal expansion is \( \alpha_c = \alpha_0 + \alpha_T T \), where \( T \) is temperature in °C and \( \alpha_c \) is the coefficient of thermal expansion, cm/cm°C.

2. Young's modulus of the cladding: SIEX assumes \( E_c = E_0 + E_T T \), where \( T \) is temperature in °C, and \( E_c \) is Young's modulus in dynes/cm².

3. Poisson's ratio for the cladding which is a constant.

4. Cladding thermal conductivity: This may be input as a constant as described in card input section. If no input is encountered, SIEX assumes a temperature dependent conductivity of \( K_c = K_0 + K_T T \), where \( K_c \) is in watts/cm°C and \( T \) is in °C. A single iteration of the temperature dependence is programmed into the evaluation of the conductivity equation, i.e.,

\[
K_c = K_0 + K_T^C \left[ T_0^C + \frac{.5t \times q}{2\pi(r_0^C - 0.5t)(K_0^C + K_T^C T_0^C)} \right]
\]

where \( \frac{.5t \times q}{2\pi(r_0^C - 0.5t)(K_0^C + K_T^C T_0^C)} \) is, of course, a temperature correction.
to the initial estimate of the cladding temperature, $T_0^c$. $T_0^c$ is the cladding surface temperature, $q$, heat rate, $r_0^c$ cladding radius, and $t$ is the cladding thickness.

The fuel properties for thermal expansion and Young's modulus are of the form

$$\alpha_f^f = \alpha_0^f + \alpha_T^f \times T, \, \text{cm/cm - ^0C}$$

$$E_f^f = E_0^f + E_T^f \times T, \, \text{dynes/cm}^2,$$

respectively, where $T$ is temperature° C. No "override" options are provided via input but these values may be changed by changing the block data routine.

Card Input

Card input is by NAMELIST input. Though this does not conform to ANSI standard, its user convenience is justification for its use. NAMELIST input is free field, non-formatted,* and does not require that all variables be input when multiple cases are run. For parametric studies, only a title card and the variables of interest need to be input. The NAMELIST variable is IPT. A typical input deck with a series of cases would be set up as shown in Figure 4. Table II is a listing of the NAMELIST variables (and code variables), units, and a description of each.

Parameter Input

Values for parameters in correlated models and coefficients for material properties are transferred to the code through labeled common. These values are placed in memory in the block data routine BLKDAT by means of data statements. This centralization of code parameters eliminates the need to change entire blocks of code when changing values for the model. The routine itself is well "commented" to assist in making any desired changes.

OUTPUT

SIEX output is structured to produce a series of "tables" dealing with a particular model or calculational procedure. Explanation of the output is accomplished by example. Table III is the computer-generated output for the first deck listed in Figure 4 of the input description.

*The sequence or position of the variables in Figure 4 is not important.
FIGURE 4. SIEX Input Deck Set-Up.
### TABLE II
DESCRIPTION OF SIEX INPUT

<table>
<thead>
<tr>
<th>Input Parameter Name</th>
<th>Definition of Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLEN</td>
<td>Active fuel column length</td>
<td>inches</td>
</tr>
<tr>
<td>E</td>
<td>The value of E provides the axial flux and power profiles as follows:</td>
<td>inches</td>
</tr>
<tr>
<td></td>
<td>E &gt; 0 (E is the extrapolation distance for a &quot;chopped&quot; cosine curve)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E = 0 (Interpolate from internally supplied data tables)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 &gt; E ≥ -1 (Evaluate user-supplied functions)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E &lt; -1 (Interpolate from a user supplied table which is read from input,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[E] values are expected)</td>
</tr>
<tr>
<td>FD</td>
<td>Fuel diameter</td>
<td>inches</td>
</tr>
<tr>
<td>VOID</td>
<td>Fuel (fabricated) central annulus diameter</td>
<td>inches</td>
</tr>
<tr>
<td>DP</td>
<td>Cladding outer diameter</td>
<td>inches</td>
</tr>
<tr>
<td>CT</td>
<td>Cladding wall thickness</td>
<td>inches</td>
</tr>
<tr>
<td>PM</td>
<td>Maximum pin heat rate</td>
<td>kW/ft</td>
</tr>
<tr>
<td>CMF</td>
<td>Coolant mass flow rate</td>
<td>lb/hr</td>
</tr>
<tr>
<td>CP</td>
<td>Coolant specific heat (If no namelist input is supplied, the SIEX supplied value of CP</td>
<td>Btu/lb-°F</td>
</tr>
<tr>
<td></td>
<td>is used)</td>
<td></td>
</tr>
<tr>
<td>HF</td>
<td>Cladding-to-coolant heat transfer coefficient</td>
<td>Btu/ft²-°F-hr</td>
</tr>
</tbody>
</table>
TABLE II (Continued)

DESCRIPTION OF SIEX INPUT

<table>
<thead>
<tr>
<th>Input Parameter Name</th>
<th>Definition of Parameter</th>
<th>Input Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>HG</td>
<td>Fuel-to-cladding heat transfer coefficient (also used as an initial estimate for subsequent gap conductance calculations)</td>
<td>Btu/ft²⁻F-hr</td>
</tr>
<tr>
<td>CK</td>
<td>Cladding thermal conductivity</td>
<td>Btu/ft-hr⁻⁰°F</td>
</tr>
<tr>
<td></td>
<td>CK &gt; 0 (the value of CK is used independent of temperature)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CK &lt; 0 (the SIEX programmed temperature-dependent conductivity is used)</td>
<td></td>
</tr>
<tr>
<td>TI</td>
<td>Inlet coolant temperature</td>
<td>°F</td>
</tr>
<tr>
<td>TB</td>
<td>Temperature to use for the prediction of the columnar grain growth radius</td>
<td>°C</td>
</tr>
<tr>
<td></td>
<td>TB &gt; 0 (the value of TB is used in making the prediction of the columnar grain growth radius)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TB &lt; 0 (the SIEX programmed value is used to predict the columnar grain growth radius)</td>
<td></td>
</tr>
<tr>
<td>TEMP2</td>
<td>Temperature to use for the prediction of the equiaxed grain growth radius</td>
<td>°C</td>
</tr>
<tr>
<td></td>
<td>TEMP2 &gt; 0 (the value of TEMP2 is used to predict the equiaxed grain growth radius)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TEMP2 &lt; 0 (the SIEX programmed value is used to predict the equiaxed grain growth radius)</td>
<td></td>
</tr>
<tr>
<td>DENLO</td>
<td>Fraction of theoretical density of the fabricated fuel</td>
<td></td>
</tr>
<tr>
<td>DENHI</td>
<td>Fraction of theoretical density of the fuel in the columnar grain growth region</td>
<td></td>
</tr>
<tr>
<td>Input Parameter Name</td>
<td>Definition of Parameter</td>
<td>Input Units</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------------------------------------------------------------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>TD</td>
<td>Fuel theoretical density</td>
<td>gm/cc</td>
</tr>
<tr>
<td>DISH</td>
<td>Fraction of the fuel volume (pellet or total column volume) which is occupied by voidage due to fabricated end dishes in the fuel pellets.</td>
<td>fraction</td>
</tr>
<tr>
<td>Pu</td>
<td>Fraction of the metal in the fuel which is Pu$^{239}$ or Pu$^{241}$.</td>
<td>fraction</td>
</tr>
<tr>
<td>U$^{235}$</td>
<td>Fraction of the metal in the fuel which is U$^{235}$.</td>
<td>fraction</td>
</tr>
<tr>
<td>SEGNUM</td>
<td>Number of axial segments desired. An additional node at the top of the fuel pin is added by SIEX (maximum value for SEGNUM is 21)</td>
<td></td>
</tr>
<tr>
<td>PBU</td>
<td>Peak burnup to be achieved (needs to be specified if EFPD, below, is zero, otherwise is overridden by computed burnup)</td>
<td>Mwd/MTM</td>
</tr>
<tr>
<td>EFPD</td>
<td>Final time, effective full power days</td>
<td>EFPD</td>
</tr>
<tr>
<td>STEPS</td>
<td>Output burnup and time increments as follows:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>STEPS &lt; 0 The</td>
<td>STEPS</td>
</tr>
<tr>
<td></td>
<td>STEPS = 0 (output peak burnup results only)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>STEPS = 1 (output zero and peak burnup results)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>STEPS &gt; 1 (output results at zero burnup, peak burnup, and at each PBU/STEPS interval)</td>
<td></td>
</tr>
</tbody>
</table>

15
TABLE II (Continued)

<table>
<thead>
<tr>
<th>Input Parameter Name</th>
<th>Definition of Parameter</th>
<th>Input Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>This STEPS logic pertains to EFPD in the same manner as it does to PBU if EFPD is used for time dependency.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z1</td>
<td>Fraction of fission gas release from fuel columnar region</td>
<td>fraction</td>
</tr>
<tr>
<td>Z2</td>
<td>Fraction of fission gas release from fuel equiaxed region</td>
<td>fraction</td>
</tr>
<tr>
<td>Z3</td>
<td>Fraction of fission gas release from unstructured region</td>
<td>fraction</td>
</tr>
<tr>
<td></td>
<td>Z3&lt;0 (calculate using fission gas release model)</td>
<td></td>
</tr>
<tr>
<td>CCPGM</td>
<td>Sorbed gas from fabrication per gram of fuel exclusive of water vapor</td>
<td>cc(STR)/gm oxide</td>
</tr>
<tr>
<td>FN</td>
<td>Fraction of sorbed gas which is not Helium or Hydrogen. This gas is assumed to have the thermal conductivity of nitrogen.</td>
<td>fraction</td>
</tr>
<tr>
<td>PPM</td>
<td>Parts per million water vapor in the fabricated fuel</td>
<td>ppm</td>
</tr>
<tr>
<td>EPL</td>
<td>Effective plenum length</td>
<td>inches</td>
</tr>
<tr>
<td>XEFIL</td>
<td>Percent xenon tag in the fill gas</td>
<td>percent</td>
</tr>
<tr>
<td>KRFIL</td>
<td>Percent krypton tag in the fill gas</td>
<td>percent</td>
</tr>
<tr>
<td>ALPHAO</td>
<td>The coefficient of cladding thermal expansion ((\alpha_c)) is assumed to be linear with temperature ((T)) increase. In the expression (\alpha_c = \alpha_0 + \alpha_T T), ALPHAO is the intercept, (\alpha_0). (If no namelist input is supplied, the SIEX value of ALPHAO is used)</td>
<td>in/in-°F</td>
</tr>
<tr>
<td>ALPHAS</td>
<td>In the expression above, ALPHAS is the slope, (\alpha_T). (If no namelist input is supplied, the SIEX value of ALPHAS is used)</td>
<td>in/in-°F^2</td>
</tr>
<tr>
<td>YMODO</td>
<td>Young's modulus ((E)) is also assumed to be linear with temperature ((T)) increase. In the expression (E^c = E_0 + E_T T), YMODO is the intercept, (E_0). (If no namelist input is supplied, the SIEX value of YMODO is used)</td>
<td>lb/in^2</td>
</tr>
<tr>
<td>Input Parameter Name</td>
<td>Definition of Parameter</td>
<td>Input Units</td>
</tr>
<tr>
<td>----------------------</td>
<td>------------------------------------------------------------------------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>YMODS</td>
<td>In the expression above, YMODS is the slope, E. (If no namelist input is supplied, the</td>
<td>1b/in²-oF</td>
</tr>
<tr>
<td></td>
<td>SIEX value of YMODS is used)</td>
<td></td>
</tr>
<tr>
<td>PNU</td>
<td>Cladding Poisson's ratio (If no namelist input is supplied, the SIEX value of PNU is</td>
<td></td>
</tr>
<tr>
<td></td>
<td>used.)</td>
<td></td>
</tr>
<tr>
<td>PFLUX</td>
<td>Peak flux (neutrons with energy &lt; 0.1 MeV).</td>
<td>N/cm²·sec</td>
</tr>
<tr>
<td>TMSWC</td>
<td>Switch for desired cladding swelling model as follows:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TMSWC = 1.0 (304 annealed ss)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TMSWC = 2.0 (306 annealed ss)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TMSWC = 3.0 (316 20% cold worked ss)</td>
<td></td>
</tr>
<tr>
<td>EXTERP</td>
<td>External pressure</td>
<td>psig</td>
</tr>
<tr>
<td>ITAB1</td>
<td>Fission gas release and plenum pressure option:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ITAB1 = 0 (no calculations and no output)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ITAB1 = 1 (calculations and output results)</td>
<td></td>
</tr>
<tr>
<td>ITAB2</td>
<td>Fuel and cladding diameter increase option:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ITAB2 = 0 (no calculations and no output)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ITAB2 = 1 (calculations and output results)</td>
<td></td>
</tr>
<tr>
<td>ITAB3</td>
<td>Fuel-cladding heat transfer coefficients calculation option:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ITAB3 = 0 (use input HG as a constant)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ITAB3 = 1 (calculation of the gap coefficient)</td>
<td></td>
</tr>
</tbody>
</table>

* ITAB1 through ITAB4 are the only namelist input variables which are FORTRAN integers.
<table>
<thead>
<tr>
<th>Input Parameter Name</th>
<th>Definition of Parameter</th>
<th>Input Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITAB4</td>
<td>Cladding elastic stress option:</td>
<td>*</td>
</tr>
<tr>
<td>ITAB4 = 0</td>
<td>(no calculations - no output)</td>
<td></td>
</tr>
<tr>
<td>ITAB4 = 1</td>
<td>(calculations and output results)</td>
<td></td>
</tr>
<tr>
<td>TIINCR</td>
<td>If STEPS is less than zero, the time increments at which output and calculations are desired.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(</td>
<td>\text{STEPS}</td>
</tr>
<tr>
<td>PRATIO</td>
<td>The ratio of power to the input peak power (PM) during the corresponding time increment of above (10 maximum). At time zero PM is used.</td>
<td></td>
</tr>
<tr>
<td>CRATIO</td>
<td>The ratio of the coolant mass flow rate to the input value (CMF) during the corresponding time increment of above (10 maximum). At time zero CMF is used.</td>
<td></td>
</tr>
<tr>
<td>READX</td>
<td>If ( E &lt; -1 ), the positions along the length of the pin at which power, flux, average neutron energy and ratio of flux &gt;0.1 MeV to total flux are to be read to form tables for interpolation. Values of READX are to be normalized to FLEN.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(</td>
<td>E</td>
</tr>
<tr>
<td>READFP</td>
<td>Axial flux profile (relative to PFLUX) corresponding to the locations in READX. (</td>
<td>E</td>
</tr>
<tr>
<td>READP</td>
<td>Axial power profile (Relative to PM) corresponding to the locations in READX. (</td>
<td>E</td>
</tr>
<tr>
<td>READEB</td>
<td>Axial distribution of average neutron energy corresponding to locations in READX. (</td>
<td>E</td>
</tr>
<tr>
<td>READTF</td>
<td>Axial distribution of the ratio of neutrons with energy greater than 0.1 MeV to the total neutron flux. (</td>
<td>E</td>
</tr>
</tbody>
</table>
The descriptions of the different parts of Table III are:

Part 1 is a listing of all input variables along with a description of each variable and its units. If the user provides either the axial profiles or the time increment controls, additional output listing the input quantities will be added to Part 1. An example of this additional output can be obtained from the second example listed in the input description.

Part 2 is a listing of the predicted coolant temperature, cladding and fuel boundary temperatures, power, and gap conductance for all axial nodes. The variables listed here are produced by the routines CSINTR, FSINTR, and HGAP.

Part 3 is a listing of the predicted fuel microstructure, melting location (if one exists), and the temperatures at which the fuel restructuring is evaluated for each axial location. The variables listed in Part 3 are produced by the routines STRUCT and FSINTR.

Part 4 is the fuel radial temperature distribution for each axial position. These temperatures are computed in the routine FSINTR.

Part 5 deals with the gaseous fission products and gas components used in computing the plenum pressure and fuel-cladding heat transfer coefficient. An axial and radial distribution of fission gas generated, released, and retained is provided. A summary of the origin of the gas components in the plenum (and fuel-cladding gap) as well as the plenum pressure is given. The variables are computed in FISGAS and PPRES.

Part 6 provides the predicted fuel and cladding dimensional changes at all axial positions. Fuel permanent deformations, cladding swelling, and fuel outer postirradiation radius, may be obtained from the columns labeled "cladding swelling %" and "fuel-cladding cold gap." All other values in this part are in the "hot" condition, that is, they include the calculated thermal expansion. The values in this part are computed in CDELD and FDELD.

Part 7 is an example of the method used to generate output required by the user. Part 7 is a calculation of thermal and pressure (combined) cladding stresses using thick-walled stress equations. These are computed by the routine STRESS.
Table III
SIEX OUTPUT

SIEX -- REF MEDL-THE 74-99  SIEX TEST CASE NO.1 -- ALL DEFAULT USER OPTIONS
---------- SIEX ANALYSIS ----------

DATE 03/12/75

INPUT PARAMETERS USED FOR THIS ANALYSIS

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>NAME</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACTIVE FUEL COLUMN LENGTH</td>
<td>PEN</td>
<td>3.1130E+01 IN</td>
</tr>
<tr>
<td>EXTRAPOLATION DISTANCE</td>
<td>E</td>
<td>0.00</td>
</tr>
<tr>
<td>FUEL DIAMETER</td>
<td>FO</td>
<td>1.4150E+01 IN</td>
</tr>
<tr>
<td>FUEL CENTRAL ANNULUS DIAMETER</td>
<td>VOID</td>
<td>0.00</td>
</tr>
<tr>
<td>PIN DIAMETER</td>
<td>DP</td>
<td>2.6120E+01 IN</td>
</tr>
<tr>
<td>CLADDING THICKNESS</td>
<td>CT</td>
<td>1.9100E+02 IN</td>
</tr>
<tr>
<td>MAXIMUM FUEL HEATING RATE</td>
<td>CFM</td>
<td>2.0000E+01 IN/Ft</td>
</tr>
<tr>
<td>COOLANT MASS FLOW RATE</td>
<td>CM</td>
<td>2.4500E+02 LB/HR</td>
</tr>
<tr>
<td>COOLANT SPECIFIC HEAT</td>
<td>CF</td>
<td>1.2000E+01 FT/HR</td>
</tr>
<tr>
<td>FILM COEFFICIENT</td>
<td>CFM</td>
<td>2.0000E+01 FT/HR</td>
</tr>
<tr>
<td>CONDUCTIVITY</td>
<td>C</td>
<td>0.00</td>
</tr>
<tr>
<td>INLET COOLANT TEMPERATURE</td>
<td>T1</td>
<td>7.0000E+02 DEG F</td>
</tr>
<tr>
<td>TEMP. AT COL. BOUNDARY</td>
<td>TEMP</td>
<td>0.00</td>
</tr>
<tr>
<td>PHONONICAL DENSITY</td>
<td>PEN</td>
<td>1.0000E+01 HND/TH</td>
</tr>
<tr>
<td>FUEL THEORETICAL DENSITY</td>
<td>PEN</td>
<td>1.0000E+01 HND/TH</td>
</tr>
<tr>
<td>FRACTION OF FUEL VOLUME OCCUPIED</td>
<td>DIS</td>
<td>1.0000E+02</td>
</tr>
<tr>
<td>COOLANT WHICH IS UO2</td>
<td>DIS</td>
<td>1.0000E+02</td>
</tr>
<tr>
<td>NUMBER OF AXIAL SEGMENTS</td>
<td>SN</td>
<td>1.0000E+01</td>
</tr>
<tr>
<td>OPERATING TIME EFFECTIVE</td>
<td>EP</td>
<td>2.1100E+03 DAYS</td>
</tr>
<tr>
<td>POWER DAYS</td>
<td>EP</td>
<td>2.1100E+03 DAYS</td>
</tr>
<tr>
<td>NUMBER OF CALCULATIONS/PRINTOUTS</td>
<td>NF</td>
<td>0.00</td>
</tr>
<tr>
<td>RATIO OF FUEL RELEASE COL.</td>
<td>ZI</td>
<td>1.0000E+00</td>
</tr>
<tr>
<td>FUEL RELEASE ARE SINTERED ZONE</td>
<td>ZI</td>
<td>1.0000E+00</td>
</tr>
<tr>
<td>FRACTION OF FUEL IN THE FLUID</td>
<td>CC</td>
<td>2.0000E+00</td>
</tr>
<tr>
<td>PERCENT OF FUEL IN THE COL.</td>
<td>CC</td>
<td>2.0000E+00</td>
</tr>
<tr>
<td>EFFECTIVE PLENUM LENGTH</td>
<td>ELF</td>
<td>1.1500E+01</td>
</tr>
<tr>
<td>PERCENT OF SPAND IN THE FUEL</td>
<td>XELF</td>
<td>1.1500E+01</td>
</tr>
<tr>
<td>PERCENT OF HSPAND IN THE FUEL</td>
<td>PELF</td>
<td>1.1500E+01</td>
</tr>
<tr>
<td>YOUNG'S MODULUS - INTERCEPT</td>
<td>YMO</td>
<td>3.0000E+03 LB/IN+2-DEG</td>
</tr>
<tr>
<td>YOUNG'S MODULUS - SLOPE</td>
<td>YMO</td>
<td>3.0000E+03 LB/IN+2-DEG</td>
</tr>
<tr>
<td>POISSONS RATIO</td>
<td>RNM</td>
<td>3.0000E+03</td>
</tr>
<tr>
<td>MATERIAL (ANNEALED TYPE 508 55</td>
<td>PFLX</td>
<td>2.0000E+00</td>
</tr>
<tr>
<td>2 ANNEALED TYPE 516 55</td>
<td>TNC</td>
<td>2.0000E+00</td>
</tr>
<tr>
<td>EXTERNAL PRESSURE</td>
<td>EXEAP</td>
<td>3.5000E+01 PSIG</td>
</tr>
<tr>
<td>FISSION GAS RELEASE/PLIEUM PRESS</td>
<td>ITAB1</td>
<td>1.0000E+00 IN/CA/08/MM/08/PASS</td>
</tr>
<tr>
<td>PIN DELTA DIO OPTION</td>
<td>ITAB2</td>
<td>1.0000E+00 IN/CA/08/MM/08/PASS</td>
</tr>
<tr>
<td>NUCLEI COEFFICIENT OPTION</td>
<td>ITAB3</td>
<td>1.0000E+00 IN/CA/08/MM/08/PASS</td>
</tr>
</tbody>
</table>

** INPUT OPTIONS ON CODE SUPPLIED VALUES CAN BE USED. SEE THE USER MANUAL IN MEDL-THE 74-99.**
Table III (Cont'd)
SIEX OUTPUT

<table>
<thead>
<tr>
<th>TIME</th>
<th>9.35 PEAK BURN UP</th>
<th>2214</th>
<th>SIEX TEST CASE NO.1 — ALL DEFAULT USER OPTIONS</th>
<th>PAGE 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>AXIAL SEGMENT NUMBER</td>
<td>DIST FROM BOTTOM OF FUEL, IN</td>
<td>COOLANT TEMP, DEG F</td>
<td>CLAD OD TEMP, DEG F</td>
<td>CLAD ID TEMP, DEG F</td>
</tr>
<tr>
<td>1</td>
<td>0.670</td>
<td>703</td>
<td>727</td>
<td>799</td>
</tr>
<tr>
<td>2</td>
<td>2.028</td>
<td>725</td>
<td>745</td>
<td>823</td>
</tr>
<tr>
<td>3</td>
<td>3.300</td>
<td>743</td>
<td>765</td>
<td>847</td>
</tr>
<tr>
<td>4</td>
<td>4.732</td>
<td>762</td>
<td>745</td>
<td>869</td>
</tr>
<tr>
<td>5</td>
<td>5.034</td>
<td>781</td>
<td>804</td>
<td>889</td>
</tr>
<tr>
<td>6</td>
<td>7.036</td>
<td>801</td>
<td>824</td>
<td>907</td>
</tr>
<tr>
<td>7</td>
<td>6.280</td>
<td>820</td>
<td>842</td>
<td>921</td>
</tr>
<tr>
<td>8</td>
<td>10.100</td>
<td>838</td>
<td>859</td>
<td>933</td>
</tr>
<tr>
<td>9</td>
<td>11.402</td>
<td>855</td>
<td>874</td>
<td>945</td>
</tr>
<tr>
<td>10</td>
<td>12.800</td>
<td>871</td>
<td>886</td>
<td>951</td>
</tr>
<tr>
<td>TOP</td>
<td>13.520</td>
<td>878</td>
<td>895</td>
<td>957</td>
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</table>
Table III (Cont'd)

SIEX OUTPUT

<table>
<thead>
<tr>
<th>TIME</th>
<th>9.5S PEAK BURN UP</th>
<th>221A.</th>
<th>SIEX TEST CASE NO. 1 -- ALL DEFAULT USER OPTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AXIAL SEGMENT NUMBER</td>
<td>DIST FROM BOTTOM OF FUEL, IN</td>
<td>FUEL EQUIVALENT ZONE RADIUS, INCHES</td>
<td>EQUIVALED TEMPERATURE, DEG C</td>
</tr>
<tr>
<td>1</td>
<td>0.676</td>
<td>0.675</td>
<td>1570.0</td>
</tr>
<tr>
<td>2</td>
<td>2.026</td>
<td>0.711</td>
<td>1570.0</td>
</tr>
<tr>
<td>3</td>
<td>3.740</td>
<td>0.736</td>
<td>1570.0</td>
</tr>
<tr>
<td>4</td>
<td>4.752</td>
<td>0.750</td>
<td>1570.0</td>
</tr>
<tr>
<td>5</td>
<td>6.084</td>
<td>0.757</td>
<td>1570.0</td>
</tr>
<tr>
<td>6</td>
<td>7.436</td>
<td>0.758</td>
<td>1570.0</td>
</tr>
<tr>
<td>7</td>
<td>8.783</td>
<td>0.752</td>
<td>1570.0</td>
</tr>
<tr>
<td>8</td>
<td>10.140</td>
<td>0.740</td>
<td>1570.0</td>
</tr>
<tr>
<td>9</td>
<td>11.492</td>
<td>0.719</td>
<td>1570.0</td>
</tr>
<tr>
<td>10</td>
<td>12.844</td>
<td>0.690</td>
<td>1570.0</td>
</tr>
</tbody>
</table>
### Table III (Cont'd)

#### SIEX OUTPUT

<table>
<thead>
<tr>
<th>TIME</th>
<th>PEAK BURN UP</th>
<th>RADIUS (INCHES)</th>
<th>RADIUS (OUTER RADIUS)**2</th>
<th>2214.</th>
<th>SBIEX TEST CASE NO.1 — ALL DEFAULT USER OPTIONS</th>
<th>PAGE 8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.097</td>
<td>0.087</td>
<td>0.077</td>
<td>0.068</td>
<td>0.059</td>
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<tr>
<td></td>
<td></td>
<td>0.000</td>
<td>0.010</td>
<td>0.040</td>
<td>0.040</td>
<td>0.010</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SEG</th>
<th>INCH</th>
<th>TEMPERATURE (FAHRENHEIT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.676</td>
<td>1550, 1910, 2200, 2600, 2900, 3114, 3203, 3397, 3456, 3491</td>
</tr>
<tr>
<td>2</td>
<td>2.028</td>
<td>1500, 1910, 2325, 2722, 3008, 3245, 3425, 3540, 3595, 3595</td>
</tr>
<tr>
<td>3</td>
<td>3.389</td>
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<td>1622, 2026, 2429, 2805, 3070, 3301, 3410, 3503, 3531, 3532</td>
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Table III (Cont'd)

SIEX OUTPUT

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SIEX TEST CASE NO. 1 -- ALL DEFAULT USER OPTIONS

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<th>DIST FROM BOT FUEL</th>
<th>GENERATED FISSION GAS</th>
<th>- VOLUME OF FISSION GAS RELEASED</th>
<th>RETAINED FISSION GAS</th>
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<td>0.01</td>
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<td>0.03</td>
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PERCENT FISSION GASReleased: 18.77

VOLUME OF RELEASED FISSION GAS: 0.57 (CC AT STP)

VOLUME OF SORBED GAS: 1.40 (CC AT STP)

VOLUME OF WATER VAPOR: 1.96 (CC AT STP)

EFFECTIVE PLENUM VOLUME: 5.71 (CC AT 20 DEG C)

VOLUME OF FILL GAS: 5.32 (CC AT STP)

PLENUM PRESSURE: 50. (PSIG)

EXTERNAL PRESSURE: 35. (PSIG)

MOLES OF HELIUM: 2.11E-04

MOLES OF TELLURIUM: 4.97E-05

MOLES OF KRYPTON: 2.46E-06

MOLES OF NITROGEN: 6.26E-06

MOLES OF ARGON: 6.26E-07
### Table III (Cont'd)

#### SIEX OUTPUT

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<th>TIME (SEC)</th>
<th>9.95 PEAK BURN UP</th>
<th>221a</th>
<th>SIEX TEST CASE NO.1 — ALL DEFAULT USER OPTIONS</th>
<th>PAGE 6</th>
</tr>
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<tr>
<td>AXIAL GEMENT NUMBER</td>
<td>FLUENCE MEV/CM²</td>
<td>CLADDING SHELLING %</td>
<td>CLAD OUTER RADIUS, INCH</td>
<td>FUEL OUTER RADIUS, INCH</td>
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### Table III (Cont'd)

**SIEX OUTPUT**

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<td>TANGENTIAL AXIAL EFFECTIVE</td>
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IV. MATHEMATICAL MODELS

FSINTR: FUEL TEMPERATURE CALCULATIONS

The FSINTR subroutine computes the steady state radial temperature distribution of the fuel material of a cylindrical fuel rod. The method uses the integral of the thermal conductivity. This allows for temperature-dependent thermal conductivity and densification (conductivity and fuel geometry changes). The theoretical basis has been documented in Reference 2, and is reviewed here for completeness. Also presented is the currently used fuel thermal conductivity equation and the method used to incorporate it into the code.

The temperature, T, within the fuel is assumed to be described by the steady state heat conduction equation

$$\nabla \cdot (k \nabla T) = - q$$

k = conductivity (temperature dependent)
q = the volumetric heat generation rate.

In cylindrical coordinates for axial symmetry and long cylinders (no axial heat transfer), this becomes

$$\left[ \frac{1}{r} \frac{\partial}{\partial r} (rk \frac{\partial T}{\partial r}) \right] = - q(r)$$

Let \( r_o \) and \( r_m \) be defined as in Figure 5, multiply (1) by r and integrate from \( r_m \) to some radius r. We then have

$$rk \frac{\partial T}{\partial r} = - \int_{r_m}^{r} cq(\zeta)d\zeta$$

(2)

Dividing (2) by r and integrating from r to \( r_o \) we have

$$\int_{r}^{r_o} k dt = - \int_{r}^{r_o} \frac{1}{\xi} \int_{r_m}^{\xi} cq(\zeta)d\zeta d\xi$$

(3)

If we can assume \( q(\zeta) \) is a constant within an annular ring, we can perform the integration in (3) and obtain the following:
FIGURE 5
FUEL AND CLADDING HEAT TRANSFER GEOMETRY

- OUTER CLADDING RADIUS, $r_o$
- INNER CLADDING RADIUS, $r_i$
- OUTER FUEL RADIUS, $r_f$
- COLUMNAR GRAIN GROWTH RADIUS, $r_g$
- CENTRAL VOID FORMED BY DENSIFICATION, $r_c$
- FABRICATED CENTRAL VOID, $r_m$
Figure 6. FSINTR Flow Chart
Routines Associated with the Fuel Thermal Conductivity.

No flow charts are provided for these routines because of their simplicity.

S: Evaluation of the integral of the fuel thermal conductivity.

The thermal conductivity equation is of the form:

\[ K_f = K_D \left[ \frac{1}{K_1 + K_2 x T} + K_3 x T^3 \right] \]

where \( K_f \) = thermal conductivity, w/cm\(^{-1}\)°K
\( K_D \) = \( K_f \) x \( P \) x \( (1. + (1. + 10.x(1-P)) \times (1-P))^{-1} \)
\( T \) = temperature, °K
\( P \) = fraction of theoretical density
\( K_p, K_1, K_2, K_3 \) are coefficients in the equation.

The SIEX program requires that this be integrated with respect to \( T \), resulting in:

\[ \int K_f dT = K_D \left[ \frac{\ln(K_f + K_2 x T) + .25K_3 x T^4}{K_2} \right] \] (6)

This function, \( S \), is programmed to evaluate Equation (6). A call to SINPUT calculates the density dependent coefficients. These then are used to compute a table of values for \( \int k_{dt} \) at every 200°C for use in the table interpolation routine to be described in the next section.

T: Routine to find a value of temperature given a value for \( \int k_{dt} \).

The routine uses simple linear interpolation between values of \( T \) and \( \int k_{dt} \) at intervals of 200°C. A routine to numerically find the inverse of Equation (6) could be provided if the increased accuracy is desired.

RFIND: Routine to find a radius corresponding to a given temperature.

In order to find restructuring and melt radii, it is necessary to find the inverse of Equation (5), i.e., given \( T, S_0, q \), find a value of \( r \). The numerical solution is simply the Newton-Raphson method (reference 3). To put Equation (5) in the proper form, we evaluate \( \int k_{dt} \) at the desired temperature to obtain the quantity \( S_T \). We then have

\[ 4(S_T - S_0)/q = r_o^2 - r^2 - 2r_m \ln (r_0/r). \] (7)
Define \( T = r_0^2 - 4(S_T - S_o)/q \),
then (7) reduces to
\[
0 = r^2 + 2r_m^2 \ln (r_o/r) - T
\]
which can be solved for \( r \) numerically.

CSINTR: Computes coolant temperature and cladding temperature distributions.

The increase in coolant temperature along the pin is computed by adding the heat deposited in the coolant at each axial node. The amount of heat passing into the coolant from each axial segment is:
\[
q_x \Delta T_c = q_x (r_0^2 - r_m^2)
\]
where \( q_x = q_x \pi (r_0^2 - r_m^2) \) the linear heat rate at the pin surface evaluated at the center of each element

\[
h = \text{the element length},
\]
thus causing a change in temperature given by:
\[
\Delta T_c = q_x h / (C_p M_F)
\]
where \( C_p = \text{the heat capacity} \)
\( M_F = \text{the coolant mass flow rate}. \)

Each of these temperature increases are accumulated over the length of the fuel pin. The SIEX code considers the mass flow rate* as uniform around and along the pin.

The temperature increase across the thin film of coolant immediately adjacent to the cladding is simply given by applying the definition of a heat transfer coefficient, i.e.,
\[
\Delta T = \frac{q_x}{AH}
\]
where \( H = \text{the film coefficient} \)

\( A = \text{the surface area per unit length}; \)
or, to compute the outer cladding temperature
\[
T_o^c = T_c + \frac{q_x}{2\pi r_0^2 H}
\]

*Mass flow rates for EBR-II subassemblies are obtained from COBRA analyses.
where $T^c_0$ = the outer cladding temperature

$T_c$ = the coolant temperature

$r^c_0$ = the outer cladding radius.

The cladding temperature distribution is calculated using Equation (1) with $q$ set equal to zero; viz.,

$$\frac{1}{r} \frac{a}{ar} \left( r k \frac{aT}{ar} \right) = 0$$

or

$$\frac{a}{ar} \left( \frac{Q}{r} \right) = 0$$

where $Q = -k \frac{aT}{ar}$ is the heat flux vector.

Integrating from $r^c_0$ to $r$, we have

$$- k \frac{aT}{ar} = \frac{r^c}{o} \frac{Q_0}{r}$$

Integrating again, we obtain

$$T = T^c_0 + \frac{r^c}{o} \frac{Q_0}{k} \ln \left( \frac{r}{r^c_0} \right)$$

(11)

SIEX uses this equation to compute the inner cladding surface temperature when: $T^c_0$, $k$, $r^c_0$, and $q_\ell$ (the linear heat rate) are given. Now $Q_0 = q_\ell / 2\pi r^c_0$, so that the SIEX application of (11) is

$$T^c_i = T^c_0 + \frac{q_\ell}{2\pi k r^c_0 c} \ln \left( \frac{r^c_i}{r^c_0} \right)$$

Figure 7 shows the CSINTR logical flow.

CDELD: Computation of Dimensional Changes of the Cladding Material.

The thermal expansion of the cladding is computed from an input linear function of temperature; that is, the change in the radius of the cladding is given by:

$$\Delta L/L = (\alpha^c_0 + \alpha^c_T) \left( T - T_R \right)$$
FIGURE 7
CSINTR FLOW CHART

CSINTR

CALCULATE FREQUENTLY USED QUANTITIES

DO TO 10 FOR NUMBER OF SEGMENTS

COMPUTE THE COOLANT TEMPERATURE INCREASE

COMPUTE THE TEMPERATURE DROPS ACROSS THE FILM AND CLADDING

COMPUTE THE CLADDING INSIDE AND OUTSIDE TEMPERATURES

10 CONTINUE

RETURN
where $a^c_0$ and $a^c_T$ are input quantities, $T_R$ is room temperature, $T$ is the average cladding temperature, and $\Delta L/L$ is the fraction of length change.

Three functions are currently programmed into the code to compute the cladding swelling, depending on cladding material type. For annealed stainless steel Type 304 (Reference 4),

$$%\Delta V/V_c = A(\phi t)^m + B$$

where

$$A = 2.65 \times 10^{-8}a_3^3 - 1.54 \times 10^{-5}a^2 + 2.24 \times 10^{-3}$$

$$B = \frac{0.2[1 - \exp(-1.12 \phi t)]}{[1 + \exp(0.1 \times (T - 480))]}$$

$$m = 0.872 + 2.98 \times 10^{-3}T$$

$$a = T - 348$$

$T$ = Temperature, °C

$\phi t$ = Fluence, neutrons/cm² $\times 10^{-22}$ ($E > 0.1$ MeV)

$%\Delta V/V_c$ = % swelling.

For annealed stainless steel Type 316 (Reference 4),

$$%\Delta V/V_c = f(T)\{\phi t\}^{N(T)}$$

where

$$f(T) = \left\{\frac{\exp(C)}{1 + \exp(C)}\right\} \left\{\frac{0.02}{(1 + \exp(A)) + (1 + \exp(B))}\right\}$$

$$N(T) = \left\{2 + 3 \exp(D)\right\}/\left\{1 + \exp(D)\right\}$$

$$A = 0.05 (T - 600)$$

$$B = 0.06 (T - 460)$$

$$C = 0.09 (T - 340)$$

$$D = 0.05 (T - 475)$$

$%\Delta V/V_c$ = % swelling

$T$ = Temperature, °K

$\phi t$ = Fluence, neutrons/cm² $\times 10^{-22}$ ($E > 0.1$ MeV)
And for 20% cold-worked stainless steel Type 316
\[
\% \Delta V/V_c = f(T) \left\{ \phi t \right\} N(T)
\]
where
\[
f(T) = \left\{ \frac{\exp(C)/(1 + \exp(C))}{(1 + \exp(A)) + (1 + \exp(B))} \right\}
\]
\[
N(T) = \left\{ \frac{2 + 3. \exp(D)}{1 + \exp(D)} \right\}
\]
\[
A = 0.05 (T - 600)
\]
\[
B = 0.06 (T - 460)
\]
\[
C = 0.09 (T - 340)
\]
\[
D = 0.05 (T - 475)
\]
\[
\% \Delta V/V_c = \% \text{ swelling}
\]
\[
T = \text{Temperature, } ^\circ K
\]
\[
\phi t = \text{Fluence, neutrons/cm}^2 \times 10^{-22} \ (E > 0.1 \text{ MeV}).
\]
The cladding radius is then computed by
\[
r'_c = r'^c \times (1 + \Delta L/L) \times (1 + \Delta V/3V)
\]
where \( r'^c \) is the fabricated dimension.

**FDELD: Computation of Fuel Dimensional Changes**

The fuel thermal expansion is computed by finding the volumetric average radial displacement. At each node, the displacement is computed using the coefficient of thermal expansion given by:
\[
\alpha^f = \alpha^f_0 + \alpha^f_T \times T
\]
where \( \alpha^f_0 \) = Coefficient of thermal expansion, cm/cm-°C
\[
T = \text{Temperature, } ^\circ C.
\]
The volumetric average thermal expansion is then computed by
\[
\frac{\Delta D}{D} = \frac{\int \Delta D/D \ r dr}{\int r dr}
\]
\[
= \frac{\int_0^r \alpha^f_T r \ dr}{r_c} = \frac{\int_0^r \alpha^f_T r \ dr}{1/2(r^2_c - r^2_c)}
\]
\[
\text{(13)}
\]

36
The integration in (13) is performed numerically by using the trapezoidal rule.

The fuel swelling, \( \Delta D_S \), is supplied by the empirical routine FSWEL which will be discussed in Section III. The fuel radius at operating conditions is then computed by using:

\[
\displaystyle r_f' = (r_0 + \Delta D_S) \times (1 + \frac{\Delta D}{D})
\]

(14)

where \( r_f' \) is the "hot" fuel radius.

PPRES: Computation of Plenum Pressure.

The source of gases which can contribute to a rise in plenum pressure are assumed to be:

- fill gas brought to operating conditions, \( V_f^* \)
- sorbed gases in the fuel, \( V_S \)
- water vapor in the fuel, \( V_W \)
- released fission product gases, \( V_R \)

The pressure is then computed by:

\[
\displaystyle P_p = \frac{(V_f + V_S + V_W + V_R) \times T_c \times P_{atm}}{273 \times V}
\]

(15)

where

- \( T_c \) = The coolant outlet temperature, \(^0\text{K}\)
- \( P_{atm} \) = One atmosphere of pressure
- \( V \) = The effective plenum volume.

The effective plenum volume, sorbed gas, and water vapor are input quantities. The volume of released gaseous fission products is supplied from the FISGAS routine which contains a correlated fission gas release model.

* This volume is computed from the "Effective Plenum Length" and taken to be at 1 atm at 20\(^\circ\)C.
V. CORRELATED MODELS

This section describes those portions of SIEX which are correlations to data obtained from Hanford Engineering Development Laboratory (HEDL) fuel pins irradiated in EBR-II. The power-burnup range is shown in Figure 8. The data set contains a wide range of fuel densities, three types of cladding material (annealed 304 SS, annealed 316 SS, and 20% CW 316 SS), and two fuel fabrication methods (pressed and preslugged).

The measurements of concern are:
- Postirradiation fuel-cladding gap
- Fuel columnar grain growth radius
- Fuel equiaxed grain growth radius
- Fission gas present in the plenum region
- Axial location of incipient melting (P-19), See reference 5

Figure 9 shows the interaction of these measured quantities and the models to be developed. Each of the correlations will be discussed individually and in some detail, but physically the interaction of correlations and the sequence of the correlations are important. Data are transferred to the right and upward to complete a correlation. Once a model has been developed and correlated, it is used in subsequent model development replacing the data from which it was derived. To ensure a consistent data set, only data from fuel pins for which \( ^{148} \text{Nd} \) burnup analysis was available were used. The time average power for each pin was then calculated* in a consistent manner and adjusted to the energy assumed deposited in the fuel element.**

* For EBR-II pins the following constants were used:

<table>
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<tr>
<th></th>
<th>Average Fission Cross-Section</th>
<th>Nd-148 Fission Yields</th>
<th>Total Energy Per Fission Deposited in the Reactor</th>
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<td>(Reference 35)</td>
<td>(Reference 36)</td>
<td>(Reference 37)</td>
</tr>
<tr>
<td>U-235</td>
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<tr>
<td>Pu-239</td>
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</tr>
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</table>

**Based on Reference 33, it was assumed the energy deposited in an element was 9.2 MeV/fission less than the total energy deposited in the reactor core, blanket, and reflector.
FIGURE 8. DATA FIELD FOR POSTIRRADIATION FUEL-CLADDING GAP CORRELATION
DATA

RESIDUAL GAP (232 SECTIONS)

POWER-TO-MELT (P-19, 26 MELT POSITIONS)

COLUMNAR AND EQUIAXED RADII (208)

FISSION GAS MEASUREMENT (76 PINS)

MODEL

REGRESSION

GAP CLOSURE

\( \Delta G = \Delta G(P, B, C, G) \)

GAP CONDUCTANCE

RESTRUCTURING MODELS

FISSION GAS RELEASE MODEL

CORRELATED THERMAL PERFORMANCE MODEL

HEDL 7408-83.1

FIGURE 9. DATA INTERACTION AND USAGE FOR SIEX CORRELATIONS
FSWEL: Residual Gap Correlation

It is necessary to predict the fuel-cladding hot gap in order to accurately predict the fuel-cladding heat transfer coefficient. It is assumed that the postirradiation fuel-cladding gap (as measured from postirradiation metallography) along with the differential thermal expansion can be used for calculating the hot fuel-cladding gap during the irradiation of a mixed-oxide fuel pin. A similar analysis is presented in Reference 6.

Detailed analysis of the fuel deformation mechanisms can be accomplished with the LIFE (Reference 7) and PECT codes. In these cases, running times are long because a small time step is required to solve the rate equations. In keeping with the philosophy of SIEX being a faster running code, a correlation to postirradiation gap data is used.

The data for postirradiation fuel-cladding gap were measured from 75X photomosaics of transverse fuel pin cross-sections, in the as-polished condition. Measurements were taken at four equally spaced angles, as shown in Figure 10. These four measurements were then averaged to provide an effective postirradiation diametral fuel-cladding gap.

The correlation was developed by regression analysis of 232 averaged residual gap measurements using the computer code REEP (Reference 8). The model is assumed to be dependent on local linear heat rate, local burnup, fabricated gap, and the number of reactor cycles. The correlation is of the form

\[
G' = G \left\{ 1 - a(1 - \exp(-G_3 x C)) + G_4 (1 - \exp(-G_5 x q_x x B)) + (G_6 - a)(1 - \exp(-G_7 x B)) \right\}
\]

(16)

Where

- \( G' \) = The "cold" postirradiation diametral gap, cm
- \( G \) = Fabricated fuel-cladding gap, cm
- \( a \) = \( G_1 x q_x x (q_x - G_2) \)
- \( q_x \) = Local linear heat rate, kW/ft
- \( B \) = Local burnup, MWD/kg
- \( C \) = Number of full power reactor cycles
- \( G_1 \) through \( G_7 \) are fitting coefficients
MEASUREMENT LOCATION

AS-FABRICATED FUEL SURFACE

FIGURE 10. POST IRRADIATION GAP MEASUREMENT

LINEAR HEAT RATING ≈ ≈ 12.2 kw/ft
BURNUP ≈ 57 MWd/kg
FABRICATED GAP = 5.7 mils
POST IRRADIATION GAP = 4.2 mils
The quality of fit to data is shown in Figure 11, along with the approximate variance of the data (root mean squared deviation). Other parameters which might influence the residual gap observed in a fuel pin were investigated, namely cladding material, fuel geometry, pellet fabrication method, and pin diameter. In each of the above cases, no significant contribution of the variable to residual gap could be found.

Figure 12 demonstrates the model behavior under certain hypothetical conditions. Three power levels for a 6 mil diametral gap pin were used to evaluate equation (16) as a function of burnup and the number of cycles. The cyclic behavior and indeed the majority of the gap closure, occurs during the early operating life of the fuel element. Although the imposed cyclic behavior of one cycle every MWd/kg is arbitrary, it is typical of conditions experienced by the fuel elements in the data set.

HGAP: Fuel-Cladding Gap Conductance

The SIEX gap conductance is a simplification of the Ross-Stoute gap conductance model similar to those models presented in References 9 and 10. Certain procedures of the model have been simplified for efficiency and because there is a lack of precise input values for some of the constants. The gap conductance model has three identified parameters which have been adjusted by calibrating to postirradiation observation of fuel pin performance, namely observations of melt locations in the P-19 experiment (Reference 5).

The model considers three components contributing to the heat transfer across the fuel-to-cladding gap. When the fuel and cladding are not in contact, the mechanisms are radiant heat transfer and heat conduction through the gas in the fuel-cladding gap. If the fuel and cladding come into contact, the third component, solid-solid conduction at points along the fuel-cladding interface is used. In this case, there is still heat transfer through "pockets" of gas trapped between the points of contact. Schematic representations of the geometry in these two cases are shown in Figure 13.
FIGURE 11. POSTIRRADIATION DIAMETRAL FUEL-CLADDING GAP CORRELATION
FIGURE 12. FUEL-CLADDING POSTIRRADIATION GAP MODEL
FIGURE 13. FUEL-CLADDING HEAT TRANSFER SCHEMATIC
Radiant Heat Transfer

The radiant heat transfer relationship for two concentric cylinders can be written as: (Reference 11)

\[ \frac{q_x}{A_f} = \sigma \left[ \frac{1}{T_f} + \frac{1}{T_c} - 1 \right] \frac{A_f}{A_c} \left( \frac{1}{e_f} - \frac{1}{e_c} \right) -1 \left[ T_f^4 - (T_c^4) \right] \] (17)

where \( T_f \) and \( T_c \) are the fuel and cladding temperatures (°K), \( A_f \) and \( A_c \) the heat transfer areas per unit length, \( e_f \) and \( e_c \) their respective emissivities, and \( \sigma \) the Stefan Boltzman constant. If the gap coefficient is defined as:

\[ H_r = \frac{q_x}{T_f - T_c} \]

and is substituted into equation (17), the following expression is obtained:

\[ H_r = \sigma \left[ \frac{1}{e_f} + \frac{A_f}{A_c} \left( \frac{1}{e_c} - 1 \right) \right] \left[ T_f^2 + (T_c^2) \right] \left[ T_f + T_c \right] \] (18)


The gas gap conductance of Ross and Stoute (Reference 12) is given by:

\[ H_{gas} = \frac{k_m}{C \left( r_f + r_c \right) + (g_f + g_c) + GAP} \] (19)

where \( k_m \) = the conductivity of the gas mixture in the fuel-cladding gap
\( GAP \) = fuel-cladding hot gap
\( g_f, g_c \) = the temperature jump distances to be described below
\( C (r_f + r_c) \) = a term dealing with the fuel and cladding surface roughness
\( C \) = a fitting parameter.

The temperature jump distances, \( g_f \) and \( g_c \), represent temperature increases at the fuel and cladding surfaces as a result of incomplete energy interchanges between the surfaces and the gas (Reference 13) and can be written as:

\[ g' = \frac{2 - a}{a} \left( \frac{2 \pi R_m T}{(Y + T) C_v p_p} \right)^{1/2} \]

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where $a = \text{accommodation coefficient reflecting the extent of energy transfer}$

$R_m = \text{the gas constant for the mixture}$

$p_P = \text{the gas pressure of the gap}$

$\gamma = \text{ratio of } C_p/C_v$

$T = \text{temperature at the fuel surface for } g_f \text{ or at the cladding surface for } g_c$

$C_v = \text{specific heat at constant volume for the mixture.}$

$g'$ is to be evaluated at both the fuel and cladding surfaces to produce $g_f + g_c$. This expression was simplified by combining terms and making assumptions about the behavior of the variables. Factoring and combining terms, we obtain:

$$g_f + g_c = \frac{2 - a}{a} \frac{\sqrt{2\pi R_m}}{(1 + \gamma) C_v p_P} \left( k_m \sqrt{T_f} + k_m \sqrt{T_c} \right)$$

If it is assumed that the last term can be replaced by: $2k_m \sqrt{T}$ where $T = 0.5(T_f + T_c)$ and $k_m$ is $k_m$ evaluated at $T$, the expression reduces to:

$$g_f + g_c = 2 \frac{2 - a}{a} \frac{\sqrt{2\pi R_m}}{1 + \gamma C_v p_P} k_m \sqrt{T}$$

We now substitute the following known values and approximations:

$2\pi = 6.2832$

$(1 + \gamma) = 1.659$

$R_m = 8.308/\bar{W}$

$C_v = 2.988/\bar{W}$

$\bar{W}$ is the atomic weight of the mixture

The following expression is obtained:

$$g = (g_f + g_c) = 1373 \left( \frac{2 - a}{a} \right) \frac{k_m \sqrt{T}}{p_P}, \text{ cm}$$

**Solid to Solid Heat Transfer Component**

Ross and Stoute (Reference 12) have suggested that the solid to solid heat transfer coefficient be written as:

$$H_s = k_s A_o x r^{1/2} H, \text{ W/cm}^2 - \text{°C}$$

where $k_s = 2K^c x K^f/(K^c + K^f)$, the effective solid conductance, W/cm - °C
\[
\begin{align*}
    r &= \left( \frac{r_c^2 + r_f^2}{2} \right)^{1/2}, \text{ the root mean squared roughness, cm} \\
    P &= \text{ the interfacial pressure, dynes/cm}^2 \\
    H &= \text{ the Meyer hardness, dynes/cm}^2 \\
    A_0 &= \text{ a constant used in fitting, cm}^{1/2}
\end{align*}
\]

Simplification of this expression was accomplished by substituting into the expression the values for the roughness term and Brinell hardness* (Reference 14), which was assumed to be proportional to the yield strength, to obtain:
\[
H_s = A \times K_s \times P/Y
\]

where \( Y \) is the cladding yield strength and \( A \) is a parameter to be determined by data correlation and includes the yield strength at room temperature, \( A_0 \), \( r_1^{1/2} \), and the Brinell hardness.

Gas Conductivity

The fuel-cladding gas gap is assumed to be filled with a mixture comprised of helium, nitrogen, argon, xenon, and krypton. Data for gas component conductivities are analysed using standard regression techniques to obtain a quadratic of the form \( k_i = A_i + B_i T + C_i T^2 \), where \( T \) is in °C. The coefficients thus derived are given in Appendix B. From these component conductivities a gas mixture conductivity is computed using Brokaw's law: (Reference 15)
\[
k_m = 0.5 \left( \sum x_i k_i + \frac{1}{\sum x_i/k_i} \right)
\]

where \( x_i \) is the molar fraction of the \( i \)th component.

Accommodation Coefficient

An expression relating the accommodation coefficient to the atomic weight of a gas was derived by regression techniques to the values presented in Reference 16. The expression is of the form:
\[
a = A_1 \exp \left( -\left[ \ln(\bar{W}) - A_2 \right]^2/A_3 \right).
\]

The accommodation coefficient is then based on the average molecular weight of the mixture, \( \bar{W} \), which was discussed previously and \( A_1 \), \( A_2 \) and \( A_3 \) which are fitting coefficients.

* Because of lack of Meyer hardness data this is taken to be the Brinell hardness
Calculation of Interface Pressure

The interface pressure calculation is computed as if only elastic deformation occurs. If, as is shown in Figure 14, the fuel outer radius exceeds the cladding inner radius by $\Delta r$, it is assumed that the cladding and fuel deform elastically by this amount. For the derivation of the interface pressure the following symbols are defined:

$\sigma^c_r, \sigma^c_\theta =$ cladding radial and hoop stresses at $r_{fc}$
$\sigma^f_r, \sigma^f_\theta =$ fuel radial and hoop stresses at $r_{fc}$
$\epsilon^c_r, \epsilon^c_\theta =$ cladding radial and hoop strains at $r_{fc}$
$\epsilon^f_r, \epsilon^f_\theta =$ fuel radial and hoop strains at $r_{fc}$
$E_f, E_c =$ fuel and cladding Young's Moduli
$\nu^f_c =$ fuel and cladding Poisson's radios
$P_p =$ plenum pressure
$P_e =$ external cladding pressure
$P =$ interface pressure
$r_{fc} =$ fuel-cladding interface radius
$r_f =$ fuel inner radius
$r_c =$ cladding outer radius
$\Delta r =$ fuel-cladding interference.

For the radial stress relationships we have from Reference 17.

$$\sigma^c_r = \frac{E^c}{1 - (\nu^c)^2} \{\epsilon^c_r + \nu^c_\theta \epsilon^c_\theta\} = -P \text{ at } r_{fc} \quad (1p)$$

$$\sigma^f_r = \frac{E^f}{1 - (\nu^f)^2} \{\epsilon^f_r + \nu^f_\theta \epsilon^f_\theta\} = -P \text{ at } r_{fc} \quad (2p)$$
FIGURE 14. ELASTIC FUEL-CLADDING MECHANICAL INTERACTION SCHEMATIC
For the hoop stress relationships

$$\sigma_{\theta} = \frac{E^c}{1 - (v^c)^2} \left\{ \epsilon_{\theta} + v^c \epsilon_r \right\} = \frac{p(r_c^2 + r_{fc}^2)}{(r_c^2 - r_{fc}^2)} + \frac{2p r_c^2}{r_c^2 - r_{fc}^2}$$

$$\sigma_{\theta} = \frac{E^f}{1 - (v^f)^2} \left\{ \epsilon_{\theta} + v^f \epsilon_r \right\} = -p\left( \frac{r_{fc}^2 + r_f^2}{r_{fc}^2 - r_f^2} \right) + \frac{2p p_f^2}{r_{fc}^2 - r_f^2}$$

$$\epsilon^c_{\theta} - \epsilon^f_{\theta} = \Delta r/r$$

Solving (3p) for $$\epsilon^c_r$$

$$\epsilon^c_r = \frac{p(r_c^2 + r_{fc}^2)(1 + (v^c)^2)}{(r_c^2 - r_{fc}^2)v^c E^c} - \epsilon^c_{\theta}/v^c + \frac{2p r_c^2(1 + (v^c)^2)}{(r_c^2 - r_{fc}^2)v^c E^c}$$

Solving (4p) for $$\epsilon^f_r$$

$$\epsilon^f_r = \frac{- p(1 + (v^f)^2)(r_{fc}^2 + r_f^2)}{v^f E^f(r_{fc}^2 - r_f^2)} - \epsilon^f_{\theta}/v^f + \frac{2p p_f^2(1 + (v^f)^2)}{(r_{fc}^2 - r_f^2)v^f E^f}$$

Substituting (6p) and (7p) in (1p) and (2p), we have

$$-p = \frac{p(r_c^2 + r_{fc}^2)}{v^c(r_c^2 - r_{fc}^2)} - \frac{E^c}{1 - (v^c)^2} \left( \frac{E^c}{\epsilon_{\theta}} - \epsilon^c_{\theta} \right) + \frac{2p r_c^2}{(r_c^2 - r_{fc}^2)v^c}$$

or

$$-p = \frac{p(r_c^2 + r_{fc}^2)}{v^c(r_c^2 - r_{fc}^2)} - \frac{E^c}{v^c} \epsilon^c_{\theta} + \frac{2p r_c^2}{(r_c^2 - r_{fc}^2)v^c}$$

and

$$-p = \frac{-p(r_{fc}^2 + r_f^2)}{v^f(r_{fc}^2 - r_f^2)} - \frac{E^f}{v^f} \epsilon^f_{\theta} + \frac{2p p_f^2}{(r_{fc}^2 - r_f^2)v^f}$$
The preceding equations can be written as

\[
e^C = \frac{v^C + \left( \frac{r^2_c + r^2_{fc}}{r^2_c - r^2_{fc}} \right)}{P/E^C} \left[ \frac{2P}{E^C} \left( \frac{r^2_c - r^2_{fc}}{r^2_c - r^2_{fc}} \right) \right] \tag{8p}
\]

and

\[
e^f = \frac{v^f - \left( \frac{r^2_{fc} + r^2_f}{r^2_{fc} - r^2_f} \right)}{P/E^f} \left[ \frac{2P}{E^f} \left( \frac{r^2_{fc} - r^2_f}{r^2_{fc} - r^2_f} \right) \right] \tag{9p}
\]

Subtracting (9p) from (8p)

\[
e^C - e^f = \left[ v^C + \frac{r^2_c + r^2_{fc}}{r^2_c - r^2_{fc}} \right] \left[ \frac{2P}{E^C} \left( \frac{r^2_c - r^2_{fc}}{r^2_c - r^2_{fc}} \right) - v^f \right] \frac{E^C}{E^f} \frac{P}{E^C}
\]

\[
+ \left[ \frac{2P}{E^C} \left( \frac{r^2_c - r^2_{fc}}{r^2_c - r^2_{fc}} \right) \right] \frac{E^C}{E^f} \frac{P}{E^C}
\]

or solving for \( P \) and substituting (5p)

\[
P = \left\{ \frac{\Delta r}{r} E^C + 2 \left[ \frac{P}{r^2_c - r^2_{fc}} + \frac{P}{r^2_{fc} - r^2_f} (E^C/E_f) \right] \right\} v^C + \frac{r^2_c + r^2_{fc}}{r^2_c - r^2_{fc}} \left[ \frac{E^C}{E_f} \right] \tag{10p}
\]

The thermal stress contribution has been neglected for these calculations because for extended steady state operation it can be shown that it relaxes to nearly zero due to creep mechanisms.

The pressure calculated by (10p) is limited to the pressure which would cause cladding yield.

**Fuel to Cladding Heat Transfer Correlation**

The gap conductance calculation was correlated, Figure 15, to data obtained from the P-19 power-to-melt test (Reference 5). The test was designed to provide data necessary to define operating (power) limits for startup conditions. The data provides a well defined indication of fuel temperature (melt location) under
**FIGURE 15. SIEX PREDICTED LINEAR HEAT RATE TO INCIPIENT MELT**

- **SIEX CALCULATED POWER-TO-MELT**
- DATA NORMALIZED TO:
  - INSIDE CLADDING TEMPERATURE = 1060°F
  - PELLET DENSITY = 90.4% OF THEORETICAL
  - FUEL PIN DIAMETER = 0.230 INCHES
conditions of well characterized fuel parameters for various fabricated gap widths. Because of the test design, the data represent early-in-life operating history of a fuel pin, thus eliminating major uncertainties in many of the variables (fuel-cladding gap gas composition, hot gap width, burnup effects on fuel conductivity, etc.). This is suggested as the best possible data set to be used for normalizing fuel pin thermal performance to pins under actual irradiation conditions.

The correlation coefficients A and C (a function of interface pressure) in equations 21 and 19 were adjusted to obtain a "best" fit to the data obtained using a Simplex technique to adjust parameters.

The correlation to well defined data, along with postirradiation gap data and a quasi theoretical model for gap conductance, is used to provide estimates of gap conductance throughout the life of the fuel pin.

Figure 16 shows the HGAP flow chart.

STRUCT: Fuel Microstructure (Restructuring) Correlation

Calculation of fuel microstructure characteristics traditionally has proceeded using two different methods. One is a phenomenological approach in which pore migration and coalescence is accounted for. A version of this method has been programmed into the LIFE code (Reference 7). Another method is to find a temperature at which the microstructure stabilizes to a clearly identifiable characteristic. This is sometimes referred to as a grain growth temperature. Such a temperature may be time-dependent, as was reported by Christensen (Reference 18) or a constant. The grain growth method was selected for use in SIEX for two reasons: first, knowing the locations of the grain boundaries and their densities is sufficient to permit calculation of fuel temperature distribution; second, the phenomenological method requires much longer computer times. This is because the calculations must be performed repeatedly at relatively small time intervals to assure that a balance is accurately kept as pores and gas bubbles move across boundaries.
FIGURE 16. HGAP FLOW CHART
The measurements of fuel microstructure, columnar and equiaxed grain growth radii, were taken from photomosaics at the time the previously mentioned "residual gaps" were measured. The columnar grain growth radius was taken to be the extent of observed lenticular voids and columnar (radial elongation) grains. The equiaxed grain growth radius was identified as the region (extent) where equiaxed grains (non-elongated) did not appear to be separated from each other by gas on the grain boundaries.

Temperatures at which columnar and equiaxed grain growth were observed, were calculated for the measured restructuring radii at several burnup levels. In all cases, the maximum temperature occurred on startup (arbitrary burnup of 60 MWd/MTM). Analysis of the data did not show a time dependence of the temperatures used for the prediction of fuel microstructure. A simple statistical analysis of the data was then performed resulting in a gradient dependent function for the "columnar grain growth" and a constant for the "equiaxed grain growth" temperature.

Figures 17 and 18 show the "quality of fit" of the SIEX prediction of the extents of columnar and equiaxed grain growth.

A flow chart of the STRUCT routine is given in Figure 19. In operation, STRUCT predicts fuel microstructure radii at startup. For each succeeding time step the predicted fuel microstructure is compared with the beginning of life microstructure, and the larger of the two is used. Checks to save computation time are incorporated, i.e., if no restructuring had previously been predicted, the comparison would not be executed.

FISGAS: Fission Gas Release Correlation

The SIEX fission gas release model is similar to that presented in Reference 19. A report describing a model closely resembling that in SIEX has recently been published, see Reference 20.

The mechanisms of fission gas release are bubble migration to the central void and diffusion in the high fuel temperature regions, and release through grain boundaries in medium and lower temperature zones. The model assumptions for this analysis are:

- In the fuel region characterized by grain growth, very little
FIGURE 17. EQUIAXED GRAIN GROWTH CORRELATION
FIGURE 18. COLUMNAR GRAIN GROWTH CORRELATION
FIGURE 19. STRUCT FLOW CHART
of the generated fission gas can be retained because of high temperature and temperature gradients, and consequently there is rapid diffusion and release of the gases.

In the unrestructured region, a considerable amount of the generated gaseous fission products is retained. Release is controlled by a combination of thermal and irradiation-induced diffusion processes.

The fraction of generated gas which is released is then governed by the equation

\[ F = F_r A_r + F_u A_u, \]

where \( F \) is the total fraction released, \( F_r \)'s and \( A_r \)'s are respectively the release fractions and areas of the restructured and unrestructured regions.

When applying this model, the \( A_r \)'s and \( F_r \)'s are evaluated at each axial mode in order to account for axial profiles. Various functional forms of \( F \) were investigated during the data analysis.

The data for fission gas release were obtained from fuel elements irradiated in the EBR-II. The total gas recovered from each pin was measured and the percent fission gas identified by mass spectrometry. In all cases a \(^{148}\text{Nd}\) chemical analysis was available to determine the fuel element burnup.

The data analysis was done using the regression analysis code REEP, and resulted in the following expressions for the fractional releases from each of the zones:

\[ F_r = F_1 + (1. - F_1) \times (1. - F_2 (1. - \exp(-B/F_3))/B) \]

\[ F_u = 0, \quad B < F_5 \]
\[ = 1. - F_4 (1 - \exp(-B - F_5)/F_5)) \exp(-F_6 \times q_f)/B \times F'(B), \quad B \geq F_5 \]

where
\[ B = \text{the local burnup, MWd/kg} \]
\[ q_f = \text{the local linear heat rate, W/cm} \]
\[ F'(B) = 1 \quad B > F_7 \]
\[ = F_8 (B-F_7), \quad B < F_7 \]
The FISGAS routine evaluates the area present in each of the three critical regions, the amount of fission gas generated, and also the fraction of fission gas released according to the previous model, at a user specified number of axial segments. The volume of gas released from each segment is then computed, either from input fractional releases or the correlated model. The volume of gas released from each segment is then accumulated over the length of the fuel pin to determine the total volume of gas released to plenum area. This value is then used to compute a "pin" fraction release. A flow chart for FISGAS is shown in Figure 22.

The SIEX predicted fraction release and measured release fractions are plotted in Figure 20 to demonstrate the quality of fit. Figure 21 is an evaluation of the release rate at three different power levels for a fuel pin similar to that of the input example of Section I as a function of burnup. The latter plot demonstrates the burnup behavior of the gas release model and predicted plenum pressures.
FIGURE 20. FISSION GAS RELEASE CORRELATION
FIGURE 21. FISSION GAS RELEASE VS. BURNUP
FISGAS

COMPUTE WEIGHT OF METAL PER SEGMENT

INITIALIZATION

DO TO 20 FOR THE REQUIRED NUMBER OF AXIAL SEGMENTS

COMPUTE FUEL VOLUMES IN EACH OF THE THREE FUEL REGIONS

IF THE GAS RELEASE MODEL IS USED: COMPUTE RELEASE RATES

COMPUTE THE AMOUNT OF FISSION GAS GENERATED PER SEGMENT

COMPUTE THE VOLUME OF GAS RELEASED PER SEGMENT FROM EACH OF THE REGIONS

COMPUTE THE VOLUME RELEASED PER SEGMENT

COMPUTE RETAINED GAS PER SEGMENT

SUM THE FISSION GAS GENERATED AND RELEASED

20 CONTINUE

COMPUTE PERCENT GAS RELEASE

RETURN

FIGURE 22. FISGAS FLOW
VI. REFERENCES


22. Ibid. (Section A3-205.1)

23. Ibid. (Section A205.5)

24. Ibid. (Section A3-301.2)


31. ENDF/B Nuclear and Cross Section Files, Version 4, Available From Brookhaven National Laboratory.


**APPENDIX A GLOSSARY**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>FORTRAN Equivalent</th>
<th>Description</th>
<th>Code Units</th>
<th>Input/Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_c )</td>
<td>( \text{ALPHAO} )</td>
<td>Cladding mean coefficient of thermal expansion ( (\alpha_c = \alpha_{0} + \alpha_{CT}) )</td>
<td>cm/cm-°C</td>
<td>in/in-°F</td>
</tr>
<tr>
<td>( \alpha_{0} )</td>
<td>( \text{ALPHAS} )</td>
<td>Intercept in the linear equation for the mean coefficient of thermal expansion</td>
<td>cm/cm-°C</td>
<td>in/in-°F</td>
</tr>
<tr>
<td>( \alpha_{CT} )</td>
<td>( \text{BU(I)} )</td>
<td>Slope in the linear equation for the mean coefficient of thermal expansion</td>
<td>cm/cm-°C²</td>
<td>in/in-°F²</td>
</tr>
<tr>
<td>B</td>
<td>( \text{BU(I)} )</td>
<td>Local Burnup</td>
<td>Mwd/kg</td>
<td>MWD/kg</td>
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<tr>
<td></td>
<td>( \text{BU(I)} )</td>
<td>Burnup in an axial segment</td>
<td>Mwd/MTM</td>
<td>MWD/MTM</td>
</tr>
<tr>
<td></td>
<td>( \text{BU(I)} )</td>
<td>Burnup increment in an axial segment</td>
<td>Mwd/MTM</td>
<td>MWD/MTM</td>
</tr>
<tr>
<td></td>
<td>( \text{CCPGM} )</td>
<td>Sorbed gas in fabricated fuel</td>
<td>cc/gm of oxide</td>
<td>cm/gm of oxide</td>
</tr>
<tr>
<td>( T_{ci} )</td>
<td>( \text{CLIDT(I)} )</td>
<td>Cladding inner surface temp.</td>
<td>°C</td>
<td>°F</td>
</tr>
<tr>
<td>( T_o )</td>
<td>( \text{CLODT(I)} )</td>
<td>Cladding outer surface temp.</td>
<td>°C</td>
<td>°F</td>
</tr>
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<td>a</td>
<td>( \text{COEF} )</td>
<td>Accommodation Coefficient</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>( K^C )</td>
<td>( \text{CK} )</td>
<td>Cladding conductivity</td>
<td>W/cm-°C</td>
<td>Btu/hr-ft-°F</td>
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<tr>
<td>( M_F )</td>
<td>( \text{CMF} )</td>
<td>Coolant mass flow rate</td>
<td>gm/sec</td>
<td>lb/hr</td>
</tr>
<tr>
<td>( G^t )</td>
<td>( \text{COLDGP(I)} )</td>
<td>Fuel-cladding radial gap (postirradiation)</td>
<td>cm</td>
<td>inches</td>
</tr>
<tr>
<td>( \text{CRATIO(L)} )</td>
<td></td>
<td>User Specified coolant mass flow rate ratio (for unequal time steps)</td>
<td>--</td>
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<td>( k_i )</td>
<td>( \text{CON} )</td>
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<td>Btu/hr-ft-°F</td>
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<tr>
<td>( c_p )</td>
<td>CP</td>
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<td>W-sec/gm-(^\circ)C</td>
<td>Btu/lb-(^\circ)F</td>
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<td>CY</td>
<td>Number of reactor cycles</td>
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<td>( % A/V_c )</td>
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<td>( r'_c )</td>
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<td>( E_c )</td>
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<td>dynes/cm(^2)</td>
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<td>( E_f )</td>
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<td>Active fuel column length</td>
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<td>( \phi_t )</td>
<td>FLUENCE(I)</td>
<td>Fluence at each axial node (Energy &gt; .1 MeV)</td>
<td>Neutrons/cm(^2)</td>
<td>Neutrons/cm(^2)</td>
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<th>Input/Output Units</th>
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<td>Fluence at each axial node (Energy &gt; .1 MeV)</td>
<td>Neutrons/(\text{cm}^2)</td>
<td>Neutrons/cm²</td>
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<td>Fraction of the sorbed gas which -- is not helium or hydrogen. This gas is assumed to have the physical characteristics of the nitrogen.</td>
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<td>(X_i)</td>
<td>(\text{GMOL(K)})</td>
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<td>Moles or molar fraction</td>
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<td>&quot;Jump&quot; distances for calculation of fuel to cladding heat transfer coefficient</td>
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<td>Btu/hr-ft²-°F</td>
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<td>HG1</td>
<td>Gap conductance correlation coefficient</td>
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<td>Output option selector for geometry changes</td>
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<td>W/cm°C Btu/hr-ft-°F</td>
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<td>MWD/MTM MWD/MTM</td>
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<td>Peak (axial) neutron flux (greater than 0.1 MeV)</td>
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<td>Percent Percent</td>
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<td>Peak linear heat rate Linear heat</td>
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<td>Fuel Poisson's ratio</td>
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<td>Btu/ft³-hr</td>
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<td>Central void radius (restructured)</td>
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<td>Cladding outer radius</td>
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<td>Outer fuel radius</td>
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<td>Btu/hr-ft</td>
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<td>Number of time intervals at which calculations/output is desired</td>
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<td>°C</td>
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<td>gm/cc</td>
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<td>TCG(I)</td>
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<td>Equiv. full power days</td>
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<td>TCG(I)</td>
<td>Calculated weight of metal in the fuel column</td>
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<td>Vr</td>
<td>TOTFGR</td>
<td>&quot;Pin&quot; volume of fission gas released</td>
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<td>cc @ STP</td>
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<td>VFG(I)</td>
<td>TVFGR(I)</td>
<td>Volume of fission gas released in each axial segment</td>
<td>cc @ STP</td>
<td>cc @ STP</td>
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<td>Tf</td>
<td>TZ</td>
<td>Fuel surface temperature</td>
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<td>°F</td>
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<td>Fraction of the metal in the fuel which is 235U</td>
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<td>VFG(I)</td>
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<td>cc @ STP</td>
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<td>VFGR(K,I)</td>
<td>Volume of fission gas released in each region at each axial segment</td>
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<td>cc @ STP</td>
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<tr>
<td>V_f</td>
<td>VOFG</td>
<td>Volume of fill gas</td>
<td>cc @ STP</td>
<td>cc @ STP</td>
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<td>Fabricated fuel central void diameter</td>
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<td>V_s</td>
<td>VSG</td>
<td>Volume of sorbed gas in fuel excluding water vapor</td>
<td>cm @ STP</td>
<td>cc @ STP</td>
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<td>V_w</td>
<td>VWV</td>
<td>Volume of water vapor in fuel</td>
<td>cc @ STP</td>
<td>cc @ STP</td>
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<td>Average molecular weight of the gas in the fuel-cladding gap</td>
<td>gm/mole</td>
<td>gm/mole</td>
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<td>Distance above the bottom of the fuel of the center of each axial segment</td>
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<td>K_s</td>
<td>XKM</td>
<td>Effective solid to solid conductivity</td>
<td>W/cm °C</td>
<td>Btu/hr-ft °F</td>
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<td>K_mm</td>
<td>XKMIX</td>
<td>Conductivity of the gas in the fuel-cladding gap</td>
<td>W/cm °C</td>
<td>Btu/hr-ft °F</td>
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<td>Y</td>
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<td>Cladding yield strength</td>
<td>dynes/cm²</td>
<td>1b/in²</td>
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<td>YMODO</td>
<td>Intercept of the linear expression for cladding Young's modulus</td>
<td>dynes/cm²</td>
<td>1b/in²</td>
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<td>Slope of the linear expression for cladding Young's modulus</td>
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<tr>
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<tr>
<td>$F_c$</td>
<td>Z1</td>
<td>Fraction of produced fission gas released from columnar grain growth region</td>
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<tr>
<td>$F_e$</td>
<td>Z2</td>
<td>Fraction of produced fission gas released from equiaxed grain growth region</td>
<td>--</td>
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<tr>
<td>$F_u$</td>
<td>Z3</td>
<td>Fraction of produced fission gas released from the unrestructured fuel region</td>
<td>--</td>
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APPENDIX B

Material Properties and Correlation

Coefficient Values

Current values used for material properties and correlated model coefficients are given in the following table. These values are programmed into SIEX in the form of data statements located in the routine BLKDAT and transferred to the respective models through the labeled common PARCOM. References and code units are given where appropriate.

TABLE B.1

MATERIAL PROPERTY AND CORRELATION COEFFICIENT VALUES

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<tr>
<th>Model/Parameter</th>
<th>FORTRAN Equivalent</th>
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<td>Cladding Thermal Expansion</td>
<td>(Reference 21)</td>
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<td>$\alpha_0$</td>
<td>ALPHAO</td>
<td>$16.2 \times 10^{-5}$ (cm/cm - °C)</td>
</tr>
<tr>
<td>$\alpha_T$</td>
<td>ALPHAS</td>
<td>$3.79 \times 10^{-9}$ (cm/cm - °C$^2$)</td>
</tr>
<tr>
<td>Cladding Young's Modulus</td>
<td>(Reference 22)</td>
<td></td>
</tr>
<tr>
<td>$E_0^C$</td>
<td>YMODO</td>
<td>$2.12 \times 10^{12}$ (dynes/cm$^2$)</td>
</tr>
<tr>
<td>$E_T^C$</td>
<td>YMODS</td>
<td>$9.2 \times 10^8$ (dynes/cm$^2$ - °C)</td>
</tr>
<tr>
<td>Cladding Poissons Ratio</td>
<td>(Reference 23)</td>
<td></td>
</tr>
<tr>
<td>$\gamma^C$</td>
<td>PNU</td>
<td>.3</td>
</tr>
<tr>
<td>Cladding Thermal Conductivity</td>
<td>(Reference 24)</td>
<td></td>
</tr>
<tr>
<td>$K_0^C$</td>
<td>CK1</td>
<td>$0.133$ (W/cm - °C)</td>
</tr>
<tr>
<td>$K_T^C$</td>
<td>CK2</td>
<td>$1.300 \times 10^{-4}$ (W/cm - °C$^2$)</td>
</tr>
<tr>
<td>Cladding Yield Strength</td>
<td>(Reference 25)</td>
<td></td>
</tr>
<tr>
<td>--</td>
<td>YEO</td>
<td>$4.82 \times 10^{9}$ (dynes/cm$^2$)</td>
</tr>
<tr>
<td>--</td>
<td>YES</td>
<td>$-1.076 \times 10^{7}$ (dynes/cm$^2$ - °C)</td>
</tr>
<tr>
<td>Cladding Emissivity</td>
<td>(Reference 26)</td>
<td></td>
</tr>
<tr>
<td>$\epsilon_C$</td>
<td>EMC</td>
<td>.9</td>
</tr>
<tr>
<td>Property</td>
<td>Value</td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
<td>---------------------</td>
<td></td>
</tr>
<tr>
<td>Fuel Thermal Expansion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha_f^0$</td>
<td>FALFO $6.58 \times 10^{-6}$ (cm/cm °C)</td>
<td></td>
</tr>
<tr>
<td>$\alpha_f^T$</td>
<td>FALFT $3.00 \times 10^{-9}$ (cm/cm °C²)</td>
<td></td>
</tr>
<tr>
<td>Fuel Young's Modulus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_f^0$</td>
<td>YMODFO $2.50 \times 10^{12}$ (dynes/cm²)</td>
<td></td>
</tr>
<tr>
<td>$E_f^T$</td>
<td>YMODFS $4.46 \times 10^8$ (dynes/cm² °C)</td>
<td></td>
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<tr>
<td>Fuel Poisson's Ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma^f$</td>
<td>PNU $0.3$</td>
<td></td>
</tr>
<tr>
<td>Fuel Thermal Conductivity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_p^f$</td>
<td>FKD $1.133$</td>
<td></td>
</tr>
<tr>
<td>$K_1^f$</td>
<td>FK1 $0.78$</td>
<td></td>
</tr>
<tr>
<td>$K_2^f$</td>
<td>FK2 $0.02935$</td>
<td></td>
</tr>
<tr>
<td>$K_3^f$</td>
<td>FK3 $6.60 \times 10^{-13}$</td>
<td></td>
</tr>
<tr>
<td>Fuel Emissivity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$c_c$</td>
<td>EMF $0.80$</td>
<td></td>
</tr>
<tr>
<td>Gas Conductivities (See Table B.2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Postirradiation Gap (Correlation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$G_1$</td>
<td>RG1 $3.87 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>$G_2$</td>
<td>RG2 $126$</td>
<td></td>
</tr>
<tr>
<td>$G_3$</td>
<td>RG3 $-0.522$</td>
<td></td>
</tr>
<tr>
<td>$G_4$</td>
<td>RG4 $0.395$</td>
<td></td>
</tr>
<tr>
<td>$G_5$</td>
<td>RG5 $-0.01684$</td>
<td></td>
</tr>
<tr>
<td>$G_6$</td>
<td>RG6 $0.600$</td>
<td></td>
</tr>
<tr>
<td>$G_7$</td>
<td>RG7 $1.1 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>Fuel to Cladding Heat Transfer (Correlation):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A$</td>
<td>HG1 $13.7$</td>
<td></td>
</tr>
</tbody>
</table>
**TABLE 6.1 (Continued)**

**Fuel to Cladding Heat Transfer (Correlation) (Cont.):**

\[ C = C_HG2 \times \exp(-HG3 \times P) \]

- \( HG2 = 1.1095 \)
- \( HG3 = -3.394 \times 10^{-9} \)

**Grain Growth Temperatures (Correlation)**

- **Equiaxed grain growth temperature**
  - FR1: 1570. (°C)
- **Columnar grain growth temperature**
  - FR2: 1886. (°C)
- FR3: 0.49 (°C - cm/W)

**Fission Gas Yield**

**(Reference 31)**

- Krypton from \(^{239}\text{Pu}\) 
  - FYPUK: 0.022 (atoms/fission)
- Xenon from \(^{239}\text{Pu}\) 
  - FYPUX: 0.233 (atoms/fission)
- Krypton from \(^{235}\text{U}\) 
  - FYU5K: 0.048 (atoms/fission)
- Xenon from \(^{235}\text{U}\) 
  - FYU5X: 0.218 (atoms/fission)
- Krypton from \(^{238}\text{U}\) 
  - FYU8K: 0.031 (atoms/fission)
- Xenon from \(^{238}\text{Pu}\)
  - FYU8X: 0.214 (atoms/fission)

**Fission Gas Release (Correlation)**

<table>
<thead>
<tr>
<th>( F )</th>
<th>( FG )</th>
<th>Value</th>
</tr>
</thead>
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<tr>
<td>( F_1 )</td>
<td>( FG1 )</td>
<td>5890</td>
</tr>
<tr>
<td>( F_2 )</td>
<td>( FG2 )</td>
<td>0.86498</td>
</tr>
<tr>
<td>( F_3 )</td>
<td>( FG3 )</td>
<td>3515</td>
</tr>
<tr>
<td>( F_4 )</td>
<td>( FG4 )</td>
<td>7.345</td>
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<tr>
<td>( F_5 )</td>
<td>( FG5 )</td>
<td>49170</td>
</tr>
<tr>
<td>( F_6 )</td>
<td>( FG6 )</td>
<td>(-2.88 \times 10^{-4})</td>
</tr>
<tr>
<td>( F_7 )</td>
<td>( FG7 )</td>
<td>0.0824</td>
</tr>
<tr>
<td>( F_8 )</td>
<td>( FG8 )</td>
<td>0.0125</td>
</tr>
</tbody>
</table>

**Accommodation Coefficient (Correlation),**

<table>
<thead>
<tr>
<th>( A )</th>
<th>( AC )</th>
<th>Value</th>
</tr>
</thead>
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<tr>
<td>( A_1 )</td>
<td>( AC1 )</td>
<td>0.8121</td>
</tr>
<tr>
<td>( A_2 )</td>
<td>( AC2 )</td>
<td>4.516</td>
</tr>
<tr>
<td>( A_3 )</td>
<td>( AC3 )</td>
<td>7.714</td>
</tr>
<tr>
<td></td>
<td>(Reference 12)</td>
<td>(cm)</td>
</tr>
<tr>
<td>----------------</td>
<td>----------------</td>
<td>------</td>
</tr>
<tr>
<td>Cladding Roughness</td>
<td>$r_c$</td>
<td>$1.78 \times 10^{-4}$</td>
</tr>
<tr>
<td>Fuel Roughness</td>
<td>$r_f$</td>
<td>$3.3 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

The values used for the EBR-II axial flux profile, axial power profile, average neutron energy, and ratio of total flux to flux greater than 1 MeV were obtained from Reference 33. These values are used when the appropriate option for axial profiles is selected. See page 13 for details.
### TABLE B.2

GAS CONDUCTIVITIES (Reference 34)

For Gas Conductivity Expressed As:

\[ k_i = A + BT + CT^2, \quad \text{watts} \ \frac{\text{cm}}{\text{cm}^{-2} \text{C}}; \ T \ \text{in} \ ^\circ\text{C} \]

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Helium</th>
<th>Nitrogen</th>
<th>Xenon</th>
<th>Argon</th>
<th>Krypton</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.308x10^{-3}</td>
<td>2.540x10^{-4}</td>
<td>5.739x10^{-5}</td>
<td>1.716x10^{-4}</td>
<td>9.560x10^{-5}</td>
</tr>
<tr>
<td>B</td>
<td>3.696x10^{-6}</td>
<td>5.651x10^{-7}</td>
<td>1.451x10^{-7}</td>
<td>4.122x10^{-7}</td>
<td>2.136x10^{-7}</td>
</tr>
<tr>
<td>C</td>
<td>-5.848x10^{-10}</td>
<td>-7.336x10^{-11}</td>
<td>-2.323x10^{-11}</td>
<td>-8.075x10^{-11}</td>
<td>-3.506x10^{-11}</td>
</tr>
</tbody>
</table>
APPENDIX C COMPUTER CODE LISTING

FUNCTION CON MIX (X, Y, Z, N)
C
CALCULATES THE THERMAL CONDUCTIVITY OF A THREE GAS MIXTURE AT TEMP
C USING BROKAS'S EQUATION
C
DIMENSION G mol(5), X mol, X mol, G mol, N G mol, N gas, E, E equation, T, T
C
DO 10 X = 1, N gas
C
C
10 CONTINUE
C
END
C
RETURN
C

FUNCTION CON (N, X)
C
evaluates conductivity equations for the gas called by index n
C
C
COMMON/COM/X(5), G mol(5), E, E equation
C
CON (N) = A(N) + A(N) + A(N) + A(N)
C
RETURN
C
END
C

FUNCTION T ERP (X, Y, Z, N)
C
Routine to linearly interpolate for a value corresponding to Z,
C
given the vectors X (independent variables) and Y (dependent
C
variables) each of length N
C
C
DIMENSION X(N), Y(N)
C
DO 10 X = 1, N
C
10 IF (X < X(1)) GO TO 20
C
10 CONTINUE
C
TERM = Y(N)
C
RETURN
C
20 IF (X > X(N)) GO TO 30
C
TERM = (Y(N) - Y(N-1)) * (X - X(N)) / (X(N-1) - X(N))
C
RETURN
C
30 RETURN
C
END
C
RETURN
C

FUNCTION CON MIX (X, Y, Z, N)
C
CALCULATES THE THERMAL CONDUCTIVITY OF A THREE GAS MIXTURE AT TEMP
C USING BROKAS'S EQUATION
C
DIMENSION G mol(5), X mol, X mol, G mol, N G mol, N gas, E, E equation, T, T
C
DO 10 X = 1, N gas
C
C
10 CONTINUE
C
END
C
RETURN
C

FUNCTION CON (N, X)
C
evaluates conductivity equations for the gas called by index n
C
C
COMMON/COM/X(5), G mol(5), E, E equation
C
CON (N) = A(N) + A(N) + A(N) + A(N)
C
RETURN
C
END
C

FUNCTION T ERP (X, Y, Z, N)
C
Routine to linearly interpolate for a value corresponding to Z,
C
given the vectors X (independent variables) and Y (dependent
C
variables) each of length N
C
C
DIMENSION X(N), Y(N)
C
DO 10 X = 1, N
C
10 IF (X < X(1)) GO TO 20
C
10 CONTINUE
C
TERM = Y(N)
C
RETURN
C
20 IF (X > X(N)) GO TO 30
C
TERM = (Y(N) - Y(N-1)) * (X - X(N)) / (X(N-1) - X(N))
C
RETURN
C
30 RETURN
C
END
C
RETURN
SURROUNTE N INPUT (DEWHI,DEHLD)

COMMON/FACCONS/
  + MG1,MG2,MC3,MA4,AB2,AB3,AG1,AG2,AG3,AG5,AG6,AG7,
  + FYUS, FYUS, FYUS, FYUS, FYUS, FYUS, FYUS, FYUS, FYUS,
  + CUS35, CUS35, CUS35, CUS35, EUG3, EUG3, EU33, EU33, EU33
  + FG1,FG2,FG3,FG4,FG5,FG6,FG7,FG8,FG9,FG10,FG11,FG12
  + C1, C2, YEG, YES, YMOFO, YMOOF, YMOFW, YMOFW, YMOFW

COMMON/STK(5,ST2,18),MT1,MT2,TCENT(17),C(2,4)

DO 60 IN1=1,2
  IF1,1,1  DO=DEMLO
  IF1,1,2  DO=DEWHI
C(1,1)=X(0)/(1.0(1.0)+1.0(1.0))
C(1,2)=X(1)
C(1,3)=X(2)
C(1,4)=X(3)+.25
CONTINUE

DO 60 IN1=10,25
  DO 70 JN1=IN1,11
  ST(1,2)=T(1,2)
  ST(1,4)=T(1,4)
  A=1000.
RETURN
END

S= 20
F= 24
T= 30
O= 31
R= 32
A= 33
T= 34
E= 35
S= 36
D= 37
O= 38
M= 39
E= 40
H= 41
I= 42
C= 43
U= 44
O= 45
R= 46
T= 47
E= 48
N= 49
R= 50
A= 51
T= 52
E= 53
S= 54
R= 55
N= 56
D= 57
SUBROUTINE FSINTN  T4/T4  OPT1  TRACE  FTN 0.2+74351  03/12/75  12:00:05.  PAGE 2

I = J
C-----------------------------------------------

60 C FUEL SURFACE TEMPERATURE
C-----------------------------------------------

65 C EVALUATE INTEGRAL K DT AT FUEL SURFACE TEMP

69 C DETERMINE THE FUEL MICROSTRUCTURE

75 C DETERMINE THE FUEL CENTER TEMPERATURE WITH RESTORING

85 C DETERMINE THE EXTENT OF MELTING (IF IT OCCURS)

95 C COMPARE THE COMPLETE RADIAL TEMPERATURE DISTRIBUTIONS AT TEN

SUBROUTINE FSINTN  T4/T4  OPT1  TRACE  FTN 0.2+74351  03/12/75  12:00:05.  PAGE 3

115 END

FSINTN  91
SUBROUTINE FISGAS (IS)  
FISGAS 2  
FISGAS 3  
FISGAS COMPUTES THE VOLUME OF GAS GENERATED+RELEASED TO THE PLENUM  
AND RETAINED IN THE FUEL.  
FISGAS 4  
FISGAS 5  
VARIABLES DEFINED IN FISGAS  
FISGAS 6  
VFJG(J) = VOLUME OF FISSION GAS GENERATED FOR EACH FUEL SEGMENT  
FISGAS 7  
VFGR(J,J) = VOLUME OF FISSION GAS RELEASED FROM EACH SEGMENT  
FISGAS 8  
TOTFGR = TOTAL VOLUME OF FISSION GAS RELEASED TO THE PLENUM  
FISGAS 9  
PGR = PER CENT OF THE FISSION GAS GENERATED WHICH IS RELEASED  
FISGAS 10  
RETJG(J) = VOLUME OF FISSION GAS RETAINED IN THE FUEL  
FISGAS 11  
FISGAS 12  
FISGAS 13  
REAL KFIEL  
COMMON/IPT,FLEV,EPD,FU015,DP,ATF,TFH,CHF,CPF,CFH,CF5,CF11,TR,TEMP2  
COMMON 2  
1  
DENISH,MDH,TD,DIS,PU4235,SEG55,PU64,EPD,STEPS,ZIZZ,IZ3  
COMMON 3  
CCGM,FN,PM,EPF, XFIL,ALPHA4,ALPHA5  
COMMON 4  
YMOD,YMODS,PW,PFUX,TMCG,EXTERNAL,ITAB1,ITAB2,ITAB3,ITAB4  
COMMON 5  
4ITINCRI(10),PARAT(10),PARAT(10)  
COMMON 6  
1  
FU235,FU239,FU238,EPBFAR,PERM,PT,PS,PP2  
COMMON 7  
Z(10),X(22),PEXI(22),RAK27,RAK22,RAK23,RAK24,RAK25,RAK26,RAK27  
COMMON 8  
R90050(22)  
COMMON 9  
3P(22),HP22(22),RT(10,22),CLOT(22),CLOI(22),TCD(22),TCD(22)  
COMMON 10  
4T(22),TE(22),TCG(22)  
COMMON 11  
5RISWE(22),DELTAC(22),OPSEL(22),DSWE(22),CLOGR(22)  
COMMON 12  
6VFGR3(22),VFGR4(22),VFGR5(22),VFGR6(22),VFGR7(22),VFGR8(22),VFGR9(22)  
COMMON 13  
7TREP1(22),VFGRD(22),VFGRD(22),VFGRD(22),VFGRD(22),VFGRD(22)  
COMMON 14  
8ST1(22),ZY(22),STR1(22),STO1(22),SRT01(22),STR01(22)  
COMMON 15  
9FICN1(22),FLUNCI(22),BU12(22),BII(22)  
COMMON 16  
COMMON/PARCOM/  
COMMON 17  
* MFG1,MFG2,MFG3,MFG4,A1,A2,A3,AK1,RK1,RG1,RG2,RG3,RG4,RG5,RG6,RG7  
COMMON 18  
* FYUS,FYUS,FYUS,FYUS,FYUS,FYUS,FYUS,FYUS,FYUS,FYUS  
COMMON 19  
* CSUS,CUS,CUS,CUS,CUS,CUS,CUS,CUS,CUS,CUS  
COMMON 20  
* FG1,FG2,FG3,FG4,FG5,FG6,FG7,FG8,FG9,FG10  
COMMON 21  
* CK1,CK2,CK3,CK4,CK5,CK6,CK7,CK8,CK9,CK10  
COMMON 22  
IF(J,LT,0) GO TO 50  
COMMON 23  
CALCULATE METRIC TONS METAL  
COMMON 24  
R90050=1000-AM2  
COMMON 25  
METRIC TONS METAL PER SEGMENT  
COMMON 26  
RTHM=THM/SEG3N  
COMMON 27  
RTHM = 1.005/RTHM  
COMMON 28  
TOTFGR=0  
COMMON 29  
DO 40 J=1,NSEG3N  
COMMON 30  
CALCULATE THE NUMBER OF FISSION EVENTS BASED ON THE AVERAGE ENERGY  
RELEASED PER FISSION  
COMMON 31  
FISONS=RJ(J) * RTHM * 5.3923/MFBD  
COMMON 32  
CALCULATE VOLUME OF FISSION GAS GENERATED  
COMMON 33  
VFGR(J,J) = FISONS * (FU235,FU238,FU239,FU238,FU239)  
COMMON 34  
* /6.02523
SUBROUTINE CSINTR

CSINTR COMPUTES COOLENT AND CLADDING TEMPERATURE DISTRIBUTIONS.
VARIABLES OFFINED IN CSINTR

5
TCCOL(1) - COOLENT TEMPERATURES, DEG C
CLCIT(1) - CLADDING INNER BOUNDARY TEMPERATURE, DEG C
CLCIT(1) - CLADDING OUTER BOUNDARY TEMPERATURE, DEG C

REAL NFIN

10 COMMON /INT/FLN.E.FD,YI00,DP,CT,PH,CMF,CP,HC,CH,TI,TO,TEMP2,
CTZG,DE,N,FIX,DFV,FMF,FCM,CMF,CON,PVD,STEPS,T2,22,23.

15 COMMON /NP/EC,FP,DU,PPLK,TC,TCM,CMF,CMF,CMF,CMF,CMF,CMF,
CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,
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CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,
CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,CMF,
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DETERMINE THE CLADDING ID AND OD TEMPERATURES

CLODT(J) = TCOOL(J) + DTF

IF(CH,LE,0.0) D2 = ALOG(OP/HIDP)/(2.*PI*(CRI+CR2=CLODT(J)*P(J)
+ ALOG(OP/HIDP)/(2.*PI*(CRI+CR2=CLODT(J)/))
DTC=P(J)*D2
CLODT(J) = CLODT(J) + DTC
CONTINUE
RETURN
END
FUNCTION APP, OPT1, TRAC3

FUNCTION APP(X,E,FLEN)

C THIS FUNCTION PROVIDES SPECTRUM RADIUS FROM CHEMICAL FORMULA
C
C THERM USER SELECTED ORIGINE DEPENDING ON THE INPUT VALUE FROM THE
C
C EXTRAPOLATION DISTANCE (E) AS FOLLOWS -------
C
C IF (E,L.0.AND.E,GT.-1) USE A USER SPECIFIED EQUATION (SEE TABLE 30)   
C IF (E,E.GT.0) USE INTERPOLATION FROM INPUTTED DATA TABLES
C IF (E,E.GT.0) USE CHAPPOED COSINE CURVE WITH EXTRAPOLATION DISTANCE E

C
C COMMON/PRODC/NOPPD,DATA(21),DFAPP(21),DEBAR,DFPP,
C READ(21),READFP(21),READBP(21),READFP(21),READFP(21)
C
C IF (E) 300,200,100
C 100 CONTINUE

C FUNCTION FOR A CHAPPOED COSINE CURVE WITH EXTRAPOLATION DISTANCE E

C
C XNLTE3,16159/FLEN=2,E)
C XNLTE3(X,E)=XLT
C APP=3(XNLTE3)
C RETURN

C CONTINUE

C FUNCTION FOR INTERPOLATION FROM INPUTTED TABLES

C NOPPD,NOPPP
C XNLTE/FLEN
C APP=3XNPX/DATAX,DFAPP,X,FLEN
C RETURN

C 300 CONTINUE
C IF (E,LT.-1.) GO TO 500

C FUNCTION FOR USER SPECIFIED EQUATION

C APP=1/2*2460+0.3236**.-0.0095*X**2
C RETURN

C CONTINUE

C FUNCTION FOR INTERPOLATION FROM A SET OF INPUTTED DATA

C NOPPE=E,DEL
C XNLTE/FLEN
C APPX=3XNPX
C RETURN
END
FUNCTION EB(X,E,FLEN)

C FUNCTION TO PROVIDE THE AXIAL DISTRIBUTION OF THE AVERAGE NEUTRON ENERGY(MEV). SEE APF FOR OPTIONS AND EXPLANATION OF VARIABLES.

C COMMON/PROF,NOFP,DATAE(21),DATAF(21),DEBAN,DTFX,
C + REACT(21),READP(21),READT(21),READF(21)

C IF(E.EQ.0.0) CONTINUE

C FUNCTION FOR EBAN FOLLOWING A CHOPPED COSINE WITH EXTRAPOLATION DE

C FPCEBAR RETURN

C IF(E) 300,200,100

C FUNCTION FOR INTERPOLATION FROM DATA TABLES

C FPCEBAR RETURN

C CONTINUE IF(E.LT.-1.) GO TO 400

C FUNCTION FOR USE OF A USER SPECIFIED EQUATION

C EBAR=0.3314**0.5772**2 = 0.02851*(X/2,45)**2

C RETURN

C CONTINUE

C FUNCTION TO INTERPOLATE FROM A SET OF INPUTTED DATA

C NOFP=1,001

C XXX/X,XXX

C RETURN(READ,READER,XXX,NOFP)

RETURN
FUNCTION TFX(Y,E,FLEN)

C FUNCTION TO PROVIDE THE AXIAL DISTRIBUTION OF THE RATIO OF NEUTRON FLUX TO THE TOTAL NEUTRON FLUX. SEE APP FOR OPTIONS AND EXPLANATION OF VARIABLES.

COMMON/PHOC,PHOFDP,SATAY(21),SATAPP(21),DEAP,DFRF,
+ REAX(21),READP(21),READX(21),READT(21),READP(21)

C IF(E) 300,200,100

10

C FUNCTION FOR A CHOPPED COSINE WITH EXTRAPOLATION DISTANCE E

C IF(E) 300,200,100

C 100 CONTINUE

C FUNCTION FOR INTERPOLATION FROM A SET OF DATA VALUES

C IF(E) 300,200,100

15

C IF(E) 300,200,100

C RETURN

200 CONTINUE

C FUNCTION FOR USER SPECIFIED EQUATION

C IF(E) 300,200,100

25

C IF(E) 300,200,100

C RETURN

300 CONTINUE

C FUNCTION FOR INTERPOLATION FROM AN INPUTTED DATA SET

C IF(E) 300,200,100

35

C IF(E) 300,200,100

C RETURN

END
SUBROUTINE COELD

COELD COMPUTES THE CLADDING DIMENSIONAL CHANGES DUE TO THERMAL EXPANSION AND IRRADIATION INDUCED SWELLING.

VARIABLES DEFINED IN COELD

DELTA(T) - PERCENT CLADDING SWELLING

DSWEL(T) - OUTER CLADDING RADIUS (HOT)

ISWEL(T) - INNER CLADDING RADIUS (HOT)

REAL KRFIL


DO 20 J = 1, NSEG

CLDNS(T) = (CLCDTN(J) - CLCDTN(1)) / 2.0

DELTA = CLDNS(T) - CLDNS(T)

ALPHA = ALPHA + ALPHA

GO TO 10

IF (FLUENC(T) <= 1.0E+6) GO TO 20

IF (FLUENC(T) <= 1.0E+6) GO TO 20

CONVERT CLADDING MIDWALL TEMP TO KELVIN

CLMT = CLMT + 273.

IF (TRAN >= 0.00001)

GO TO 10

REFERENCE -- MEDL-TME 71-139

A = 2.24E-3 * ALF - 1.54E-5 * ALF ** 2 + 2.65E-8 * ALF ** 3

ALF = CLMT - 348
SUBROUTINE COMELD 74/74 OPT=1 TRACE FTN 4.2*74351 04/10/75 07:57:26 PAGE 2

PONET=0.872*2.98E-3*CLMTFC
C=1.9*EXP(-1.2*(CLMTFC-480.))
DELTA(DJ)=DELTA(DJ)*A*(((FLUENC(DJ)*1.E-22)**PONET-((FLUENC(DJ)
+ -FLUNCI(DJ))*1.E-22)**PONET)*+2*E(-1.12E-22*(FLUENC(DJ)
+ -FLUNCI(DJ)))/C

REFERENCE -- MEDL-TME.71-139

COEF3=10.
GO TO 4

COEF3=1.
A = .05*(CLMTFC-600.)
R = .06*(CLMTFC-460.)
U = .05*(CLMTFC-475.)
PONET=(2.03*EXP(D)/1.3*EXP(D))/C
COEF1=EXP(C)/1.3*EXP(C)
COEF2=COEF3*.002/(1.3*EXP(A))/.006/(1.3*EXP(B))
DELTA(DJ)=DELTA(DJ)+COEF1*COEF2/3.*(FLUENC(DJ)*1.E-22)**PONET-
1.(FLUENC(DJ)-FLUNCI(DJ))*.1.E-22)**PONET

CONTINUE?

C----------- COMPUTE THE CLADDING DIMENSIONAL CHANGES

DPSWEL(DJ)=DP*.5*(1.0+.01*DELTA(DJ))*(1.0+ALPHA*DELTA)
RISWEL(DJ)=RIS*2*(1.0+.01*DELTA(DJ))*(1.0+ALPHA*DELTA)
CONTINUE

RETURN
END
SUBROUTINE STRUCT
THE OPTIMAL TRACE

SUBROUTINE STRUCT(SLOT, SHUTY, J, ISAV)

STRUCT IS USED TO DETERMINE THE LOCATION (RADIAL EXTENT) OF FUEL
MICROSTRUCTURE CHARACTERISTICS.

5

STRUCT

VARIABLES DEFINED IN STRUCT
TEC(J) = THE TEMPERATURE USED TO LOCATE THE EXTENT OF
COLUMNAR CHAIN GROWTH
TEC(J) = THE TEMPERATURE USED TO LOCATE THE EXTENT OF
EQUATED GRAIN GROWTH
RJE(J) = THE RADIAL EXTENT OF COLUMNAR CHAIN GROWTH
RCJ(J) = THE RADIAL EXTENT OF EQUATED GRAIN GROWTH

15

REAL KAFL
COM=CVJ(1)1/FLEN, FD, FNO, DFP, CT, PK, CM, CF, HF, MCG, CK, KJ, T8, TEMP2, COM = 3
1 DLNC, PNF, T1, D15, PO, H5, FEPJ, PUE, EFPJ, STEPS, 21, 22, 23,
1 ECFIT, FNPJ, PK, CM, CF, HFL, ALPHADO, ALPHAS,
3 SYMOD, YMOD, PNU, FUPU, ITSMC, FETEP, ITARJ, ITAR2, ITAR3, ITABJ,
6 ITLMCl(10), PRLTM1(10), PRLTM2(10),
COM=CVHJ(C), RHO, W, P, R2, R3, R4, R5, R6, NHSEG, NHSEGJ, NHSEG2,
1 F2J35, F1J25, F3J25, F6J25, FMJ25,
2*(10), IF(22), FCX(22), FCX(22), HCX(22), HCX(22), HHSX(22), RESX(22), HMLX(22),
HOSX(22),

20

HCML(22), MCLH(22), CLDH(22), HCLH(22), TCOL(22), TH(22),
TCL(22), TCJ(22), TLCG(22),
SHEH(22), CHEH(22), OSPHEL(22), DFSHEL(22), COLDEL(22),
VFGR(522), VFGR(522), VFGR(522), VFGR(522),
KHEFG(22), KFCC(22), VFCC(22), VFCC(22), VFCC(22),

25

STL(22), SHTIL(22), SHTIL(22), STOIL(22), SITOIL(22), STRS(22),
STRS(22),

30

FLXNCH(22), FLMNCH(22), FLXNLH(22), FLXNLH(22),

35

COM=CVJS(CMDO)

1 MCH, MCHC, MCGZ, MCG, ALJ2, AS, PCh, PC2, RC2, RCG, RCG, RCG, RCG,
2 FLJ5, FJ5, FJ5, FJ5, FJ5, FJ5, FJ5, FJ5, FJ5, FJ5,
3 CSU2J, CSU2J, CSU2J, CSU2J, CSU2J, CSU2J, CSU2J, CSU2J, CSU2J,
4 FGJ, FCJ, FGJ, FCJ, FGJ, FGJ, FGJ, FGJ, FGJ, FGJ,
5 CHJ, CPJ, CPJ, YEH, PHNQD, FR1, FR1, FA1, FAL1, FAL1, FAL1,

40

COM=CVJS(CDO)

C EVALUATE THE COLUMNAR AND EQUATED GRAIN GROWTH TEMPERATURES
STRUCT

45

TGC(J) = TEMP(J) + P*(J)
IF (TGC(J) < 0.0) TGC(J) = T6
IF (TEMP1, CT, 0.001) TEC(J) = TEMP

50

C CALCULATE THE RADIUS OF THE EQUATED GRAIN GROWTH ZONE
STRUCT

REBRS
IF (TLC(12), JT, TGC(J)) GO TO 10
SJ0TEN(SOTT/EPRINT1, J, KO, RM)
REBRSND(SLOTE/PPRINT1, KO, RM)
IF (REAV(J), LE9, RM) GO TO 20
IF (RELT, REAV(J)) REM REAV(J)

55

PAGE 1
SUBROUTINE STRUCT    74/74    OPT#1    TRACE

20 PE2=PE1+RE

60 C CALCULATE THE COLUMNAR GRABH GROWTH RADIUS

C

30 IF(TCL(J),LT,TCG(J)) GO TO 30

55 SOTCG(TCG(J),J)

30 SOTCG=SLOT0+SL0TO

30 IF(NB(SAV(J),J,E,KM) GO TO 40

30 IF(RE,LT,NBSAV(J)) GO TO 40

70 RNB=NB(SAV(J))

70 XTB1(1.502-5+R+2,0.02+ALOG(PD/UB))=TERM1+SL0TO,1

40 XTB2(1.502-5+R+2,0.02+ALOG(PD/UB))=TERM1+SL0TO,1

C C SAVE THE VALUES COMPUTED FOR RB, RE, AND RE

C

80 R=PI(1)=RE

80 R(1)=R

80 X(1)=RC

80 IF(ISA,NX,E,1) GO TO 50

80 NBSAV(I)=RB

80 RNSAV(J)=RB

80 RETURN

END
PROGRAM SIEK

SIEK CONTROLS ROUTINE CALLED SUBROUTINE CALL SEQUENCE AND
INCREMENT TIME, BURNUP, AND FLUENCE.

VARIABLES DEFINED IN SIEK:
- ELAPSED TIME, EFFECTIVE FULL POWER DAYS
- PP = PEAK POWER, MW/TH
- CFF = COOLANT MASS FLOW RATE, GPM/SEC
- RFU = PEAK RUNUP, MW/TH
- FLUENCE[1] = SEGMENT FLUENCE, NEUTRONS/C C M**2
- RLU(r) = SEGMENT FLUENCE INCREMENT, NEUTRONS/C M**2
- P(r) = SEGMENT PROF, WATTS/CM

REAL KEFF

COMMON /VAPT/ TLEN, F, VOLD, R, CT, PW, CFF, CP, MF, ING, CK, TI, TB, TEMP,
1 OENL, PFF1, TO, 0.5, FLU, 0.25, SEG2M, PRU, EPRD, STEPS, 21, 22, 23,
3 CCRY, CP, WAP, EPL, EFFL, MPPL, ALK, XH, HAPM, AP, AP, CP, MP,
4 SYMOD, YMOD, RNU, MFLU, ISENT, ITA, ITA, ITA, ITA,
7 TILM(101,101), TILM(101,101), CACTION(101)
10 COPA, RAY, RAY, RAY, RAY, RFUP, RPK, RAC, NSEG, DERM, TEM, MSEG1, MSEG1, MIGHT,
11 I=1, ITA, ITA, ITA, ITA, ITA, ITA,
14 P(101), (101), (101), (101), (101), (101), (101), (101), (101), (101)
20 XMUSO(101), XMUSO(101), XMUSO(101), XMUSO(101), XMUSO(101), XMUSO(101), XMUSO(101), XMUSO(101), XMUSO(101), XMUSO(101)
25 TNMVLLO(22), TNMVLLO(22), TNMVLLO(22), TNMVLLO(22), TNMVLLO(22), TNMVLLO(22), TNMVLLO(22), TNMVLLO(22), TNMVLLO(22), TNMVLLO(22)
30 TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22)
35 TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22)
40 TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22)
45 TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22), TKN(22)

COMMON /PARCHY/
+ MG1, MG2, MG3, MG4, MG5, MG6, MG7, MG8,
+ FYU, FYU, FYU, FYU, FYU, FYU, FYU, FYU,
+ CSVL, CSVL, CSVL, CSVL, CSVL, CSVL, CSVL, CSVL,
+ FGG, FGG, FGG, FGG, FGG, FGG, FGG, FGG,
+ CK1, CK2, CK3, CK4, CK5, CK6, CK7, CK8,

DIMENSION VAP(101)

COMM /INPUT/

COMMON /CALL/ I=1, I=1, I=1, I=1, I=1, I=1, I=1, I=1, I=1, I=1

COMM /TIME INCREMENT CONTROL=

increment time, burnup, and fluence.

DIMENSION PBLU, BOP, SECHIC, ISTEP, D0, K, K, EPPD, EPPD, EPPD

IF (.EQ. 1) GO TO 20

IF (.EQ. 11) GO TO 20
SUBROUTINE HAGAP 7276 OPT=1 TRACE

C CALCULATE COMPOSITION OF GAS PRESENT IN GAP

C TM0=0.0 HAGAP 34
C 20 TM0=0.131 HAGAP 35
C DD 20 TM0=0.1 HAGAP 36
C DD 30 TM0=0.1 HAGAP 37
C 36 GMOL1=GMOl1+PMOL
C H0=HAP+HAP
C H0=H0

C DETECT THERMAL EFFECTS OF FUEL AND CLAD SURFACES (JUMP DISTANCE)

C COEF = A1 + EXP((CALOR/(NBAR)) * (2)**2 / A3)
C PRMXP(LPENP+1013*2)
C *=EXP(COE2/CORE)
C LOOP THRU ALL SEGMENTS TO COMPUTE A FUEL TO CLADDING HEAT TRANSFER

C COEFFICIENT

C CO.F0 J1+3SEG
C TX=TX(J1)

C DEFINE HOT GAP WIDTH IF CLOSURE OCCURS: CALCULATE INTERFACIAL

C PRESSURE

C PCAP+PRM
C GAP=GAP+LJ+DPS+EL(J)
C IF (GAP,G0,0) GO TO 50

C IF (IPS+FL(J)+IFS+EL(J)+2)*IP(S+EL(J)+2)+2*EC+2*FF)+2))/PMU
C +1*RIS+L(J)+DPS+FL(J)+2)/PMU
C IF (IP(S+EL(J)+2)+DPS+FL(J)+2)*IP(S+EL(J)+2)+2*EC+2*FF)+2))/PMU
C =1+IP(S+EL(J)+2)+2*EC+2*FF)+2))/PMU
C IF (PCAP,G0,PMU) PGAP+PMU
C 50 CONTINUE

C THE FACTORS HG2 AND HG1 SIMULATE THE PLASTIC AND TIME DEPENDENT
C DEFORMATION OF THE SURFACE ROUGHNESS. THESE FACTORS HAVE BEEN
C USED FOR CORRELATION OF THE GAP CONDUCTANCE CALCULATION.

C HG2=HG2*(HG2+PCAP)
SUBROUTINE HGA8  74/75  CPTx1  TRACE  PRT 3,4/75  03/02/75   13:10:59   PAGE  3

115
HGXX = EXP(-EPXX*HGC)  
IF(MXX<LT,HGX) HGXX=HGXX  
EPS=HGXX + GVX

120
OPEN GAP = CALCULATE GAP CONDUCTANCE BY CLASSICAL THEORY OF GAS MIX

125
TC=XAT
THC=CLIDT(J)+273.  
TF=273.
XRAD = 5.65E+12 * (TF*2+TC**2) + (TF*TC) / (1./EMF)
+ (GAS=EL(J)/FISVEL(J))+(1./FRC=1.3)
HGASXX=1/(AMAX(HGAP,0.0)*EPS)
HGAS,0
IF(GAP,GT,0.01) GO TO 60

130
CLOSED GAP = TEMPERATURE PROP ACROSS FUEL CLADDING INTERFACE IS
CALCULATE BY A METHOD SIMILAR TO THAT PROPOSED BY ROSS AND STOUT

135
IF(FLG<15) 5(T=5.11)5(T=1.11))/10.

140
60  
IF(S=0) (HGAS*HGC/AMAX(HGAS,0.0)) / YIELD
HGCP(J)+HGAS = s5 + XRAD
TC=CLIDT(J)+P(J)/HGCP(J)+6.2832*FISVEL(J)
IF(AMX(TICHA,GT,10.) GO TO 60
CONTINUE

145
CLOSED GAP CONVERGENCE CRITERIA

150
IF(TT1=TT1)1

155
TGAS = FLSP.
IF (T=31) ,X=0  
IF(X=0) H=1) + XAV(J)) = H(J,GAP,J,0,0) TOCA,TRUE

160
CONTINUE

165
IF (X=0) 50 TO 10
C
END

100 FORMAT (* HGA8 HAS FAILED TO CONVERGE IN 25 ITERATIONS * )

END
SUBROUTINE INPUT

DIMENSION C(51)

CODALENCE (C(1:1),FLEN)

CUMXH,F/MXH/CXPP,DATA(21,DATAPP(21),CDBH,CTX)

* PFALL(21),REACKOFF(21),READER(21),WEAKT(21),READP(21)

CODERXH/LXH/FLXH(1),IFIRST

REAL *X

SUBROUTINE INPUT  74/74  OPT=1  TRACE

TI=TI+1.8*32.
EPL=EPL*2.54
ALPHA0=ALPHA0/1.8
ALPHA=ALPHA*1.24
YMDO=YMDO+6.8947E+4*1.8
YMDO=YMDO+6.8947E+4
EXERP=EXERP+6.8947E+4

READ THE INPUT DATA

READ (5,1P1)

LIST INPUT DATA WITH EXPLANATION OF SYMBOLS AND UNITS REQUIRED

CARDS TO ALLOW OLD DECKS WITH FLEN AND E IN FT. TO BE RUN

IF (FLEN.LT.4) FLEN=FLEN*12.
IF (E.LT.2.0 AND E.GT.0.0) E=E*12.
WRITE (6,170)

WRITE (6,130) (C(I),I=1,9)
WRITE (6,140) (C(I),I=1,10,18)
WRITE (6,150) (C(I),I=1,14,20)
WRITE (6,160) (C(I),I=1,27,35)
WRITE (6,170) (C(I),I=1,35,62)

D,System=1
D,31=1
D,32=1
D,33=1
D,34=1
WRITE (6,180) D,system=1,D,31,D,32,D,33,D,34

CONVERSION OF INPUT VALUES TO CGS UNITS

EFPDS=EFPD
PUS=PRU
FLEN=FLEN*2.54
IF (E.GT.0.0) E=E*2.54
FD=FD*2.54
VOID=VOID*2.54
DP=DP*2.54
CT=CT*2.54
PM=PM*(1000./(12.*2.54))
CMF=CMF*1260
CP=CP*4.186
Felsen=5.6761E-4
H=H=5.6761E-4
CK=CK*0.017
T=TI+1.8*1.8
EPL=EPL*2.54
ALPHA0=ALPHA0/1.8
ALPHA=ALPHA*1.24
YMDO=YMDO+6.8947E+4*1.8
YMDO=YMDO+6.8947E+4
EXERP=EXERP+6.8947E+4
MSEG=SEGNUM+1.
SUBROUTINE INPUT 74/76 OPTIM TRACF

115 SEGMENT SEGNUM
120 SEGMENT LENGTH
125 WEIGHT OF THE FUEL COLUMN (MTN)
130 COMPUTE THE FRACTION OF FISSION EVENTS FROM EACH METAL
135 COMPETE THE AVERAGE ENERGY RELEASED FOR EACH FISSION EVENT
140 EFHAR = EU235 + EU239 + EU238 + EU1 + FPW
145 IF (STEP) 15, 30, 15
150 CONTINUE
155 IF (STEP) 15, 30, 15
160 CONTINUE
165 IF (FPW) 15, 30, 15
170 CONTINUE

INPUT 91
INPUT 92
INPUT 93
INPUT 94
INPUT 95
INPUT 96
INPUT 97
INPUT 98
INPUT 99
INPUT 100
INPUT 101
INPUT 102
INPUT 103
INPUT 104
INPUT 105
INPUT 106
INPUT 107
INPUT 108
INPUT 109
INPUT 110
INPUT 111
INPUT 112
INPUT 113
INPUT 114
INPUT 115
INPUT 116
INPUT 117
INPUT 118
INPUT 119
INPUT 120
INPUT 121
INPUT 122
INPUT 123
INPUT 124
INPUT 125
INPUT 126
INPUT 127
INPUT 128
INPUT 129
INPUT 130
INPUT 131
INPUT 132
INPUT 133
INPUT 134
INPUT 135
INPUT 136
INPUT 137
INPUT 138
INPUT 139
INPUT 140
INPUT 141
INPUT 142
INPUT 143
INPUT 144
INPUT 145
INPUT 146
INPUT 147
SUBROUTINE INPUT 74/76 OPT=1 TRACE

175 CONTINUE

180 CONTINUE

190 CONTINUE

200 CONTINUE

210 CONTINUE

220 CONTINUE

230 CONTINUE

71 72 73 74

05/12/75 12.07.08 PAGE 8
SUBROUTINE INPUT  7D/7S  OPT#1  TRACE  

230  
* 21X, 001  ACTIVE FUEL COLUMN LENGTH  
* GM IN.  
17X, 001  
* GM EXTRAPOLATION DISTANCE  
* CM IN.  
21X, 001  FUEL DIAMETER  
* GM IN.  
21X, 001  FUEL CENTRAL ANNULUS DIAMETER  
* GM IN.  
21X, 001  PIN DIAMETER  
* GM IN.  
21X, 001  CLADDING THICKNESS  
* GM IN.  
21X, 001  MAXIMUM PIN HEATING RATE  
* TM kW/T.  
21X, 001  COOLANT MASS FLOW RATE  
* TM L/W.  
21X, 001  COOLANT SPECIFIC HEAT  
* 16H RT/UL-DEG F  

140  
* 21X, 001  HELIX COEFFICIENT  
* TM RTU/FT+2-DEG F/V  
* 21X, 001  SUSPENSION COEFFICIENT  
* TM RTU/FT+2-DEG F/V  
* 17X, 001  
* 21X, 001  CLADDING RESISTIVITY  
* TM IN.  
* 21X, 001  INLET COOLANT TEMPERATURE  
* TM Deg. C  

150  
* 21X, 001  TEMP, AT COLUMNS (SINTERING) BOUNDARY  
* TM Deg. C  
* 21X, 001  TEMP, AT EQUIVOLVED GRAIN BOUNDARY  
* TM Deg. C  
* 21X, 001  FRACTION OF THEORETICAL DENSITY-U/UNITED  
* 21X, 001  FRACTION OF THEORETICAL DENSITY-SINTERED  
* 21X, 001  FUEL THEORETICAL DENSITY  
* TM CH/CC  

270  
* 21X, 001  FRACTION OF FUEL VOLUME OCCUPIED BY DISH  
* GM IN.  
* 21X, 001  FRACTION OF METAL WHICH IS PU 2000  
* GM IN.  
* 21X, 001  FRACTION OF METAL WHICH IS URANUM 235  
* GM IN.  
* 21X, 001  NUMBER OF AXIAL SEGMENTS  
* GM IN.  
* 21X, 001  FUEL PEAK BURN UP  
* GM IN.  
* 21X, 001  OPERATING TIME-EFFECTIVE FULL POWER DAYS  
* 6M DAYS  
* 21X, 001  NUMBER OF CALCULATIONS/PRINTOUTS  
* 21X, 001  NUMBER OF CALCULATIONS/PRINTOUTS  
* GM IN.  

285  
* 21X, 001  FRACTION GAS RELEASE - COLUMNS ZONE  
Z1  

PAGE 5
<table>
<thead>
<tr>
<th>SUBROUTINE INPUT</th>
<th>7A/7B</th>
<th>OPT#1</th>
<th>TRACE</th>
<th>PTH 9,2 7/4 351</th>
<th>03/17/75 12:07.00</th>
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<td>.I1,12%M1 INUT CMF, SST, AMPS, PATE</td>
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<td>3.01, TOP</td>
<td>51, 100DI (FPID)</td>
<td>SST, 100DI (FPID)</td>
<td>IPE, TR (RATIO)</td>
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<td>31, 500K/FT</td>
<td>50, TR (RATIO)</td>
<td>50, MCRE/CM</td>
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<td>200 FORMAT(6X,13,9X,7.1, 8X,7.1,10X,F5,2,11X,F5,2,9X,F5,2,9X,F5,2,9X)</td>
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<td>04/10/75 07.57.38.</td>
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<td>FISSION GAS YIELDS — XENON,KRYPTON AND TOTAL FOR U235+U238 AND PU</td>
<td>BLKDAT 34</td>
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<td>DATA FYUSF, FYUSG, FYUSK, FYUSL</td>
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<td>REF= P. E. LILLY, THERMAL CONDUCTIVITY OF 46 GASES AT ATMOSPHERE</td>
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<td>115</td>
<td>PRESSURE PROC FOURTH SYM ON THERMOPHYSICAL PROP. APRIL 1968</td>
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<td>DATA (A(I*J) + 1.3) / 1.3884E-3, 3.6961E-6, 5.848E-10</td>
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<td>DATA PI * PI / 3.1415927 * 6.28318</td>
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<td>TEMPERATURES USED IN THE TABLE LOOK UP PROCEDURE FOR INTEGRAL KDT</td>
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<td>135</td>
<td>DATA T0CEN / 0.0, 100.0, 200.0, 300.0, 400.0, 500.0, 600.0, 700.0, 800.0, 900.0, 1000.0, 1100.0, 1200.0, 1300.0, 1400.0, 1500.0, 1600.0, 1700.0, 1800.0, 1900.0, 2000.0, 2100.0, 2200.0, 2300.0, 2400.0, 2500.0, 2600.0, 2700.0, 2800.0, 2900.0, 3000.0, 3100.0, 3200.0, 3300.0, 3400.0, 3500.0, 3600.0, 3700.0, 3800.0, 3900.0, 4000.0, 4100.0, 4200.0, 4300.0, 4400.0, 4500.0, 4600.0, 4700.0, 4800.0, 4900.0, 5000.0, 5100.0, 5200.0, 5300.0, 5400.0, 5500.0, 5600.0, 5700.0, 5800.0, 5900.0, 6000.0, 6100.0, 6200.0, 6300.0, 6400.0, 6500.0, 6600.0, 6700.0, 6800.0, 6900.0, 7000.0, 7100.0, 7200.0, 7300.0, 7400.0, 7500.0, 7600.0, 7700.0, 7800.0, 7900.0, 8000.0, 8100.0, 8200.0, 8300.0, 8400.0, 8500.0, 8600.0, 8700.0, 8800.0, 8900.0, 9000.0, 9100.0, 9200.0, 9300.0, 9400.0, 9500.0, 9600.0, 9700.0, 9800.0, 9900.0, 10000.0, 10100.0, 10200.0, 10300.0, 10400.0, 10500.0, 10600.0, 10700.0, 10800.0, 10900.0, 11000.0, 11100.0, 11200.0, 11300.0, 11400.0, 11500.0, 11600.0, 11700.0, 11800.0, 11900.0, 12000.0, 12100.0, 12200.0, 12300.0, 12400.0, 12500.0, 12600.0, 12700.0, 12800.0, 12900.0, 13000.0, 13100.0, 13200.0</td>
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<td>CALL ( f(x) = x^2 )</td>
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<td>CALL</td>
<td>( \int_0^1 x^2 , dx )</td>
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SUBROUTINE OUTPUT    T=0.1  GPT=1  TRASE

DF 20 J=1,10  OUTPUT 10
10 C
20 RT(J,1)MT(J,1)*1,0,32.  OUTPUT 35
30 CONTINUE  OUTPUT 36
40 C
50 OUTPUT TABLE I -- BOUNDARY TEMPERATURES, POWER AND GAP CONDUCTANCE  OUTPUT 37
60 C
70 WRITE(6,100) II, X(T), TCOOL(I), CLD(T), CLD(T), RT(I,1), TCE(I).  OUTPUT 41
80 C
90 WRITE(6,300) X(MSEG), TCOOL(MSEG), CLD1(MSEG), CLD2(MSEG)  OUTPUT 42
100 C
110 CALL SPACE  OUTPUT 43
120 C
130 OUTPUT TABLE II -- FUEL STRUCTURE INFORMATION  OUTPUT 44
140 C
150 WRITE(6,110)  OUTPUT 45
160 C
170 WRITE(6,120) J, X(J), RX(J), RER(J), TCR(J), TCE(J), RMT(J), RCE(J), J  OUTPUT 46
180 C
190 WRITE(6,130) JSEG(J)  OUTPUT 47
200 C
210 OUTPUT TABLE III -- FUEL RADIAL TEMPERATURE DISTRIBUTIONS  OUTPUT 48
220 C
230 WRITE OUT X(J) AND TEMPERATURES FOR EACH SEGMENT  OUTPUT 49
240 C
250 CALL SPACE  OUTPUT 50
260 C
270 WRITE(6,140) P*(4), X=1.10  OUTPUT 51
280 C
290 WRITE(6,150)  OUTPUT 52
300 C
310 WRITE(6,160) P*(4), X=1.10  OUTPUT 53
320 C
330 WRITE(6,170) J, X(J), RX(J), RER(J), J=1,10, JSEG(J)  OUTPUT 54
340 C
350 OUTPUT TABLE IV -- FUSION GAS INFORMATION  OUTPUT 55
360 C
370 CALL SPACE  OUTPUT 56
380 C
390 WRITE(6,180) P*(4), X=1.10  OUTPUT 57
400 C
410 WRITE(6,190)  OUTPUT 58
420 C
430 WRITE(6,200) P*(4), X=1.10  OUTPUT 59
440 C
450 WRITE(6,210)  OUTPUT 60
460 C
470 OUTPUT TABLE V -- EJECTION RATIO  OUTPUT 61
480 C
490 IF (20) GO TO 60  OUTPUT 62
500 C
510 CALL SPACE  OUTPUT 63
520 C
530 WRITE(6,220) TEG(J), VEG(J), WEG(J), VEG(J), WEG(J), WEG(J), VEG(J), WEG(J)  OUTPUT 64
540 C
550 WRITE(6,230) GM1, GM2  OUTPUT 65
560 C
570 IF (20) GO TO 60  OUTPUT 66
580 C
590 CALL SPACE  OUTPUT 67
600 C
610 WRITE(6,240)  OUTPUT 68
620 C
630 CALL SPACE  OUTPUT 69
640 C
650 OUTPUT TABLE VI -- FUEL AND CLODING GEOMETRY CHANGES  OUTPUT 70
660 C
670 WRITE(6,250)  OUTPUT 71
680 C
690 WRITE(6,260)  OUTPUT 72
700 C
710 WRITE(6,270)  OUTPUT 73
720 C
730 IF (20) GO TO 60  OUTPUT 74
740 C
750 CALL SPACE  OUTPUT 75
760 C
770 OUTPUT TABLE VII -- FUEL AND CLODING GEOMETRY CHANGES  OUTPUT 76
780 C
790 WRITE(6,280)  OUTPUT 77
800 C
810 GAPRINS(J)=CFSHEL(J)  OUTPUT 78
820 C
830 IF (GAP, L=0, D=0) GAP=0  OUTPUT 79
840 C
850 WRITE(6,290) J=1, J=10, J=1, J=10, J=1, J=10, J=1, J=10  OUTPUT 80
860 C
870 GAP=COLD(J)  OUTPUT 81
880 C
890 CONTINUE  OUTPUT 82
900 C
910 WRITE(6,300) NSEG, ENLEN(NSEG), ENLEN(NSEG), ENLEN(NSEG), ENLEN(NSEG)  OUTPUT 83
920 C
930 IF (30) GO TO 80  OUTPUT 84
940 C
950 CALL SPACE  OUTPUT 85
960 C
970 WRITE(6,310)  OUTPUT 86
980 C
990 CONTINUE  OUTPUT 87
1000 C
1010 WRITE(6,320)  OUTPUT 88
1020 C
1030 DO 70 J=1,10  OUTPUT 89
```
SURROUTINE OUTPUT 7/37 OPTICAL TRACE

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- **175**
  - //SIM VOLUME OF BORRED GAS
  - //SIM VOLUME OF WATER VAPOR
  - //SIM EFFECTIVE PLENUM VOLUME
  - //SIM VOLUME OF SALT WATER VAPOR
  - //SIM VOLUME OF FILL GAS

- **180**
  - //SIM BASIC PRESSURE
  - //SIM EXTERNAL PRESSURE

- **230**
  - FORMAT(33M HOLE OF MELTIC
  - //SIM MCM OF ZENON
  - //SIM HOLE OF KRYPTON
  - //SIM HOLE OF NITROGEN
  - //SIM HOLE OF ARGON

- **190**
  - 190 M, DOMINATION CLADDING CLAD OUTER FUEL OUT
  - 100 SPENT FUEL SHELLING, RADIUS, RADIUS, RADIUS

- **195**
  - 250 FORMAT(/33J,6X,F11.2,1PE12.3,2X,1PE12.3,0PF10.6,2F12.4,2F12.4)
  - 260 FORMAT(/16X,2X,INSIDE STRESS ---,15X,2X,OUTSIDE STRESS

- **200**
  - 35 SEG
    - 85M TANGENTIAL AXIAL EFFECTIVE TANGENTIAL
    - AXIAL EFFECTIVE
    - 85M --

- **230**
  - //SIM MCM OF MELTIC
  - //SIM MCM OF ZENON
  - //SIM HOLE OF KRYPTON
  - //SIM HOLE OF NITROGEN
  - //SIM HOLE OF ARGON

- **250**
  - 190 M, DOMINATION CLADDING CLAD OUTER FUEL OUT
  - 100 SPENT FUEL SHELLING, RADIUS, RADIUS, RADIUS

- **260**
  - 195 FORMAT(/33J,6X,F11.2,1PE12.3,2X,1PE12.3,0PF10.6,2F12.4,2F12.4)
  - 200 FORMAT(/,35H TOP, 5X, F7.3, 5X, 0PF7.0, 6X, F7.0, 6X, F7.0, 3X, F7.2)
  - END

**Output Values:**
- OUTPUT 100
- OUTPUT 140
- OUTPUT 150
- OUTPUT 152
- OUTPUT 153
- OUTPUT 154
- OUTPUT 155
- OUTPUT 156
- OUTPUT 157
- OUTPUT 158
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- OUTPUT 180