Scoping Calculations of Power Sources for Nuclear Electric Propulsion

F. C. Difilippo

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# TABLE OF CONTENTS

ACKNOWLEDGEMENTS .................................................... vii
ABSTRACT ........................................................................ viii

1.0 FOREWORD .................................................................... Page 1-1

2.0 SUMMARY ..................................................................... Page 2-1

3.0 INTRODUCTION .......................................................... Page 3-1
   3.1 TYPES OF REACTORS CONSIDERED ............................ Page 3-1

4.0 NEUTRONIC CALCULATIONS ......................................... Page 4-1
   4.1 NERVA DERIVATIVE DATA BASE ............................... Page 4-1
      4.1.1 Neutronic Properties of the Core .......................... Page 4-1
      4.1.2 Reactivity Worth of Beryllium Reflector .......... Page 4-1
      4.1.3 Reactivity Worth of Burn-Up ............................ Page 4-1
      4.1.4 Depletion of $^{235}\text{U}$ ................................. Page 4-1
      4.1.5 Reactivity Worth of $\text{B}_4\text{C}$ Sheet ....................... Page 4-2
   4.2 FUEL PIN DATABASE ............................................... Page 4-10
      4.2.1 Neutronic Properties of the Core ............................ Page 4-10
      4.2.2 Reactivity Worth of Beryllium Oxide Reflector .......... Page 4-10
      4.2.3 Reactivity Worth of Burnup and Isotopes ............... Page 4-10
      4.2.4 Reactivity Worth of the Pressure Vessel .......... Page 4-15
      4.2.5 Reactivity worth of $\text{B}_4\text{C}$ sheets ....................... Page 4-16

5.0 SHIELDING CALCULATIONS ........................................ Page 5-1
   5.1 NEUTRON SHIELDING ............................................. Page 5-1
   5.2 GAMMA SHIELDING ................................................ Page 5-1

6.0 THERMALHYDRAULICS ............................................. Page 6-1
   6.1 BULK CONDITIONS OF COOLANT .............................. Page 6-4
      6.1.1 Bulk Conditions of the Helium Coolant .................. Page 6-4
      6.1.2 Bulk Conditions of the Liquid Lithium ............... Page 6-6
   6.2 WALL TEMPERATURE ................................................ Page 6-6
      6.2.1 Wall Temperature of the NERVA Derivative Fuel Element Page 6-7
      6.2.2 Wall Temperature of the Fuel Rods ..................... Page 6-7
   6.3 FROM WALL TO FUEL TEMPERATURES ......................... Page 6-7
      6.3.1 Fuel Temperature of the NERVA Derivative Reactor ........ Page 6-7
      6.3.2 Fuel Temperature of the Fuel Pin Reactor ............. Page 6-8
   6.4 THERMALHYDRAULIC FEEDBACK VIA THE PRESSURE VESSEL Page 6-8

7.0 ORGANIZATION OF THE CODES .................................. Page 7-1
   7.1 SELECTION AND CALCULATION OF A DESIGN ............... Page 7-1
   7.2 DESIGN OF THE CONTROL DRUMS ............................... Page 7-2
   7.3 SOME DETAILS OF THE CODE NEPNERVA ..................... Page 7-3
   7.4 SOME DETAILS OF THE CODE NEPPIN ......................... Page 7-3

8.0 INPUT AND OUTPUT DESCRIPTIONS ................................. Page 8-1
   8.1 INPUT TO NEPNERVA ............................................. Page 8-1
   8.2 OUTPUT FROM NEPNERVA ....................................... Page 8-4
   8.3 INPUT TO NEPPIN ................................................ Page 8-13
   8.4 OUTPUT FROM NEPPIN ............................................ Page 8-15
LIST OF TABLES

Table 1. Reactivity worth of B$_4$C sheets ................................................. Page 4-2
Table 2. Reactivity worth (%) of 25 cm BeO reflector for the fuel pin core .......... Page 4-10
Table 3. Reactivity worth (%) of 1 cm thick astar alloy pressure vessel .......... Page 4-16
Table 4. Reactivity worth (%) of 360°, 2 cm thick, 90% enriched B$_4$C sheets ...... Page 4-16
Table 5. Power and flow conditions .............................................................. Page 6-1
LIST OF FIGURES

Fig. 1. $^{235}\text{U}$ critical mass of the core and mass of the core plus reflector for the NERVA derivative reactor. ................................................. Page 4-3

Fig. 2. $k_{\text{eo}}$ and migration length for the NERVA derivative core. .............................. Page 4-4

Fig. 3. Reactivity effects of a 30 cm thick radial Be reflector. ................................. Page 4-5

Fig. 4. Worth of the Be reflector (relative to 30 cm thickness) as a function of thickness. .... Page 4-6

Fig. 5. Reactivity worth of burnup for the NERVA derivative reactor, excluding Xe and Sm. Page 4-7

Fig. 6. Fission distributions and absorption over fission ratio as a function of S/F. ............ Page 4-8

Fig. 7. Reactivity worth of a 360°, 2 mm thick, natural B$_4$C located between the core and reflector as a function of S/F, also radial peaking factors are shown. ................................. Page 4-9

Fig. 8. Fuel pin reactor, $k_{\text{eo}}$ as a function of pitch and enrichment. .......................... Page 4-11

Fig. 9. Fuel pin reactor, critical buckling (cm$^{-1}$) as a function of pitch and enrichment. .......... Page 4-12

Fig. 10. Fuel pin reactor, critical masses for spherical bare cores. .............................. Page 4-13

Fig. 11. Fuel pin reactor, spectras averaged in the core for reflected spheres. ................ Page 4-14

Fig. 12. Available energy in Mwd for the NERVA derivative reactor as a function of S/F ....... Page 7-4

Fig. 13. Available energy in Mwd for the fuel pin reactor as a function of enrichment ........ Page 7-5

Fig. 14. Scheme for the exploration of possible designs, $E_a$ is the available energy and $x$ is one of the core dimensions ($R_c$ or $H_c$). .................................................. Page 7-6
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ABSTRACT

This technical memorandum describes models and calculational procedures used to fully characterize the nuclear island of power sources for nuclear electric propulsion. Two computer codes were written: one for the gas cooled NERVA derivative reactor and the other for liquid metal cooled fuel pin reactors. These codes are going to be interfaced by NASA with the balance of plant in order to make scoping calculations for mission analysis.
1.0 FOREWORD

Systems engineering efforts initiated by NASA’s Lewis Research Center (LeRC) in FY92 under RTOP 593-72, for Nuclear Electric Propulsion (NEP), have enabled the development of detailed mathematical (computer) models to predict NEP subsystem performance and mass. The computer models are intended to help provide greater depth to NEP subsystem (and system) modeling, required for more accurately verifying performance projections and assessing the impact of specific technology developments.

The following subsystem models have been developed:

(1) Liquid-metal-cooled pin-type, and

(2) Gas-cooled NERVA (Nuclear Engine for Rocket Vehicle Applications) - derived for reactor/shield;

(3) Potassium-Rankine, and

(4) Brayton for power conversion;

(5) Heat rejection general model (includes direct Brayton, pumped loop Brayton, and shear flow condenser (Potassium-Rankine);

(6) Power management and distribution (PMAD) general model; and

(7) Magnetoplasmadynamic thruster for the electric propulsion subsystem.

These subsystem models for NEP were authored by the Oak Ridge National Laboratory (ORNL) for the reactor (NASA CR-191133, by the Rocketdyne Division of Rockwell International for Potassium Rankine (NASA CR-191134) and Brayton (NASA CR-191135) power conversion, heat rejection (NASA CR-191132), and power management and distribution (NASA CR-191137).

At the time of this writing, these eight VAX/FORTRAN source and executable codes are resident on one of LeRC’s Scientific VAX computers.
2.0 SUMMARY

The modeling of a whole nuclear electric propulsion system for cargo and piloted missions is presently being developed at NASA Lewis Research Center. The vehicles would use either a Brayton direct conversion cycle using the heated helium from a NERVA type reactor or a potassium Rankine cycle with the working fluid heated at the secondary site of a heat exchanger with lithium at the primary site coming from a fast reactor.

This report describes the two computer codes written to fully characterize, for each of the options, the nuclear islands of the system. Given a set of input conditions, the codes calculate composition, dimensions, volumes, and masses of the core, reflector, control system, pressure vessel, neutron and gamma shields as well as the thermalhydraulic conditions of the coolant, clad and fuel. Input conditions are power, core life, burnup, pressure, and temperature of the coolant at the inlet of the core, and either the temperature of the coolant at the outlet of the core or the coolant mass flow.

Using state-of-the-art neutron cross sections and transport codes, a database was created for the neutronic performance of both reactor designs. The free parameters of the models are the moderating/fuel element ratio for the NERVA reactor and the enrichment and the pitch of the lattice for the fast reactor. Reactivity and energy balance equations are simultaneously solved to find the reactor design. Thermalhydraulic conditions are calculated by solving the one-dimensional versions of the equations of conservation of mass, energy, and momentum with compressible flow. The additional input conditions for the fluences and integrated doses at a cargo area of radius $r$ located at distance $z$ determines the dimensions, volumes, and masses of the neutron and gamma shields. The assumption was made to use either LiH in a stainless steel matrix or B$_4$C for the neutron shielding and tungsten for the gamma shielding.
3.0 INTRODUCTION

As a consequence of a collaborative agreement between NASA and ORNL, the Engineering Physics and Mathematics Division has been involved in the development of models and calculational procedures for the analysis (neutronic and thermalhydraulic) of power sources for nuclear electric propulsion.

The boundaries of the system to be modeled are the inlet and outlet plenums and the design variables of interest are the compositions, dimensions, volumes, and masses of the core, reflector, control system, pressure vessel, and neutron and gamma shields. The thermalhydraulic conditions of the coolant are also determined. Main input variables are power, core life, burnup, pressure, and temperature of the inlet coolant and its temperature at the outlet.

The computer codes developed are going to be coupled with the calculations of the balance of plant and ion generation and acceleration to perform scoping calculations for mission analysis. It was required then to develop codes that are fast running on PCs or workstations. For that reason, although the requested parameters are quite comprehensive, the models were kept as simple as possible.

The range of input conditions specified for this task were: a power range of 10 to 50 Mw(th); operating lifetimes of 2 to 10 years; and outlet coolant temperature ranging from 1200 to 2200° K.

3.1 TYPES OF REACTORS CONSIDERED

Two types of reactors were chosen for this analysis: the high temperature gas-cooled reactor of the NERVA derivative type and the lithium-cooled advanced fuel pin reactor, referred to as NERVA derivative and fuel pin for short.

The elements of the core of a NERVA derivative reactor are: (a) fuel elements with ZrC cladding, a dispersion of UC-ZrC in a graphite matrix, and 19 coolant holes (diameter 2.88 mm); and (b) support elements with ZrH₂ on an inconel tube with pyrolitic graphite and graphite as a thermal shield. Both elements are hexagonal with 1.913-cm flat-to-flat distance; by changing the ratio (S/F) of support to fuel elements the neutron spectrum can be modified considerably; the core is cooled by pumping He, which drives a turbine in a direct Brayton cycle. The reflector is made of beryllium, which contains the control drums that rotate the control boron carbide (B₄C) sheets. The pressure vessel is located at the periphery of the reflector.

The core of the fuel pin reactor consists of bundles of rods containing UN pellets. The coolant, liquid lithium, removes heat from the core to boil potassium at the secondary side of a heat exchanger which drives a turbine using a Rankine cycle. The fuel rods have 6.4 mm outside diameter (O.D.) with 0.635-mm-thick cladding of the tantalum alloy Astar. A tungsten liner, 0.122-mm-thick, lays between the clad and the UN pellet, 4.786 mm in diameter with a 0.025-mm-thick He gap surrounding the fuel pellet. The reflector is made of BeO which contains the control drums with the B₄C absorber. The pressure vessel is located between the core and the reflector.

Common to both reactors are the material of the reflector pressure vessel (Astar alloy), the neutron shielding materials (lithium hydride (LiH) in a stainless steel matrix or B₄C), and the gamma shielding material (tungsten).
4.0 NEUTRONIC CALCULATIONS

In order to find the volume of the core, a reactivity balance is performed where the reactivity effects of the reflector, burnup, pressure vessel, structural materials, and desired reactivity at end of life (EOL) are added to the multiplication constant of the bare core. It was then necessary to create a database for all these parameters; this section describes the criterion and results. Both reactors are intended to be controlled with absorbing materials in the reflector. Thus, the excess reactivity is produced by the reflector with the bare core near critical state. Other factors like compact designs and low masses favor cylindrical shapes with the core diameter ($2R_c$) approximately the same as the core height ($H_c$) (i.e., $R_c/H_c = 0.541$, this is the ideal shape from a neutron economy standpoint). Many of the data were then generated for a critical core of ideal shape with the transport code XSDRNPM\(^1\) using a very detailed cross section library.\(^2\)

4.1 NERVA DERIVATIVE DATA BASE

The two free parameters of this design are the concentration of the fuel (highly enriched, 93\%, $^{235}\text{U}$) in the fuel element and the number of support-to-fuel-elements ratio. A plot of the critical mass of $^{235}\text{U}$ and the mass of the core plus the 24-cm reflector is presented in Fig. 1 showing that beyond ~500 g of $^{235}\text{U}$ per liter of fuel element the total mass is not substantially reduced (note that Fig. 1 is for an ideal shape, for odd shapes the situation might be different). It was decided to fix the fuel concentration to 500 g of $^{235}\text{U}$/L fuel; the database depends then on S/F alone.

4.1.1 Neutronic Properties of the Core

Multiplication constants, $k_{\infty}$, for the infinite lattice and migration lengths, $M$, are plotted in Fig. 2 as a function of S/F.

4.1.2 Reactivity Worth of Beryllium Reflector

The reactivity effects of a 30 cm thick radial reflector are shown in Fig. 3 as a function of S/F. It is defined as $\Delta k = (k\text{ (reflected)} - k\text{ (bare)}) \times 100$, where $k$'s are the multiplication constants. The effects of the thickness of the Be reflector are shown in Fig. 4. This shape of the curve is used for all S/F although Fig. 4 corresponds to S/F = 0.195 and a fuel density of 374.7 g of $^{235}\text{U}$/L of fuel.

4.1.3 Reactivity Worth of Burn-Up

The reactivity worths of the burnup, expressed as a percentage of the $^{235}\text{U}$ loading at beginning of life (BOL), are shown in Fig. 5. The values shown were calculated by depleting the number densities of $^{235}\text{U}$ by the percentage burnup and simulating the fission products as a lumped 1/v absorber calibrated at 50 barn per fission at an energy of 0.025 eV.

Because the reactor can have a thermal spectrum because of the presence of support elements, the effects of Xe and Sm at steady state and after transients were computed with formulas taken from Ref. 3. Effective cross sections for these formulas are obtained by collapsing a four-group cross section set and spectras used by the program; in this way, transition from thermal (where Xe poisoning is important) to epithermal spectras (where Xe is irrelevant) can be made gradually. Note that because of the way we computed its effects, 10% burnup means 10% depletion via fission and capture.

4.1.4 Depletion of $^{235}\text{U}$

Figure 6 illustrates how the fission distributions change as a function of S/F. The change of spectra affects the values of the absorption to fission ratio by as much as 10%. This functional dependence is taken into account by the program.
4.1.5 Reactivity Worth of B₄C Sheet

The reactivity worth of 360° sheets of B₄C located between the core and the reflector are shown in Table 1, which was prepared for a core with S/F = 0 where the neutron spectra is the hardest. The maximum value would correspond to the removal of the reflector. Table 1 shows that a 2 mm thick sheet of natural B₄C is very effective, so it was decided to use it as control material. The reactivity worths of 360°, 2 mm thick natural B₄C sheets are shown in Fig. 7 as a function of S/F and for a 30 cm thick reflector; in general, as the moderation in the core is increased the reflector and anything within it is less important, including the control drums. The worth of the B₄C is then multiplied by the factor given by Fig. 4 to compensate for effects of reflector thickness. Figure 7 also shows the peaking factor in the radial direction of the power density at BOL, i.e., with fresh fuel and control drums in.

Table 1. Reactivity worth of B₄C sheets*

<table>
<thead>
<tr>
<th>Sheet</th>
<th>Δk (%)</th>
<th>(Δk/Δk)max</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 mm Nat B</td>
<td>21.0</td>
<td>0.70</td>
</tr>
<tr>
<td>2 mm 80% B</td>
<td>24.0</td>
<td>0.80</td>
</tr>
<tr>
<td>5 mm 90% B</td>
<td>25.9</td>
<td>0.86</td>
</tr>
</tbody>
</table>

*Core: S/F = 0, Rₑ = 59.25 cm, Hₑ = 109.11. Reflector: 30 cm Be (Δk)max = 30.14% (removing the Be reflector).
Fig. 1. $^{235}\text{U}$ critical mass of the core and mass of the core plus reflector for the NERVA derivative reactor.
Fig. 2. $k_{\infty}$ and migration length for the NERVA derivative core.
Fig. 3. Reactivity effects of a 30 cm thick radial Be reflector.
Fig. 4. Worth of the Be reflector (relative to 30 cm thickness) as a function of thickness.
Fig. 5. Reactivity worth of burnup for the NERVA derivative reactor, excluding Xe and Sm.
Fig. 6. Fission distributions and absorption over fission ratio as a function of S/F.
Fig. 7. Reactivity worth of a 360°, 2 mm thick, natural B₄C located between the core and reflector as a function of S/F, also radial peaking factors are shown.
4.2 FUEL PIN DATABASE

The two free parameters of this design are the enrichment and the pitch of the hexagonal lattice; a possible third one, the diameter of the fuel rod, was fixed to 6.4 mm.

4.2.1 Neutronic Properties of the Core

Figures 8 and 9 show $k_\infty$ and critical bucklings as function of enrichment and pitch to diameter ratio, $P/d$. The corresponding critical masses for spherical bare reactors are shown in Fig. 10. The comparison of this figure with Fig. 1 shows that a considerably larger amount of fuel can be assembled with the fuel pin option. Figure 11 shows spectras averaged in the core for reflected spheres.

4.2.2 Reactivity Worth of Beryllium Oxide Reflector

The reactivity worth of a 25 cm thick BeO reflector is shown in Table 2 as function of enrichments and $P/d$. The worths were calculated as the difference between the multiplication constant of radially reflected and bare critical cylindrical cores with optimum shape. For a different reflector thickness the worth of the reflector is multiplied by the factor of Fig. 4 due to the incomplete database.

<table>
<thead>
<tr>
<th>P/d</th>
<th>Enrichment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>93.0</td>
</tr>
<tr>
<td>1.1</td>
<td>19.26</td>
</tr>
<tr>
<td>1.2</td>
<td>18.57</td>
</tr>
<tr>
<td>1.3</td>
<td>17.65</td>
</tr>
<tr>
<td>1.4</td>
<td>16.61</td>
</tr>
<tr>
<td>1.5</td>
<td>15.50</td>
</tr>
</tbody>
</table>

4.2.3 Reactivity Worth of Burnup and Isotopics

Because of the lack of a database for this effect a simplified analytical approach was chosen. Assuming that the leakage does not change with burnup, the change in the multiplication constant because of the burnup (BU) is:

$$\Delta k(BU) = k(BU) - k(0) = \frac{k(BU)}{k(0)} - 1$$ (1)
Fig. 8. Fuel pin reactor, $k_\infty$ as a function of pitch and enrichment.
Fig. 10. Fuel pin reactor, critical masses for spherical bare cores.
Fig. 11. Fuel pin reactor, spectra averaged in the core for reflected spheres.
where the multiplication constant for the infinite lattice is

$$k_m = \frac{\nu_5 n_5 \sigma_{f5} + \nu_8 n_8 \sigma_{f8} + \nu_9 n_9 \sigma_{f9}}{n_5 \sigma_{a5} + n_8 \sigma_{a8} + n_9 \sigma_{a9} + n_{fp} \sigma_{a,fp} + \sum r} \quad (2)$$

where indexes 5, 8, and 9 stand for $^{235}$U, $^{238}$U, and $^{239}$Pu, $fp$ for fission products, and $r$ for the rest of the mixture. The $\sigma$'s stand for cross sections averaged in the neutron spectra and $n_5$, $n_8$, $n_9$, and $n_{fp}$ are the isotopic concentrations which are functions of the burnup. The burnup is defined as the integrated number of fissions relative to the initial concentration of $^{235}$U atoms,

$$BU = \frac{f_2 + f_8 + f_9}{n_5(0)} \quad (3)$$

Note, that because of the way we compute the burnup this definition refers only to depletion via fission and is slightly different with respect to the case of the NERVA reactor.

Writing and solving the buildup and depletion equations for the isotopic and assuming that there is no Pu at BOL, we obtain

$$BU = \frac{\sigma_{f2}}{\sigma_{a8}} \left(1 - e^{-\sigma_{a8} \phi_t} \right) + \frac{\sigma_{f8}}{\sigma_{a8}} \left( \frac{1}{\epsilon} - 1 \right) \left(1 - e^{-\sigma_{a8} \phi_t} \right)$$

$$+ \frac{\sigma_{a8}}{\sigma_{a9} - \sigma_{a8}} \left( \frac{1}{\epsilon} - 1 \right) \left[ \frac{\sigma_{f9}}{\sigma_{a8}} \left(1 - e^{-\sigma_{a8} \phi_t} \right) - \frac{\sigma_{f9}}{\sigma_{a8}} \left(1 - e^{-\sigma_{a8} \phi_t} \right) \right] \quad (4)$$

where indices $f$, $a$, and $c$ stand for fission, absorption and capture, $\epsilon$ is the initial enrichment, and the $\sigma$'s were taken from Ref. 4. For an input burnup, $BU$, Eq. 4 is solved for the fluence $\phi_t$ which is then used to find the isotopic concentrations necessary to evaluate Eqs. (1) and (2).

4.2.4 Reactivity Worth of the Pressure Vessel

Because in this design the pressure vessel is located between the core and the reflector it is relevant to the reactivity balance. Table 3 shows the reactivity worths as a function of enrichment and P/d.
Table 3. Reactivity worth (%) of 1 cm thick astar alloy pressure vessel*

<table>
<thead>
<tr>
<th>P/d</th>
<th>Enrichment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>93.0</td>
</tr>
<tr>
<td>1.1</td>
<td>5.69</td>
</tr>
<tr>
<td>1.2</td>
<td>5.39</td>
</tr>
<tr>
<td>1.3</td>
<td>5.12</td>
</tr>
<tr>
<td>1.4</td>
<td>4.77</td>
</tr>
<tr>
<td>1.5</td>
<td>4.41</td>
</tr>
</tbody>
</table>

*Worth is negative, 25 cm BeO reflector, critical bare cylindrical core with optimum shape.

The worth of the pressure vessel is multiplied by the factor given by Fig. 4 to consider the effects of a different reflector thickness.

4.2.5 Reactivity worth of B$_4$C sheets

The reactivity worths of 360° 2 cm thick, 90% enriched B$_4$C sheets located between the pressure vessel and the BeO reflector are shown in Table 4.

Table 4. Reactivity worth (%) of 360°, 2 cm thick, 90% enriched B$_4$C sheets*

<table>
<thead>
<tr>
<th>P/d</th>
<th>Enrichment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>93.0</td>
</tr>
<tr>
<td>1.1</td>
<td>6.73</td>
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<tr>
<td>1.2</td>
<td>6.64</td>
</tr>
<tr>
<td>1.3</td>
<td>6.37</td>
</tr>
<tr>
<td>1.4</td>
<td>6.07</td>
</tr>
<tr>
<td>1.5</td>
<td>5.73</td>
</tr>
</tbody>
</table>

*Worth is negative, 25 cm BeO reflector, critical bare cylindrical core with optimum shape and a 1 cm thick astar alloy pressure vessel.

The table shows low effectiveness of the B$_4$C sheet because of the shielding effects of the 1 cm thick pressure vessel. Better location for the sheet might be found, but no additional data is available. Corrections to the database because of different thicknesses for the pressure vessel and the B$_4$C sheets are discussed in Section 6.
5.0 SHIELDING CALCULATIONS

The materials for the shielding are LiH in a stainless steel matrix, or B₄C, for the neutrons, and tungsten for the gammas, in a shadow shield configuration. The input parameters for the designs are accepted values for fluences and integrated gamma doses for the entire duration of the mission at a cargo area located at \( z \) meters from the base of the reactor and with radial size \( r \).

After its evaluation, the source term for each radiation is affected by the self shielding of the reactor materials. Removal cross sections and buildup factors are used to calculate the thickness of the shield and the radial sizes are chosen by assuming the shield plate is at the base of the reactor and that there is no line of sight from any point of the reactor to the cargo area. Both shielding requirements were calculated together because one type of shielding material shields, marginally, the other type of radiation.

5.1 NEUTRON SHIELDING

For an input power, the source term of fast neutrons is calculated assuming a value of 200 Mev per fission. The self shielding, \( f_s \), for an uncollided current of fast neutrons in spherical geometry, and uniform composition within radius \( R \), is

\[
f_s = \frac{3}{a} \left\{ \frac{1}{2} - \frac{1}{a^2} [1 - e^{-a} (1 + a)] \right\},
\]

where \( a = 2 \Sigma R \) and \( \Sigma \) is the removal cross section. We had used an equivalent \( R \) for the total volume of the core, reflector and pressure vessel and a uniform density of materials with removal cross section from Ref. 5. Given the source term, the self shielding \( f_s \), the accepted fluence, and the removal cross sections of the LiH-ss or B₄C, the thickness of the neutron shield is fixed.

5.2 GAMMA SHIELDING

The source term is calculated from the total number of fissions and captures, both determined by the power level. The capture reaction rate is then distributed into their material components with relative capture rates read from tables (case of NERVA derivative) or calculated with one-group capture cross sections (the case of the fuel pin). The next step is to multiply capture and fissions rates with the 9 group gamma production spectra per atom taken from Ref. 5.

The self shielding factor is given also by Eq. (5) but with the final value attenuated by the buildup factor due to the scattering of gamma rays. Removal cross sections and buildup factor parameters are also from Ref. 5. The definition of buildup factors for a mixture, even homogeneous, is not obvious; we have interpolated the tables with an equivalent atomic number for the mixture defined with the \( Z \) of the components weighted with their total gamma reaction rates. Given the source terms, the self shielding \( f_s \) and the accepted gamma dose, the thickness of the tungsten plate is determined after reading cross sections and buildup factors from the data base for the 9 energy groups.
6.0 THERMALHYDRAULICS

Thermalhydraulic conditions are calculated with the approximation of one-dimensional equations for the conservation of mass, energy and momentum. Three steps are involved in the calculations related with the calculations of the bulk conditions of the coolant, the temperature of the wall of the channel and the temperatures within the fuel.

Thermalhydraulic variables depend on power and flow conditions. Four are considered in this analysis and are described in Table 5.

Table 5. Power and flow conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>Power distribution</th>
<th>Flow distribution</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r,θ</td>
<td>z</td>
<td>r,θ</td>
</tr>
<tr>
<td>1</td>
<td>Uniform</td>
<td>Uniform</td>
<td>Uniform</td>
</tr>
<tr>
<td>2</td>
<td>Uniform</td>
<td>Cosine</td>
<td>Uniform</td>
</tr>
<tr>
<td>3</td>
<td>Not uniform</td>
<td>Cosine</td>
<td>Proportional to local power</td>
</tr>
<tr>
<td>4</td>
<td>Not uniform</td>
<td>Cosine</td>
<td>Uniform</td>
</tr>
</tbody>
</table>

Case 1 is the most relaxed and case 4 the most extreme; intermediate cases 2 and 3 give very similar results. Please note that fuel grading, cases 1 and 2, implies reactivity penalties not considered in the balance of reactivity in Section 3.

Power density, released as heat, at the location of the fissile material is

\[ \rho_p = \bar{\rho}_p \left( \frac{f_1}{f_2} \right) F(r,\theta,z) \tag{6} \]

where \( \bar{\rho}_p = P / \pi R_c^2 H_c \) is the fission power density averaged into core of radius \( R_c \) and height \( H_c \). \( f_1 \) is the fraction of the fission power released as heat inside the core, \( f_2 \) is the volumetric fraction of the fissile material relative to the core volume and \( F(r,\theta,z) \) is the power distribution of the homogenized core,

\[ F(r,\theta,z) = \frac{\pi R_c^2 H_c \psi(r,\theta,z)}{\int_{\text{core}} \psi(r,\theta,z) \, dV} \tag{7} \]
We assume the distribution $\Psi$ can be written as

$$\Psi(r, \theta, z) = R(r, \theta) Z(z) .$$  \hfill (8)

Consequently

$$F(r, \theta, z) = f_z f_{r, \theta}$$  \hfill (9)

where

$$f_z = \frac{Z(z)}{\frac{1}{H_c} \int Z(z) dz}$$  \hfill (10)

and

$$f_{r, \theta} = \frac{R(r, \theta)}{\frac{1}{\pi R_c^2} \int r dr \int R(r, \theta) d\theta}$$  \hfill (11)

We further assume that $Z(z)$ can be approximated as

$$Z(z) = \sin \frac{\pi z}{H_c'} ,$$  \hfill (12)

where $H_c' = H_c + 2\delta$, with $\delta$ being the extrapolated length and the fuel occupying the space between $z = \delta$ and $z = H_c + \delta$. Eq (10) can then be approximated as

$$f_z = \frac{\alpha}{\sin \alpha} \sin \frac{\pi z}{H_c'}$$  \hfill (13)

where $\alpha = \pi H_c/(2H_c')$. 

Page 6-2
Because of the even distribution of control drums around the reflector and because the assumed even movement of the absorbing sheets, \( R(r, \theta) \) is a periodic function in \( \theta \) with period \( \theta_d = 2 \pi / \theta_d \) where \( \theta_d \) is the number of drums, \( R(r, \theta) \) can then be expanded in Fourier series, resulting in

\[
\hat{f}_{r,\theta} = a_0(r) + \sum_{n=1}^{\infty} \left[ a_n(r) \cos n2\pi \frac{\theta}{\theta_d} + b_n(r) \sin n2\pi \frac{\theta}{\theta_d} \right],
\]

where

\[
a_n = \frac{\bar{R}_n(r)}{\pi R_c^2 \int_0^{\theta_d} \bar{R}_0(r) 2\pi rdr} \tag{15}
\]

\[
b_n = \frac{\bar{R}_n'(r)}{\pi R_c^2 \int_0^{\theta_d} \bar{R}_0(r) 2\pi rdr} \tag{16}
\]

\[
\bar{R}_n(r) = \frac{1}{\theta_d} \int_0^{\theta_d} R(r, \theta) \cos \left( n2\pi \frac{\theta}{\theta_d} \right) d\theta \tag{17}
\]

and

\[
\bar{R}_n'(r) = \frac{1}{\theta_d} \int_0^{\theta_d} R(r, \theta) \sin \left( n2\pi \frac{\theta}{\theta_d} \right) d\theta \tag{18}
\]

At BOL and with the absorbing sheets looking to the core, we assume that \( f_{r,\theta} \) is maximum at the center of the core, where \( a_n = b_n = 0 \) for all \( n \neq 0 \), i.e.,

\[
f_{r,\theta} \mid_{\text{max}} = a_0(r = 0) \tag{19}
\]

and that \( f_{r,\theta} \) is minimum at \( r = R \) and in front of the absorbing sheet

\[
f_{r,\theta} \mid_{\text{min}} = a_0(r = R_c) - \Delta_\theta \tag{20}
\]
where $-\Delta_\theta$ is the sum of Eq. (14) evaluated at $r = R_c$ and the $\theta$ corresponding to the minimum, or

$$f_{r,\theta} \text{,min} = a_0(R_c) \left[ 1 - \frac{\Delta_\theta}{a_0(R_c)} \right].$$

We had tabulated $a_0(r)$ by using the approximation of considering a continuous $360^\circ$ sheet of absorber rather than a collection of discrete strips around the core. Also the angular tilt in the bracket of Eq. (21) was left as an input variable in the programming. In this way, and for cases 3 and 4 of Table 5, the program computes the thermalhydraulic conditions for the two extreme channels.

6.1 BULK CONDITIONS OF COOLANT

For the case of the bulk conditions of the coolant and considering no gravitational effects and one phase flow, the equations of conservation are

$$\rho v = \rho_i v_i$$

(22)

$$h + \frac{v^2}{2} = h_i + \frac{v_i^2}{2} + \frac{P_i}{w}$$

(23)

and

$$w \frac{dv}{dz} + A \frac{dp}{dz} + \frac{1}{2} \rho v^2 f P_f = 0$$

(24)

where the channel was subdivided into nodes, subindex $i$ refers to the inlet conditions and the unsubscripted variables refer to the outlet conditions. Variables $\rho, v, h$ and $P$ are density velocity, enthalpy and pressure of the fluid, $w$ is the constant mass flow through a constant area $A$, $P_i$ is the power delivered to the node, $f$ is the friction factor and $P_f$ the wet perimeter.

6.1.1 Bulk Conditions of the Helium Coolant

Because of the compressible flow and the high speed of the coolant, Eqs. (22) to (24) have to be solved without further simplifications. Combining Eqs. (22) and (23) we obtain

$$F(p,T) = h - h_i - \frac{P_i}{w} - \frac{v_i^2}{2} \left( 1 - \frac{\rho_i^2}{\rho^2} \right) = 0.$$
Using the equation of state, Eq. (24) can be written as

\[
\frac{dP}{dz} \left[ 1 - \frac{v^2}{c^2} \right] + \frac{w^2}{A^2 p} \left[ \frac{fP_f}{2A} - \frac{1}{\rho} \frac{\partial \rho}{\partial T} \frac{dT}{dz} \right] = 0
\]  

(26)

where \( c = 1/(\partial \rho/\partial p)_T \) is the isothermal speed of sound. Integrating Eq. (26) along the node we have

\[ G(p,T) = p - p_i + \bar{F}_1 \Delta z + \bar{F}_2 (T - T_i) = 0 \]  

(27)

where \( \bar{F}_1 \) and \( \bar{F}_2 \) are the average values within the node of

\[ F_1 = \frac{w^2 fP_f}{2A^3 \rho} \left( 1 - \frac{v^2}{c^2} \right) \]  

(28)

and

\[ F_2 = \frac{w^2 \frac{\partial \rho}{\partial T}}{A^2 \rho^2} \left( 1 - \frac{v^2}{c^2} \right) . \]  

(29)

The averages are approximated by weighing the inlet and outlet conditions

\[ \bar{F}_e = \frac{1}{1 + x} \left[ F_e(p_i, T_i) + x F_e(p, T) \right], \; e = 1, 2 \]  

(30)

where \( x \) is the relative weight. The outlet conditions, \( p \) and \( T \), are obtained by the simultaneous solutions of Eqs. (25) and (27). Because Eq. (25) is mainly dependent on \( T \), a first estimation of the temperature \( T^{(1)} \) is made by using \( p_i \) instead of \( p \) in Eq. (25). With \( T^{(1)} \), Eq. (27) is solved for \( p \) to obtain a first estimation of \( p, p^{(1)} \); then \( F \) and \( G \) are linearized around \( p^{(1)}, \; T^{(1)} \) to find \( p, T \). In the whole process \( x \) is an input value.

When \( v \) approaches sonic velocities the entire one dimensional approach is no longer valid. If this condition occurs, the program prints warnings and restarts calculations relaxing inlet and power conditions.
Friction factors, thermodynamics, and transport properties of the He were taken from Ref. 6. For Reynolds, Re, number below 2,000, \( \frac{f}{Re} = \frac{16}{Re} \) ,

and above \( Re = 2000 \) the Moody approximation to the Colebrook-White correlation was used

\[
f = 0.001375 \left[ 1 + \left( 20,000 \frac{\varepsilon}{d} + \frac{10^6}{Re} \right)^{\frac{1}{3}} \right],
\]

which includes \( \varepsilon \), the rugosity of the channel with diameter \( d \).

6.1.2 Bulk Conditions of the Liquid Lithium

Considerable implications are possible in this case; because the dependence of the enthalpy with the pressure is negligible as well as the velocity terms, Eq. (25) is used to evaluate \( T \) which then defines \( p \) and the velocity. With the known velocity gradient and the average of the friction term in the node also known, Eq. (24) can be immediately integrated to find \( p \).

The fuel rods are assembled in hexagonal bundles and they are separated with helicoidal spacing wires. One result of this arrangement is that there are three types of cells, central, lateral and at the corner with different flow fractional areas. The thermalhydraulics calculations are done for the 3 cells and the average conditions across the bundle are then calculated. For the calculation of the average pressure distribution in the bundle, we have used the Novendstern correlation taken from reference 7 which includes the effects of the spacing wire and the different geometries of the 3 cells within the bundle. The temperature of the hottest point in the coolant is monitored against the saturation temperature to warn the user about potential local boiling. Thermodynamics and transport properties of Li were taken from reference 8.

6.2 WALL TEMPERATURE

After the calculation of the bulk temperature of the coolant, the wall temperature, \( T_w \), is calculated with the equation

\[
T_w = T_b + \frac{j}{h},
\]

where \( j \) is the power current and \( h \) is the heat transfer coefficient, obtained from correlation for the Nusselt number \( Nu = hD/k \).
6.2.1 Wall Temperature of the NERVA Derivative Fuel Element

Although velocities of the He coolant are not very high for NEP, the program was prepared to deal with the case of high speed flow, like in the case of NTP. At very high speed, \( T_b \) in Eq. (33) is substituted by \( T'_b \) which is given by

\[
F_R = \frac{T'_b - T_b}{T_s - T_b}
\]  

(34)

where the recovery factor, \( F_R = \sqrt[3]{Pr} \) (Prandtl number, \( Pr = C_p \mu / k \)) and the stagnation temperature, \( T_s \), is given by

\[
h(T_s, p) = h(T_b, p) + \frac{v^2}{2}
\]  

(35)

The correlation of Mc Eligot et al. \( \text{6} \) was chosen for the Nusselt number. It is the well known Dittus-Boelter correlation with corrections because of entry effects and non-negligible differences between wall and bulk temperatures. The complications of all these corrections make the wall temperature an implicit variable so an iterative method is necessary.

6.2.2 Wall Temperature of the Fuel Rods

Because of the excellent heat conductivity of the liquid lithium and the higher density we do not have the complications of the previous case, namely aerodynamics and temperature gradient effects, so explicit calculations with Eq. (33) are possible and no iterations are necessary. The correlations for the Nusselt number in pages 189, 190 of Ref. 7 were used; the correlations depend mainly on the Peclet number, \( P_e = Re Pr \), and are specially fitted for rods in a bundle. They are parametric in \( P/d \) and in the effective ratio of the eddy diffusivity of heat to momentum, \( \Psi \), which depends on Prandtl and Reynolds numbers and \( P/d \).

6.3 FROM WALL TO FUEL TEMPERATURES

Once the wall temperature is known, the temperature distributions inside the solid fuel element are calculated by solving the one dimensional (this time the radial direction) heat conduction equation. The maximum fuel temperature is then compared with the melting temperature of the fuel to warn the user to relax the input requirements.

6.3.1 Fuel Temperature of the NERVA Derivative Reactor

The coolant flows through holes in the hexagonal fuel element; centered in the coolant hole and for increasing radius \( r \) we find the wall at \( r = r_0 \), the fuel at \( r = r_1 \) and the boundary of the heat cell at \( r = r_2 \). Between \( r_0 \) and \( r_1 \) we have the ZrC clad, and between \( r_1 \) and \( r_2 \) a mixture of graphite and UC - ZrC; the radius of the cell, \( r_2 \), is determined by distributing the area of the mixture evenly between the nineteen holes.

The temperature distribution equations are subject to the boundary conditions \( T(r = r_0) = T_w \) (from Section 5.2) and \( \partial T / \partial r \bigg|_{r=r_2} = 0 \).
The heat conductivity ($k$) of the different materials was taken from the available literature. If better values become available the subroutines could be reprogrammed easily. The $k$ of the cladding was taken from Ref. 10, $k(\text{ZrC}) = 0.2077 \, \text{watt/cm}^\circ \text{K}$; the $k$ of the mixture is calculated as

$$k(\text{mix}) = x(\text{UC}) k(\text{UC}) + x(\text{ZrC}) k(\text{ZrC}) + x(\text{graph}) k(\text{graph})$$

(36)

where the $x$'s are the mass fractions in the mixture. The temperature dependent $k(\text{UC})$ values were taken from Ref. 9. The $k$ of graphite exhibits large anisotropic and irradiation effects;\(^\text{10}\) no intentions were made to introduce these additional complications so average temperature dependent $k$'s without irradiation effects were used. Graphite melts at $3889^\circ \text{K}$ above the melting temperature of the $\text{UC-ZrC}$ mixture which depends on the relative concentration. Melting temperatures of the UC-ZrC mixture were taken from Ref. 10.

6.3.2 Fuel Temperature of the Fuel Pin Reactor

Centered in the fuel rod we have the $\text{UN}$ fuel pin to $r = r_p$, the He gap to $r = r_e$ and the tungsten liner and astar alloy clad up to $r = r_c$. Heat conductivities were taken from reference 4 and the heat transfer of the He gap was computed as $k(\text{He})/\text{gap thickness}$, with $k(\text{He})$ from Ref. 6. This value is a simplification; very detailed discussions about this parameters can be found in Ref. 7. Boundaries conditions are $T(r = r_e) = T_w$ (from Section 5.2.2) and $\partial T/\partial r),_{r=0} = 0$. Melting temperature of $\text{UN}$ and $W$ quoted in the program are from Ref. 11.

6.4 THERMALHYDRAULIC FEEDBACK VIA THE PRESSURE VESSEL

Strictly speaking the thermalhydraulic conditions have an effect over the neutronic calculations of Section 3. This feedback was not considered because it is a small effect in comparison with the scoping nature of the calculations and the uncertainties of the models. The exception is the pressure vessel for the case of the fuel pin reactor. The thickness $d$ of the pressure vessel is determined in general by the equation\(^\text{12}\)

$$d = \frac{pR}{\sigma}$$

(37)

where $R$ is the external radius of the Be reflector for the NERVA derivative reactor or the radius of the core for the fuel pin reactor, $p$ is the pressure, and $\sigma$ is the maximum stress allowable for the pressure vessel. We have used a subroutine from the ALKASYS\(^\text{4}\) code to calculate $\sigma$, determined by the temperature and the life of the reactor. The temperature of the pressure vessel is an input variable. If it is not specified, the code chooses the exit temperature of the coolant as the temperature of the pressure vessel.

Because the pressure vessel has an impact on the reactivity balance (see Table 3) its worth is included in the reactivity balance.
7.0 ORGANIZATION OF THE CODES

In order to find a design that meets the input demands two balance equations have to be simultaneously solved; one for the reactivity, the other for the energy. The major input variables are the reflector thickness, $\delta_R$, the burnup at EOL, $BU$, the power level, $P$, the operation time, $D$, and the boundary conditions for the thermalhydraulics: inlet conditions of the coolant, $P_i$ and $T_i$, and either its outlet temperature, $T_o$, or mass flow, $w$, and the temperature of the pressure vessel, $T_{pv}$.

The coolant outlet temperature or its flow is then calculated with an enthalpy balance equation neglecting the pressure drop along the reactor. If $T_{pv}$ is not specified the code uses $T_o$ as the temperature of the pressure vessel. $T_{pv}$ and $D$ are used then to compute $\sigma$, the maximum stress for the astor alloy.

7.1 SELECTION AND CALCULATION OF A DESIGN

In order to write the reactivity balance equation, the worth of each component is read from tables or computed. The reactivity worth of the radial reflector, $\Delta k(R)$, is read from tables for a reference thickness and then modified by the factor of Fig. 4 because of the effects of input $\delta_R$. The worth of axial reflectors, if any, is computed in the same way with the additional factor of 1/2, which is the ratio for axial over radial leakages for ideal shaped cylinders.

The reactivity worth of the burnup $\Delta k(BU)$ is also read from tables or computed, and the reactivity worth of the pressure vessel $\Delta k(PV)$ is parameterized in terms of $\sigma$ and the radius of core; additional terms are the desired reactivity at EOL, $\Delta k(EOL)$, and an estimation of the reactivity effects of structural parts $\Delta k(SP)$ which are assumed input variables.

The reactivity balance equation is then written as:

$$k(EOL) = 1 + \Delta k(EOL) = k_b + \Delta k(R) - \Delta k(BU) - \Delta k(PV) - \Delta k(SP)$$

where the multiplication constant of the bare core is:

$$k_b = \frac{k_n}{1 + M^2 B^2}$$

and the geometrical buckling is

$$B^2 = \left(\frac{\pi}{H_e}\right)^2 + \left(\frac{2.405}{R_c}\right)^2.$$  

Equations (38) and (39) are then solved for the size of the core by specifying either ideal shape ($R_e/H_e = 0.54$), $R_e$ or $H_e$; in this process, some of the $\Delta k$'s might be a function of the size so iterations are necessary (see next sections).

With $R_c$ and $H_c$ and the composition of the core, the total mass of fuel can then be calculated. Given this mass, the burnup and the scaling of 200 MeV per fission, the calculation of the available energy, $E_a$, that the reactor can release during time $D$ is determined.

Figures 12 and 13 are examples of the available energy for both reactors. In order to match the requested energy $Er = PD$, the free parameters of each design are iterated until $E_a = Er$. If this cannot be done because of contradictions between the requests and what is possible, the codes relax, under options, the input conditions.
The organization of the codes follows the shapes of Figs. 12 or 13. The scheme for the exploration of possible designs is shown in Fig. 14. For a given set of input conditions, the possible designs are within the region of the \((E_a, x)\) plane limited by parametric curves \(p_1\) and \(p_n\). For example, \(p_1 = S/F = 2\), and \(p_n = S/F = 0\), for the NERVA reactors and \(p_1 = \text{enrichment} = 93\%\) and \(p_n = \text{enr} = 50\%\) for the fuel pin reactors with \(P/d = 1.1\). The parametric curves have a minimum corresponding to the ideal shape, vertical asymptotic lines \(A_1, A_n\) to the left and monotonic growth to the right. For example, if \(x\) is the radius of the core, to the left of the minimum we have cigar shape designs while pancake shapes correspond to the region to the right.

For each parameter, the codes calculate the asymptotic lines and the energy available for the optimum shapes, \(E_o\); under a test option these values are printed together with \(E_a\) as function of \(R_e\) and \(H_c\).

If the requested energy has a value, \(E_{r1}\), below the minimum of the \(E_o, E_{o\text{min}}, i.e.,\), if \(E_r\) is in region 1 of Fig. 14, there is a warning message and the codes, under option, proceed to change the requested input burnup, lowering it until \(E_{o\text{min}}\) is smaller than \(E_{r1}\) and choosing the ideal shape disregarding any input \(R_c\) or \(H_c\).

If the requested energy has a value, \(E_{r2}\), intermediate between the minimum and maximum of \(E_o\), i.e., \(E_r\) is in region 2 of Fig. 14, two things can happen: (1) if the ideal shape was chosen the codes proceed with their calculation, or (2) if the user chooses \(R_e\) or \(H_e\) then the codes compute the allowable ranges \(x_1\) and \(x_2\) in Fig. 14 which are then compared with the input dimension. If consistent, the codes proceed with the calculations; if not and under option the codes change the input dimension to 0.5 \((x_1 + x_2)\).

If the requested energy has a value of \(E_{r3}\) within region 3 of Fig. 14, designs are only possible between \(x_1\) and \(x_2\) and between \(x_3\) and \(x_4\) and ideal shape designs are not feasible. The codes then compute \(x_1, x_2, x_3, \) and \(x_4\) and switch the option for the shape to a core with dimension \(x = 1.01\ x_3\) if allowed.

Assured now that the requested energy and shape are within curves \(p_1\) and \(p_n\) of Fig. 14, designs with parameters \(p_1\) and \(p_n\) bracket the demand so the codes iterate until a value \(p_r\) is found that produces the required energy \(E_r\).

The calculations are then continued with the computation of the number densities and masses of the core, the reflector and the pressure vessel. For the case of the fuel pin reactor, the entire process is made for \(P/d = 1.1, 1.2, 1.3, 1.4, \) and \(1.5\); one design is then chosen either by the user or by the code which chooses the design with the lowest total mass from those that have a pressure drop below a prescribed input value. With a design chosen, the codes proceed to calculate the geometries and masses of the neutron and gamma shieldings and the thermalhydraulic conditions for the most and least heated channels.

### 7.2 DESIGN OF THE CONTROL DRUMS

The number of control drums is, in principle, an input variable, \(n_d\), but it can be changed by the program. It is compared with the maximum number \(n_{d\text{(max)}} = \text{Integer}(2\pi/\Delta \theta)\) where \(\Delta \theta = 2 \arcsin(r_d/(R_f + r_d))\) is the central parallax of the drums, \(r_d\) is the radius of the drums (1/2 of the reflector thickness) and \(R_f\) is the internal radius of the reflector; if larger the program continues with \(n_d = n_{d\text{(max)}}\). The reactivity worth per unit angle is calculated as \(w_\theta = \Delta k(B_c C)/2\pi\) where the numerator is read from tables as indicated in Sections 3.1.5 and 3.2.5; the maximum reactivity of the drums, \(w_\theta \Delta \theta n_{d\text{(max)}}\), is then compared with the reactivity to control \(\Delta k_c = k(\text{BOL}) - 1. - \Delta k(\text{SP}) + \Delta k(\text{SUB})\), where \(\Delta k(\text{SUB})\) is the desired subcriticality with the absorbers facing the core. If the maximum worth of the drums is smaller than \(\Delta k_c\) a warning message is printed and the program bypasses what follows.
The input number of drums is used to compute their maximum worth \( \Delta k_d = w_0 \Delta \theta n_d \) and if smaller than \( \Delta k_c, n_d \) is increased to a value \( n_d' \) such that \( \Delta k_d = w_0 \Delta \theta n_d' > \Delta k_c \). With \( n_d \) now fixed the central parallax of the absorbing part of the drum is computed as \( \Delta k_c = w_0 \Delta \theta n_d \) and then converted to local parallax (centered in the drums).

### 7.3 SOME DETAILS OF THE CODE NEPNERVA

The burnup contributions to the reactivity Eq. (38) is split as the sum of three terms \( \Delta k(Xe), \Delta k(Sm) \) and the \( \Delta k \) corresponding to \(^{235}\)U depletion and other fission products as discussed in Section 3.1.3; this was done because as S/F increases the reactor becomes more moderated making necessary the special treatment for the large thermal neutron absorbers \(^{135}\)Xe and \(^{149}\)Sm. The transition of the importance of these isotopes, from irrelevant at S/F = 0 to very serious at S/F = 2, is made smoothly with cross sections that depend on S/F.

Steady and transient Xe and transient Sm reactivity effects depends on the flux; because for a given power the flux depends on the volume, Eq. (38) becomes then implicit on the size of the core and it has to be iterated. Equations for steady and transient reactivity effects for Xe and Sm were taken from Ref. 3.

### 7.4 SOME DETAILS OF THE CODE NEPPIN

Because of the fast spectrum, the effects described in the previous sections do not appear in this case, instead an iteration because of the pressure vessel becomes necessary when solving the reactivity Eq. (38). The reactivity effects of the pressure vessel of thickness \( d \), around a core of radius \( R_c \) inside a reflector of thickness \( \delta_r \), was parameterized as

\[
\Delta k(PV) = \Delta k_n(PV) \left( \frac{d}{d_n} \right) \left( \frac{R_{en}}{R_c} \right) f\left( \frac{\delta_r}{\delta_m} \right) \tag{41}
\]

where \( \Delta k_n(PV) \) are the values quoted in Table 3 at nominal values, \( d_n = 1 \text{ cm}, R_{en} \) and \( \delta_{rm} = 25 \text{ cm} \). The values of the function \( f\left( \frac{\delta_r}{\delta_m} \right) \) was taken from Fig. 4 due to the lack of better data. Because \( d \) is proportional to \( R_c \) (Eq. (37)), in general \( \Delta k(PV) \) does not depend on \( R_c \) and the iteration is not necessary. There is a lower limit to the reflector thickness, 0.4 cm, a value from Ref. 4; when \( d = 0.4 \text{ cm} \) an iteration on \( R_c \) is then necessary.

Because of the effects of the pressure vessel on the worth of the B\(_4\)C sheets a simple correlation was used to compute \( \Delta k(B_4C) \) from the nominal values quoted in Table 4:

\[
\Delta k(B_4C) = A e^{-\Sigma_d} (1 - e^{-\Sigma_d d_c}) f\left( \frac{\delta_r}{\delta_m} \right), \tag{42}
\]

where the first exponential refers to the effects of pressure vessel of thickness \( d \) and the second to the B\(_4\)C sheet of thickness \( d_c \); the third factor is related to the changes due to reflector thickness, like in Eq. (41). Equation (42) was calibrated with the data of Table 4 that were calculated for \( d = 1 \text{ cm} \) and \( d_c = 2 \text{ cm} \).
Fig. 12. Available energy in Mwd for the NERVA derivative reactor as a function of S/F, the radius of the core and for the following input conditions: 30 cm Be reflector, 2% reactivity worth for structural parts and desired end of life reactivity, and 15% burnup.
Fig. 13. Available energy in Mwd for the fuel pin reactor as a function of enrichment, the radius of the core and fixing P/d = 1.1. Other fixed input variables are 30 cm of BeO reflector, 2% reactivity worth for structural parts and end of life desired reactivity and 15% burnup.
Available Energy

Fig. 14. Scheme for the exploration of possible designs, $E_a$ is the available energy and $x$ is one of the core dimensions ($R_c$ or $H_c$).
8.0 INPUT AND OUTPUT DESCRIPTIONS

This section describes the input and output of the codes NEPNERVA and NEPPIN for, respectively, the helium cooled NERVA derivative and liquid lithium cooled fuel pin reactors. The names of the variables are those of the codes and in parenthesis some typical values.

8.1 INPUT TO NEPNERVA

ittest/0,1/: Do not/run test, when itest = 1 the code prints the energy available for the set of input conditions.

ndt: Number of points, in the tabulation of the available energy as function of \( R_e \) or \( H_c \), between the asymptotic and optimum values of \( R_e \) or \( H_c \).

itmax: Maximum number of iterations.

icont/0,1/Do not/continue calculation after test.

input: Total number of points in the tabulation of the available energy.

Pow (Mw): Fission power.

D (years): Time during which the reactor is on.

BU (%): Burnup at end of life, i.e., percentage of \(^{235}\text{U} \) atoms that disappeared by fission and capture.

eps (0.001): Iterations are stopped within this relative change.

der (1.01): Relative increment to compute derivatives.

drr (cm): Thickness of the radial Be reflector.

dral (cm): Thickness of the top axial Be reflector.

dra2 (cm): Thickness of the bottom axial Be reflector.

dkstr (%/2): Reactivity of structural components.

dkeol (%/2): Reactivity at end of life.

dksu (%/2): Subcritical reactivity with drums in.

For test runs only the input might finish here.

ncr: number of drums.

nnodo: number of axial nodes for thermalhydraulic calculations (≤ 50).

nfu: number of radial nodes for temperature calculations of the fuel mixture.

ishape/1,2,3/: Shape of the core

1: ideal shape (\( R_e/H_c = 0.54 \))

2: input \( R_e \)

3: input \( H_c \)

iboun/0,1/: Input coolant flow/Outlet coolant temperature.

iopath/1,2,3,4/: Assumptions about the power and flow conditions

1: 3D uniform power distribution.

2: 2D(\( r,\theta \)) uniform power distribution, cosine axial distribution (1 and 2 with uniform flow distribution).

3: \( r,\theta \) power distribution corresponding to uniform fuel load, cosine axial distribution and uniform flow distribution.

4: Like 3, but with \( (r,\theta) \) flow distribution proportional to power distribution.

iexpl/0,1/: No/Yes explicit thermalhydraulic, iexpl = 1 eliminates the iterations of Section 5.1.1.

ifri/0,1/: No/Yes inclusion of friction factors in pressure calculations.

iditus/0,1/: No/Yes Dittus correlation for heat transfer coefficient, if iditus = 0 there is a correction because of radial gradient of temperatures.

iprth/0,1/: No/Yes print details of thermalhydraulic calculations.
**iouth/1,2,3/:** Printing of thermalhydraulic condition of
1: Maximum power density channel
2: Minimum power density channel
3: Both

**iwre/0,1/:** No/Yes printing of iterations.

**ishm/1,2/:** Selection of neutron shielding
1: LiH stainless steel matrix
2: B$_4$C

**ichoose /0,1/:** For the case of contradictions between demand and availability;
0: Program chooses alternative demands.
1: Program stops for new demands from user (after printing some advices).

**pin(MPa),tin(°K):** Pressure and temperature at the inlet of reactor.

**ps(MPa),ts(°K):** Pressure and temperature in support elements, the thermalhydraulics of these elements are not calculated by the code, ps and ts are used just to compute the He density.

**flowt(kg/s):** Total coolant flow if iboun = 0.

**toult(°K):** Outlet temperature of coolant if iboun = 1.

**ru:** rugosity of the coolant channel.

**xi(l.):** x in Eq. (30).

**fact(0.97):** Factor for the conversion of fission power to thermal power.

**ripple(0.1):** Maximum ripple of the power distribution in the azimuthal direction (see Eq. (21)).

**tempv(°K):** Temperature of the pressure vessel, if input < 0 program chooses toult as the value of this variable.

**depvw(cm):** Maximum allowed for pressure vessel thickness.

**fastf(llcm$^2$):** Maximum fast fluence at cargo bay.

**dose(rad):** Maximum gamma dose at cargo bay.

**zload(m):** Distance of cargo bay to base of reactor.

**rload(m):** Radius of cargo bay.

**R(cm):** Radius of core if ishape = 1.

**H(cm):** Length of core if ishape = 3.

The input file for the sample case follows.
Problem #1 NERVA Application to NEP

<table>
<thead>
<tr>
<th>itest/#</th>
<th>dR/itma/cont?/ # of points in test</th>
<th>Format I5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>1 31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pow(Mw)</th>
<th>Life(y)</th>
<th>Burnup(%)</th>
<th>Tolerance/Rel delta</th>
<th>E10.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.</td>
<td>2.</td>
<td>20.</td>
<td>0.001</td>
<td>1.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radial</th>
<th>Top</th>
<th>Bottom Reflector Thickness(cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.</td>
<td>0.</td>
<td>0.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Struct.</th>
<th>End Life</th>
<th>Subcrit</th>
<th>Reactivities(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.</td>
<td>2.</td>
<td>2.</td>
<td></td>
</tr>
</tbody>
</table>

| #drum/#axi/#rad/ishape:1,2,3; ideal, choose R, choose H |
| 12       | 50       | 3       | 1               |

| ibou/iopth:1,2,3,4(Power, flow conditions); iboun:0,1 Boundary Condition |
| 1       | 3       |        |                 |

| iexpl/iifri/idit/iporth:1,2,3,4(Power, flow conditions); iboun:0,1 Boundary Condition |
| 0       | 1       | 0       | 1 3             |

| iwrtelnshield/Ichoose/wrte its, LiH-SS or B4C?, Ichoose or Program? |
| 0       | 0       | 0       |                 |

<table>
<thead>
<tr>
<th>Pin(MPa)</th>
<th>Tin(K)</th>
<th>Pin</th>
<th>Tin</th>
<th>Inlet Conditions Fuel, Support Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.</td>
<td>400.</td>
<td>5.</td>
<td>400.</td>
<td></td>
</tr>
</tbody>
</table>

| iboun=0 input total coolant flow(Kg/s), iboun=1 input outlet T(K) |
| 1700.    |       |     |     |

<table>
<thead>
<tr>
<th>rugosity</th>
<th>Implicit</th>
<th>Fraction/P Ripple Angular Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>1.</td>
<td>0.97</td>
</tr>
</tbody>
</table>

| pressure vessel temperature/max permissible thickness(cm) |
| 800.       | 10.      |

| Max fast n/Dose(RAD)/z(m) | /r(m) Shielding at z,r for input dose |
| e+13 1000000. 15.0 5. |

| ishape/1,2,3/ (skip, input R, input H(cm)) |
| 60. |

Page 8-3
8.2 OUTPUT FROM NEPNERVA

The output from running the code with the input file of the previous section follows.

Problem #1 NERVA Application to NEP

INPUT TO THE PROGRAM

Power(Mw) 50.00  Core life 2.000 years
Energy Released(Mwday) 36525.00  Burn-up(%) 20.00
Neutron reflector, radial thickness(cm) 30.00
top " 0.00
bottom " 0.00

The following design can produce that energy within the relative numerical precision of 0.1591E-03

Minimum Core Volume Chosen: R/H= 0.541315

And it has the following reactivity balance
Delta k required(%) 11.46 with components
Fission Products(%) 7.46
" (except Xe,Sm)(%) 6.52
Structural(%) 2.00
End of Life(%) 2.00
keff at BOL(No structural mat) 1.1146 Components
Bare Reactor 0.8206
Reflector 0.2940

Support/Fuel Ratio= 0.0554  Steady Xe reactivity(%) 0.45
Xe Reactivity after trip(%) 0.45 Peak at time(hr) 1.30
Sm Reactivity (%) Steady 0.46 Peak after trip(%) 0.49
Sm saturates at days 64.80

Neutron Flux(1/cm2sec)(core average) >100. Kev 0.4209E+15
" " " " >100. ev 0.2291E+15
" " " " > 3. ev 0.1133E+14
" " " " < 3. ev 0.3727E+13

12 Drums with absorbing angle(d) 55.83 each
Control dk(%)= 11.46

NUMBER DENSITIES AND MASSES OF NERVA DERIVATIVE REACTOR
GENERAL DESCRIPTION

265.412 Kg of U235. U enrichment 0.9300  Core Volume(L) 560.24
Ratio Support/Fuel Elements 0.05542
Core Radius(cm) 45.86  Height(cm) 84.78
Number of elements 2085 Support 110 Fuel 1975
Hexagonal Elements. Flat to flat distance(cm) 1.9130

FUEL ELEMENTS (INDIVIDUAL)
Molar UC fraction in UC-ZrC mix is 0.5000 ZrC clad thickness (mm) is 0.10
There are 19 coolant holes of mm 2.79 diameter
with He coolant at 2.000 MPa 1049.45 K

Volume fractions in Fuel Element

Page 8-4
Coolant 0.3676  
Clad Coolant 0.0545  
Clad Fuel E1 0.0208  
Fuel Mix 0.5571

Volumetric Fractions in Fuel Mix * Density(g/cm^3)

<table>
<thead>
<tr>
<th>Material</th>
<th>Volumetric Fraction</th>
<th>Density(g/cm^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UC</td>
<td>0.07829</td>
<td>1.01545</td>
</tr>
<tr>
<td>ZrC</td>
<td>0.06328</td>
<td>0.42394</td>
</tr>
<tr>
<td>Graphite</td>
<td>0.85843</td>
<td>1.45934</td>
</tr>
</tbody>
</table>

Fuel microcell (Number Densities 10**24 atoms/cm^3)
Excludes outer cladding

<table>
<thead>
<tr>
<th>Material</th>
<th>Number Densities 10**24 atoms/cm^3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant</td>
<td>0.00013774</td>
</tr>
<tr>
<td>ZrC in fuel</td>
<td>0.03908465</td>
</tr>
<tr>
<td>ZrC in Clad</td>
<td>0.00247308</td>
</tr>
<tr>
<td>He (Coolant)</td>
<td>0.00017312</td>
</tr>
</tbody>
</table>

FUEL ELEMENTS (ALL)
Volume of Fuel Elements (L) 530.685  
Mass (kg) 1124.972  
gU5/L(FE) 500.131

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass (kg)</th>
<th>Fractions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite</td>
<td>431.466</td>
<td>38.353</td>
</tr>
<tr>
<td>UC</td>
<td>300.228</td>
<td>26.688</td>
</tr>
<tr>
<td>ZrC (in fuel)</td>
<td>125.343</td>
<td>11.142</td>
</tr>
<tr>
<td>ZrC (in Clad)</td>
<td>267.757</td>
<td>23.801</td>
</tr>
<tr>
<td>He (Coolant)</td>
<td>0.179</td>
<td>0.016</td>
</tr>
</tbody>
</table>

SUPPORT ELEMENTS (ALL)
Volume of Support Elements (L) 29.557  
Mass (kg) 91.755

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass (kg)</th>
<th>Fractions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>0.028</td>
<td>0.016</td>
</tr>
<tr>
<td>Inconel</td>
<td>10.430</td>
<td>11.368</td>
</tr>
<tr>
<td>ZrH2</td>
<td>59.067</td>
<td>64.374</td>
</tr>
<tr>
<td>Graphite</td>
<td>22.230</td>
<td>24.228</td>
</tr>
</tbody>
</table>

SUPERCELL CONFIGURATION (Number Densities 10**24 atoms/cm^3)

Support Element
<table>
<thead>
<tr>
<th>Material</th>
<th>Number Densities 10**24 atoms/cm^3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant</td>
<td>0.00089003</td>
</tr>
<tr>
<td>Inconel</td>
<td>0.06664123</td>
</tr>
<tr>
<td>ZrH2</td>
<td>0.03616986</td>
</tr>
<tr>
<td>Coolant</td>
<td>0.00089003</td>
</tr>
<tr>
<td>Pyrographite</td>
<td>0.08523275</td>
</tr>
<tr>
<td>Graphite</td>
<td>0.08523275</td>
</tr>
</tbody>
</table>

Ring of Fuel Elements, Average Densities
<table>
<thead>
<tr>
<th>Material</th>
<th>Number Densities 10**24 atoms/cm^3</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>0.000005063</td>
</tr>
<tr>
<td>Zr</td>
<td>0.00432113</td>
</tr>
<tr>
<td>U5</td>
<td>0.00128138</td>
</tr>
</tbody>
</table>

HOMOGENIZED DENSITIES IN CORE
<table>
<thead>
<tr>
<th>Material</th>
<th>Number Densities 10**24 atoms/cm^3</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>0.000569895</td>
</tr>
<tr>
<td>Zr</td>
<td>0.04076312</td>
</tr>
<tr>
<td>U5</td>
<td>0.00009645</td>
</tr>
</tbody>
</table>

Page 8-5
From Fuel Elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>0.00004796</td>
</tr>
<tr>
<td>C</td>
<td>0.00539829</td>
</tr>
<tr>
<td>Zr</td>
<td>0.00409316</td>
</tr>
<tr>
<td>Gr</td>
<td>0.03861255</td>
</tr>
<tr>
<td>U5</td>
<td>0.00121377</td>
</tr>
<tr>
<td>U8</td>
<td>0.00009136</td>
</tr>
</tbody>
</table>

From Support Elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>0.00000756</td>
</tr>
<tr>
<td>Ni</td>
<td>0.00013941</td>
</tr>
<tr>
<td>Fe</td>
<td>0.00001405</td>
</tr>
<tr>
<td>Ti</td>
<td>0.00000855</td>
</tr>
<tr>
<td>Zr</td>
<td>0.0068097</td>
</tr>
<tr>
<td>H</td>
<td>0.00136193</td>
</tr>
<tr>
<td>Gr</td>
<td>0.00198940</td>
</tr>
</tbody>
</table>

REFLECTOR

External Radius (cm) 75.8626

Be 0.12348490

Moderation by C. C/U235= 37.8985
Moderation by H. H/U235= 1.1221

VOLUMES AND MASSES OF REACTOR AND SHIELDINGS

Volume (L) | Fraction (%) |
------------|-------------|
Reactor     | 1563.72      | 42.65       |
N Shield    | 1811.01      | 49.39       |
G Shield    | 291.85       | 7.96        |
Total       | 3666.59      |

Mass (Kg) | Fraction (%) |
-----------|--------------|
Reactor    | 3533.29      | 32.06       |
N Shield   | 1854.48      | 16.83       |
G Shield   | 5632.66      | 51.11       |
Total      | 11020.43     |

DIMENSION OF THE SHIELDINGS

Load at Z (M) = 15.00 With Radius (M) = 5.00

G Shield Thickness (cm) 9.12 With Radius (cm) 99.69 102.19
N Shield Thickness (cm) 75.22 With Radius (cm) 102.19 122.79

Pressure Vessel Evaluated at T (K) = 800.00 PRESS (MPa) = 2.00
and Full Power Life (y) 2.00

DISTRIBUTION OF MASSES AND VOLUMES IN THE REACTOR

Fraction of Core Occupied by Fuel (% Vol) 94.724

<table>
<thead>
<tr>
<th>MASSES (Kg)</th>
<th>Fractions (%)</th>
<th>Volume (L)</th>
<th>Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Elem</td>
<td>1124.972</td>
<td>530.685</td>
<td>33.937</td>
</tr>
<tr>
<td>Support E</td>
<td>91.755</td>
<td>29.557</td>
<td>1.890</td>
</tr>
<tr>
<td>Reflector</td>
<td>1797.472</td>
<td>972.658</td>
<td>62.201</td>
</tr>
<tr>
<td>Pr Vessel</td>
<td>519.092</td>
<td>30.825</td>
<td>1.971</td>
</tr>
</tbody>
</table>

Pressure Vessel thickness (cm) 0.40

DETAILS OF THE SHIELDINGS

Neutron Source (1/sec) 0.3808E+19
Self Shielding by Reactor Materials 0.9953E-01
Equivalent R (cm) = 72.00 Sigma Removal 0.103711
2.00 Years Fast Fluence (1/cm2) without Any Shielding 0.7997E+18
" " " " " " with (n, gamma) " 0.1000E+14
" " " " " " Requested 0.1000E+14

All at 15.00 meters

Neutron Shielding Thickness (cm) 75.22
Neutron Shielding Thickness if no W is present, cm 89.53
NEUTRON SHIELDING: LiH-Stainless Steel Matrix

TOTAL PRODUCTION OF GAMMA RAYS (1/sec)

<table>
<thead>
<tr>
<th>GROUP</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-1MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-1MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-1MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-1MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-1MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;9MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

% FRACTION PRODUCED BY U235
99.05 95.67 94.01 63.32 24.66 0.00 79.38

Equivalent Z for Build up factors
34.65 26.86 27.32 31.76 35.89 39.13 41.82

Gamma Self shielding by Core, Reflector and PV
0.101662 0.193773 0.190531 0.212077 0.216133 0.215108 0.213580

The same but without Buildup factor
0.048616 0.095106 0.109257 0.143415 0.159791 0.168326 0.171213

Integrated Dose (Rad) without any shielding (n or gamma)
1.380E+09 1.984E+09 9.781E+08 5.971E+08 2.422E+08 1.352E+07 3.852E+07

Integrated Dose with W and Neutrons Shieldings
3.878E-02 9.709E+04 1.984E+05 4.868E+05 1.967E+05 6.884E+03 1.370E+04

Integrated Dose without Any Shielding, Total (Rad) 0.5233E+10
Integrated dose with Shieldings (W and Neutrons), Total (Rads) 0.10E+07
Tungsten Thickness (cm) 9.12
Tungsten Thickness (cm) 11.65 if no Neutron Shield Present

Requested Dose (Rad) 1000000.00 at 15.00 meters

THERMALHYDRAULICS CALCULATIONS
Average Temperature of the Coolant at Core Exit (K) 1698.90

BOUNDARY CONDITION: OUTLET TEMPERATURE

***PROFILE OF CHANNEL WITH MAXIMUM POWER DENSITY***

Problem #1 Nerva Application to NEP

Thermodynamic profile of a He cooled channel
Inlet pressure (MPa) = 2.000000 Inlet temperature (K) = 400.00
Diameter (cm) = 0.28 Rugosity = 0.010000 der parm = 1.010000 ep = 0.0010000
Total Power (Mw) = 50.000 No. Orifices = 37525
Total Flow (Kg/sec) = 7.186
Factor that multiplies Power = 0.9700000

Average Power Density (Mw/L of active mix) = 0.1640 Channel Length (cm) = 84.78

Cosine Axial Power Distribution = \( \text{roav} \times \text{Pfact} \times \text{Cos} (\pi \times \text{z} / \text{H}) \)
\( \text{Pfact} (\text{Axial} \times \text{Radial} \times \text{Azim}) = 2.3949 \) Extrapolated Delta (cm) = 5.00

Attention Implicit Calculation!! \( \xi = 1.000000 \)

Twall/Tbulk correction to Dittus-Boelter Correlation for Nu
Uniform Coolant Flow Assumed

Flow (g/s) = 0.191

<table>
<thead>
<tr>
<th>Node</th>
<th>z (cm)</th>
<th>Po (W/cm)</th>
<th>Pr (MPa)</th>
<th>T (K)</th>
<th>V (m/s)</th>
<th>Re</th>
<th>Mach</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>6.02</td>
<td>2.00</td>
<td>400.00</td>
<td>13.06</td>
<td>3600.</td>
<td>0.011</td>
</tr>
<tr>
<td>2</td>
<td>1.70</td>
<td>8.04</td>
<td>2.00</td>
<td>411.99</td>
<td>13.46</td>
<td>3528.</td>
<td>0.011</td>
</tr>
<tr>
<td>3</td>
<td>3.39</td>
<td>10.02</td>
<td>2.00</td>
<td>427.39</td>
<td>13.97</td>
<td>3440.</td>
<td>0.011</td>
</tr>
<tr>
<td>4</td>
<td>5.09</td>
<td>11.98</td>
<td>2.00</td>
<td>446.15</td>
<td>14.59</td>
<td>3340.</td>
<td>0.012</td>
</tr>
<tr>
<td>5</td>
<td>6.78</td>
<td>13.90</td>
<td>2.00</td>
<td>468.21</td>
<td>15.31</td>
<td>3231.</td>
<td>0.012</td>
</tr>
<tr>
<td>6</td>
<td>8.48</td>
<td>15.77</td>
<td>1.99</td>
<td>493.51</td>
<td>16.15</td>
<td>3116.</td>
<td>0.012</td>
</tr>
</tbody>
</table>
From the Coolant Channel to the Uranium Carbide

<table>
<thead>
<tr>
<th>Node</th>
<th>z(cm)</th>
<th>J(Kw/cm²)</th>
<th>Twall(K)</th>
<th>Tclad(K)</th>
<th>TcladAv</th>
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<th>TfuelAv</th>
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Number of fuel nodes: 3

265411.72 grams of U235 in 530.68 Liters of Fuel Volume

From the Coolant Channel to the Uranium Carbide
Radius(cm) Orificies, Clad, Cell 0.1397 0.1497 0.2280
Averages Densities(g/cm³) Volumetric Fraction
Total 2.8990
UC 1.0155 0.0783
ZrC 0.4243 0.0633
Graphite 1.4592 0.8584

Number of fuel nodes 3
265411.72 grams of U235 in 530.68 Liters of Fuel Volume
dQ: heat to coolant (joule/kg) $0.11343 \times 10^8$

Give Density (g/cm$^3$) $0.0008961$

Axial Average Conditions in the Channel

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Give Density (g/cm$^3$) 0.0008961

Average Density 0.0008960

Wall Temperature (K) 1815.332

Clad Temperature (K) 1816.019

Fuel Temperature (K) 1818.830

Mol Fraction of UC in UC-ZrC mix 0.500000 Melting Temperature (K) 3343.50

**HEAT BALANCE FOR THE CHANNEL**

dQ: heat to coolant (joule/kg) $0.11343 \times 10^8$
dH: change of enthalpy (joule/kg) $0.11340 \times 10^8$
dKin change kinetic energy (joule/kg) $0.35955 \times 10^4$

relative dKin/dQ 0.000317

Balance (dH+ dKin)/dQ 1.000000

***PROFILE OF CHANNEL WITH MINIMUM POWER DENSITY***
Problem #1 Nerva Application to NEP

Thermodynamic profile of a He cooled channel

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Average Power Density (MW/L of active mix) 0.1640 Channel Length (cm) 84.78

Attention Implicit Calculation!! xi = 1.000000

Twall/Tbulk correction to Dittus-Boelter Correlation for Nu

Uniform Coolant Flow Assumed

Flow (g/s) = 0.191

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<td>1034.69</td>
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<tr>
<td>44</td>
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<td>1048.84</td>
<td>1048.38</td>
<td>1049.00</td>
</tr>
<tr>
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<td>74.61</td>
<td>0.00573</td>
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<tr>
<td>46</td>
<td>76.30</td>
<td>0.00514</td>
<td>1052.46</td>
<td>1052.70</td>
<td>1052.58</td>
<td>1053.09</td>
</tr>
</tbody>
</table>
Axial Average Conditions in the Channel

- Coolant Pressure (MPa): 1.954
- Temperature (K): 643.987
- Give Density (g/cm³): 0.0014554
- Average Density: 0.0014553
- Wall Temperature (K): 808.533
- Clad Temperature (K): 808.729
- Fuel Temperature (K): 809.296

Mol Fraction of UC in UC-ZrC mix: 0.50000
Melting Temperature (K): 3343.50

HEAT BALANCE FOR THE CHANNEL

- dQ: heat to coolant (joule/kg): 0.32449E+07
- dH: change of enthalpy (joule/kg): 0.32444E+07
- dKin: change kinetic energy (joule/kg): 0.52293E+03
- relative dKin/dQ: 0.000161
- Balance (dH+dKin)/dQ: 1.0000002
8.3 INPUT TO NEPPIN

itest/0,1/: Do not/run test, when \( \text{itest} = 1 \), the code prints the energy available for the set of input conditions.

ndt: Number of points, in the tabulation of the available energy as function of \( R_c \) or \( H_c \), between the asymptotic and optimum values of \( R_c \) or \( H_c \).

itmas: Maximum number of iterations.

icont/0,1/: Do not/continue calculation after test.

iboun/1,2/: Input coolant flow/outlet coolant temperature.

input: Total of points in the tabulation of the available energy.

Pow(Mw): Fission power.

D(years): Time during which the reactor is on.

BU(%): Burnup at end of life, see Eq. (3).

eps(0.001): Iterations are stopped within this relative change.

der(1.01): Relative increment to compute derivatives.

drr(cm): Thickness of the radial Be reflector.

dra1(cm): Thickness of the top axial Be reflector.

dra2(cm): Thickness of the bottom axial Be reflector.

tduc(mm): Thickness of the duct of the bundle.

dkstr(%2): Reactivity of structural components.

dkeol(%2): Reactivity at end of life.

dksu(%2): Subcritical reactivity with drums in.

pin(MPa),tin(°K): Pressure and temperature at the inlet of reactor.

pHe(MPa),THe(K): Pressure and temperature of the He in the gap of the fuel rod.

temp(°K): Temperature of the pressure vessel, if input < 0 program chooses toutl as the value of this variable.

flowt(Kg/s): Total coolant flow if iboun = 1.

toutl(°K): Outlet temperature of coolant if iboun = 2.

User might stop input here for a test only run.

ncr: Number of drums.

nnodo: Number of axial nodes for thermalhydraulic calculations (\( \leq 50 \)).

npin: Number of radial nodes for temperature calculations in fuel pin.

ishape/1,2,3/: Shape of the core.

1: Ideal shape (\( R_c/H_c = 0.54 \)).

2: \( R_c \).

3: \( H_c \).

iorth/1,2,3,4/: Assumptions about the power and flow conditions.

1: 3D uniform power distributions.

2: 2D \((r,\theta)\) uniform power distribution, cosine axial distribution (1 and 2 with uniform flow distribution.

3: \( r,\theta \) power distribution corresponding to uniform fuel load, cosine axial distribution and uniform flow distribution.

4: Like 3, but with \((r,\theta)\) flow distribution proportional to power distribution.

ifri/0,1/: No/Yes Inclusion of friction factors in pressure calculations.

ipth/0,1/: No/Yes Print details of thermalhydraulic calculations.

iouth/1,2,3/: Printing of thermalhydraulic condition of

1: Maximum power density channel.

2: Minimum power density channel.

3: Both.

iwte/0,1/: No/Yes Printing of iterations.
ish/1.2/ Selection of neutron shielding.

1: LiH in stainless steel matrix.
2: B$_4$C

ichoose/0,1/: For the case of contradictions between demand and availability:

0: Program chooses alternative demands.
1: Program stops for new demands from user (after printing some advices).

ichoode/0,1...5/: Selection of a design

5 designs are calculated for P/d = 1.1, 1.2, 1.3, 1.4, and 1.5. If ichoode = 0 the code selects a design based on the $\Delta p$ along the channel and the total mass: the user can override the selection process by choosing one of the five.

fact(0.97): Factor for the conversion of fission power to thermal power.

ripple(0.1): Maximum ripple of the power distribution in the azimuthal direction (see Eq. (21)).

hod: The lead of the helicoidal wire spacing divided the diameter of the fuel rod.

d(c): Thickness of the B$_4$C control sheet.

delp(Pa): Maximum pressure drop for the coolant, this value is used to select a design.

fastf(1/cm$^2$): Maximum fast fluence at cargo bay.

dose(rad): Maximum gamma dose at cargo bay.

zload(m): Distance of cargo bay to base of reactor.

rload(m): Radius of cargo bay.

R(cm): Radius of core if ishape = 2.

H(cm): Length of core if ishape = 3.

The input file for the sample case follows:

Problem #1 Fuel Pin Application to NEP

itest/# dR/itma/cont?/ibound/# of points in test/ Format I5

0 10 450 1 1 2 3 1

Pow(Mw) /Life(y) /Burnup(%) /Tolerance/Rel delta/ E10.0
50. 4.0 10. 0.001 1.010

Radial /Top /Bottom Reflector Thickness(cm)/duct thick(mm)
3.0. 0. 1.0

Struct. /End Life /Subcrit/ Reactivities(%)
2. 2. 2.

Pin(MPa) /Tin(K) /PHe /The(Inlet and He gap Conditions)/press vell temp
2. 500. 0.1 300. 800.

iboun=1 input total coolant flow(Kg/s), iboun=2 input outlet T(K)

1200.

#drum/#axi/#rad/ishape:1,2,3(ideal, choose R, choose H)/# rods per Bundle
12 3 3 1 19

3

ifri/irpth/iouth/friction Y/N;Print Details Y/N;Print Max,Min,Both?
1 1 3

iwrte/Nshield/Ichouse/Ichoode;wrte its,LiH-SS/B4C, Ichouse or Program?/ design?
0 1 0

Pow Fract/Ripple Angular Power/wirelead/d/B4C thick(cm) in drums
0.97 0.1 0.2

Max delta p acceptable(Pa)
51700.

Max fast n/Dose(RAD)/z(m) /r(m) Shielding at z,r for input dose
1. e+13 1000000. 15.0 5.

ishape(1,2,3) (skip,input R,input H(cm))
75.
ATTENTION  
Sampling p/d = 1.5000  
You requested Mwdays 73050.00  
And burn-up(%) 10.00  
With radial Be reflector thickness(cm) 30.00  
" top " 0.00  
" bottom " 0.00  
End of Life delta k(%) 2.00  
Structural delta k(%) 2.00  

Trying to satisfy reactivity balance, it happens your core is too large (and it would produce more energy you need). You might:  
1) Reduce the input burn-up, and/or  
2) Increase the reflector thickness, and/or  
3) Reduce delta k at end of life, and/or  
4) Reduce delta k structural  

Program will change burn-up for this p/d design and choose ishape=1  

<table>
<thead>
<tr>
<th>BU</th>
<th>Mwday</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.00</td>
<td>77233.00</td>
</tr>
<tr>
<td>9.00</td>
<td>66788.17</td>
</tr>
</tbody>
</table>

Sampling of Designs  
Mass=Masses of core, pressure vessel and reflector  
Max delta p(Pa) acceptable = 0.5170E+05  

<table>
<thead>
<tr>
<th>I</th>
<th>p/d</th>
<th>Enr</th>
<th>BU</th>
<th>Mass(Kg)</th>
<th>U5(Kg)</th>
<th>DeltaP(Pa)</th>
<th>coreR(cm)</th>
<th>coreH(cm)</th>
<th>ishape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.100</td>
<td>0.530</td>
<td>10.00</td>
<td>6424.6</td>
<td>769.0</td>
<td>0.1003E+04</td>
<td>39.96</td>
<td>73.27</td>
<td>1</td>
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<tr>
<td>2</td>
<td>1.200</td>
<td>0.615</td>
<td>10.00</td>
<td>6064.9</td>
<td>768.3</td>
<td>0.1199E+04</td>
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<td>74.26</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1.300</td>
<td>0.715</td>
<td>10.00</td>
<td>5750.4</td>
<td>768.2</td>
<td>0.1423E+04</td>
<td>40.90</td>
<td>75.01</td>
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<tr>
<td>4</td>
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<td>10.00</td>
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<td>769.4</td>
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<tr>
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<td>0.894</td>
<td>9.00</td>
<td>6010.7</td>
<td>854.8</td>
<td>0.6080E+04</td>
<td>43.70</td>
<td>79.94</td>
<td>1</td>
</tr>
</tbody>
</table>

Problem #1 Fuel Pin Application to NEP  

INPUT TO THE PROGRAM  
Power(Mw) 50.00 Core life 4.000 years  
Energy Released(Mwday) 73050.00 Burn-up(%) 10.00  

Be reflector, radial thickness(cm) 30.00  
" top " 0.00  
" bottom " 0.00  

The following design can produce that energy within the relative numerical precision of 0.1000E-02  

Minimum Core Volume Option Chosen: R/H = 0.541315  

And it has the following reactivity balance  
Delta k required(%) 13.99 with components  
Fission Products(%) 8.23  
Pressure Vessel(%) 1.76  
Structural(%) 2.00
**End of Life (%)** 2.00  
**keff at BOL (No structural mat)** 1.1399 Components  
Bare Reactor 0.9941  
Reflector 0.1458  

Enrichment = 0.8292  
Pitch/Diameter = 1.40  

From Control  
Radius Drums (cm) 15.00  
Central Parallax (degree) 30.78  
Thickness B4C sheet on Control Drums, cm 2.00  

You cannot control this reactor only with control drums in the reflector  
The reactivity worth of 11 drums (max value) is 6.17%  
and the reactivity to control is 13.99%  
Absorbing angle of each drum would be 149.22 degrees

**NUMBER DENSITIES AND MASSES OF FUEL PIN REACTOR**  
**GENERAL DESCRIPTION**

<table>
<thead>
<tr>
<th>Core Volume (L)</th>
<th>400.42 Active (UN) Volume (L)</th>
<th>80.94</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Radius (cm)</td>
<td>41.12 Height (cm)</td>
<td>75.37</td>
</tr>
<tr>
<td>Number of rods</td>
<td>5871 Bundles</td>
<td>309 (19 rods per bundle)</td>
</tr>
</tbody>
</table>

Neutron Flux (1/cm²/sec) (core and time average) 0.5748E+15  
" Fluence (1/cm²) " " after 4.00 years 0.7256E+23

Masses (Kg) of Fissile Materials and Fission Products

<table>
<thead>
<tr>
<th></th>
<th>BOL</th>
<th>EOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-235</td>
<td>769.399</td>
<td>681.867</td>
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<tr>
<td>U-238</td>
<td>160.488</td>
<td>157.337</td>
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<tr>
<td>Pu-239</td>
<td>0.000</td>
<td>1.731</td>
</tr>
<tr>
<td>Fiss Prod</td>
<td>0.000</td>
<td>77.274</td>
</tr>
</tbody>
</table>

1.868 Kg produced

**FUEL RODS**  
Rod diameter (mm) is 6.4000  
Astar Alloy clad thickness, mm 0.6350  
W Liner, mm 0.1270  
He gap, mm 0.0250  
UN pin diameter, mm 4.8260

Volume fractions in Fuel Cell #1  
Coolant 0.5126  
Spacing Wire 0.0247  
Fuel Rod 0.4627

Fuel Cell type 1 (Number Densities 10**24 atoms/cm³)  
Spacing Wire is diluted in clad

Region | Radius (cm) | Isotope | Concentration | Volumetric Fraction |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>Coolant</td>
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<td>Li6</td>
<td>0.000307001</td>
<td>0.512619</td>
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<tr>
<td>&quot;</td>
<td>Li7</td>
<td>0.03830476</td>
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<td></td>
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<tr>
<td>Clad</td>
<td>0.3200</td>
<td>Ta181</td>
<td>0.05059388</td>
<td>0.176834</td>
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<tr>
<td>&quot;</td>
<td>W182</td>
<td>0.00117159</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;</td>
<td>W183</td>
<td>0.00063544</td>
<td></td>
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<tr>
<td>&quot;</td>
<td>W184</td>
<td>0.00135207</td>
<td></td>
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<tr>
<td>&quot;</td>
<td>W186</td>
<td>0.00125367</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;</td>
<td>Re185</td>
<td>0.00020190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;</td>
<td>Re187</td>
<td>0.00034274</td>
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</table>
AVERAGES IN BUNDLE (INCLUDING DUCT)

<table>
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<th>Volumetric Fractions:</th>
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<tbody>
<tr>
<td>Rods: 0.3555</td>
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<tr>
<td>Spacing Wire: 0.0210</td>
</tr>
<tr>
<td>Li Coolant: 0.5358</td>
</tr>
<tr>
<td>Duct: 0.0878</td>
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</tbody>
</table>

Isotope Concentration
(Number Densities 10^{24} atoms/cm^3)

- Li_6: 0.00164494
- Li_7: 0.02052410
- Ta181: 0.01192968
- W182: 0.000635304
- W183: 0.00034334
- W184: 0.00073055
- W186: 0.00067738
- Re185: 0.00004761
- Re186: 0.00008082
- Hf: 0.00009713
- He: 0.00000010
- U235: 0.00492296
- U238: 0.00101391
- NI4: 0.00593687

Moderation by Li, Li/U235 = 4.5032

VOLUME(L) AND MASSES(KG) INSIDE THE CORE

<table>
<thead>
<tr>
<th>Part</th>
<th>Volume</th>
<th>Fraction</th>
<th>Masses</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rods</td>
<td>142.34</td>
<td>0.355479</td>
<td>2006.38</td>
<td>0.706037</td>
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<tr>
<td>Coolant</td>
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<td>0.535811</td>
<td>102.33</td>
<td>0.036009</td>
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<tr>
<td>Duct</td>
<td>35.14</td>
<td>0.087755</td>
<td>591.74</td>
<td>0.208232</td>
</tr>
<tr>
<td>Spacing</td>
<td>8.39</td>
<td>0.020955</td>
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<tr>
<td>Total</td>
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<td></td>
<td></td>
<td>2841.75</td>
</tr>
</tbody>
</table>

VOLUME(L) AND MASSES(KG) OF REACTOR

<table>
<thead>
<tr>
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<th>Volume</th>
<th>Fraction</th>
<th>Masses</th>
<th>Fraction</th>
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</thead>
<tbody>
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<td>Core</td>
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<td>0.327118</td>
<td>2841.75</td>
<td>0.517700</td>
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<td>Press Ves</td>
<td>12.16</td>
<td>0.009935</td>
<td>204.79</td>
<td>0.037308</td>
</tr>
<tr>
<td>Reflector</td>
<td>811.51</td>
<td>0.662947</td>
<td>2442.64</td>
<td>0.444992</td>
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<tr>
<td>Total</td>
<td>1224.09</td>
<td></td>
<td>5489.18</td>
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</tr>
</tbody>
</table>

VOLUMES AND MASSES OF REACTOR AND SHIELDINGS

<table>
<thead>
<tr>
<th>Volume(L) Fraction(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor: 1224.09</td>
</tr>
<tr>
<td>N Shield: 1691.15</td>
</tr>
<tr>
<td>G Shield: 255.87</td>
</tr>
<tr>
<td>Total: 3171.11</td>
</tr>
</tbody>
</table>
### Mass (Kg) Fraction (%)

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (Kg)</th>
<th>Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>5489.18</td>
<td>45.82</td>
</tr>
<tr>
<td>N Shield</td>
<td>1731.73</td>
<td>14.46</td>
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<tr>
<td>G Shield</td>
<td>4759.17</td>
<td>39.73</td>
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<tr>
<td>Total</td>
<td>11980.08</td>
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</table>

### Dimension of theShieldings

- **Load at Z (M) = 15.00 with Radius (M) = 5.00**
- **G Shield Thickness (cm) = 9.21 with Radius (cm)**: 92.76, 95.32
- **N Shield Thickness (cm)**: 79.60, 92.76, 95.32, 117.51

### Evaluation of Pressure Vessel

- Evaluation at T(K) = 800.00, PRESS (MPa) = 2.00, Full Power Life (y) = 4.00
- **Pressure Vessel Thickness (cm)**: 0.40

### Details of the Shieldings

- **Neutron Source (1/sec)**: 0.3808E+19
- **Self Shielding by Reactor Materials**: 0.8751E-01
- **Equivalent R (cm)**: 66.36, Sigma Removal: 0.128256
- **4.00 Years Fast Fluence (1/cm^2)**: without Any Shielding: 0.1415E+19
- **with (n, gamma)**: 0.1000E+14
- **Requested**: 0.1000E+14

- **All at 15.00 meters**
- **Neutron Shielding Thickness (cm)**: 79.60
- **Neutron Shielding Thickness if no W is present, cm**: 94.05

### Neutron Shielding: LiH-Stainless Steel Matrix

### Total Production of Gamma Rays (1/sec)

<table>
<thead>
<tr>
<th>Group</th>
<th>0-1 Mev</th>
<th>1-2</th>
<th>2-3</th>
<th>3-5</th>
<th>5-7</th>
<th>7-9</th>
<th>&gt;9</th>
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<tr>
<td>1</td>
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<td>7.140E+18</td>
<td>3.132E+18</td>
<td>1.474E+18</td>
<td>1.815E+17</td>
<td>1.493E+15</td>
<td>1.097E+16</td>
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### Equivalent Z for Buildup Factors
- **Gamma Self-shielding by Core, Reflector and PV**: 0.040546, 0.098502, 0.095939, 0.101189, 0.097540, 0.093919, 0.089193
- **The same but without Buildup factor**: 0.022152, 0.050559, 0.057265, 0.070490, 0.074171, 0.074878, 0.073508

### Integrated Dose (Rad) without any shielding (n or gamma)
- 1.133E+09, 2.262E+09, 1.266E+09, 8.799E+08, 1.474E+08, 1.471E+06, 1.154E+07

### Integrated Dose with W and Neutrons Shieldings
- 1.837E-02, 8.058E+04, 2.003E+05, 6.097E+05, 1.045E+05, 6.534E+02, 3.629E+03

### Integrated Dose without Any Shielding, Total (Rad)
- 0.5701E+10

### Integrated Dose with Shieldings (W and Neutrons), Total (Rads)
- 0.10E+07

### Tungsten Thickness (cm)
- 9.21

### Tungsten Thickness (cm)
- 11.95 if no Neutron Shield Present

### Requested Dose (Rad) 1000000.00 at 15.00 meters
THERMALHYDRAULICS CALCULATIONS

Average Temperature of the Coolant at Core Exit(K) 1200.00

BOUNDARY CONDITION: OUTLET TEMPERATURE

****PROFILE OF CHANNEL WITH MAXIMUM POWER DENSITY****

Problem #1 Fuel Pin Application to NEP

Thermodynamic profile of a liquid Li cooled channel

* Remember Li melts at 453.70 K !!!! *

Inlet temperature(K) = 500.00
Diameter Rod(cm) = 0.64
Total Power(Mw) = 50.000 No. Rods 5871 No. Bundles 309 (19 rods/bundle)
Total Flow(Kg/sec) = 16.139
Active Volume(L of UN) = 80.937
Factor that multiplies Power = 0.9700000

Average Power Density(Mw/L(UN)) = 0.5992 Channel Length(cm) = 75.37

FLOW CONDITIONS:
Pitch/drod = 1.400 Lead wire spacer/drod = 10.000

Cell Type (per bundle):
1 2 3 Bundle

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<th>Number of Cells</th>
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<th>6</th>
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<td>Flow Area(cm²),per cell</td>
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<td>Flow Area(cm²),per rod</td>
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<td>Wet Perimeter(cm) Total</td>
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<td>Effective Diameter(cm)</td>
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<td>0.5516</td>
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(*) 1,2,3 in units of cell 1 area

Parameters of the bundle for friction correlations: X= 0.995 Del/DT= 0.994

Boundary Condition: Fix outlet flow temperature 1200.00
Cosine Axial Power Distribution=roav*Pfact*Cos(Pi*z/H)
Pfact(Axial*Radial*Azim)= 2.3752 Extrapolated Delta(cm) = 5.00
Uniform Coolant Flow Assumed

AVERAGE CONDITIONS IN THE BUNDLE

Inlet Press(MPa) = 2.000000

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<thead>
<tr>
<th>Node</th>
<th>z(cm)</th>
<th>Po(w/cm)</th>
<th>Pr(KPa)</th>
<th>T(K)</th>
<th>(Tsat)</th>
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Thermodynamics Conditions of Cells

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<th>Node</th>
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</table>

Delta pressure(KPa) because Tl>T(average) 1738.05

From the Coolant Channel to fuel pin temperature

- Rod Diameter(mm): 6.4000
- Clad+Liner Thickness("): 0.7620
- He gap (: ) 0.0250
- Fuel Pin Diameter (" ): 4.8260

CONDITIONS FOR MAX HEATED ROD OF THE BUNDLE(Type 1 cell)
Axial Average Conditions in the Channel
  - Coolant Pressure(MPa)  2.000
  - Temperature(K)      1089.432
  - Wall Temperature(K) 1313.155
  - Heat Transfer(w/cm²K) 12.70
  - Clad Temperature(K) 1319.526
  - Fuel Temperature(K) 1416.165

HEAT BALANCE FOR THE BUNDLE

dQ: heat to coolant (joule/kg) 0.50566E+07

**PROFILE OF CHANNEL WITH MINIMUM POWER DENSITY***

Problem #1 Fuel Pin Application to NEP

Thermodynamic profile of a liquid Li cooled channel

***************************************************************

Inlet temperature( K)= 500.00
Diameter Rod(cm)= 0.64
Total Power(Mw)  50.000 No. Rods 5871 No. Bundles 309(19 rods/bundle)
Total Flow(Kg/sec) 16.139
Active Volume(L of UN) 80.937
Factor that multiplies Power 0.970000

Average Power Density(Mw/L(UN)) 0.5992 Channel Length(cm) 75.37

FLOW CONDITIONS:

  Pitch/drod  1.400 Lead wire spacer/drod 10.000

Cell Type (per bundle) 1 2 3 Bundle

Number of Cells 24 12 6
Flow(g/s) Total 24.2455 23.2914 4.6917 52.2286
Flow Area (*) 0.5126 0.9849 0.3968 0.5874
Flow Area(cm²), per cell 0.1782 0.3424 0.1379 0.2130
Flow Area(cm²), per rod 0.3564 0.6848 0.8276 0.4849
Wet Perimeter(cm) Total 1.1394 2.1024 1.0002 58.5741
Effective Diameter(cm) 0.6256 0.6514 0.5516 0.6291

(*) 1,2,3 in units of cell 1 area

Parameters of the bundle for friction correlations: X= 0.995 Del/DT= 0.994
Boundary Condition: Fix outlet flow temperature 2152.68
Cosine Axial Power Distribution = roav Pfact Cos(Pi*z/H)
Pfact (Axial * Radial * Azim) = 0.5662 Extrapolated Delta(cm) 5.00
Uniform Coolant Flow Assumed

AVERAGE CONDITIONS IN THE BUNDLE
******************************************************************************
********** Inlet Press(MPa) 2.000000 **********
******************************************************************************

<table>
<thead>
<tr>
<th>Node</th>
<th>z(cm)</th>
<th>Po(w/cm)</th>
<th>Pr(KPa)</th>
<th>T(K)</th>
<th>Tsat</th>
<th>V(m/s)</th>
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Thermodynamics Conditions of Cells

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<th>Cell Type</th>
<th>z Node</th>
<th>Max(T-T&lt;&gt;)</th>
<th>T Saturation</th>
<th>P(kPa)</th>
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Delta pressure(KPa) because Tl>T(average) 0.01

<c> in f=c/Re**0.25 is 0.19946

From the Coolant Channel to fuel pin temperature

Rod Diameter(mm): 6.4000
Clad+Liner Thickness( "): 0.7620
He gap " ( "): 0.0250
Fuel Pin Diameter ( "): 4.8260
## CONDITIONS FOR MAX HEATED ROD OF THE BUNDLE (Type 1 cell)

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<th>z(cm)</th>
<th>J(Kw/cm²)</th>
<th>Twall(K)</th>
<th>Tclad(K)</th>
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<th>Tfuel(K)</th>
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</table>

**Axial Average Conditions in the Channel**
- **Coolant Pressure (MPa):** 2.000
- **Temperature (K):** 636.312
- **Wall Temperature (K):** 688.931
- **Heat Transfer (W/cm²K):** 10.20
- **Clad Temperature (K):** 690.450
- **Fuel Temperature (K):** 719.981

**HEAT BALANCE FOR THE BUNDLE**
- **dQ:** heat to coolant (joule/kg) 0.12054E+07
- **dH:** change of enthalpy (joule/kg) 0.12054E+07
- **dKin:** change kinetic energy (joule/kg) 0.72267E-03
- **relative dKin/dQ:** 0.000000
- **Balance (dH+dKin)/dQ:** 0.9999923
9.0 References


APPENDIX A. LISTING OF CODE NEPNERVA

c program to estimate preliminary design of Nerva derivative reactor for
c space applications.
c Assumptions
c 1) fuel cell: He coolant,ZrC clad,UC-ZrC mix in Graphite matrix
c 2) support cell: He coolant,Inconel support for ZrH, coolant,Pyrolitic
c graphite and graphite (last two as thermal shield for ZrH

c character *80 tit,aldum

dimension buw(5,5),bup(5),aux(5),wbeth(8),th(8),pfr(5),sofl(5)
*,pfrm(5),Sogam(7),Pr5(7),Emin(5),Ras(5),Has(5),Rop(5),Hop(5)

c

common /Soze/ its,epss

common /MaBaSi/ R,H,ishape

common /Bala/ Ereq,buwo(5),relr,relal,rela2,dkeol,dkstr,BU,Vcor,
*U5m,dkbu,dxkses,dxxep,dksms,dkbe,rkra,eps,itmmax,dcr
*,itest,aofis

common /cont/ Rad,drr,dref,rasp,refec,ncr,dksu,dkest,relar

common /Fluxo/ Pow,Vc,sofr,fluxn(4),xedks,xedkt,tmmax,smdks,smdkt,
*tem,D,iwxe

common/thermo/ tit,nnodo,iexpl,ifri,imax,norif,iditus,nfu,pin,tin
*,dcn,ru,xi,der,eps0,powt,rjs,flowt,Gu235,Vact,Enr,PuC,Rouc,Ro2ZrC
*,RGraf,dclad,Hact,Pfacr,Daxi,act,pf,tf,fe,iprth,iopth,iouth,
Pfacaz,iop,flowbal,iboun

common /fphe/ imaxt,epsi,dero

common /Gamsh/ coBe,coTa,coC,coZr,coU,coH,coNi,coFe,coCr,coTi,coSi
*,dist,Req,shg(7),shgnb(7),Zeq(7),Dosewg(7),Dosseg(7),itmag,epsng
*,aten,Dosen,Doseng(7)

Common /CROSS/ AU,BBU,signe,ishin,ishig

open(unit=7,file='nepnerva.1',status='old')
open(unit=8,file='nepnerva3.out',status='unknown')

read(7,11) tit
format(a80)

read(7,11) aldum
read(7,20) itest,ndt,itmmax,icont,nput
read(7,11) aldum
read(7,10) Pow,D,BU,eps,der
read(7,11) aldum
read(7,10) drr,drat,dra2
read(7,11) aldum
read(7,10) dkstr,dkeol,dksu

dkest=dkstr
if(icont.eq.0) go to 2378
read(7,11) aldum
read(7,20) ncr,nnodo,nfu,ishape
read(7,11) aldum
read(7,20) iboun,iopth
read(7,11) aldum
read(7,20) iexpl,ifri,iditus,iprth,iouth
read(7,11) aldum
read(7,20) iwrte,ishn,ichoose
read(7,11) aldum

Page A-1
read(7,10) pin,tin,ps,ts
read(7,11) aldim
if(iboun.eq.0) read(7,10) flowt
if(iboun.eq.1) read(7,10) toutl
read(7,11) aldim
read(7,10) ru,xi,fact,Ripple
read(7,11) aldim
read(7,10) tempv,depvw
read(7,11) aldim
read(7,10) fastf,Dose,zload,rload
read(7,11) aldim
if(ishape.eq.1) go to 2378
if(ishape.eq.2) read(7,10) R
if(ishape.eq.3) read(7,10) H
continue

epso=eps
epsi=eps
epss=eps
dero=der
Powt=Pow
Daxi=5.

Ereq=Pow*D*365.25

INPUT DESCRIPTION FOR REALS

Pow(Mw): power; D(years): core life; BU(at%): percent U235 atoms
burned;
Inlet flow conditions:
pin,tin(MPa,K)) pressure and temperature of the inlet coolant(fuel el
ps,ts pressure and temperature coolant(sup el), just for
book-keeping
drr,dra1,dra2 (cm) thickness of Be reflector: radial, top-bottom axial
dkstr(%): reactivity structural materials(estimated)
dkeol(%): subcritical reactivity required at BOL with drums in
eps: tolerance for iterations (like energy)
r,rugosity coolant channel; xi: /0.,1.0/ fully explicit to implicit
der=1.01 (compute derivatives)
fact: fission fission energy/thermal
flowr(kg/s) total coolant flow(applicable if iboun=0)
Daxi(cm): extrapolation length axial cos power distribution
Ripple: Relative amplitude of power distribution as function of angle
at R=Rcore
tempv(K): Temperature of Pressure Vessel: if <0. program chooses tout
depvw(cm): Max thickness of the pressure vessel acceptable
toutl(K): outlet temperature of coolant(applicable if iboun=1)
fastf(1/cm2): fast fluence (during time D) at payload area
zload(m): axial distance from the base of reactor to payload plane
rload(m): radius of load area
Dose(Rad): integrated gamma dose(during time D) required for payload
ddt(cm): delta r and delta h for test curve Eavailable=f(R) or f(H)

format(7e10.0)
imax=itmax
imaxt=itmax
itmag=itmax
its=itmax

INPUT DESCRIPTION FOR INTEGERS
itmax: max number iterations for reactor search
ncr: number of control drums
ishape/1,2,3/ Shape: ideal(minimum volume),R input,H input
iwrite=1 write iterations
itest=0/1 no,yes run and print test to know your options
nnod: number nodes in coolant channel
iexpl/0,1/ implicit,explicit solution of coolant channel
ifri/0,1/ no,yes friction factors;iditus/0,1/ no,yes Dittus Correlation
nfu; number of nodes inside fuel mix
iprth/0,1/no,yes print details cooling channel
iopath=1 3-D uniform power density assumed
    =2 2-D (r,theta) uniform power density assumed
    =3 Uniform Fuel load/uniform coolant flow assumed
    =4 Uniform Fuel load/Coolant flow proportional to power density

iouth=1 Thermodynamic profile at Max power density channel is printed
iouth=2 " Min " " Max and Min "
iouth=3 " " " "
iBOUND=0 Input Coolant Flow
iBOUND=1 Input Outlet Temperature of Coolant
ishn=1,2 Choose Neutron Shielding LiH+SS/ B4C
icont/0,1/ no,yes continue calculation after test
ndt: number of intervals between Xas and Xop to compute Energy=f(R)
or f(H), nput total number of points in tabulation
ichoose=0,1 no,yes correction, by program, of incompatible request

format(14i5)
if(BU.gt.50.) write(8,32) BU
format(///: YOUR VALUE FOR BURN UP',f8.2, ' IS TOO LARGE FOR'
    ' A REASONABLE EXTRAPOLATION OF THE DATA BASE''//
    ' PROGRAM STOPS '///)
if(BU.gt.50.) stop
if(drr.gt.40..or.dral.gt.40..or.dra2.gt.40.)
    write(8,31) drr,dral,dra2
format(///: YOUR VALUE OF REFLECTOR THICKNESS(CM)',3f8.2/
    ' ARE TOO LARGE FOR A REASONABLE EXTRAPOLATION'/
    ' OF THE DATA BASE''//
    ' PROGRAM STOPS '///)
if(drr.gt.40..or.dral.gt.40..or.dra2.gt.40.) stop

data enr,ff,dh,dc,puc,dref,nh/.93,1.913,2.794,0.1,0.5,30.,19/
enr: enrichment(at %);
fuel element; ff(cm): flat to flat distance hexagonal element
dh(mm) coolant hole; dc(mm) cladding thickness
puc: mole fraction of UC in mix UC-ZrC
d dref(cm): thickness of Be reflector(for data base)
nh number of coolant holes per fuel element(data base calculated,nh=19)
dcm=0.1*dh
dclad=0.1*dc
data r1,r2,r3,r4,r5/0.15,0.25,0.65,0.75,0.85/
Support Element, radius of different regions(cm)
r1, coolant;r2, Inconel;r3, Zr,H;r4, coolant;r5, PyroGraphite
data base calculated with these values
data pee,Av,ABe,xop/3.1415926,0.602202.
* 9.01219,0.541315/

data au5,ah,ahs,azr,ac,ani,acr,afe,ati,asi,au8/235.044,1.00797,4.0
026,91.22,12.0115,58.71,51.996,55.847,47.90,28.086,238.0508/

data au8:U235; ah:H; ahe:He; azr: Zr; ac: C; ani: Ni; acr: Cr; afe: Fe

data xhl,xh2,xc12,xc13/.99985,0.00015,.9889,.0111/

data rouc,rozrc,rgraf,rgrap,roin,rozrh/12.97,6.7,1.7,1.7,8.90,5.6/

data xni,xcr,xfe,xTi,xsi,roBe,RoAst,RoW,RoLis,RoBC
0.73,0.15,0.07,0.025,0.025,1.848,16.84,19.3,1.024,2.92/

data (pfr(i),i=1,5)/1.67,1.71,1.77,1.77,1.81/

data (pfrm(i),i=1,5)/0.577,0.423,0.311,0.311,0.257/

data (buw(i),i=1,5)/0.,0.,0.,0.,0./
data (buw(2,i),i=1,5)/3.42,2.28,1.75,1.73,2.21/
data (buw(3,i),i=1,5)/7.17,4.82,3.77,3.80,4.86/
data (buw(4,i),i=1,5)/11.35,7.70,6.14,6.33,8.10/
data (buw(5,i),i=1,5)/16.09,11.01,9.03,9.50,12.13/
data (bup(i),i=1,5)/0.,0.10.,0.20.,0.30.,0.40./
data (wbeth(i),i=1,8)/0.,0.2728,0.3947,0.5026,0.6778,0.8524,
0.9517,1.000/
wbeth: relative (to 30 cm) worth of Be as function of its thickness

\[
\text{th(cm)} (\text{input next})
\]

\[
\text{data (th(i), i=1,8)/0., 3.67, 5.67, 7.67, 11.67, 17.67, 24., 30.}/
\]

\[\text{burn-up worths for input BU, stored at buwo()}
\]

\[
\text{RoAt} = \text{RoAt}/1000. \,
\text{isofl} = 5 \,
\text{ibup} = 5 \,
\text{icart} = 1
\]

\[
\begin{align*}
\text{continue} & \,
\text{do 101 } i = 1, \text{isofl} \,
\text{do 102 } j = 1, \text{ibup} \,
\text{aux(j)} = \text{buw(j, i)} \,
\text{call Inter(bup, aux, ibup, BU, y)} \,
\text{buwo(i)} = y
\end{align*}
\]

\[
\text{relative worth of Be reflectors: relr, radial; relal, rela2: axial}
\]

\[
\text{ibe} = 8 \,
\text{call Inter(th, wbeth,ibe, drr, relr)} \,
\text{relar} = \text{relr} \,
\text{call Inter(th, wbeth,ibe, dra1, relal)} \,
\text{call Inter(th, wbeth,ibe, dra2, rela2)} \,
\text{relal} = 0.5 \times \text{relal} \,
\text{rela2} = \text{rela2} \times 0.5
\]

\[
\begin{align*}
\text{if itest} & = 1 \text{ print your options:} \\
\text{T T T T E E E E S S S S T T T T} & 1) \text{ Energy available with optimum shape} \\
\text{T T E E S S T T} & 2) \text{ Radius of infinite cylinder} \\
\text{T T E E S S T T} & 3) \text{ Height of infinite "pancake"} \\
\text{T T E E E E S S S S T T} & 4) \text{ Energy available as function of R and H}\,
\end{align*}
\]

\[
(2 \text{ or 3 would produce "infinite" energy})
\]

\[
\text{ish} = \text{ishape} \,
\text{RRRr} = r \,
\text{HHHh} = h
\]

\[
\text{itpr} = \text{ittest} \,
\text{if (itpr.eq.1)} \,
\text{*write(8,6133) Ereq, BU, drr, dr1, dr2, dkeol, dkstr}
\]

\[
6133 \text{ format(//' INPUT'/' You requested Mwdays', f10.2/}
\]

\[
\text{* ' And burn-up(', f5.2/}
\]

\[
\text{* ' With radial Be reflector thickness(cm)', f6.2/}
\]

\[
\text{* ' top', ' ', ' ', ' ', ', f6.2/}
\]

\[
\text{* ' bottom', ' ', ' ', ' ', ', f6.2/}
\]

\[
\text{* End of Life delta k(%)', ', f6.2/}
\]

\[
\text{* Structural delta k(%)', ', f6.2/}
\]

\[
\text{if (itpr.eq.1)} \,
\text{*write(8,1632)}
\]

\[
1632 \text{ format(' Run Test, Energy Available (Mwd) for Optimum Shape'/'}
\]

\[
\text{' with corresponding Rop and Hop'/'}
\]

\[
\text{Rc for Infinite Reactor'/'}
\]

\[
\text{Hc'/'}
\]

\]

\[
\text{compute Energy available for ideal shape Emin()} \,
\text{and asymptotic radius Ras() and height Has()}
\]
c
itest=1
do 1633 is=1,isofl
ishape=1
sofac=sofl(is)
Ene=Balance(ibu,sofac)
Emin(is)=Ene
Rop(is)=R
Hop(is)=H
Ropo=R
Hopo=H
ishape=2
Edu=Balance(ibu,sofac)
Rcri=dcr
Ras(is)=Rcri
ishape=3
Edu=Balance(ibu,sofac)
Hcri=dcr
Has(is)=Hcri
  
if(itpr.eq.1) write(8,1634) sofac,Ene,Ropo,Hopo,Rcri,Hcri
continue
  
1634 format(f6.3,f12.1,4f12.2)
  
itest=itpr
if(itest.eq.0) go to 1631
  
compute curves Eavailable as function of radius and Height of core and
S/F in order to illustrate the user about the options.
  
do 5782 is=1,isofl
sofac=sofl(is)
  
write(8,5783) sofac,Ereq
  
5783 format(//' AVAILABLE ENERGY(MWDAYS) AS FUNCTION OF S/F AND R,H'/'
/'S/F=',f8.4/' Required Energy(Mwd)',f10.2//' */I',4x,'R(CM)',6x,'R/H',7x,'EAVAI',4x,'H(CM)',6x,'R/H',,7x,'EA
*VAI'//)
  
Rs0=Ras(is)*der
Hs0=Has(is)*der
rnt=ndt
ddr=(Rop(is)-Rs0)/rnt
ddh=(Hop(is)-Hs0)/rnt
ndt=ndt+1
do 5782 idt=1,nput
ridt=idt-1
ishape=2
Rs=Rs0+ridt*ddr
R=Rs
Ener=Balance(ibu,sofac)
xra=R/H
ishape=3
Hs=Hs0+ridt*ddh
H=Hs
EneH=Balance(ibu,sofac)
xh=R/H
  
write(8,5784) idt, Rs, xra, Ener, Hs, xh, EneH
  
5784 format(i5,2(f9.2,f9.3,f12.0))
  
Page A-6
c 5782 continue

    EEEE N N D TTTTT EEEEEE SSSSS TTTTT
    E   NN N D D T E   S    T
    E EEE NN N D D T EEE S    T
    E   N NN D D T E   SS   T
    EEEE E N N D T EEEE SSSSS T

c 1631 bypass prints and some checks on energy

1631 continue

c Stop here if your intentions are only to run the test

c if(icont.eq.0) stop
ishape=ish
r=RRR
h=HHH
itest=0

c check if you are requesting too little energy

c Emino=Emin(isof1)
if(Ereq.ge.Emino) go to 337
if(icart.eq.1) *write(8,5133) Ereq,BU,drr,dr1,dr2,dkeol,dkstr
5133 format(/' ATTENTION'/, 'You requested Mwdays',f10.2/
     *   And burn-up(%)',f5.2/
     *' With radial Be reflector thickness(cm)',f6.2/
     *' top'   ' '   ' '    ',f6.2/
     *' bottom' ' '   ' '    ',f6.2/
     *' End of Life delta k(%)   ',f6.2/
     *' Structural delta k(%)    ',f6.2/
     *' Trying to satisfy reactivity balance, it happens your core'/
     *' is too large (and it would produce more energy you need).'/
     *' You might:/
     *' 1) Reduce the input burn-up, and/or'/
     *' 2) Increase the reflector thickness, and/or'/
     *' 3) Reduce delta k at end of life, and/or'/
     *' 4) Reduce delta k structural')
if(ichoose.eq.1) write(8,1424)
1424 format(/' I choose=1, Program stops'/)
if(ichoose.eq.1) stop
if(icart.eq.1) write(8,1426)
1426 format(/' Program will change burn-up'/
     *' BU Mwday'/)
icart=0
write(8,1425) BU,Emino
1425 format(2f12.2)
BUA=BU
BU=BU-1.
if(BU.le.0.) BU=BUA/2.
go to 1274
337 continue

c check if there is enough energy for ideal shape(ishape=1)

c iwae=0
if(Ereq.le.Emin(1)) go to 357
iwae=1

c set the warning flag iwae=1 for potential strange shapes: cigar/pancake
and calculate R1,R2,R3,R4 and H1,H2,H3,H4 which are the limits for R
c and H for the input conditions (reactivity, required Energy) in the

c bifurcation region

const
Here is the plain text representation of the document:

```fortran
ittest=1
ishape=2
sofac=sofl(isofl)
Das=Ras(isofl)
Dop=Rop(isofl)
call Size(Das,Dop,Ereq,sofac,R11,R41)
sfr14=sofac
hr4=h
hr1=Vcor/(pee*r11**2)
vr14=Vcor/1000.
sofac=sofl(1)
Das=Ras(1)
Dop=Rop(1)
call Size(Das,Dop,Ereq,sofac,R21,R31)
sfr23=sofac
hr3=h
vr23=Vcor/(pee*R21**2)
ishi=3
sofac=sofl(isofl)
Das=Has(isofl)
Dop=Hop(isofl)
call Size(Das,Dop,Ereq,sofac,H1,H4)
sfh14=sofac
rh4=R
rh1=sqrt(Vcor/(pee*H1))
vh14=Vcor/1000.
sofac=sofl(1)
Das=Has(1)
Dop=Hop(1)
call Size(Das,Dop,Ereq,sofac,H2,H3)
sfh23=sofac
rh2=sqrt(Vcor/(pee*H2))
vh23=Vcor/1000.
write(8,369) Ereq,Emin(1),Rll,R21,R31,R41,sfr14,vr14,hr1,hr4,sfr23
*,vr23,hr2,hr3

369 format(/// ATTENTION:/'
** You requested Mwdays',f10.2,' larger than',f10.2/
** which is the largest energy available for ideal shape.'/
** Strange shapes(cigar/pancake) can appear as solutions,'/
** the following designs are possible:'/
** ishape=2 with R(cm) between'/
** R1',f8.2,' and R2',f8.2/
** or R(cm) between' /
** R3',f8.2,' and R4',f8.2/
** R1 and R4 corresponds to S/F=',f8.3,' with core Vol(L)',f9.1/
** with H(cm), Respectively=',2f10.2/
** R2 and R3 corresponds to S/F=',f8.3,' with core Vol(L)',f9.1/
** with H(cm), Respectively=',2f10.2/
write(8,412) H1,H2,H3,H4,sfh14,vh14,rh1,rh4,sfh23,vh23,rh2,rh3

412 format(/// Or ishape=3 with H(cm) between' /
** H1',f8.2,' and H2',f8.2/
** or H(cm) between' /
** H3',f8.2,' and H4',f8.2/
** H1 and H4 corresponds to S/F=',f8.3,' with core Vol(L)',f9.1/
** with R(cm), Respectively=',2f10.2/
** H2 and H3 corresponds to S/F=',f8.3,' with core Vol(L)',f9.1/
** with R(cm), Respectively=',2f10.2/
write(8,7133) BU,drr,dr1,dr2,deol,dkstr

7133 format(/// The previous data corresponds to your input conditions'/'
*/ Burn-up(%)',f6.2/
** Radial Be reflector thickness(cm)',f6.2/
** Top " " "',f6.2/
** Bottom " " "',f6.2/
** End of Life delta k(%) ',f6.2/
```
"Structural delta k(%)",f6.2/
"If awkward values of Radius/Height appear YOU MIGHT:'///
  1) Increase the burn-up, and/or'/'
  2) Decrease the reflector thickness, and/or'/
  3) Increase delta k at end of life, and/or'/
  4) Increase delta k structural'/'
  ' #1 is very effective, #2, 3 and 4 not so much'/'
  ' If problem persist better try other kind of reactor'///)

itest=0
ishape=ish
R=RRR
H=HHH
continue
if(ishape.eq.1.or.iwae.eq.1) go to 434
c
begin check of input R or H if E requested is not in bifurcation
c
itest=1
if(ishape.eq.2) then
  sofac=sofl(isofl)
  Das=Ras(isofl)
  Dop=Rop(isofl)
call Size(Das,Dop,Ereq,sofac,R11,R21)
R=RRR
if(R11.lt.R.and.R.lt.R21) go to 443
if(ichoose.eq.1) write(8,4551) ichoose,R,R11,R21
   format('/' ' I choose Flag=',i5,' Your R=',f8.2/
   ' Outside Possible Range',2f10.2/
   ' Program stop'///)
if(ichoose.eq.1) stop
R=0.5*(R11+R21)
write(8,4552) ichoose,R,R11,R21,R
   format('/' ' I choose Flag=',i5,' Your R=',f8.2/
   ' Outside Possible Range',2f10.2/
   ' Program continues with average, R=',f8.2//)
4551 continue
c
else
  sofac=sofl(isofl)
  Das=Has(isofl)
  Dop=Hop(isofl)
call Size(Das,Dop,Ereq,sofac,H1,H2)
H=HHH
if(H1.lt.H.and.H.lt.H2) go to 454
if(ichoose.eq.1) write(8,4553) ichoose,H,H1,H2
   format('/' ' I choose Flag=',i5,' Your H=',f8.2/
   ' Outside Possible Range',2f10.2/
   ' Program stop'///)
if(ichoose.eq.1) stop
H=0.5*(H1+H2)
write(8,4554) ichoose,H,H1,H2,H
   format('/' ' I choose Flag=',i5,' Your H=',f8.2/
   ' Outside Possible Range',2f10.2/
   ' Program continues with average, H=',f8.2//)
4553 continue
c
endif
4554 continue
itest=0
continue
if(iwae.eq.0) go to 1004
go to(1001,1002,1003),ishape
1001 continue
if(ichoose.eq.1) write(8,4555) ichoose
   format('/' ' I choose Flag=',i3,' Not enough available energy'/
Page A-9
if (ichoose.eq.1) stop
ishape=2
R=R31*1.01
write(8,4555) R
format(//' Not enough energy for ishape=1(input), program continues with'/' //
* with R='f8.2,' toward pancake shape'//)
go to 1004
1002 continue
if(R11.lt.R.and.R.lt.R21) go to 1004
if(R31.lt.R.and.R.lt.R41) go to 1004
if(ichoose.eq.1) write(8,4556) ichoose,R
format(//' I choose Flag=',i3,' Your input R=',f8.2,' Out Possible Range'/'//
* Program stop')
if(ichoose.eq.1) stop
Rin=R
R=R31*1.01
write(8,4557) Rin,R
format(//' Your input R='f8.2,' is outside possible range, program'/' //
* continues with R='f8.2,' toward pancake shape'//)
go to 1004
1003 continue
if(H11.lt.H.and.H.lt.H2) go to 1004
if(H31.lt.H.and.H.lt.H4) go to 1004
if(ichoose.eq.1) write(8,4558) ichoose,H
format(//' I choose Flag=',i3,' Your input H='f8.2,' Out Possible Range'/'//
* Program stop')
if(ichoose.eq.1) stop
Hin=H
H=H2*0.99
write(8,4559) Hin,H
format(//' Your input H='f8.2,' is outside possible range, program'/'//
* continues with H='f8.2,' toward pancake shape'//)
continue
ibu=0
sofal=sol1(1)
bball=Balance(ibu,sofal)
if(ibu.eq.1) write(8,597)
format(' Stop trying to bracket demand')
if(ibu.eq.1) stop
sofa2=sol1(isofl)
bal2=Balance(ibu,sofa2)
if(ibu.eq.1) write(8,597)
if(ibu.eq.1) stop
c
if we successfully arrived to this point, it means we bracket the demand
Then:
bisect Balance until Eavailable=Erequested
c
it=0
sofa=0.5*(sofal+sofa2)
Erema=Balance(ibu,sofa)
if(ibu.eq.1) write(8,597)
if(ibu.eq.1) stop
test=abs(Erema)/Ereq
if(test.lt.eps) go to 144
it=it+1
if(iwrite.eq.1) write(8,219)
format(' it',7x,'sofal',8x,'sofa',7x,'sofa2',8x,'ball',7x,'Erem',
*8x,'bal2')
if (iwrte.eq.1) write(8,218) it, sofal, sofa, sofa2, ball, Erema, bal2
format(i4,3f12.6,3f12.3)
call bisect(sofal, sofa2, sofa, ball, bal2, Erema, iwa)
if(it.le.itmax.and.iwa.eq.0) go to 145
continue
if(it.gt.itmax.or.iwa.eq.1) then
write(8,146) sofal, ball, sofa2, bal2, it, iwa
146 format('/// Problems trying to bisect Balance/'
* , sof=','e12.4,' ball=','e12.4/
* , sof2=','e12.4,' bal2=','e12.4/
* , iteration=','i5/
     iwa=','i5/)
stop
else
continue
endif
c successful end of reactor search, calculate number densities and masses
c
GU235=U5m
Vact=0.001*Vcor/(1.+sofa)
U5m=U5m/1000.
rasp=sofa
sofr=sofa
Vc=Vcor
C
C with power level , s/f and volume of the core, compute fluxes and
C reactivities of Xe and Sm
Call Flux
C choose R as near possible to ideal R with integer number of elements
  ae=0.86602540*ff**2
  ne=pee*R**2/ae
  re=ne
  if(rasp.eq.0.) then
    nf=ne
    rf=nf
    nse=0
    rse=0.
  go to 1975
  else
    rf=rf/(1.+rasp)
    nf=rf
    nse=ne-nf
    rse=nse
  endif
1975 R=sqrt(ne*ae/pee)
    H=Vcor/(ne*ae)
    Hact=H
C
C fuel microcell, calculation of geometry and concentrations
C assume clad around coolant hole and around fuel element
C aae is the active area of ae, acl is the area of the clad around hole
C and ac2 is the area of the clad around fuel element
C aco is the area of the coolant hole
C
dcc=0.1*dc
    rh=dh*0.1/2.
    acl=pee*dcc*(2.*rh+dcc)*nh
    b=ff/1.7320508
    bp=b-dcc/0.86602540
    ac2=3. *(b+bp)*dcc
    aco=pee*rh**2*nh
    aae=ae-acl-ac2-aco
C
c volumetric fractions
C
fe=aae/ae
f1=ac1/ae
f2=ac2/ae
fco=acco/ae

c radius of microcell: rml, coolant; rm2, clad; rm3 microcell:

c 
rm1=rh
rm2=rh+dcc
amicro=pee*rm2**2+aae/nh
rm3=sqrt(amicro/pee)

c Calculate outlet condition, ie. if iboun=0 (flow is input) > houtlet
if iboun=1 (t is input) > flow
See: 1) no velocities in energy conservation (see effects in detailed
of the channel)
2) tout=f(hout, pinlet) (reasonable approximation)
3) from 1) and 2) tout is reasonable.

pino=pin*1.e+6
call phe(hin, pino, tin, rhor, vis, cp, pr, a, rrrk, xx, 0)
if(iboun.eq.0) go to 391
call phe(hout, pino, tout1, rhor, vis, cp, pr, a, rrrk, xx, 0)
flowt=fact*Pow*l.e+6/(hout-hin)

c alternative flow in case of problem in thermo

call phe(hina,1.e+7,20.,rh,visa,cpa,pra,aa,rka,xxa,0)
call phe(houta,1.e+7,tout1,rh,visa,cpa,pra,aa,rka,xxa,0)
flowal=fact*Pow*1.e+6/(houta-hina)

391 hout=hin+fact*Pow*1.e+6/flowt
call phe(hout, pino, tout, rhor, vis, cp, pr, a, rrrk, xx, 1)

c calculate maximum stress(sigma) for the Astar Pressure Vessel

c if(tempv.lt.0.) tempv=tout
call desstr(tempv,1,D, sigma, sigrod, itmax, ipresv)

c number densities; for He: estimate taverage as the next statement
tav=0.5*(tin+tout)
rhe=rho(pino, tav)
rf=0.001*rhe*Av/Ahe
ru5=1000.*u5m/(rf*aae*H)
u5n=ru5*Av/Au5
u8n=ru5*Av/Au5
u5n=ru5*Av/Au5
u8n=ru5*Av/Au5

nc Assume UC+ZrC (puc molar fraction)
c
un=u5n+u8n
cn2=(1./puc-1.)*un
zrn2=cn2
rzrca=(cn2*ac+zrn2*azr)/av
cn2=cn2+un
c Calculate space occupied by the graphite
rouca=(un+u5n+u8n+u8n*au8+un*ac)/av
c Volumetric fraction in UC-ZrC-Graphite mix
xuc=rouca/rouc
xzrca=rzrca/rozrc
xgraf=1.-xuc-xzrca
rgraa=xgraf*rgraf
grafn=rgraa*av/ac
c densities in clad
cn1=rozrc*av/(ac+azr)
zrn1=cn1

c Average densities in fuel element (including outer clad)
hen=hen*fco

Page A-12
cna=cnl*(f1+f2)+cn2*fe
crn=zn1*(f1+f2)+zn2*fe
cgraf=grafn*fe
cu5=nu5*fe
cu8=nu8*fe
Vcore=Vcor/1000.
c
write(8,11) tit
cwrite(8,51) Pow,D,Ereq,BU,drr,drat,dra2,test
c51 formt('/'INPUT TO THE PROGRAM'/' Power(Mw)'7f8.2,' Core life',7f
*8.3,' years'7f10.2,' Burn-up()',7f6.2//' * Be reflector, radial thickness(cm)',7f6.2/
* top '' ',7f6.2/
* bottom '' ',7f6.2/
* The following design can produce that energy within the relative
*'/'numerical precision of',e12.4)
c
if(ishape.eq.1) write(8,317) xop
cformat('/' Minimum Core Volume Chosen: R/H=',f9.6/)c317 if(ishape.eq.2) write(8,318) R
cformat('/' Core Radius Chosen: R(cm)=',f7.2/)c318 if(ishape.eq.3) write(8,319) H
cformat('/' Core Height Chosen: H(cm)=',f7.2/)c319 dkfp=dkbu+dkxep+dkm
dkreq=dkfp+dksr+dkeol
dkbe=dkbo/100. rc
rec=krk+dk
cc
write(8,52) dkreq,dkfp,dkbu,dkstr,dkm,rc,rc,dk
cc52 format('/' And it has the following reactivity balance'/
* Delta k required(',7f6.2,' with components'/
* Fission Products(',7f6.2/
* " (except Xe,Sm)(',7f6.2/
* Structural(',7f6.2/
* End of Life(',7f6.2/
* keff at BOL(No structural mat)',7f7.4, ' Components'/
* Bare Reactor',7f7.4/
* Reflector',7f7.4/)c52
cc
write(8,521) sofr,xe
c521 format('/' Support/Fuel Ratio=',7f8.4,' Steady Xe reactivity(',7f6.2)
if(iwxe.eq.0) write(8,1521) xedk,tm
c5211 format(/' Xe Reactivity after trip(',7f6.2,' Peak at time(hr)',7f6.2)
if(iwxe.eq.1) write(8,1522)
c522 formt(/' No Xe peak after shutdown')
c522 format(/' (fluxn(i)',i=1')
c5221 format(/' Sm Reactivity (%) Steady',7f6.2,' Peak after trip(',7f6.2/
* Sm saturates at days',7f8.2/
/* Neutron Flux(1/cm2sec)(core average) >100.Kev',e12.4/
* " " " " " " " " 100. ev',e12.4 /
* " " " " " " " " > 3. ev',e12.4/
* " " " " " " " " < 3. ev',e12.4//)
cRad=R
c call control to design control drums

Call Control

write(8,30) u5m, enr, Vcore, rasp, R, H, ne, nse, nf, ff

format(' NUMBER DENSITIES AND MASSES OF NERVA DERIVATIVE REACTOR'/
* GENERAL DESCRIPTION'/
* /f10.3, ' Kg of U235. U enrichment', f7.4, ' Core Volume(L)', f10.2/
* ' Ratio Support/Fuel Elements', f10.5/
* ' Core Radius(cm)', f10.2, ' Height(cm)', f10.2/
* ' Number of elements', i6, ' Support', i6, ' Fuel', i6/
* ' Hexagonal Elements. Flat to flat distance(cm)', f10.4//)

write(8,40) puc, dc, nh, dh, pin, tav

format(' FUEL ELEMENTS(INDIVIDUAL)'/
* Molar UC fraction in UC-ZrC mix is', f7.4, ' ZrC clad thickness
* (mm) is', f6.2, '/ There are', i4, ' coolant holes of mm', f7.2, ' diamet
* er/' with He coolant at', f7.3, ' MPa', f8.2, ' K'/)

write(8,50) fco, fl, f2, fe

format(' Volume fractions in Fuel Element'/
' Coolant', f7.4/
' Clad Coolant', f7.4/
' Clad Fuel El', f7.4/
' Fuel Mix', f7.4)

write(8,41) xuc, rouca, xzrc, rzrca, xgraf, rgraa

format(' Volumetric Fractions in Fuel Mix * Density(g/cm3)'/
' UC', f10.5, f13.5/
' ZrC', f10.5, f13.5/
' Graphite', f10.5, f13.5//)

write(8,60) rm1, hen, rm2, cn1, zr1, rm3, cn2, zr2, graf, u5n, u8n

format(' Fuel microcell(Number Densities 10**24 atoms/cm3)'/
' Excludes outer cladding'/
' Coolant Radius(cm)', f7.4, ' He', f12.8/
' Clad Radius (cm)', f7.4, ' C', f12.8, ' Zr', f12.8/
' Cell Radius (cm)', f7.4, ' C', f12.8, ' Zr', f12.8/
' Graphite', f12.8, ' U235', f12.8/
' U238', f12.8)

Total mass of the fuel elements

Vact=rf*ae*H/1000.
Gfuel=Vact*(hena*ahe+cnac+zrna*azr+graf*aac+u5na*a5+u8na*u8)/a
wUC=GUC*100./Gfuel
wZrC=GZrC*100./Gfuel
wGraf=graf*aac/av
wHe=GHe*100./Gfuel
write(8,71) Vact,Gfuel,rou5,Ggraf,wGraf,GUC,wUC,GZrCf,wZrCf,GZrCc,*wZrCc,GHe,wHe

71 format(//:
   'FUEL ELEMENTS(ALL)'//
   ' Volume of Fuel Elements(L)',f10.3/
   ' Mass(kg)',f10.3,' gU5/L(FE)',f10.3//
   ' Masses(kg) * Fractions(%)'//
   ' Graphite',f10.3,f13.3/
   ' UC',f10.3,f13.3/
   ' ZrC(in fuel)',f10.3,f13.3/
   ' ZrC(in Clad)',f10.3,f13.3/
   ' He(Coolant)',f10.3,f13.3)

c Number densities and masses of Support Elements

r6=sqrt(ae/pee)
a1=pee*r1**2
a2=pee*r2**2-a1
a3=pee*r3**2-(a1+a2)
a4=pee*r4**2-(a1+a2+a3)
a5=pee*r5**2-(a1+a2+a3+a4)
a6=ae-(a1+a2+a3+a4+a5)
f1=a1/ae
f2=a2/ae
f3=a3/ae
f4=a4/ae
f5=a5/ae
f6=a6/ae
p=ps*l.e6
rhe=rho(p,ts)
ches=0.001*rhe*av/ahe
cni=roin*xni*av/ani
cfe=roin*xfe*av/afe
cscr=roin*xcr*av/acr
csi=roin*xsi*av/asi
czr=rozrh*av/(azr+2.*ah)
ch=2.*czr
cgraf=rgraf*av/ac
cgrap=rgrap*av/ac

aves in support Elements
ches=(f1+f4)*ches
cnisa=cnis*f2
cfe=cfef2
ccra=ccrf2
csi=csif2
cczr=cczr*f3
cha=chf3
cggr=(f5*cgraf+f6*cgraf

Volume and masses of Support Elements
Vsup=nse*ae*H*0.001
Ghes=Vsup*(f1+f4)*0.001*rhe
GInc=Vsup*f2*roin
GZrh=Vsup*f3*rozrh
Ggras=Vsup*(f5*rgrap+f6*rgraf)
Gsup=Ghes+GInc+GZrh+Ggras
fh=1.
fInc=1.
fZrh=1.
fGras=1.
if(rasp.eq.0.) go to 1763
fh=100.*Ghes/Gsup
fInc=100.*GInc/Gsup
fZrh=100.*GZrh/Gsup
fGras=100.*Ggras/Gsup
C

1763 write(8,73) Vsup,Gsup

73 format('   SUPPORT ELEMENTS(ALL)'/
   *   , 'Volume of Support Elements(L)',f10.3/
   *   , 'Mass(Kg)',f10.3/)

write(8,74) Ghes,fhes,GInc,fInc,GZrh,fZrh,Ggras,fgras

74 format('   Masses(Kg) * Fractions(%)'/
   *   , 'He',f10.3,f13.3/
   *   , 'Inconel',f10.3,f13.3/
   *   , 'ZrH2',f10.3,f13.3/
   *   , 'Graphite',f10.3,f13.3/)

write(8,636)

636 format('/// SUPERCHEL CONFIGURATION(Number Densities 10**24atoms/cm**3)///)

if(rasp.eq.0.) go to 1349

write(8,72) rl,ches,r2,cni,cfe,ccr,cti,csi,r3,czr,ch,r4,ches,r5,cgra
   *ap,r6,cgraf

72 format('Support Element'/
   *   , 'Coolant Radius(cm)',f7.4,' He',f12.8/
   *   , 'Inconel Radius(cm)',f7.4,' Ni',f12.8,' Fe',f12.8/
   *   , '  ', ' Cr',f12.8,' Ti',f12.8/
   *   , '  ', ' Si',f12.8/
   *   , 'ZrH2 Radius   (cm)',f7.4,' Zr',f12.8,' H',f12.8/
   *   , 'Coolant Radius(cm)',f7.4,' He',f12.8/
   *   , 'Pyrographite R(cm)',f7.4,' Gr',f12.8/
   *   , 'Graphite Radii(cm)',f7.4,' Gr',f12.8/)

rsup=sqrt(r6**2+rf*ae/(pee*rse))

write(8,70) rsup, hena, cna, zrna, grafa, u5na, u8na

70 format('Ring of Fuel Elements. Average Densities'/
   *   , 'Coolant Radius(cm)',f7.4,' He',f12.8,' C',f12.8/
   *   , '  ', ' Zr',f12.8,' Gr',f12.8/
   *   , '  ', ' U5',f12.8,' U8',f12.8)

Homogenized Densities in Supercell
1349 ff=rf/re
   fsup=rse/re
   hena=hena*ff
   cna=cna*ff
   zrna=znna*ff
   grafa=grafaf*ff
   u5na=u5na*ff
   u8na=u8na*ff
   ches=ches*(f1+f4)*fsup
   cni=cin*ff*fsup
   cfe=cmef2*fsup
   ccr=ccrf2*fsup
   cti=ctif2*fsup
   csi=csif2*fsup
   czr=czrf3*fsup
   ch=chf3*fsup
   cgra=(f5*caf+6*cgraf)*fsup
   cBe=roBe*Av/Abe
RBe=R+drr

write(8,91)R,henas,cna,znas,graft,u5na,u8na,ches,cni,cfes,ccrs,ctis,cstras,csis,czrs,chr,cras,RBe,cBe

format(///' HOMOGENIZED DENSITIES IN CORE'/
**'Radius(cm)','f9.4'
**'From Fuel Elements'/'
*   He','f12.8,' C','f12.8/
*   Zr','f12.8,' Gr','f12.8/
*   U5','f12.8,' U8','f12.8/
*/'From Support Elements'/'
*   He','f12.8,' Ni','f12.8/
*   Fe','f12.8,' Cr','f12.8/
*   Ti','f12.8,' Si','f12.8/
*   Zr','f12.8,' H','f12.8/
*   Gr','f12.8//

**' External Radius(cm)','f9.4'
   Be','f12.8)

c rec=(graft+cra+fna)/u5na
   reh=ch/u5na

c write(8,92) rec,reh

c format///' Moderation by C. C/U235=','f10.4/
   Moderation by H. H/U235=','f10.4)

c Compute pressure vessel (if(ipresv.ne.0))

c Volpv=0.
   Gpv=0.
   delpv=0.
   Rcr=R+drr
   Hcr=H+dral+dra2
   if(ipresv.eq.0) go to 590
   delpv=(pin/sigma)*Rcr
   if(delpv.lt.0.4) delpv=0.4
   if(delpv.gt.depvw) ipresv=0
   if(ipresv.eq.0) go to 590
   Volpv=2.*pee*(Rcr+delpv)**2*delpv
   Volpv=Volpv+pee*((Rcr+delpv)**2-Rcr**2)*Hcr
   Gpv=Volpv*RoAst
   Volpv=Volpv/1000.
   continue
   ipresv=(pee*((R+drr)**2-R**2)*H/1000.
   Vref=Vref+pee*((R+drr)**2*(dra1+dra2))/1000.
   Gref=Vref*roBe
   Vres=Vsup+Vact+Vref+Volpv
   fsup=100.*Gsup/Grea
   ffue=100.*Gfuel/Grea
   fref=100.*Gref/Grea
   fmpv=100.*Gpv/Grea
   fvc=100.*Vact/Vres
   fvpv=100.*Volpv/Vres
   fvs=100.*Vsup/Vres
   fre=100.*Vref/Vres
   Vcor=Vact+Vsup
   fcor=100.*Vact/Vcor
   fcore=(fvs+fvc)*0.01
   Hrea=Hcr+2.*delpv
   Rrea=Rcr+delpv

Page A-17
calculation of neutron shielding
compute fast source Sn
\[ Sn = \text{Pow} \times 1.6 \times r_{nu}/w_{fi} \]
compute shielding by core, reflector and pressure vessel: f_{sh}
concentrations smoothed in Vol=V_{sup}+V_{fuel}+V_{ref}+V_{pv}
\[ \text{coBe} = \text{cBe} \times f_{re} \times 0.01 \]
\[ \text{coTa} = f_{vpv} \times A_{v} \times 10. \times R_{oa} / 181. \]
\[ \text{coC} = f_{core} \times (c_{na} + g_{gra} + c_{gra}) \]
\[ \text{coZr} = f_{core} \times (Z_{rna} + c_{Zr}) \]
\[ \text{coU} = f_{core} \times (U_{5na} + U_{8na}) \]
\[ \text{coH} = f_{core} \times c_{h} \]
\[ \text{coFe} = f_{core} \times c_{fe} \]
\[ \text{coCr} = f_{core} \times c_{cr} \]
\[ \text{coTl} = f_{core} \times c_{Tl} \]
\[ \text{coSi} = f_{core} \times c_{Si} \]
\[ \text{Sigma} = \text{coBe} \times \text{remBe} + \text{coTa} \times \text{remTa} + \text{coC} \times \text{remC} + \text{coZr} \times \text{remZr} + \text{coU} \times \text{remU} + \]
\[ + \text{coH} \times \text{remH} + (\text{coNi} + \text{coCr}) \times \text{remNi} + (\text{coFe} + \text{coTl} + \text{coSi}) \times \text{remFe} \]
\[ R_{eq} = (7.5 \times V_{res} / \text{pee})^{0.33333333} \]
\[ \text{sire} = (\text{SIGMA} \times R_{eq}^{2}) \]
\[ f_{sh} = (0.5 - (1 - (1. \times \text{Sire}) \times e^{(-\text{Sire})}) / \text{Sire}^{2}) / \text{Sire} \]
\[ \text{Sns} = \text{Sn} \times f_{sh} \]
Fast fluence without shielding is flufa, at distance dist
\[ \text{dist} = 100. \times z_{load} + 0.5 \times H_{rea} \]
\[ \text{flufa} = \text{flufa} \times \text{tiempo} \]
Calculate Neutron Shield for zero gamma Shield
\[ \text{tne} = \text{shieldn} (\text{flufa}, \text{fastf}, \text{ishn}, 0.00, \text{igam}) \]
if (ishn .eq. 0) tne = 0.
Now, Calculation Gamma Source Sogam()
\[ \text{Call Gamso(Sn, aofis, sofr, Sogam, Pr5)} \]
First, Gamma Shield with no Neutron Shield
\[ \text{Call Shieldga(Sogam, Dose, Doses, Dosew, tiempo, tgam0, 0., igam1, ishn, 0)} \]
Now, Coupled with n shield
\[ \text{Call Shieldga(Sogam, Dose, Doses, Dosew, tiempo, tgam, tne, igam2, ishn, 1)} \]
if (igam2 .eq. 0) tne = tne0
if (igam2 .eq. 0) tgam = 0.
Volume and Masses of shieldings
\[ \text{Tgt} = \text{Tan}(100. \times \text{rload} - \text{Rrea}) / (100. \times \text{zload} + \text{Hrea}) \]
\[ \text{rr1} = \text{Hrea} \times \text{Tgt} + \text{Rrea} \]
\[ \text{rr2} = (\text{Hrea} + \text{tgam}) \times \text{Tgt} + \text{Rrea} \]
\[ \text{rr3} = (\text{Hrea} + \text{tgam} + \text{tne}) \times \text{Tgt} + \text{Rrea} \]
\[ \text{h1} = \text{rr1} / \text{Tgt} \]
\[ \text{h2} = \text{rr2} / \text{Tgt} \]
\[ \text{h3} = \text{rr3} / \text{Tgt} \]
\[ \text{V1} = \text{pee} \times \text{RR1} \times 2 + h1 \times 0.33333333 \]
\[ \text{V2} = \text{pee} \times \text{rr2} \times 2 + h2 \times 0.33333333 \]
\[ \text{V3} = \text{pee} \times \text{rr3} \times 2 + h2 \times 0.33333333 \]
\[ \text{Volg} = (\text{v2} - \text{v1}) / 1000. \]
\[ \text{Voln} = (\text{v3} - \text{v2}) / 1000. \]
Gg=RoW*Volg
if(ishn.eq.1) Ron=RoLiS
if(ishn.eq.2) Ron=RoBC
Gne=Voln*Ron
Vols=Vres+Voln+Volg
Gsis=Grea+Gne+Gg
fresv=100.*Vres/Vols
fnev=100.*Voln/Vols
fgv=100.*Volg/Vols
fresg=100.*Grea/Gsis
fneg=100.*Gne/Gsis
fgg=100.*Gg/Gsis

write(8,789) Vres,fresv,Voln,fnev
789 format(' VOLUMES AND MASSES OF REACTOR AND SHIELDINGS'//
*' VOLUME(L) Fraction(%)'//
*' Reactor ',f10.2,f10.2/
*' N Shield',f10.2,f10.2)

write(8,796) Volg,fgv
796 format(' G Shield',2f10.2)

write(8,797) Vols
797 format(' Total ',f10.2//)

write(8,798) Grea,fresg,Gne,fneg
798 format(' Mass(Kg) Fraction(%)'//
*' Reactor ',f10.2,f10.2/
*' N Shield',f10.2,f10.2)

write(8,796) Gg,fgg

write(8,806) Gsis
806 format(' Total ',f10.2//)

if(igam2.eq.0) write(8,808)
808 format(' There were numerical problem with the calculation of'/
*' gamma shield, calculations skipped'/)
if(ishig.eq.0) write(8,809)
if(ishin.eq.0) write(8,810)
809 format(' No need of gamma shield'/)
810 format(' No need of neutron shield'/)

rr2=rr2

write(8,811) zload,rload,tgam,rrl,rr2,tne,rr21,rr3
811 format(' DIMENSION OF THE SHIELDINGS'//
*' LOAD AT Z(M)=',F8.2,' WITH RADIUS(M)=',F8.2/
*' G Shield Thickness(cm)=',f8.2,' WITH Radius(cm)=',2f8.2/
*' N " " " " " " " " " ',2f8.2)
write(8,758) tempv, pin, D

format(*' Pressure Vessel Evaluated at T(K)='.,f8.2, *' PRESS(MPa)=',f8.2/
and Full Power Life(y)',f8.2//)

if(ipresv.eq.0) write(8,626)
format(*' You have problems to contain your reactor, pressure Vesse
*l'/'calculations skipped, not included in shielding or balance'//)

write(8,75) fc, Gfuel, ffue, Vact, fvc, Gsup, fsup, Vsup, fvs,
* Gref, fre, Vref, fre

format(*' DISTRIBUTION OF MASSES AND VOLUMES IN THE REACTOR'//
*' Fraction of Core Occupied by Fuel(fVol)',f10.3//
*' Masses(Kg) * Fractions(%) Volume(L) * Fraction(%)'//
*'Fuel Elem', f10.3, f13.3, 5x, f10.3, f13.3/
*'Support E', f10.3, f13.3, 5x, f10.3, f13.3/
*'Reflector', f10.3, f13.3, 5x, f10.3, f13.3)

if(ipresv.ne.0) write(8,637) Gpv, fmpv, Volpv, fvpv, delpv
format(*' Pr Vessel', f10.3, f13.3, 5x, f10.3, f13.3//
*' Pressure Vessel thickness(cm)', f8.2//)

flush=flufa
if(ishin.eq.1) flush=fastf
if(ishig.eq.1.and.igam2.ne.0) flush=flufa*aten

write(8,757) Sn, fsh, Req, sigre, D, flufa, flush, fastf, Zload, tne, tne0

format(*' DETAILS OF THE SHIELDINGS'//
*' Neutron Source(1/sec)', el2.4 // ' Self Shielding by Reactor
*Materials', el2.4 / ' Equivalent R(cm)', f8.2, ' Sigma Removal', f12.6/
*f6.2, ' Years Fast Fluence(1/cm2) without Any Shielding', e12.4
/* ' '' '' '' '' '' with (n,gamma) '' ', e12.4
/* ' '' '' '' '' '' Requested ', e12.4
/* ' All at', f6.2, ' meters'
*'Neutron Shielding Thickness(cm)', f10.2/
*'Neutron Shielding Thickness if no W is present, cm', f10.2//)

if(ishn.eq.1) write(8,767)
format(*' NEUTRON SHIELDING: LiH-Stainless Steel Matrix'//)

if(ishn.eq.2) write(8,768)
format(*' NEUTRON SHIELDING: B4C'//)

write(8,771) format(*' TOTAL PRODUCTION OF GAMMA RAYS(1/sec)'//
*'GROUP 1 2 3 4 5 6 7'/
*' 0-1Mev 1-2 2-3 3-5 5-7 7-9'
* >9'/)

write(8,772) (sogam(i),i=1,7)

format(1P7e10.3/)
write(8,*) ' % FRACTION PRODUCED BY U235'
write(8,773) (Pr5(i),i=1,7)
format(7f10.2)
write(8,*) ' Equivalent Z for Build up factors'
write(8,773) (Zeq(i),i=1,7)
write(8,*) ' Gamma Self shielding by Core, Reflector and PV'
write(8,774) (shg(i),i=1,7)
format(7f10.6)
write(8,*) ' The same but without Buildup factor'
write(8,774) (shgnb(i),i=1,7)
write(8,*)'Integrated Dose(Rad) without any shielding(n or gamma)'.
write(8,772) (Dosewg(i),i=1,7)

if(ishig.eq.0.and.ishin.eq.1)
 *write(8,*)'Integrated Dose Neutrons Shieldings(and no W)'
if(ishig.eq.0.and.ishin.eq.1) write(8,772) (DosenG(i),i=1,7)
if(ishig.eq.1.and.igam2.ne.0)
 *write(8,*)'Integrated Dose with W and Neutrons Shieldings'
if(ishig.eq.1.and.igam2.ne.0) write(8,772) (DoseG(i),i=1,7)
write(8,775) Dosew
Format(' Integrated Dose without Any Shielding,Total(Rad)',el2.4)

if(ishig.eq.1.and.igam2.ne.0) Dosos=Doses
if(ishig.eq.0) Dosos=Dosen
write(8,776) Dosos,tgam,tgam0
format(' Integrated dose with Shieldings(W and Neutrons), Total (R
*ads)',el2.2/
* ' Tungsten Thickness(cm)',f10.2/
* ' Tungsten Thickness(cm)',f10.2,' if no Neutron Shield Present'//)
write(8,804) Dose, Zload
format('/' Requested Dose(Rad)',f10.2,' at ','f6.2,' meters'/)
SOLVE THERMALHYDRAULIC
norif=nh*nf
write(8,2367) tout
2367 format(/' THERMALHYDRAULICS CALCULATIONS'/
  * Average Temperature of the Coolant at Core Exit(K)',f10 *.2/)
if(iboun.eq.0) write(8,3478)
3478 format(/' BOUNDARY CONDITION: INPUT FLOW'//)
if(iboun.eq.1) write(8,3479)
3479 format(/' BOUNDARY CONDITION: OUTLET TEMPERATURE'//)
c check if this is a calculation assuming uniform power distribution
c if(iopth.gt.2) go to 674
c here if 3D or 2D power density is constant
  Pfacr=1.
Pfacaz=1.
Call Thermohe
program end
674 continue
c here if we have uniform loading ie spacial dependent power density
if(iouth.eq.2) go to 671
c c Thermo at Max power density
c Pfacaz=1.
c write(8,687)
687 format(/' ****PROFILE OF CHANNEL WITH MAXIMUM POWER DENSITY****'//)
Call Inter(sofl,pfr,isofl,sofa,Pfacr)
Call Thermohe
if(iprob.eq.1) stop
671 continue
if(iouth.eq.1) go to 677
c c Thermo at Min power density
c Pfacaz=1.-Ripple
c write(8,697)
697 format(/'***PROFILE OF CHANNEL WITH MINIMUM POWER DENSITY***'//)
Call Inter(sofl,pfrm,isofl,sofa,Pfacr)
Call Thermohe
677 continue
Stop
End
c He density(kg/m3) function of p(Pa) and t(K)
c from page 405, ANS book "Thermal and Flow Design of Helium-Cooled
Reactors", G. Melese and R. Katz
c Function rho(p,t)
R=2077.22
rho=p/(r*t+p*b(t))
return
end

c Function b(t)(used by rho)
c
Function b(t)
data cl,c2,c3,c4,c5/9.489433e-4,9.528079e-4,3.420680e-2,
* 2.739470e-3,9.409120e-4/
b=c1+c2/(1.-c3*t)+c4/(1.+c5*t)
return
end

c Subroutine: Interpolate Table
c
Subroutine Inter(x,y,np,xi,yi)
Dimension x(20),y(20)
ii continue
if(xi.lt.x(1)) go to 10
if(xi.ge.x(np)) go to 20
i=1
continue
if(x(i).gt.xi) go to 12
i=i+1
go to ii
12 continue
go to 30
i=2
go to 30
i=np
30 yi=y(i-1)+(y(i)-y(i-1))/(x(i)-x(i-1))*(xi-x(i-1))
return
end

c Compute available energy or
difference between available and requested energies
as function of S/F(other thing too)
c
Function Balance(ibu,sofa)
c
For input S/F=sofa and when itest=0:
this function calculate the volume of the core that satisfies the
reactivity balance; and then the energy balance(Mwday)
Balance=Available-Requested. If ishape=2 or 3 (input R or H) the
function checks if R(or) H is compatible with reactivity balance
if not, set flag ibu=1 and RETURN
if itest=1 and for input sofa calculate
available energy
c radius infinite core that satisfies reactivity balance if ishape=2
height of infinite " " " " " " " " " " " 3

c
common /Bala/ Ereq, buwo(5), relr, relal, rela2, dkeol, dkstr, BU, Vcor, *
* U5m, dkbu, dkxes, dkxep, dksms, dksmp, dkbe, rkre, eps, itmax, dcr
*, itest, aofi

c
common /MaBaSi/ R,H, ishape

c
common /Fluxo/ Pow, Vc, sofr, fluxn(4), xedks, xedkt, tmax, smdks, smdkt
*, tsrm, D, iwxe

dimension rm(8), sof(8), sof1(5), aof(5), bew(5)
*, rki(8)

data (rm(i), i=1,8)/17.40,14.86,13.71,11.65,10.41,9.499,8.958,8.76/
c

Page A-23
c for the following Support/Fuel element ratio
data (sof(i),i=1,8)/0.0,0.1,0.2,0.5,1.0,2.0,3.4/
data (rki(i),i=1,8)/1.62228,1.58272,1.59454,1.62315,1.67140,1.67186,1.62773,1.56044/

rki k\text{-infinite as function of S/F}
data (aof(i),i=1,5)/1.372,1.407,1.373,1.325,1.276/
aof: absorption to fission ratio in U\text{235} for the following S/F ratios
data (sofl(i),i=1,5)/0.0,0.2,0.5,1.0,2.0/
sofl: Support/Fuel ratio
data (bew(i),i=1,5)/30.14,27.47,27.24,26.40,23.80/
bew(): \% delta k; reactivity worth of 30 cm Be radial reflector as function of S/F (sofl(i),i=1,5)
data dext,rofu/2.29,0.5/
dext(cm) extrapolation length for bare core
rofu (g/cm\text{3}) density of U\text{235} corresponding to data base
data pee,xop,pisq3/3.1415926,0.541315,5.441398/
xop: optimum shape for cylindrical reactors=Radius/Height
pisq3=\pi*\sqrt{3}
sofr=sofa
ibu=0
isof=8
isofl=5
ibup=4
ibe=8
sofo=sofa

compute k\text{inf} and migration length
call Inter(sof,rki,isof,sofo,rkin)
call Inter(sof,rm,isof,sofo,rm)

compute A/F for U\text{235} at S/F=sofo
call Inter(sof,aof,isof,sofo,aofi)

compute delta k BU
call Inter(sofl,buwo,isofl,sofo,dkbu)

compute delta k of Be reflectors
call Inter(sofl,bew,isofl,sofo,wbe)
wber=wbe*relr
wbeal=wbe*relal
wbea2=wbe*rela2
dkeb=wber+wbeal+wbea2

Reactivity effects of Xe and Sm
Simultaneous solution of \(dk(\text{Xe,Sm})=g(Vc)\) and \(Vc=f(dk(\text{Xe,Sm}))\)
bisect function \(h=g-h\) where \(h\) is inverse \(f\)
it=0
rkrem=1.+(dkbu+dkstr+dkeol-dkeb)/100.
c buck buck(0.Xe)
   buck=sqrt(rkin/rkrem-1.)/rmi
   go to (2001,2002,2003), ishape

  c if ishape=1, optimum shape---->2001
2001 hp=pi^2/buck
   rp=xop*hp
   R=rp-dext
   H=hp-dext*2.
   Vcl=pee*R**2*H
   Vc=Vc1
   Call Flux
   Ful=xedkt+smdkt
   Vc2=Vc1
   Vc2=Vc2+Vc1
   it=it+1
   H=(Vc2/(pee*xop**2))**0.33333333
   R=xop*H
   bge=(2.405/(R+dext))**2+(pee/(H+2.*dext))**2
   h2=rkin/(1.+rmi**2*bge)-rkrem
   h2=100.*h2
   Vc=Vc2
   Call Flux
   Fu2=xedkt+smdkt-h2
   if ((Ful*Fu2).gt.0..and.it.le.itmax) go to 728
   if (it.lt.itmax) go to 739
   write(8,201)
   stop
728 Vc2=Vc2+Vc1
   H=(Vc2/(pee*xop**2))**0.33333333
   R=xop*H
   bge=(2.405/(R+dext))**2+(pee/(H+2.*dext))**2
   ha=rkin/(1.+rmi**2*bge)-rkrem
   ha=100.*ha
   Vc=Vc2
   Call Flux
   Fua=xedkt+smdkt-ha
   call bisect(Vcl,Vc2,Vca,Ful,Fu2,Fua,iwa)
   test=abs(Vcl-Vca)/Vca
   if (test.gt.eps.and.iwa.eq.0) go to 748
   if (it.lt.itmax.and.iwa.eq.0) go to 749
   write(8,201)
   stop
739 continue
748 Vca=(Vc2+Vc1)*0.5
   it=it+1
   H=(Vca/(pee*xop**2))**0.33333333
   R=xop*H
   bge=(2.405/(R+dext))**2+(pee/(H+2.*dext))**2
   ha=rkin/(1.+rmi**2*bge)-rkrem
   ha=100.*ha
   Vc=Vca
   Call Flux
   Fua=xedkt+smdkt-ha
   call bisect(Vcl,Vc2,Vca,Ful,Fu2,Fua,iwa)
   test=abs(Vcl-Vca)/Vca
   if (test.gt.eps.and.iwa.eq.0) go to 748
   if (it.lt.itmax.and.iwa.eq.0) go to 749
   write(8,201)
   stop
749 continue

   c End iteration for the case optimum shape.RESULT: Volume of Core(Vc)
c that satisfies reactivity balance
c
go to 2004

c go next if ishape=2----->input Radius of core

2002 buca=buck**2-(2.405/(R+dext))**2
   dcr=2.405/buck-dext
   if (buca.le.0.) ibu=1

   c set flag ibu=1 if R(input) is too small to satisfy reactivity balance

   if (ibu.eq.1) return
   hp=pee/sqrt(buca)
   H=hp-2.*dext
   Vcl=pee*R**2*H
   Vc=Vc1
   Call Flux
   Ful=xedkt+smdkt
Vc2=Vcl

828  Vc2=Vc2+Vcl
     it=it+l
     H=Vc2/(pee*R**2)
     bge=(2.405/(R+dext))**2+(pee/(H+2.*dext))**2
     h2=rkin/(1.+rmi**2*bge)-rkrem
     h2=100.*h2
     Vc=Vc2
     Call Flux
     Fu2=xedkt+smdkt-h2
     if((Ful*Fu2).gt.0..and.it.le.itmax) go to 828
     if(it.lt.itmax) go to 839
     write(8,201)
     stop

839  continue

848  Vca=(Vc2+Vcl)*0.5
     it=it+l
     H=Vca/(pee*R**2)
     bge=(2.405/(R+dext))**2+(pee/(H+2.*dext))**2
     ha=rkin/(1.+rmi**2*bge)-rkrem
     ha=ha*100.
     Vc=Vca
     Call Flux
     Fua=xedkt+smdkt-ha
     call bisect(Vcl,Vc2,Vca,Ful,Fu2,Fua,iwa)
     test=abs(Vcl-Vca)/Vca
     if(test.gt.eps.and.iwa.eq.0) go to 848
     if(it.lt.itmax.and.iwa.eq.0) go to 849
     write(8,201)
     stop

849  continue

c End iteration for the case of input Radius. RESULT: Volume of Core(Vc)
c that satisfies reactivity balance
c go to 2004

c go next if ishape=3 >input Height of the core

2003  bucr=buck**2-(pee/(H+2.*dext))**2
      dcr=pee/buck-dext*2.
      if(bucr.le.0.) ibu=1

c set flag ibu=1 if H(input) is too small to satisfy reactivity balance

c     if(ibu.eq.1) return
     rp=2.405/sqrt(bucr)
     R=rp-dext
     Vcl=pee*R**2*H
     Vc=Vcl
     Call Flux
     Ful=xedkt+smdkt
     Vc2=Vcl
     928  Vc2=Vc2+Vcl
     it=it+l
     R=sqrt(Vc2/(pee*H))
     bge=(2.405/(R+dext))**2+(pee/(H+2.*dext))**2
     h2=rkin/(1.+rmi**2*bge)-rkrem
     h2=h2*100.
     Vc=Vc2
     Call Flux
     Fu2=xedkt+smdkt-h2
     if((Ful*Fu2).gt.0..and.it.le.itmax) go to 928
     if(it.lt.itmax) go to 939
     write(8,201)
     stop

939  continue
948 \[ V_{ca} = (V_{c2} + V_{cl}) \times 0.5 \]
\[ it = it + 1 \]
\[ R = \sqrt{V_{ca} / (pee \times H)} \]
\[ bge = (2.405 / (R + \text{dext})) \times 2 + (pee / (H + 2. \times \text{dext})) \times 2 \]
\[ ha = r_{kin} / (1. + r_{mi} \times 2 \times bge) - r_{krem} \]
\[ ha = 100. \times ha \]
\[ V_{c} = V_{ca} \]
\text{Call Flux} \]
Fua = xedkt + smdkt - ha
\text{call bisect}(V_{c1}, V_{c2}, V_{ca}, F_{u1}, F_{u2}, F_{ua}, iwa) \]
\text{test} = abs(V_{cl} - V_{ca}) / V_{ca} \]
if(test.gt.\text{eps}.and.iwa.eq.0) go to 948
if(it.lt.itmax.and.iwa.eq.0) go to 949
\]
\text{write}(8, 201)
\]
201 \text{format}(/' stop in Balance, trying to compute Xe, Sm'/) \]
\text{stop}
\]
949 \text{continue}
\]
\text{c End iteration for the case of input Height. RESULT: Volume of Core(Vc) that satisfies reactivity balance}
\]
2004 \text{continue}
\]
\text{c End of iterations to obtain Volume of core that satisfies reactivity balance (that includes Xe and Sm reactivities)}
\]
\text{ibu} = 0 \]
dkxes = xedks \]
dkxep = xedkt \]
dksms = smdks \]
dksmp = smdkt \]
\text{c recompute required dk from bare core}
\]
rkre = 1. + (DKBU + dkxep + dksmp + dkstr + dkeol - dkbe) / 100. \]
\text{c check available energy}
\]
Vcor = Vc \]
Vact = Vcor / (1. + sofa) \]
U5m = Vact * rofu \]
\text{c for U235 at 200 Mev/fission}
\]
Eavai = (U5m * BU) / (105.2 * aofi) \]
Balance = Eavai - Ereq \]
if(itest.eq.1) Balance = Eavai \]
\text{return}
end \]
\text{c subroutine bisect(x1,x2,xav,f1,f2,fav,iwa)} \]
if((f1 * f2).le.0.) go to 11 \]
\text{write}(8, 1) \]
1 \text{format}(/' f1*f2 >0.'//) \]
iwa = 1 \]
\text{return} \]
11 \text{iwa} = 0 \]
if((fav * f1).le.0.) go to 10 \]
f1 = fav \]
x1 = xav \]
\text{return} \]
10 \text{f2} = fav
x2=xav
return
end

compute control drums

subroutine Control
dimension cr(5),sof(5)
common /cont/ R,drr,dref,rasp,refec,ncr,dksu,dkstr,relr
R: radius core, drr: thickness reflector; dref: reference reflector
c: thickness (with which worths were calculated); rasp: S/F element ratio
c: refec: keff to control; ncr: number of control rods; dksu(%) : subcriticality
for drums in.
c: dkstr(%): dk structural part of reactor, relr: relative worth of reflector

data (cr(i),i=1,5)/21.0,19.15,18.8,18.1,16.35/
data (sof(i),i=1,5)/0.0,0.2,0.5,1.0,2.0/

if(ncr.eq.0) write(8,48)
48 format(’Your input for the number of control drums is zero’/
*’ Subroutine Control bypassed’//)
if(ncr.eq.0) return
pee=3.1415926
isof=5
Call Inter(sof,cr,isof,rasp,cdr)
c: worth of 2*pee sheet (cdr) is corrected because drr might not be =dref
c: correction factor relative worth of reflector (with respect to dref)
cdr=cdr*relr
c: rea(%) reactivity to control
rea=(refec-1.)*100.+dksu-dkstr

c: compute maximum number of drums=nmax
c
rd=0.5*drr
par=2.*asin(rd/(R+rd))
pard=par*180./pee
rd and par are the radius and the central parallax of the drums
c
nmax=2.*pee/par
cdrm=cdr*nmax*par/(2.*pee)
write(8,20) nmax,cdrm,rea,pard
20 format(’You cannot control this reactor only with control’/
*’ drums in the reflector’/
*’ The reactivity worth of’,i5,’ drums (max value) is’,f6.2,’ %’/
*’ and the reactivity to control is’,f6.2,’ %’/
*’ Parallax of each drum would be’,f8.2,’ degrees’//)
return
continue
if(ncr.gt.nmax) write(8,33) ncr,nmax
33 format(’Your input for the number of drums is’,i5/
*’ larger than the max possible’,i5,’ continue with max’)//
if(ncr.gt.nmax) ncr=nmax
rcr=ncr
cdrm=cdr*rcr*par/(2.*pee)
write(8,34) ncr,nmax
34 format(’Your input for the number of drums’,i5,’ is too small’/
*’ (max possible is’,i5,’ ) program is going to increase it’)
if(cdrm.lt.rea) then
ncr=ncr+1
continue
cdrm = cdr * ncr * par / (2. * pee)
if (cdrm .lt. rea) go to 101
rcr = ncr
eendif

para is the central parallax of the absorbing part of one drum
para = (rea / rcr) * (2. * pee / cdr)
para to local parallax (seen from center of drum) --> dtcr
bb = (R + rd) * cos (0.5 * para)
cc = R**2 + 2. * R * rd
xx = bb - sqrt (bb**2 - cc)
dtcr = 2. * asin (xx * sin (0.5 * para) / rd)
dtcd = 180. * dtcr / pee
write (8, 31) ncr, dtcd, rea
31 format (/i5, 'Drums with absorbing angle(d)', f8.2, 'each' /
     'Control dk(%)=', f5.2 //)
return
end

Four groups cross section to compute fluxes, Xe and Sm Effects
Subroutine Flux
common /Fluxo/, Pow, Vc, sof, fluxn(4), xedks, xedkt, tmax, smdks, smdkt,
* tsm, D, iwe
dimension aux(5), spec(4, 5), f5(4, 5), sof(4), sp(4), sof(5)
data (sof(i), i=1, 5) /0.0, 0.2, 0.5, 1.0, 2.0/

Neutron spectra as function of S/F and Neutron Energy

data (spec(i, 1), i=1, 4) /0.641, 0.348, 0.009, 0.002/
data (spec(i, 2), i=1, 4) /0.611, 0.335, 0.038, 0.015/
data (spec(i, 3), i=1, 4) /0.581, 0.321, 0.061, 0.037/
data (spec(i, 4), i=1, 4) /0.553, 0.305, 0.078, 0.063/
data (spec(i, 5), i=1, 4) /0.519, 0.288, 0.090, 0.102/

U235 fission cross sections as function of S/F and Energy
in core volume (supp + fuel)
data (f5(i, 1), i=1, 4) /1.28, 4.92, 37.33, 25.55/
data (f5(i, 2), i=1, 4) /1.27, 6.08, 37.33, 62.13/
data (f5(i, 3), i=1, 4) /1.27, 6.45, 37.33, 90.85/
data (f5(i, 4), i=1, 4) /1.27, 6.63, 37.33, 121.5/
data (f5(i, 5), i=1, 4) /1.27, 6.74, 37.3, 157.4/
data rou5, Av, wfi, xe23, xe4, gi, gx, xe1, rnu, 0.5, 235.044, 0.602202,
* 3.2042e-11, 1.126e+6, 0.061, 0.003, 0.092, 0.144
wfi: joules/fission, xe23, xe4: capture cross section Xe
gi, gx: Yield I135 and Xe135 per fission, rnu = number neutrons/fission
data rli, pml, sm23, sm4, gp /2.87e-5, 3.56e-6, 6.278, .29982, .0113/
xel, rli, pml: decay constants Xe135, I135 and Pm149

gp: Yield Pm149/fission, sm23, sm4: capture cross section Sm149
Vact = Vc / (1. + sof)
ro5 = rou5 * Vact / Vc

is U235 density average in core (support + fuel elements)

u5n = ro5 * Av / A5
isof = 5
ng = 4
do 10 i = 1, ng
do 20 j = 1, isof
20 aux(j) = spec(i, j)
call Inter(sof, aux, isof, sofr, spe)
sp(i) = spe
do 30 j = 1, isof
aux(j) = f5(i, j)
call Inter(sof, aux, isof, sofr, sig)
sif(i) = sig
10 continue
sigf = 0.
do 40 i = 1, ng
40 sigf = sigf + sp(i) * sif(i)
sigf = sigf * usn
flun = Pow * 1.e+6 / (Vc * wfi * sigf)
c flun: average flux in core
do 50 i = 1, ng
50 fluxn(i) = flun * sp(i)
xec = xe23 * (sp(2) + sp(3)) + xe4 * sp(4)
fluxe = xe2 * 1.e+24 / xec
xedks = 100. * (gi + gx) * flun / (rnu * (flun + fluxe))
c compute max xe after trip(iwxe = 0)
c if no max appears set flag iwxe = 1, and make xedkt = xedks
c
iwxe = 0
flumi = fluxe * gx / gi
xedkt = xedks
if (flun. le. flumi) iwxe = 1
if (iwxe .eq. 1) go to 1910
fluxi = rli * 1.e+24 / xec
tmax = 1. + (gi + gx) * (fluxi - fluxe) / (gi * (fluxe + flun))
tmax = ALOG(rli / (xel * tmax) / (ri - xel))
kedk = EXP(-xel * tmax) * (gi + gx) * flun / (fluxe + flun) +
1 * (exp(-xel * tmax) - exp(-ri * tmax)) * gi * flun / (fluxi - fluxe)
xedkt = xedkt * 100. / rnu
tmax = tmax / 3600.
1910 continue
smc = sm23 * (sp(2) + sp(3)) + sm4 * sp(4)
smc = smc * 1.e-24
flusm = PML / smc
tsm = 1. / (smc * flun)
tvida = D * 3.15576e+7
c compute sm after trip
c
tsmo = tvida / tsm
etsm = 0.
if (tsmo .lt. 50.) etsm = EXP(-tsmo)
smdks = gp * (1. - etsm) / rnu
smdkt = smdks + gp * flun / (rnu * flusm)
smdks = 100. * smdks
smdkt = 100. * smdkt
tsm = tsm / 86400.
return
end
c solve thermalhydraulic
c subroutine thermohe
c real*4 k
c
dimension pow(51), pres(51), tbulk(51), ve(51), rmach(51), z(51), rj(51)
*, tw(51), Tclad(51), Tfuel(51), Tclaa(51), Tfa(51)
c
common/thermo/ aln, nnodo, iexpl, ifri, itmax, norif, iditus, nfu, pin, tin
*, d, ru, xi, der, eps, Pow, rjs, flowt, GU235, Vact, Enr, PUC, Rouc, RoZrC,
* RoGraf, dclad, Hact, Pfacr, Daxi, fact, phav, thav, fe, iprth, iopth, iouth
*, Pfacaz, itry, flowal, iboun
common /fGu/ ifro, deri, pf, ar, dho, rug, dz
common /fph/ imaxt, epsi, dero
data pee/3.1415926/, rgas/4124.2/
character*80 aln

c
nnode: number of nodes; iexpl /0, 1/ No, Yes explicit
ifri.ne.1 : switch off friction factor
itmax: max iters, norif: number of orifices, iditus/0, 1/ no Dittus
c (means correction for Twall/Tbulk in Nussel correlation), 1 Yes Dittus
nfu: number of nodes inside fuel

c
itry=0
iexpl=1
2013

dero=der
ifro=ifri
deri=der
dho=d*0.01
rug=ru
imaxt=itmax
epsi=eps

c
pin(MPa), tin(K) inlet conditions
d(cm), ru: channel diameter and rugosity
xi/0., 1./ xi=0. fully explicit; xi=1. fully implicit
der: factor to multiply variable to compute derivative numerically
typical value 1.01; eps: tolerance to finish iterations; Powt(Mw)
total power; rjs(Kw/cm2) scale for plot heat rate

c
flowt(Kg/sec) : Total flow
flow(g/sec) : Channel flow

c
flowt=1000.*flowt/norif
Vamix=Vact*fe

c
Vact: Volume of fuel elements; Vamix: volume occupied by UC-ZrC mix in
graphite matrix; exclude coolant holes and clads

c
GU235 grams of U235 in active mix Volume Vamix(Liters) U is
Enriched (at fraction), PUC mole fraction of UC in UC-ZrC mix
RoUC, RoZrC and RoGraf (g/cm3) densities of UC, Zrc and Graphite
dclad(cm): clad thickness

c
RaUC=(1.+(1./Enr-1.)*1.012798+0.05110173/Enr)*GU235/(1000.*Vamix *)
RaZrC=(1./PUC-1.)*RaUC*0.4178467
xUC=RaUC/RoUC
xZrC=RaZrC/RoZrC
xGraf=1.-xUC-xZrC
RaGraf=xGraf*RoGraf
Ra=RaGraf+RaZrC+RaUC

c
npu=nnodo+1

c
Hact(cm): active length; Pfact: Radial Peaking factor at r position
assume cos in z and Daxi(cm) axial extrapol.
dzet=Hact/nnodo
roav=Powt*fact/Vamix

c
Pfraz: Power factor radial-azimuthal
Pfraz=1.
if(iophth.gt.2) Pfraz=Pfacr*Pfacaz

c
recompute flow according to option

c
if(iophth.eq.4) flow=flow*Pfraz
Next=Hact*2.*Daxi
we=Next/Hact
rih=pee/Hext
Pfact=Pfraz*pee/(2.*we*sin(0.5*pee/we))
do 182 i=1,npu
zzzz=Daxi+(i-1)*dzet
if(iopth.gt.1) pow(i)=roav*Pfact*sin(rih*zzzz)
if(iopth.eq.1) pow(i)=roav
z(i)=zzzz-Daxi

See: pow is power per unit volume of active mix(UC-ZrC-Graphite)
transform pow(i)(Mw/L) to power per unit length (watt/cm)

r0=d/2.
rl=r0+dclad
r2=sqrt(rl**2+Vamix*1000./(pee*Hact*norif))
fac=1000.*pee*(r2**2-rl**2)
do 123 i=1,npu
pow(i)=pow(i)*fac

z(i) (cm) boundaries of the nodes

write(8,12) aln
write(8,21) pin,tin,d,ru,der,eps,Pwrt,norif,flowt,fact

write(8,162)roav,Hact
write(8,31) flow

pres(1)=pin*10.**6
tbulk(1)=tin
ar=pee*(dho/2.)***2
pf=pee*dho

if(iopth.eq.4) write(8,1293)
format(' Coolant Flow Proportional to Power Density')
if(iopth.ne.4) write(8,1295)
format(' Uniform Coolant Flow Assumed')
* Node  z(cm)  Po(w/cm)  Pr(MPa)  T(K)  V(m/s)  Re  
* Mach'//

c
g=flow*0.001/ar
flow=flow*0.001

3001
p=pres(i)
t=tbulk(i)
call phe(h,p,t,rho,vis,cp,pr,a,k,x,0)
pi=p
ti=t
rhol=rho
hi=h
Re=dho*g/vis
Rei=Re
ve(i)=flow/(ar*rho)
c remark for future use inlet conditions
hinlet=h
echannel=0.
ri=1
pre=pres(i)*10.**(-6)
write(8,41) i,z(i),pow(i),pre,tbulk(i),ve(i),Re,rmach(1)
f=0.
c branching: if fully explicit continue, if not go to 2001
if(iexpl.eq.0.and.xi.gt.0.) go to 2001
do 30 i=2,npu
dz=z(i)-z(i-1)
po= 0.5*(pow(i)+pow(i-1))*dz
echannel=echannel+po
h=hi+po/flow
p=pi
call phe(h,p,t,rho,vis,cp,pr,a,k,x,1)
tbulk(i)=t
dl=drdp(pi,ti,der)
d2=drdt(pi,ti,der)
if(ifri.eq.1) f=fri(Rei,ru)
fl=1.-dl*(g/rhoi)**2
f2=(f*pf/(2.*ar*rhoi))*g*g
f3=-d2*(g/rhoi)**2
dz=0.01*dz
pres(i)=pres(i-1)-f2*dz/fl-f3*(tbulk(i)-tbulk(i-1))/f1
p=pres(i)
t=tbulk(i)
call phe(h,p,t,rho,vis,cp,pr,a,k,x,0)
if(i.eq.npu) houllet=h
Re=dho*g/vis
ve(i)=flow/(ar*rho)
rmach(i)=ve(i)/a
pre=pres(i)*10.**(-6)
pi=p
ti=t
rhol=rho
hi=h
Rei=Re
if(iprth.eq.1.or.i.eq.npu)
*write(8,41) i,z(i),pow(i),pre,tbulk(i),ve(i),Re,rmach(i)
continue
gamma=cp/(cp-rgas)
41 format(6,5f10.2,f10.0,f10.3)
c end calculation fully explicit

go to 4321
2001 continue
c c here begins the implicit calculation
c do 531 i=2,npu
dz=z(i)-z(i-1)
```plaintext
po = 0.5*(pow(i)+pow(i-1))*dz
echannel=echannel+po
po=po/flow

c First find an estimation of outlet explicitly

c
h=hi+po
p=pi
call phe(h,p,t,rho,vis,cp,pr,a,k,x,l)

c find where Gu changes sign as function p outlet node

c
taprox=t
dz=0.01*dz
pl=pi
it=0
Gu1=Gu(pi,taprox,pi,ti,xi,g)
p2=pi

42  p2=p2/der
   it=it+1
Gu2=Gu(p2,taprox,pi,ti,xi,g)
if((Gu1*Gu2).gt.0. and. it.le.itmax) go to 42
if(it.gt.itmax) then
   write(8,43) i,pl,Gu1,p2,Gu2
   format(//' implicit calculation, problem trying to find p2 in node
   *','i3,' pl Gu1=',2e14.6//' p2 Gu2=',2e14.6/' go to explicit'//)
expi=1
go to 3001
else
endif
it=0
start bisect to find p at outlet node

45  pav=0.5*(pl+p2)
   Guav=Gu(pav,taprox,pi,ti,xi,g)
test=abs(Guav)/p
if(test.lt.tol) go to 44
   it=it+1
call bisect(pl,p2,pav,Gu1,Gu2,Guav,iwa)
   if(it.le.itmax.and.iwa.eq.0) go to 45
continu
if(it.gt.itmax.or.iwa.eq.1) then
   write(8,46) i,pl,Gu1,p2,Gu2,pt,iwa
   format(//' implicit calculation, problem trying to find pav in node
   *','i3,' pl Gu1=',2e14.6//' p2 Gu2=',2e14.6/' p1 pav=',2e14.6//' go to explicit'//)
expi=1
go to 3001
else
endif
we have here pav,tprox values which are good estimations.
c let us improved it by Taylor expansions of Fu(p,t) and Gu(p,t)

c
vi=ve(i-1)
Fu1=Fu(pi,ti,pav,taprox,po,vi)
pprim=der*pav
Fu2=Fu(pi,ti,pprim,taprox,po,vi)
dfup=(Fu2-Fu1)/(pprim-pav)
tprim=der*taprox
Fu2=Fu(pi,ti,pav,tprim,po,vi)
dfut=(Fu2-Fu1)/(tprim-taprox)
Gu1=Gu(pav,taprox,pi,ti,xi,g)
Gu2=Gu(pprim,taprox,pi,ti,xi,g)
dgup=(Gu2-Gu1)/(pprim-pav)
Gu2=Gu(pav,tprim,pi,ti,xi,g)
```
\[ \text{dgut} = \frac{(G_{u2} - G_{u1})}{(t_{\text{prime}} - t_{\text{approx}})} \]
\[ \delta = \frac{(-F_{ul} \cdot \text{dgut} + G_{ul} \cdot \text{dfut})}{\delta} \]
\[ d_{\text{el}} = \frac{(-G_{ul} \cdot \text{dfup} + F_{ul} \cdot \text{dgup})}{\delta} \]

\[ \text{write}(8,3478) \quad \text{ful,dfup,dfut,gu1,dgup,dgut,del,delt} \]

```
format(' Ful Df/Dp Df/dt',3el4.5/' Gul Dg/Dp Dg/Dt',3el4.5/
* delta delp delt',3el4.5/)
```

\[ p = p_{av} + d_{el} \]
\[ t = t_{\text{approx}} + d_{el} \]

call phe(h,p,t,rho,vis,cp,pr,a,k,x,0)

\[ \text{if} (i \text{eq} \text{npu}) \quad \text{houtlet} = h \]
\[ \text{pre} = p_{av}^{10.**(-6)} \]
\[ \text{pres}(i) = p \]
\[ \text{t}(i) = t \]
\[ \text{ve}(i) = \text{flow} / (a \cdot \text{rho}) \]
\[ \text{Re} = \text{dho} \cdot g / \text{vis} \]
\[ \text{rmach}(i) = \text{ve}(i) / a \]

\[ \text{if} (i \text{prth} = \text{l} \text{or} i \text{eq} \text{npu}) \]
\[ * \text{write}(8,41) i,z(i),\text{pow}(i),\text{pre},\text{t}(i),\text{ve}(i),\text{Re},\text{rmach}(i) \]

\[ \text{hi} = h \]
\[ \text{pi} = p \]
\[ \text{ti} = t \]

```
continue
```

```
c End calculation coolant conditions
```

```
c Check if we did not pass speed of sound anywhere , if yes change condition at inlet and set flag iprob=l
c```

\[ \text{iprob} = 0 \]
\[ \text{do} 2297 \text{i}=2,\text{npu} \]
\[ \text{if} (\text{pres}(i) \text{gt} \text{pres}(i-1) \text{or} \text{pres}(i) \text{lt} 0.) \text{iprob} = 1 \]

```
2297 \text{continue}
```

```
c Hoping to fix the mess we change input conditions in order to relax thermalhydraulic
```

```
2308 \text{format(}' No success with the change. Program Ends'\')
```

```
if(\text{itry} = 1) \text{write}(8,2308)
```

```
2308 \text{format(}' No success with the change. Program Ends'\')
```

```
\text{if} (\text{itry} = 1) \text{return}
```

```
\text{ifri} = 0
```

```
Pfacr = 1.
Pfacaz = 1.
ioth = 1
pin = 10.
tin = 20.
itry = 1
iexpl = iexplo
```

```
\text{if} (iboun \ne 0) \text{flowt} = \text{flowal}
```

```
write(8,2314) pin,tin
```

```
2314 \text{format(}' With previous power level and input conditions'/
* 'flow velocities reach speed of sound. To relax thermalhydraulic'/
* 'we change to following conditions':/
* '1) Uniform 3D power density.'/
* '2) Assume no friction in channel.'/
* '3) Inlet p(MPa)=',f8.2/
* '4) Inlet T(K) =',f8.2//)
```

```
c Beginning calculation wall temperature
c
```

```
2303 \text{iwar} = 0
\text{do} 302 \text{i}=1,\text{npu}
\text{p} = \text{pres}(i)
\text{t} = \text{tbulk}(i)
```

Page A-35
ti=t
call phe(h,p,t,rho,vis,cp,pr,a,k,x,0)
Rei=dho*g/vis
Pri=Pr
Rki=k/dho
h=h+0.5*ve(i)**2
call phe(h,p,t,rho,vis,cp,pr,a,k,x,l)
Tfs=t

c Apply recovery factor (Rc) to stagnation temperature Tfs
Rc=(Pri)**0.33333333
Tfa=ti+Rc*(Tfs-ti)

c First estimation wall temperature
Zr=z(i)/(100.*dho)
RNus=RNu(Rei,Pri,l.,Zr)
hco=RNus*Rki
rjq=pow(i)*100./(pee*dho)

rj(i)=rjq*10.**(-7)
Tw1=Tfa+rj/hco
Tw(i)=Tw1

if(iditus.eq.1) go to 3121

c write(8,143) Twl,rjq,hco,Rc,Tfa,Tfs
it=0
Tw1=Tw1/ti
Fql=Fq(rjq,Zr,Rei,Pri,Rki,Tfa,Tri,Twl)
c write(8,144) Tw1,Fql
Tw2=Tw1
422 Tw2=Tw2*der
Tr2=Tw2/ti
it=it+l
Fq2=Fq(rjq,Zr,Rei,Pri,Rki,Tfa,Tr2,Tw2)
c write(8,144) Tw2,Fq2
if((Fq2*Fq2).gt.0. and it.le.itmax) go to 422
if(it.gt.itmax) then
write(8,431) i,Twl,Fql,Tw2,Fq2,it,iwa
143 format(' first estimation, Twl=',f10.3,' Rjg HC',2e14.5/
' Rc Tfa Tfs',3f14.3/12x, 'Tw',12x, 'Fq')
144 format(2el4.5)
431 format(' implicit calculation, problem trying to find Tw2 in node
**',i3,'Tw1 Fql=',2e14.6//' Tw2 Fq2=',2e14.6/' bypass wall ')
461 format(' implicit calculation, problem trying bisect Fq in node
**',i3,'Tw1 Fql=',2e14.6//' Tw2 Fq2=',2e14.6,' its=',i4,' iwa=',i4/
' by pass wall ')
iditus=1
iwar=1
go to 3121
else
endif
it=0

c start bisect to find T wall

c
452 Twa=0.5*(Tw1+Tw2)
Tra=Twa/ti
Fgav=Fq(rjq,Zr,Rei,Pri,Rki,Tfa,Tra,Twa)
test=abs(Fgav)/rjq
if(test.lt.eps) go to 442
it=it+l

call bisect(Tw1,Tw2,Twa,Fq1,Fq2,Fgav,iwa)
if(it.le.itmax.and.iwa.eq.0) go to 452
continue
if((it.gt.itmax.or.iwa.eq.1) then
write(8,461) i,Twl,Fql,Tw2,Fq2,it,iwa
iditus=1
iwar=1

go to 3121
else
endif
Tw(i)=Twa

3121 continue
if(xGraf.lt.0.) go to 302

cclad=RkZrC(Twa)
rcj=rcjg*10.**(4)
Pca=rcj*2.*r0/r2**2
Qh=Poa/(1.-((r1/r2)**2)

c See only one node for the clad

Tclad(i)=Tw(i)+rcj*r0*alog(r1/r0)/cclad
culo=1.+dclad/r0
Tclaa(i)=Tw(i)+rcj*r0**2*(culo*alog(culo)-(culo-1.))/(dclad*cclad)
dr=(r2-r1)/nfu
Tinl=Tclad(i)
rinl=r1
Tfa=0.
do 3021 in=1,nfu

3021 continue
Tfuel(i)=Tout

Tfua(i)=Tfa/(r2**2-r1**2)

continue
write(8,978) r0,r1,r2,Ra,RaUC,xUC,RaZrC,xZrC,RaGraf,xGraf,nfu
*,GU235,Vact
978 format(//' From the Coolant Channel to the Uranium Carbide'/'
* Radius(cm) Orifices, Clad, Cell',3f10.4/
* Averages Densities(g/cm3)'*10,x,' Volumetric Fraction'/
*,' Total',f10.4/
*,' UC',2f10.4/
*,' ZrC',2f10.4/
*,' Graphite',2f10.4//' Number of fuel nodes',i4/
*f10.2,' grams of U235 in',f10.2,' Liters of Fuel Volume')
if(iwar.eq.1) write(8,427)
427 format(//'Due to iterations difficulties we switch to Dittus Correl
*ation')
write(8,976)
976 format(///' Node z(cm) J(Kw/cm2) Twall(K) Tclad(K) TcladAv
* Tfuel(K) TfuelAv '//'
i=1
write(8,977) i,z(i),rj(i),tw(i),Tclad(i),Tclaa(i),Tfuel(i),Tfua(i)
do 1506 i=2,nfu
*write(8,977) i,z(i),rj(i),tw(i),Tclad(i),Tclaa(i),Tfuel(i),Tfua(i)
1506 continue
977 format(i5,f10.2,f10.5,5f10.2)

c calculation of axial averages

c See: <T>=(<t*rho>/rho i.e. <T> is defined according number of He molecules

c
zav=0
rohav=0.
thav=0.
phav=0.
twa=0.
tca=0.
tfa=0.
p=pres(1)
t=tbulk(1)
call phe(h,p,t,rho,vis,cp,pr,a,k,x,0)
roin=rho
do 1436 i=2,npu
dz=z(i)-z(i-1)
zav=zav+dz
phav=phav+0.5*(pres(i)+pres(i-1))*dz
twa=twa+0.5*(tw(i)+tw(i-1))*dz
tca=tca+0.5*(tcla(i)+tcla(i-1))*dz
tfa=tfa+0.5*(Tfua(i)+Tfua(i-1))*dz
p=pres(i)
t=tbulk(i)
call phe(h,p,t,rho,vis,cp,pr,a,k,x,0)
roin=rho
roav=rohav+0.5*(roin+roout)*dz
phav=rohav+rhoaav+0.5*(roin+roout)*dz
phav=rohav+0.5*(roin+roout)*dz
phav=rohav+0.5*(roin+roout)*dz
phav=rohav+0.5*(roin+roout)*dz
roin=rho
rohav=rohav+0.5*(roin+roout)*dz
thav=thav+0.5*(tbulk(i)*roout+tbulk(i)*roin)*dz
roin=roout
rohav=0.001*rohav/zav
thav=thav/zav
thav=thav*0.001/rohav
phav=phav/zav
twa=twa/zav
tca=tca/zav
tfa=tfa/zav
p=phav
t=thav
call phe(h,p,t,rho,vis,cp,pr,a,k,x,0)
roav=rho+0.001
pre=phav*0.000001
write(8,1486) pre,thav,roav,rohav,twa,tca,tfa
format(//' Axial Average Conditions in the Channel'//
*' Coolant Pressure(MPa)',f8.3,' Temperature(K)',f9.3/' Give Den
*ity(g/cm3)',f10.7/' Average Density',f10.7/
*' Wall Temperature(K)',f9.3/
*' Clad Temperature(K)',f9.3/
* Fuel Temperature(K)',f9.3)
Tcrit=Tmelt(PUC)
write(8,384) PUC,Tcrit
format(//' Mol Fraction of UC in UC-ZrC mix',f7.5,' Melting Temper
ature(K)',f10.2)
dh=coutlet-hinlet
dq=echannel/flow
dkin=0.5*(ve(npu)**2-ve(1)**2)
rel=dkin/dq
bal=(dh+dkin)/dq
write(8,987) dq,dh,dkin,rel,bal
format(//' HEAT BALANCE FOR THE CHANNEL'//
* 'dQ: heat to coolant (joule/kg)',e14.5/'dH: change of enthalpy
l(joule/kg)',e14.5/'dKin change kinetic energy(joule/kg)',e14.5/
2' relative dKin/dQ',f10.6/' Balance (dH+dKin)/dQ',f10.7)
c return
c
摩擦因数对单相流

c function fri(Re,ru)
c where Re is the Reynold's number and ru=e/d (rugosity)
c Colebrook-White correlation, page 115 ANS book about Gas Cooled Rs.
if(Re.le.2000.) then
fri=16./Re
else
fri=0.001375*(1.+(20000.*ru+1000000./Re)*0.33333333)
endif
return
c

c calculate drho/dp
function drdp(pe, te, der)
    p = pe
    t = te
    call phe(h, p, t, rho, vis, cp, pr, a, k, x, 0)
    pl = p
    rho1 = rho
    p = der * p
    call phe(h, p, t, rho, vis, cp, pr, a, k, x, 0)
    drdp = (rho1 - rho) / (pl - p)
    return
end

calculate drho/dt

function drdt(pe, te, der)
    p = pe
    t = te
    call phe(h, p, t, rho, vis, cp, pr, a, k, x, 0)
    tl = t
    rhol = rho
    t = der * t
    call phe(h, p, t, rho, vis, cp, pr, a, k, x, 0)
    drdt = (rhol - rho) / (tl - t)
    return
end

function Fu to solve in order to find t outlet node

function Fu(pi, ti, pe, te, pon, vi)
    t = ti
    p = pi
    call phe(h, p, t, rho, vis, cp, pr, a, k, x, 0)
    hi = h
    rhoi = rho
    t = te
    p = pe
    call phe(h, p, t, rho, vis, cp, pr, a, k, x, 0)
    Fu = h - hi - pon - 0.5 * vi ** 2 * (1. - (rhoi / rho) ** 2)
    return
end

c function Gu to solve in order to find p outlet node

function Gu (po, to, pi, ti, xi, g)
    common /fGu/ ifri, der, pf, ar, d, ru, dz
    c evaluate everything at outlet p, t
    p = po
t = to
call phe(h, p, t, rho, vis, cp, pr, a, k, x, 0)
d1 = drdp(po, to, der)
d2 = drdt(po, to, der)
f1 = 1. - d1 * (g / rho) ** 2
f2 = 0.5 * f1 * pf * g * g / (rho * ar)
flo = f2 / f1
f2o = f3 / f1
c evaluate everything at inlet pi, ti
p = pi
t = ti
call phe(h, p, t, rho, vis, cp, pr, a, k, x, 0)
d1 = drdp(pi, ti, der)
d2 = drdt(pi, ti, der)
f1 = 1. - d1 * (g / rho) ** 2
\[ f_3 = -d_2 \cdot (g/\rho)^{**2} \]
\[ \text{Re} = d \cdot g/\text{vis} \]
\[ f = 0 \]
\[ \text{if (ifri.eq.1)} f = \text{fri(Re,ru)} \]
\[ f_2 = 0.5 \cdot f \cdot P_f \cdot g \cdot g/(\rho \cdot \text{ar}) \]
\[ f_{li} = f_2/f_1 \]
\[ f_{2i} = f_3/f_1 \]
\[ f_{la} = (f_{li} + x_i \cdot f_{lo})/(1. + x_i) \]
\[ f_{2a} = (f_{2i} + x_i \cdot f_{2o})/(1. + x_i) \]
\[ \text{Gu} = \rho_0 - \rho_i + f_{la} \cdot dz + f_{2a} \cdot (t_0 - t_i) \]
\[ \text{return} \]
\[ \text{end} \]

c Nussel Number for one Phase Flow

c function RNu(Re,Pr,Tr,Zr)
c Where Re and Pr and Reynolds and Prandt numbers evaluated at bulk conditions
c Tr: Twall/Tbulk and Zr=z/D. Correlation Mc Eilgot page 93 ANS book about
c gas cooled reactors. The correlation is not applicable for Zr<=5., for
c this value of Zr we use the value of Nu for Zr=5.
\[ \text{if(Zr.lt.5.) Zr=5.} \]
\[ \text{RNu} = 0.021 \cdot \text{Re}^{**0.8} \cdot \text{Pr}^{**0.4} \cdot \text{Tr}^{*(-0.5)} \cdot (1.+Zr^{*(-0.7)}) \]
\[ \text{return} \]
end

c Function to solve in order to find wall temperature

c function Fq(rjq, Zr,Rei,Pri,Rki,Tfa,Tr,Tw)
RNus=RNu(Rei,Pri,Tr,Zr)
hco=RNus*Rki
Fq=rjq-hco*(Tw-Tfa)
\[ \text{return} \]
end

c Function: Thermal Conductivity of UC
c Source: Book El-Wakil

c Function RkUC(Te)
T(K) RkUC (watt/cmK)
Dimension T(20),Rk(20)
np=14
Data (T(i),i=1,14)/366.5 ,422.0 ,477.6 ,533.2 ,588.7, 644.2, 
*699.7 ,755.2 ,810.8, 922.0, 1033.1, 1144.3, 1255.4, 1366.5/
Data (Rk(i),i=1,14)/0.2557, 0.2435, 0.2333, 0.2254, 0.2193,
*0.2145, 0.2110, 0.2081, 0.2062, 0.2046, 0.2036, 0.2025,
*0.2020, 0.2003/
call Inter(T,Rk,14,Te,Cond)
RkUC=Cond
Return
End

c Function: Thermal Conductivity of ZrC
c Source: Book Bussard-DeLauer

c Function RkZrC(Te)
T(K) RkZrC(watt/cmK)
RkZrC=0.2077
Return
End

c Function: Thermal Conductivity of Graphite
c Source: Book Bussard-DeLauer

c Function RkGraf(Te)
T(K) RkGraf (watt/cmK)
Dimension Tp(20),Rc(20)
np=12
Function: Melting Temperature of Uc-ZrC mix
Source: Book busaard-DeLauer

Function Tmelt(PUC)

Tmelt(K), PUC mol fraction of Uc in UC-ZrC mix
Dimension xmol(20), T(20)
np=6
Data (xmol(i),i=1,6) / 0.0, 0.2, 0.4, 0.6, 0.8, 1.0/
Data (t(i),i=1,6) / 3758., 3594., 3437., 3250., 3022., 2687. /
call Inter(xmol,T,np,PUC,Tm)
Tmelt=Tm
Return
End

c Properties of He

Thermodynamic and Transport Properties of Helium
from Appendix B, page 405, Thermal and Flow Design of Helium-Cooled
cp=5193.
R=2077.22
x=1.

go to 10 if iflag=1 (ie input is p,h)

if(iflag.ne.0) go to 10
rho=p/(R*t+p*b(t))
h=cp*t+(b(t)-t*c(t))*p
z=1.+p*b(t)/(R*t)
a=z*sqrt(1.666*R*t)
vis=3.953e-7*t**0.687
rk=2.774e-3*t**0.701
pr=0.740*t**(-0.014)
return
10 continue

go to 10 if iflag=1 (ie input is p,h)

if(iflag.ne.0) go to 10
rho=p/(R*t+p*b(t))
h=cp*t+(b(t)-t*c(t))*p
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a=z*sqrt(1.666*R*t)
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rk=2.774e-3*t**0.701
pr=0.740*t**(-0.014)
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if(iflag.ne.0) go to 10
rho=p/(R*t+p*b(t))
h=cp*t+(b(t)-t*c(t))*p
z=1.+p*b(t)/(R*t)
a=z*sqrt(1.666*R*t)
vis=3.953e-7*t**0.687
rk=2.774e-3*t**0.701
pr=0.740*t**(-0.014)
return
10 continue

go to 10 if iflag=1 (ie input is p,h)

if(iflag.ne.0) go to 10
rho=p/(R*t+p*b(t))
h=cp*t+(b(t)-t*c(t))*p
z=1.+p*b(t)/(R*t)
a=z*sqrt(1.666*R*t)
vis=3.953e-7*t**0.687
rk=2.774e-3*t**0.701
pr=0.740*t**(-0.014)
return
10 continue

go to 10 if iflag=1 (ie input is p,h)

if(iflag.ne.0) go to 10
rho=p/(R*t+p*b(t))
h=cp*t+(b(t)-t*c(t))*p
z=1.+p*b(t)/(R*t)
a=z*sqrt(1.666*R*t)
vis=3.953e-7*t**0.687
rk=2.774e-3*t**0.701
pr=0.740*t**(-0.014)
return
10 continue

go to 10 if iflag=1 (ie input is p,h)

if(iflag.ne.0) go to 10
rho=p/(R*t+p*b(t))
h=cp*t+(b(t)-t*c(t))*p
z=1.+p*b(t)/(R*t)
a=z*sqrt(1.666*R*t)
vis=3.953e-7*t**0.687
rk=2.774e-3*t**0.701
pr=0.740*t**(-0.014)
return
10 continue

go to 10 if iflag=1 (ie input is p,h)

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z=1.+p*b(t)/(R*t)
a=z*sqrt(1.666*R*t)
vis=3.953e-7*t**0.687
rk=2.774e-3*t**0.701
pr=0.740*t**(-0.014)
return
10 continue

go to 10 if iflag=1 (ie input is p,h)

if(iflag.ne.0) go to 10
rho=p/(R*t+p*b(t))
h=cp*t+(b(t)-t*c(t))*p
z=1.+p*b(t)/(R*t)
a=z*sqrt(1.666*R*t)
vis=3.953e-7*t**0.687
rk=2.774e-3*t**0.701
pr=0.740*t**(-0.014)
return
10 continue

write(6,50) h,p
50 format(/'Program stop at phe(1). Unable to find T for input h=',&
*el4.5,' and p=',el4.5//)
stop
ta=0.5*(t1+t2)
en=ent(h,p,ta)
test=abs(en)/h
if(test.it.eps)go to 442
it=it+1
call bisect(tl,t2,ta,en1,en2,ena,iwa)
if(it.le.nit.and.iwa.eq.0) go to 452
continue
if(it.gt.nit.or.iwa.eq.1)
write(6,51) h,p
format(//'Program stop at phe(2). Unable to find T for input h=',
*e14.5,' and p=',e14.5//)
if(it.gt.nit.or.iwa.eq.1) stop
i=it
end

c(c(t) used to compute enthalpy)
c
function c(t)
data c2,c3,c4,c5
/9.528079e-4,3.420680e-2,
*2.739470e-3,9.409120e-4/
c=c2*c3/(1.-c3*t)**2-c4*c5/(1.+c5*t)**2
return
end
function ent(h,p,Te)
ent=h-5193.*Te-(b(Te)-Te*c(Te))*p
return
end

***** DESIGN STRENGTH SUBROUTINE *****
cCalculation of the Stress that Astar alloy can stand
c subroutine from Alkasys
tt(K) Temperature, n=1 or 2 (it does not matter for sigpv)
c fpl (years) power life, itma Max number iterations
c ipr 1,0 Ok, no Ok pressure vessel
c sigpv(MPa) max stress of ASTAR alloy for pressure vessel
c
subroutine desstr(tt,n,fpl,sigpv,sigrod, itma,ipr)
real tt,nr,tmat,fpl,sigpv,sigrod,rho
data tmat/9100.
integer ll, n
ipr=1
if(tt.ne.0.) then
if (tt.gt.tmat) then
rho=.604
b=67375.0
c=3.548E9
nr=1943
v=.25875
else
rho=.31
b=72614.8
c=1.995E10
nr=3768
v=.03652
endif
doi=1,n
if (ll.eq.1) then
thet=fpl*8766.139
else
thet=fpl*8766.139/2.
endif
sigma=1000
\[ \theta = \frac{1}{c} \exp \left( \frac{b - nr \log(\sigma) - v \sigma}{tt} \right) \]

\[
\text{ite} = 0
\]

\[
dowhile \left( \frac{\text{abs}((\theta - \text{thet})/\text{thet})}{\text{thet}} \right) > 0.001 \\
dtds = -\frac{\theta (nr + v \sigma)}{\sigma/\text{tt}} \\
\sigma = \sigma + \frac{(\text{thet} - \theta)}{\text{dtds}} \\
\text{ite} = \text{ite} + 1
\]

\[
\text{if} (\text{ite} > \text{itma}) \text{ ipr} = 0 \\
\text{if} (\text{ite} > \text{itma}) \text{return}
\]

\[
\text{if} (\sigma < 100) \sigma = 100
\]

\[
theta = \frac{1}{c} \exp \left( \frac{b - nr \log(\sigma) - v \sigma}{tt} \right)
\]

\[
\text{enddo}
\]

\[
\text{if} (\text{ll} = 1) \text{ then} \\
\text{sigpv} = \sigma * 6.894757e-3
\]

\[
\text{else} \\
\text{sigrod} = \sigma * 6.894757e-3
\]

\[
\text{endif}
\]

\[
\text{endif}
\]

\[
\text{return}
\]

\[
\text{end}
\]

\[
! \text{SUBROUTINE DESSTR}
\]

\[
\text{Function to compute thickness neutron shielding}
\]

\[
\text{Function Shieldn(fluin,fluout,ish,tw,igam)}
\]

\[
\text{common} / \text{cross} / \text{AA,BB,signe,ishin,ishig}
\]

\[
\text{Fluin,fluout, fast fluxes in/out; ish=1, LiH+SS}
\]

\[
\text{ish=2, B4C; tw(cm) gamma shielding (Tungstene)(if igam.ne.0)}
\]

\[
\text{data remLi,remH,remFe,remW,remBC} \\
* /1.01,1.00,1.98,3.13,5.1/ \\
\text{removal cross section for fast neutrons of Li,H,Fe,W,B4C}
\]

\[
\text{data Av,roLiH,roW,roBC,roFe,roLiss,ALiH,AFE,ABC,AW} \\
* /0.602202,0.82,19.3,2.52,7.874,1.024,7.95,55.85,55.26,183.85/ \\
\text{sigW=remW*Av*roW/AW}
\]

\[
\text{ishin=1} \text{ go to(10,20)}, \text{ish}
\]

\[
xLiH=(\text{roLiss}-\text{roFe})/(\text{roLiH}-\text{roFe})
\]

\[
xFe=1.-xLiH
\]

\[
\text{sigre=(remLi+remH)*Av*roLiH*xLiH/ALiH+remFe*Av*roFe*xFe/AFE}
\]

\[
\text{go to 30}
\]

\[
\text{sigre=remBC*Av*roBC/ABC}
\]

\[
\text{aa=aog(fluin/fluout)/sigre}
\]

\[
\text{if(aa.le.0.) ishin=0}
\]

\[
\text{bb=.sigW/sigre}
\]

\[
\text{signe=sigre}
\]

\[
\text{Shieldn=aa-bb*tw}
\]

\[
\text{return}
\]

\[
\text{end}
\]

\[
\text{Subroutine to calculate Gamma source}
\]

\[
\text{Subroutine Gamso(Sn,aof,sof,sogam,Pr5)}
\]

\[
\text{Input: Sn(1/s): neutron production; sof=S/F Elements}
\]

\[
\text{aof=A/F in U235 for sof}
\]

\[
\text{sogam(1): Gamma source between "0" and 1 Mev}
\]

\[
(2): 1 \text{ and 2}
\]

\[
(3): 2 \text{ and 3}
\]

\[
(4): 3 \text{ and 5}
\]

\[
(5): 5 \text{ and 7}
\]

\[
(6): 7 \text{ and 9}
\]

\[
(7): > \text{ around 9 Mev}
\]

\[
\text{Dimension Sogam(7),Pf(7),Fp(7),G(Ni(7),GH(7),GZr(7),GBe(7),*GU(7),GFe(7),GCr(7),Pr5(7))}
\]
PF: Prompt Fission Gammas; FP: Fission Products Gammas (Both, Per Fiss)

G Ni to GCr: Captures Gammas (per Event) for indicated Elements Ni.,..Cr

Data(Pf(i),i=1,7)/3.1,2.11,.73,.26,.0428,0.,0./
Data(Fp(i),i=1,7)/9.03,1.137,4.0.,0.,0.,0./
Data(GNi(i),i=1,7)/.84,40.,23,.23,34,.62,0./
Data(GH(i),i=1,7)/.0.,1.,0.,0.,0.,0.,0./
Data(GZr(i),i=1,7)/0.,0.,0.,.13.,35.,.04,0./
Data(GBe(i),i=1,7)/0.,0.,0.,.54,.73,.0.,0./
Data(GFe(i),i=1,7)/.54,1.78,91.,34.,0.,0.041/
Data(GCr(i),i=1,7)/.75,.60,.27,.23,35,.38,.02/
Data(FNi2,FH2,FZr2,FBe2,FU82,FFe2,FCr2
* /9.03,1.137,.4,0.,0.,0.,0./
Data(GNi0,FH0,FZr0,FBe0,FU80,FFe0,FCr0
* /0.,0.,.076,.087,.069,0.,0./
Data Rnu/2.44/

See: Total number of Absorptions = Sn(Total production)
F: total number of fission
A5: Total number of absorptions (capture + fission) in U235
C5: total number of captures in U235
Ct: 

F=Sn/Rnu
A5=F* sof
C5=A5-F
Ct=Sn-F

CHi=(FHi0+(FH2-FH0)*sof/2.)*Ct
CH=(FH0+(FH2-FH0)*sof/2.)*Ct
CZr=(FZr0+(FZr2-FZr0)*sof/2.)*Ct
CBe=(FBe0+(FBe2-FBe0)*sof/2.)*Ct
CU8=(FU80+(FU82-FU80)*sof/2.)*Ct
CFe=(FFE0+(FFE2-FFE0)*sof/2.)*Ct
CCr=(FCr0+(FCr2-FCr0)*sof/2.)*Ct
Do 10 i=1,7
Gam5=F*(Pf(i)+Fp(i))+C5*GU(i)
Sogam(i)=Gam5+CU8*GU(i)+CNi*GNi(i)+CH*GH(i)
* +CZr*GZr(i)+CBe*GBe(i)+CFe*GFe(i)+CCr*GCr(i)
Pr5(i)=100.*Gam5/Sogam(i)
10 continue
return
end

Subroutine Shieldga(Sogam,Dose,Dosea,Dosew,tiempo,tgam,igam,
* ishn,iten)
Common /CROSS/ AA, BBB, signe, ishn, ishig

Shieldga: Computes gamma shielding
Sogam(i),i=1,7 Gamma Source (photons/sec); Dose(rad): Integrated
Dose at load area; Dosew(rad): Dose without the shielding
Dose: dose for tgam
Igam: flag if =1 problems with iterations
Tgam(cm): Thickness of Tungsten
Ten(cm): thickness of n shielding, ishn=1, LiH, ishn=2, B4C
Iten/0,1/ /tenant iterated by this subroutine/
Tgam: iterated, if necessary, to have Dose= input
Index(1): Gamma Processes between "0" and 1 Mev

(2): 1 and 2
(3): 2 and 3
(4): 3 and 5
(5): 5 and 7
(6): 7 and 9
(7): around 9 Mev

common /Gamsh/ coBe, coTa, coC, coZr, coU, coH, coNi, coFe, coCr, coTi, coSi
*, dist, Req, shg(7), shgnb(7), Zeq(7), Dosewg(7), Doseg(7), itmag, epsg
*aten,Dosen,Dosen/q7

dimension Sogam(7),Be(7),GW(7),Gc(7),GZr(7),GU(7),GH(7),GFe(7),
*CTi(7),GSi(7),b(4,7),a3(4,7).a4(4,7),zb(4),a(4),a1(4),a2(4),rh(7)
*ega(7),sign(7),An(7),Ain(7),A2n(7)

data (GBe(i),i=1,7) /0.773,0.459,0.394,0.266,0.211,0.180,0.161/
data (GW(i),i=1,7) /1.125,0.492,0.437,0.402,0.418,0.438,0.465/
data (GC(i),i=1,7) /0.87,0.518,0.444,0.304,0.245,0.213,0.194/
data (GZr(i),i=1,7) /0.0851,0.0467,0.0414,0.0349,0.0344,0.0349,0.0359/
data (GU(i),i=1,7) /1.176,0.548,0.484,0.44,0.455,0.479,0.511/
data (GH(i),i=1,7) /1.173,0.103,0.0876,0.0579,0.0446,0.0371,0.0321/
data (GFe(i),i=1,7) /0.0828,0.0485,0.0424,0.033,0.0304,0.0295,0.0294/
data (GTi(i),i=1,7) /0.0876,0.0518,0.0451,0.0338,0.0302,0.0285,0.0280/
data (GSi(i),i=1,7) /0.0869,0.0517,0.0447,0.0323,0.0277,0.0254,0.0243/

c GBE...GSi are the total mass attenuation coefficients(cm²/g)
c for the 7 gamma groups. Fe(z=26),Ni(z=28) and Cr(z=24)
can be lumped
together; Ta(z=73) lumped with W(z=74);GZr(z=40) is indeed GMo(z=42)
c and GTi(z=22) is indeed GCa(z=20)
c Also Li(Z=3) and B(z=5) are lumped with Be(z=4)

data (b(1,j),j=1,7)/8.8,5.5,4.5,3.8,3.1,2.3,2.25/
data (b(2,j),j=1,7)/10.8,5.5,3.75,2.9,2.35,2.0/
data (b(3,j),j=1,7)/3.3,2.9,2.7,2.05,1.2,7,6/
data (b(4,j),j=1,7)/1.65,2.45,2.15,1.65,0.96,8,5/

data (a3(1,j),j=1,7)/11.082,0.074,0.066,0.064,0.062,0.060/
data (a3(2,j),j=1,7)/0.948,0.0895,0.0788,0.075,0.0825,0.0833,0.095/
data (a3(3,j),j=1,7)/0.043,0.069,0.086,0.118,0.171,0.205,0.212/
data (a3(4,j),j=1,7)/0.032,0.045,0.097,0.123,0.175,0.204,0.214/

data (a4(1,j),j=1,7)/0.044,0.093,0.116,0.130,0.152,0.150,0.128/
data (a4(2,j),j=1,7)/0.012,0.04,0.07,0.082,0.075,0.0546,0.0116/
data (a4(3,j),j=1,7)/0.148,0.188,0.134,0.070,0.052,0.144/
data (a4(4,j),j=1,7)/0.296,0.178,0.103,0.064,0.059,0.067,0.08/

data (zb(i),i=1,4)/13.,26.,74.,82./

c b(i,j),a2(i,j) and a4(i,j) are build up parameters for groups j
c and atomic number Z=Zb(i)

data (rh(i),i=1,7)/4.5e+5,5.5e+5,7.e+5,8.e+5,8.5e+5,9.e+5,1.e+6/
c rh(i) Gamma Flux Mev/cm²sec that produces 1 Roentgen/hour

data (Ega(i),i=1,7)/0.5,1.5,2.5,4.6,8,10./
c ega(i) Mev Average Energy of gamma group i

data ABe,ATa,AW,AC,A2r,AU,AH,ANi,AFE,Ae,ACr,ATi,ASi,Av,Row
*9.0122,180.948,183.85,12.011,91.22,235.044,1.00797,58.71,55.847,
*51.996,47.90,28.086,.602202,19.3/
data ZBe,ZTa,ZW,2C,ZZr,ZU,ZH,ZNi,2Fe,2Cr,2Ti,2Si,pee,ZLi,2Bo
*/4 .73,74,6,40,92,1,28,26,24,22,14,3.141593,3,5 /

data roLiH,roBC,RSs,roLiS /0.82,2.92,7.874,1.024/
igam=1
ishg=1
xLiH=(roLiS-RoSS)/(roLiH-RoSS)
xSS=1-xLiH

c Attenuation*Build Up factor for N Shield(which also shield gammas)
c
do 101 j=1,7
go to(111,222),ishn
c ishn=1 LiH+SS
111 sig=roLiS*(xLiH*0.8732*GBe(j)+xLiH*0.1268*GH(j)+xSS*GFe(j))
\[ \text{sigZ} = \text{RoLiS} \times (\text{ZLi} \times \text{LiH} \times 0.8732 \times \text{GBe}(j) + 2\text{H} \times \text{LiH} \times 0.1268 \times \text{GH}(j) + 2\text{Fe} \times \text{SS} \times \text{GF} \times \text{e}(j)) \]

\[ \text{ZZ} = \text{sigZ} / \text{sig} \]

go to 333

c \text{ish} = 2 B4C

\[ \text{sigZ} = \text{RoBC} \times (0.7826 \times \text{GBe}(j) + 0.2174 \times \text{GC}(j)) \]

\[ \text{ZZ} = \text{sigZ} / \text{sig} \]

c ZZ is "equivalent Z for buildup factor"

\[ \text{do 444 } i = 1, 4 \]
\[ \text{a(i)} = \text{b(i, j)} \]
\[ \text{a1(i)} = \text{a3(i, j)} \]

\[ \text{a2(i)} = \text{a4(i, j)} \]

c interpolate in table as function of Z,

\[ \text{Call Inter(zb, a, 4, zz, am)} \]
\[ \text{Call Inter(zb, a1, 4, zz, all)} \]
\[ \text{Call Inter(zb, a2, 4, zz, all2)} \]

\[ \text{An(j)} = \text{am} \]
\[ \text{A1n(j)} = \text{all} \]
\[ \text{A2n(j)} = \text{al2} \]

\[ \text{sign(j)} = \text{sig} \]

continue

c end Calculation Atenuation/build up factor for n shield

c c Start Calculation Self Shielding in Reactor

c do 10 j = 1, 7

c do 20 i = 1, 4
\[ \text{a(i)} = \text{b(i, j)} \]
\[ \text{a1(i)} = \text{a3(i, j)} \]

\[ \text{a2(i)} = \text{a4(i, j)} \]

\[ \text{sig} = \text{coBe} \times \text{Abe} \times \text{Gbe}(j) + \text{coTa} \times \text{ATa} \times \text{GW}(j) + \text{coC} \times \text{AC} \times \text{GC}(j) + \text{coZr} \times \text{AZr} \times \text{GZr}(j) + \text{coU} \times \text{AU} \times \text{GU}(j) + \text{coFe} \times \text{AFe} \times \text{GFe}(j) + \text{coNi} \times \text{ANI} \times \text{GFe}(j) + \text{coTi} \times \text{ATi} \times \text{GTi}(j) + \text{coSi} \times \text{ASI} \times \text{GSi}(j) \]

\[ \text{sig} = \text{sig} / \text{Av} \]

\[ \text{ZZ} = \text{coBe} \times \text{Abe} \times \text{Gbe}(j) \times \text{ZBe} + \text{coTa} \times \text{ATa} \times \text{GW}(j) \times \text{ZTa} + \text{coC} \times \text{AC} \times \text{GC}(j) \times \text{ZC} + \text{coZr} \times \text{AZr} \times \text{GZr}(j) \times \text{ZZr} + \text{coU} \times \text{AU} \times \text{GU}(j) \times \text{ZU} + \text{coFe} \times \text{AFe} \times \text{GFe}(j) \times \text{ZFe} + \text{coNi} \times \text{ANI} \times \text{GFe}(j) \times \text{ZNi} + \text{coCr} \times \text{ACr} \times \text{GFe}(j) \times \text{ZCr} + \text{coTi} \times \text{ATi} \times \text{GTi}(j) \times \text{ZTi} + \text{coSi} \times \text{ASI} \times \text{GSi}(j) \times \text{ZSi} \]

\[ \text{ZZ} = \text{ZZ} / \text{Av} \]

\[ \text{zz} = \text{zz} / \text{sig} \]

\[ \text{Call Inter(zb, a, 4, zz, am)} \]
\[ \text{Call Inter(zb, a1, 4, zz, all)} \]
\[ \text{Call Inter(zb, a2, 4, zz, all2)} \]

\[ \text{Zeq(j)} = \text{zz} \]
\[ \text{bl} = 2 \times \text{sig} \times \text{Reg} \times (1 - \text{all}) \]
\[ \text{b2} = 2 \times \text{sig} \times \text{Reg} \times (1 + \text{al2}) \]

\[ \text{exp1} = 0. \]
\[ \text{exp2} = 0. \]

if (bl.lt.50.) \text{exp1} = \text{exp}(-bl)
if (b2.lt.50.) \text{exp2} = \text{exp}(-b2)

\[ \text{shgn(j)} = 3 \times \text{Am} \times (0.5 - (1 - \text{exp1} * (1 + bl) / bl**2)) / bl \times (1 - \text{Am}) \times (0.5 - (1 - \text{exp2} * (1 + b2) / b2**2)) / b2 \]

\[ \text{bb} = 2 \times \text{sig} \times \text{Reg} \]

\[ \text{expo} = 0. \]

if (bb.lt.50.) \text{expo} = \text{exp}(-bb)

\[ \text{shgnb(j)} = 3 \times (0.5 - (1 - \text{expo} * (1 + bb) / bb**2)) / bb \]

continue

c c End Calculation Self shielding

c c c Dosew and Dosew() are the doses without any shield(n or gamma)
c c Dosen and Dose(n) are the doses without W(gamma shield) but inclu-
c c ding the shielding effects of the neutron shield(either input or itera-
c ted
time=tiempo/3600.
Dosew=0.
Dosen=0.
if(item.eq.1) ten=AA
if(item.eq.1.and.ishin.eq.0) ten=0.
do 30 i=1,7
tsn=Sign(i)*ten
Shin=exp(-tsn)*(An(i)*exp(-tsn*Aln(i))+(1.-An(i))*exp(-tsn*A2n(i) -
  )
Dosew(i)=time*Soam(i)*shg(i)*Ega(i)/(4.*pee*dist**2*rh(i))
Dosen(i)=Shin*Dosew(i)
Dosew=Dosew+Dosew(i)
Dosen=Dosen+Dosen(i)
if(Dosen.le.Dose) ishig=0
if(ishig.eq.0) tgam=0.
if(ishig.eq.0) return
30
c Return if there is no need for gamma shield (thick W=0.)
c
t1=0.
Dose1=Dosen
f1=Dose1-Dose
c
Starts iteration on tgam:
c First look for
t2 such that Dose(t2) <Dose
c
it=0
sig=GW(i)*RoW
51
t2=alog(Dosew(i)/Dose)/sig
dose2=0.
do 40 i=1,7
am=b(3,i)
al1=a3(3,i)
al2=a4(3,i)
sig=GW(i)*RoW
BFA=am*exp(-all*sig*t2)+(1.-am)*exp(-al2*sig*t2)
dose2=dose2+Dosew(i)*exp(-sig*t2)*BFA
if(dose2.1t.dose) go to 50
t2=1.01*t2
it=it+1
if(it.le.itmag) go to 51
igm=0
write(8,*)' Problem with Calculation of Gamma Shielding'
50
c continue
f2=Dose2-Dose
if(igm.eq.0) return
it=0
61
tgam=0.5*(t1+t2)
dosea=0.
do 41 i=1,7
am=b(3,i)
al1=a3(3,i)
al2=a4(3,i)
sig=GW(i)*RoW
BFA=am*exp(-all*sig*tgam)+(1.-am)*exp(-al2*sig*tgam)
40
c recompute neutron shielding(ten) because W also shield neutrons
c see: if ten<0. program set ten to 0. (ie no need of n shielding
c because W is enough also if ishin=0 (fluin lt prescribed flout)
c
if(item.eq.1) ten=AA-BBB*tgam
if(item.eq.0) ten=0.
if(item.eq.1.and.ishin.eq.0) ten=0.
tsn=Sign(i)*ten
Shin=exp(-tsn)*(An(i)*exp(-tsn*Aln(i))+(1.-An(i))*exp(-tsn*A2n(i))
Page A-47
Doseg(i) = Dosewg(i) * exp(-sig*tgam) * BFA * Shin

dosea = dosea + Doseg(i)

recalculate n shielding, because it might be smaller than input max flu-

cence

eco = (ten + BBB * tgam) * signe
aten = exp(-eco)
fa = Dosea - Dose
rel = abs(dosea - dose) / dose
if (rel <= epsg) go to 60

call Bisect(t1, t2, tgam, f1, f2, fa, iwa)
it = it + 1

if (it <= itmag .and. iwa .ne. l) go to 61

igam = 0

write(8, *) ' Problems with calculation of Gamma Shielding'

continue

return
end

Compute sizes for input Energy and S/F

Subroutine Size(das, dop, E, sof, dl, d2)

common /Soze/ its, epss

c

common /MaBaSi/ R, H, ishape

ri = 1.
it = 0

x1 = das * (1. + 0.01 / ri)
if (ishape.eq.2) R = x1
if (ishape.eq.3) H = x1
e1 = Balance(ibu, sof) - E
if (el.gt.0.) go to 20

ri = ri + 1.
it = it + 1
if (it.gt.its) go to 100

x2 = dop
if (ishape.eq.2) R = x2
if (ishape.eq.3) H = x2
e2 = Balance(ibu, sof) - e

it = 0

xav = 0.5 * (x1 + x2)
if (ishape.eq.2) R = xav
if (ishape.eq.3) H = xav
Ea = Balance(ibu, sof) - e
test = abs(Ea) / E
if (test .le. epss) go to 50

call bisect(x1, x2, xav, E1, E2, Ea, iwa)
it = it + 1
if (iwa.eq.1) go to 100
if (it.gt.its) go to 50

if (test .le. epss) go to 50

dl = xav

c

c right side limit

c

x1 = dop
if (ishape.eq.2) R = x1
if (ishape.eq.3) H = x1
E1 = Balance(ibu, sof) - e

it = 0

x2 = x1 * (1. + 0.10) ** (it + 1)
if (ishape.eq.2) R = x2
if (ishape.eq.3) H = x2
e2 = Balance(ibu, sof) - e
if(e2.gt.0.) go to 31
it=it+1
if(it.gt.its) go to 100
go to 41
it=0
xav=0.5*(x1+x2)
if(ishape.eq.2) R=xav
if(ishape.eq.3) H=xav
Ea=Balance(ibu,sof)-e
test=abs(Ea)/E
if(test.le.epss) go to 51
call bisect(x1,x2,xav,E1,E2,Ea,iwa)
it=it+1
if(it.gt.its.or.iwa.eq.1) go to 100
go to 36
d2=xav
return
write(8,101) it
format(//' Program stop at subroutine Size'/' iterations=',i10/)
stop
dend
APPENDIX B. LISTING OF CODE NEPPIN

c program to estimate preliminary design of fuel pin, liquid Li reactor
c for space applications.

c Assumptions
1) fuel cell: liquid Li(coolant), Astar alloy clad, W liner, He gap and
   UN pellet.
2) Astar pressure vessel, OBe reflector and B4C(90%B10) drums in
   reflector.
3) Gamma Shield: W; Neutron Shield: B4C or LiH in SS matrix
4) Data base parameters: Enrichment and pitch/drod for drod=6.4mm
   character*80 tit, aldam
   dimension aux(5), bux(5), wbeth(8), th(8), pfr(3, 3), U5md(5), isha(5),
   *pfrm(3, 3), Sogam(7), PrU(7), Emin(5, 5), Ras(5, 5), Has(5, 5), Rop(5, 5)
   *, Hop(5, 5), enri(5), podi(5), BUsi(5), Rd(5), Hd(5), dpvd(5), delp(5),
   *podip(3), enriB(3)
   common /Soze/ its, epss
   common /MaBaSi/ R, H, ishape
   common /c5e, c8e, c9e, p9, cfpe, ftin
   U5, U8, Pu9, FP concentrations at EOL (integrated fluence=ftin)
c all from subrou bupo. Per unit input volume
   common /Bala/ Ereq, relr, relal, dkeol, dkstr, BU, Vcor,
   *U5m, dbu, dbk, rkbare, dcr, sigma, pin, dpv, dpvd, tduco,
   *eps, ltest
   common /cont/ Rad, dvp, drr, enr, pod, refec, ncr, dksu, dkest, relar, dcd
   common/thermo/ tit, nnodo, ifri, npin, pint, tin, toutl, deltapa
   *, Pow, rjs, flowt, podt, duc, Rc
   *, Hact, Pfacr, Daxi, fact, iprth, iopth, ichoose
   *, Pfacaz, iboun, nrod, nbu, nrodbu, hod
   common /Conce/ coBe, coTa, coU5, coUg, coLi, coW, coRe, coHe, coN, coO
   common /Gams/ *dist, Req, shg(7), shg(7), Zeq(7), Dosewg(7), Doseg(7), itmag, epsg
   *, aten, Dosen, Doseg(7)
   Common /CROSS/ AU, BBU, signe, ishin, ishig

Tsa(ps) = 8143.0 / (8.0 - alog10(ps/0.133222))
Psa(ts) = 0.133222 * 10.0**((0.0 - 8143.0)/ts)

Tsa(ps) is saturation temperature of Li(in K) as function of ps(KPa)
Psa(ts) is " pressure of Li(in KPa)" of ts(K)

open(unit=7, file='neppinl.i', status='old')
open(unit=8, file='neppinl.out', status='unknown')

TLim=453.7
read(7, 11) tit
format(a80)
read(7,11) aldum
read(7,20) itest,ndt,itmax,icont,iboun,input
read(7,11) aldum
read(7,10) Pow,D,BU,eps,der
read(7,11) aldum
read(7,10) drr,dra1,dra2,tduc
read(7,11) aldum
read(7,10) dkstr,dkeol,dksu
dkest=dkestr
read(7,11) aldum
read(7,10) pin,tin,pHe,THe,tempv
read(7,11) aldum
if(iboun.eq.1) read(7,10) flowt
if(iboun.eq.2) read(7,10) toutl
if(icont.eq.0) go to 2379
read(7,11) aldum
read(7,20) ncr,nnode,npin,ishape,nrodbu
read(7,11) aldum
read(7,20) iopth
read(7,11) aldum
read(7,20) ifri,iprth,iouth
read(7,11) aldum
read(7,20) iwre,ishn,ichoode
read(7,11) aldum
read(7,10) fact,Ripple,hod,dcd
read(7,11) aldum
read(7,10) delpr
read(7,11) aldum
read(7,10) fastf,Dose,zload,rload
read(7,11) aldum
if(ishape.eq.1) go to 2379
if(ishape.eq.2) read(7,10) R
if(ishape.eq.3) read(7,10) H

! check if T inlet>T melt Li
! 2379 continue
if(tin.le.TLim) write(8,17) tin,TLim
17 format('/ Inlet Temperatures is(K)’,f8.2,’ smaller than’/
      * ’ Melting Temperature of Li(K),’f8.2/
      * ’ PROGRAM STOP’)
if(tin.le.TLim) stop

! compute flowt(Kg/s) or Toutlet according to option iboun
pint=pin
! go to(111,222),iboun
111 call pli(hin,pin,tin,rhoi,vis,cp,pr,k,x,0)
hout=hin+Pow*fact*1.e+6/flowt
call pli(hout,pin,toutl,rhoo,vis,cp,pr,k,x,1)
go to 333
222 call pli(hin,pin,tin,rhoi,vis,cp,pr,k,x,0)
call pli(hout,pin,toutl,rhoo,vis,cp,pr,k,x,0)
flowt=Pow*fact*1.e+6/(hout-hin)
continue
roLi=0.5*(rhoi+rhoo)/1000.

! check degree of subcooling at outlet
Ts=Tsa(pin*1000.)
if(toutl.ge.Ts) write(8,245) pin,Ts,toutl
245 format('// Your reactor is underpressurized’/
      * ’ At inlet pressure(MPa),’f8.3,’ Li boils at K’,f10.2/
      * ’ smaller than outlet temperature’,f10.2/
      * ’ PROGRAM STOP’)
if(toutl.ge.Ts) stop
if(tempv.lt.0) tempv=toutl

c compute max stress (sigma) for pressure vessel

call desstr(tempv,1,D,sigma,sigrod,itmax,ipresv)

c eps0=eps
eps1=eps
eps2=eps
dero=der
Daxi=5.
tduco=tduc

Ereq=Pow*D*365.25

c Core life in sec,multiply by 1 julian year=31,557,600. sec
tiempo=D*3.15576e+7

INPUT DESCRIPTION FOR REALS

Pow(Mw): power;  D(years): core life; BU(at%): percent U235 atoms
burned;
Inlet flow conditions:
pin, tin(MPa,K)) pressure and temperature of the inlet coolant(fuel el
pHe, The(MPa,K) initial" "" of He gap in rod.
dr,rdr1, rdr2 (cm) thickness of Be reflector: radial, top-bottom axial
dkstr(%): reactivity structural materials (estimated)
dkeol(%): " at end of life(desired)
dksu (%): desired subcritical reactivity required at BOL with drums in
eps: tolerance for iterations (like energy)
der=1.01 (compute derivatives)
fact: fraction fissiion energy/thermal
flowr(kg/s) total coolant flow(applicable if iboun=1)
Daxi(cm): extrapolation length axial cos power distribution
Ripple: Relative amplitude of power distribution as function of angle
at R=Rcore
tduc(mm): thickness of the duct of the bundle of fuel elements
hod: led of the spacing wire of the fuel rod/rod diameter
dcd(cm): thickness B4C sheet of control drums
tempv(K): Temperature of Pressure Vessel; if <0. program chooses tout
delpr(Pa): max delta pressure for core
toutl(K): outlet temperature of coolant(applicable if iboun=2)
fastf(i/cm2): fast fluence (during time D) at payload area
zload(cm): axial distance from the base of reactor to payload plane
rload(cm): radius of load area
Dose(Rad): integrated gamma dose (during time D) required for payload
ddt(cm): delta r and delta h for test curve Eavailable=f(R) or f(H)

format(7e10.0)
imax=itmax
imaxt=itmax
itmag=itmax
its=itmax

INPUT DESCRIPTION FOR INTEGERS

imax: max number iterations for reactor search
c ncr: number of control drums
c ishape=1,2,3/ Shape: ideal (minimum volume), R input, H input
c nrodbu: number of fuel rods per bundle

c iwrite=1 write iterations

c itest=0/1 no, yes run and print test to know your options

c nnodo number of nodes in coolant channel

c ifri=0,1/ no, yes friction factors;
iditus=0,1/ no, yes Dittus Correlation

c npin: number of nodes inside fuel pin

c iprth=0,1 no, yes print details cooling channel

c iopth=1 3-D uniform power density assumed
=2 2-D (r, theta) uniform power density assumed
=3 Uniform Fuel load/uniform coolant flow assumed
=4 Uniform Fuel load/Coolant flow proportional to power density

c iouth=1 Thermodynamic profile at Max power density channel is printed

c iouth=2 " " Min " " " " " " "
c iouth=3 " " Max and Min " " " " " "
c iboun=1 Input Coolant Flow

c iboun=2 Input Outlet Temperature of Coolant

c ishn=1,2 Choose Neutron Shielding LiH+SS/ B4C

c icont=0,1/ no, yes continue calculation after test

c ndt: number of intervals between Xas and Xop for test curve Energy=f(R)

c or f(H) input is the number of points in tabulation

c ichoose=0,1 no, yes correction, by program, of incompatible request

c ichooode=1,2,3,4,5/ choose design with p/d=1,1.2,1.3,1.4,1.5

c if different from /1,2,3,4,5/ program choose one for you

c c c

20
format(14i5)

if(drr.gt.40..or.dral.gt.40..or.dra2.gt.40.)
*write(8,31) drr,dral,dra2
31
format(//' YOUR VALUE OF REFLECTOR THICKNESS (CM) ',3f8.2/
* ' ARE TOO LARGE FOR A REASONABLE EXTRAPOLATION'/
* ' OF THE DATA BASE'/
* ' PROGRAM STOPS '/)

if(drr.gt.40..or.dral.gt.40..or.dra2.gt.40.) stop

data dc,dl,dhe,dpin,drod,dref/0.635,0.127,0.025,4.826,6.4,25./
c dc,dl,dhe(mm) cladding, liner and He gap thickness

data pin,drod pin rod diameters

data TLim(K) melting temperature of Li

data dref(cm): thickness of Be reflector (for data base)

d clad=0.1*dc

data pee,Av,ABe,xop/3.1415926,0.602202,9.01219,0.541315/
xop: optimum shape for cylindrical reactors; Av: Avogadro's number

data ABe: Be at-weight; pisq3=pi*sqrt(3)

data AU5,AU8,APu,AN,AHe/235.044,238.0508,239.0522,14.000307,4.0026/
data ATa,ARe5,ARe7,ALi6,ALi7/180.9480,184.9530,186.9560,6.01513,
7.01601/
data AW,ARe,AHf,AO/183.85,186.2,178.49,15.9994/
c atomic weights

c A+ chemical symbol+1 digit for isotopes

data xLi6,xLi7,xRe5,xRe7/0.0742,0.9258,.3707,.6293/

Page B-4
data xW2, xW3, xW4, xW6/0.2655, 0.1440, 0.3064, 0.2841/
catomic fractions
cx+chemical symbol+digit for isotope
c0.37% of N15, 0.0132% of Ta180 and 0.14% of W180 ignored.
data roun, row, roAst, roobe/12.172, 18.6, 16.84, 3.01/
cdensities (g/cm3)
croun: UN; row: W; roAst: Astar alloy
croobe: OBe
cAverage densities of the fuel rod
c
rrod=0.1*drod/2.
rpin=0.1*dpin/2.
rclad=rrod-dc*0.1
rliner=rclad-dl*0.1
Arod=pee*rrod**2
fclad=pee*(rrod**2-rclad**2)/Arod
fliner=pee*(rclad**2-rliner**2)/Arod
fHe=pee*(rliner**2-rpin**2)/Arod
fpin=pee*rpin**2/Arod
rorod=fpin*roUN+fliner*roW+fclad*roAst
data xTa, xW, xRe, xHf, RoLiS, RoBC
*/0.90275, 0.08, 0.01, 0.00725, 1.024, 2.92/
cweight fraction Astar alloy
cxTa: Ta; xW: W; xRe: Re; xHf: Hf
cDensities(g/cm3): Ro...
cRoLiS: LiH+Stainless Steel N'Shield
cRoBC: B4C(N' Shield)
data wfi, rnu, remLi, remBe, remO, remU, remW
*/3.2042e-11, 2.44, 1.01, 1.07, 0.92, 3.6, 3.13/
cwfi: joules/fission(200MeV); rnu: number of neutrons per fission
crem Li, Be, O, U, Ta: removal cross sections(barns) for fast neutrons
data (pfr(1, j), j=1, 3)/1.80, 1.85, 1.91/
data (pfr(2, j), j=1, 3)/1.68, 1.72, 1.76/
data (pfr(3, j), j=1, 3)/1.61, 1.63, 1.65/
cpfr(i, j)radial maximum power factor at BOL(with control drums in)
c(then at center line) for uniform load as function of enr i, podip j
data (pfrm(1, j), j=1, 3)/0.353, 0.318, 0.276/
data (pfrm(2, j), j=1, 3)/0.433, 0.410, 0.382/
data (pfrm(3, j), j=1, 3)/0.490, 0.498, 0.472/
cpfrm(i, j) minimum radial power factors at BOL( at border core)
csame restrictions as pfr
cpfr and pfrm are for enrip(i) and podip(j) bellow
data (enrip(i), i=1, 3)/0.5, 0.7, 0.93/
data (podip(j), j=1, 3)/1.1, 1.3, 1.5/
c
data (enri(i), i=1, 5)/0.5, 0.6, 0.7, 0.8, 0.93/
data (podil(i), i=1, 5)/1.1, 1.2, 1.3, 1.4, 1.5/
cenri(i): enrichment, podi(i) pitch/diameter of the data base

data (wbeth(i), i=1, 8)/0.2728, 0.3947, 0.5026, 0.6778, 0.8524, 0.9517, 1.000/
wbeth: relative(to 30 cm) worth of OBe as function of its thickness

wth(cm)(input next)

data (th(i),i=1,8)/0.,3.67,5.67,7.67,11.67,17.67,24.,30./

nenr=5
npod=5

relative worth of OBe reflectors: relr, radial;relal,rela2: axial

ibe=8
call Inter(th,wbeth,ibe,drr,relr)
relar=relr
call Inter(th,wbeth,ibe,dr1,relal)
call Inter(th,wbeth,ibe,dr2,rela2)
relal=0.5*relal
rela2=rela2*0.5

if itest=1 print your options:

TTTTT EEEEE SSSSS TTTTT

1) Energy available with optimum shape
2) Radius of infinite cylinder
3) Height of infinite "pancake"
4) Energy available as function of R and H

(2 or 3 would produce "infinite" energy)

ish=ishape
RRR=r
HHH=h

itpr=itest
if(itpr.eq.1)
write(8,6133) Ereq,BU,drr,dr1,dr2,dkeol,dkstr
*
' With radial OBe reflector thickness(cm)',f6.2/
' Top OBe reflector thickness(cm)',f6.2/
' End of Life delta k(%) ',f6.2/
' Structural delta k(%) ',f6.2/
if(itpr.eq.1)
write(8,1632)
' For your input conditions'
itest=1

do 299 ipod=1,npod
pod=podi(ipod)
if(itpr.eq.1) write(8,302) pod
format(//' Run Test, Energy Available (Mwd) for Optimum Shape'/'
' with corresponding Rop and Hop'/'
' Critical Radius(cm) for Infinite Reactor'/'
' Critical Height(cm) for Infinite Reactor'/'
' For your input conditions')

compute Energy available for ideal shape Emin()
and asymptotic radius Ras() and height Has()

Page B-6
ishape=1
enr=enri(ienr)
podt=pod
Ene=Balance(ibu,enr,pod)
Emin(ienr,ipod)=Ene
Rop(ienr,ipod)=R
Hop(ienr,ipod)=H
Ropo=R
Hopo=H
dpvo=dpv
ishape=2
Edu=Balance(ibu,enr,pod)
Rcri=dcr
dpvc=dpv
Ras(ienr,ipod)=Rcri
ishape=3
Edu=Balance(ibu,enr,pod)
Hcri=dcr
Has(ienr,ipod)=Hcri

if(itpr.eq.1) write(8,1634) enr,Ene,Ropo,dpvo,Hopo,Rcri,dpvc,Hcri
continue
continue
1634 format(f5.3,fl2.1,6f10.2)
continue
itest=itpr
if(itest.eq.0) go to 1631
compute curves Eavailable as function of radius and Height of core and
enrichment and p/d in order to illustrate the user about the options.
do 5682 ipod=1,npod
pod=podi(ipod)
do 5782 ienr=1,nenr
enr=enri(ienr)
write(8,5783) enr,pod,Ereq
format(/" AVAILABLE ENERGY(MWDAYS) AS FUNCTION OF ENRICHMENT,P/D,R AND H"/
*/'ENR=',f6.4,1Ox,'P/D=',f7.4/' Required Energy(Mwd)' ,f10.2/
*/' I',4x,'R(CM)PVcm R/H',7x,'EAVAI',4x,'H(CM)',
*/'PVcm R/H',7x,'EAVAI'//)
Rs0=Ras(ienr,ipod)*der
Hs0=Has(ienr,ipod)*der
rdt=ndt
delr=(Rop(ienr,ipod)-Rs0)/rdt
delH=(Hop(ienr,ipod)-Hs0)/rdt
do 5782 idt=1,nput
ishape=2
rit=idt-1
Rs=Rs0+rit*delr
R=Rs
Ener=Balance(ibu,enr,pod)
dpvr=dpv
xra=R/H
ishape=3
Hs=Hs0+rit*delH
H=Hs
EneH=Balance(ibu,enr,pod)
dpvh=dpv
xh=R/H

Page B-7
write(8,5784) idt, Rs, dpvr, xra, Ener, Hs, dpvh, xh, EneH

format(i5,2(f9.2,f4.1,f5.2,12.0))

continue
continue

EEEEE N N D TTTTT EEEEE SSSSS TTTTT
E   NNN N D D T   E S T
EE E NNN D D T EEE S S T
EEE N N D T EEEE SSSS T

1631 bypass prints and some checks on energy
1631 continue

Stop here if your intentions are only to run the test

if(icont.eq.0) stop

icart=1

drodc=0.1*drod

do 467 ipod=1,npod
isha(ipod)=ish
bual(ipod)=bu

467 continue

do 1391 ipod=1,npod

Start loop of designs by fixing first p/d
up to statement # 1391

pod=podi(ipod)
bual=bu(ipod)
isha=isha(ipod)

Abu and Abund(cm2) area of 19 rods bundle with and without the duct
Abu=3.4641016*drodc**2*(pod*2.73205081-0.5+tduc/drod)**2
Abund=3.4641016*drodc**2*(pod*2.73205081-0.5)**2
duct fraction
fduct=(Abu-Abund)/Abu
fLi=At/Abu
Arod=pee*rrod**2*19.
rods fraction
frod=Arod/Abu
sp spacing wire fraction
fwire=(Abund-Arod-At)/Abu

core density, averaged within bundle, is rocore
rocore=fduct*RoAst+fLi*roLi+frod*rorod+fwire*RoAst

c
r=RRR
h=HHH
itest=0

c check if you are requesting too little energy
c
iflamin=0
Emino=Emin(nenr,ipod)
if(Ereq.ge.Emino) go to 337
iflamin=1
write(8,5133) pod,Ereq,BU,drr,dr1,dr2,dkeol,dkstr
5133 format(//' ATTENTION'/' Sampling p/d=',f8.4/
* ' You requested Mwdays',f10.2/
* ' And burn-up(%)',f5.2/
* ' With radial Be reflector thickness(cm)',f6.2/
* " top " " " " ,f6.2/
* " bottom " " " " ,f6.2/
* ' End of Life delta k(%) ' ,f6.2/
* ' Structural delta k(%) ' ,f6.2/
* Trying to satisfy reactivity balance, it happens your core'/
* ' is too large (and it would produce more energy you need).'/
* ' You might:'/
* 1) Reduce the input burn-up, and/or'/
* 2) Increase the reflector thickness, and/or'/
* 3) Reduce delta k at end of life, and/or'/
* 4) Reduce delta k structural')
if(ichoose.eq.l) write(8,1424)
1424 format(//' I choose=l, Program stops')
if(ichoose.eq.l) stop
write(8,1426)
1426 format(//' Program will change burn-up for this p/d design'/
* ' and choose ishape=1'/
* ' BU Mwday')
icart=0
itest=1

Recompute Energy available for ideal shape Emin() by changing burnup

enr=enri(nenr)
ishape=1
4644 Ene=Balance(ibu,enr,pod)
Emin(nenr,ipod)=Ene
write(8,1425) BU,Ene
1425 format(2f12.2)
if(Ereq.ge.Ene) go to 4633
BUA=BU
BU=BU-1.
if(BU,le.0.) BU=BU/2.
BUal(ipod)=bu
go to 4644
4633 continue
itest=0
337 continue

c check if there is enough energy for ideal shape(ishape=1)
c
iwae=0
Emaxo=Emin(1,ipod)
if(Ereq,le.Emaxo) go to 357
iwae=1

c set the warning flag iwae=1 for potential strange shapes: cigar/pancake
c and calculate R1, R2, R3, R4 and H1, H2, H3, H4 which are the limits for R
c and H for the input conditions (reactivity, required energy) in the
c bifurcation region

```fortran
itest=1
ishape=2
enr=enri(nenr)
Das=Ras(nenr, ipod)
Dop=Hop(nenr, ipod)
call Size(Das, Dop, Ereq, enr, pod, R1, R4)
enrr14=enr
hr4=h
vr14=Vcor/(pee*r1**2)
enr=enri(1)
Das=Ras(1, ipod)
Dop=Hop(1, ipod)
call Size(Das, Dop, Ereq, enr, pod, R2, R3)
enrr23=enr
hr3=h
vr23=Vcor/(pee*R2**2)
enr=enri(nenr)
Das=Has(nenr, ipod)
Dop=Hop(nenr, ipod)
call Size(Das, Dop, Ereq, enr, pod, H1, H4)
enrh14=enr
rh4=R
vh14=Vcor/(pee*H1)
enr=enri(1)
Das=Has(1, ipod)
Dop=Hop(1, ipod)
call Size(Das, Dop, Ereq, enr, pod, H2, H3)
enrh23=enr
rh3=R
vh23=Vcor/(pee*H2)
write(8,369)pod,Ereq,Emaxo,Ri,R2,R3,R4,enrr14,vr14,hr1,hr4,enrr23
*,vr23,hr2,hr3
format(//' ATTENTION:'//
   ' Designs with p/d\_',fS.5/
   ' You requested Mwdays\_',f10.2,' larger than\_',f10.2/
   ' which is the largest energy available for ideal shape.'//
   ' Strange shapes(cigar/pancake) can appear as solutions,'//
   ' the following designs are possible:'//
   ' ishape=2 with R(cm) between'//
   ' R1' ,f8.2,' and R2' ,f8.2/
   ' R3' ,f8.2,' and R4' ,f8.2/
   ' R1 and R4 corresponds to Enr' ,f8.3,' with core Vol(L)' ,f9.1/
   ' with H(cm), Respectively=' ,2f10.2/
   ' R2 and R3 corresponds to Enr' ,f8.3,' with core Vol(L)' ,f9.1/
   ' with H(cm), Respectively=' ,2f10.2/
   write(8,412) H1,H2,H3,H4,enrh14,vH14,rh1,rh4,enrh23,vh23,rh2,rh3
format(/
   ' Or ishape=3 with H(cm) between'//
   ' H1' ,f8.2,' and H2' ,f8.2/
   ' H3' ,f8.2,' and H4' ,f8.2/
   ' H1 and H4 corresponds to Enr' ,f8.3,' with core Vol(L)' ,f9.1/
   ' with R(cm), Respectively=' ,2f10.2/
   ' H2 and H3 corresponds to Enr' ,f8.3,' with core Vol(L)' ,f9.1/
   ' with R(cm), Respectively=' ,2f10.2/
   write(8,7133) BU ,drr ,dr1 ,dr2 ,dkeol ,dkstr
format(/' The previous data corresponds to your input conditions'//
   '/ Burn-up(\%)' ,f6.2/
Page B-10
* Radial Be reflector thickness(cm)',f6.2/
* Top " " " ',f6.2/
* Bottom " " " ',f6.2/
* End of Life delta k(%) ',f6.2/
* Structural delta k(%) ',f6.2/
* If awkward values of Radius/Height appear YOU MIGHT:'///
* 1) Increase the burn-up, and/or'/
* 2) Decrease the reflector thickness, and/or'/
* 3) Increase delta k at end of life, and/or'/
* 4) Increase delta k structural'/'
* #1 is very effective, #2,3 and 4 not so much'/
* If problem persist better try other kind of reactor'///

itest=0
ishape=ish
R=RRR
H=HHH
357 continue
if(ishape.eq.1.or.iwae.eq.1) go to 434

357

if(ishape.eq.1.or.iwae.eq.1) go to 434

else

endif
itest=0

Page B-11
434  continue
  if(iwae.eq.0) go to 1004
  go to(1001,1002,1003),ishape

1001  continue
  if(ichoose.eq.1) write(8,455) ichoose
  format(//'I choose Flag=',i3,' Not enough available energy'/
   * for ishape=1 option, program stop')
  if(ichoose.eq.1) stop
  ishape=2
  R=R3*1.01
  write(8,4555) R

455  format(//' Not enough energy for ishape=1(input), program continues with'/
   *' with R=',f8.2,' toward pancake shape'/)
  go to 1004

1002  continue
  if(R1.lt.R.and.R.lt.R2) go to 1004
  if(R3.lt.R.and.R.lt.R4) go to 1004
  if(ichoose.eq.1) write(8,4556) ichoose,R

4556  format(//' I choose Flag=',i3,' Your input R=',f8.2,' Out Possible Range'/
   *' Program stop')
  if(ichoose.eq.1) stop
  Rin=R
  R=R3*1.01
  write(8,4557) Rin,R

4557  format(//' Your input R=',f8.2,' is outside possible range, program'/
   *' continues with R=',f8.2,' toward pancake shape'/)
  go to 1004

1003  continue
  if(H1.lt.H.and.H.lt.H2) go to 1004
  if(H3.lt.H.and.H.lt.H4) go to 1004
  if(ichoose.eq.1) write(8,4558) ichoose,H

4558  format(//' I choose Flag=',i3,' Your input H=',f8.2,' Out Possible Range'/
   *' Program stop')
  if(ichoose.eq.1) stop
  Hin=H
  H=H2*0.99
  write(8,4559) Hin,H

4559  format(//' Your input H=',f8.2,' is outside possible range, program'/
   *' continues with H=',f8.2,' toward pancake shape'/)

1004  continue

4 c

4 enr1 (higher enrichment) has balance<0.
  ibu=0
  enr1=enr1(nenr)
  bal2=Balance(ibu,enr1,pod)
  if(ibu.eq.1) write(8,597)

597  format(//' Stop trying to bracket demand')
  if(ibu.eq.1) stop

4 c look for enrichment that produces balance>0.
  if(ishape.eq.1.or.iwae.eq.1) then
  enr2=enr1(1)
  bal2=Balance(ibu,enr2,pod)
  if(ibu.eq.1) write(8,597)
  if(ibu.eq.1) stop
  else
    it=0
    enr2=enr1
    it=it+1
    bal2=Balance(ibu,enr2,pod)
  if(ibu.eq.1) write(8,597)
if(ibu.eq.1) stop
if(bal2.gt.0.) go to 890
if(it.lt.itmax) go to 790
write(8,794) it,enr2,pod

format(’ stop trying to find Bal>0. iterations=’,i5,’ enr=’,f10.3/
*’p/d=’,f10.3)
stop

890 continue
endif

c
if we successfully arrived to this point, it means we bracket the demand
Then:
c bisect Balance until Eavailable=Erequested
c
it=0
enra=0.5*(enrl+enr2)
Erema=Balance(ibu,enra,pod)
if(ibu.eq.1) write(8,597)
if(ibu.eq.1) stop
test=abs(Erema)/Ereq
if(test.gt.eps) go to 144
it=it+l
if(iwrte.eq.1.and.it.eq.1) write(8,219) pod,bu

219 format(’/Sampling p/d=’,f6.3,’ BU(%)=’,f7.2/
*’Iterations on enrichment’/
**’ it’,7x,’ enrl’,8x,’ enra’,7x,’ enr2’,8x,’ bal1’,7x,’ Erem’,
*’bal2’)
if(iwrte.eq.1) write(8,218)it,enrl,enra,enr2,bal1,Erema,bal2

218 format(4,3f12.6,3f12.3)
call bisect(enrl,enr2,enra,bal1,bal2,Erema,iwa)
if(it.le.itmax.and.iwa.eq.0) go to 145
continue
if(it.gt.itmax.or.iwa.eq.1) then
write(8,146) enrl,bal1,enr2,bal2,it,iwa

146 format(’/’ Problems trying to bisect Balance’/
*’ enrl=’,e12.4,’ bal1=’,e12.4/
*’ enr2=’,e12.4,’ bal2=’,e12.4/
*, iteration=’,i5/
*, iwa=’,i5/)
stop
else
continue
endif

c
successful end of reactor search, calculate masses
change R such area fit integer number of bundles
Nbu=ppe*R**2/Abu
Rbu=ppe*R**2/Abu
Rnbu=nbu
if((Rbu-Rnbu).gt.0.5) Nbu=Nbu+1
R=sqrt(Nbu*Abu/ppe)

R=Vcor/(ppe*R**2)
c
compute mass core+pressure vessel+reflector=Greactor
c
Volpv=0.
Gpv=0.
Volpv=2.*ppe*(R+dpv)**2*dpv
Volpv=Volpv+pee*((R+dpv)**2-R**2)*H
Gpv=Volpv*RoAst
Rpvp=R+dpv
Hpvp=H+dpv
Vref=pee*((Rpvp+drr)**2-Rpvp**2)*Hpvp
Vref=Vref+pee*(Rpvp+drr)**2*(dra1+dra2)
Gref=Vref*roOBe

Page B-13
GReactor = Vcor * rocore + Gpv + Gref

c compute delta pressure across core = delp

c
Hact = H
call thermoli(1)
c
remember some data for future selection
enrd(ipod) = enra
Rd(ipod) = R
Hd(ipod) = H
dpv(ipod) = dpv
GRea(ipod) = GReactor
delp(ipod) = deltpa
dkbup(ipod) = dkbu
dkpvd(ipod) = dkp
rkbare(ipod) = rkre
dkobe(ipod) = dkbe
Nbun(ipod) = Nbu
u5md(ipod) = U5m / 1000.
isha(ipod) = ishape

1391 continue

c at 1391 end of loop on p/d
c

Now choose design using Greactor and delta p as criteria
c

ich = l
Rmref = GRea(l) / 1000.
write(8,849) delpr
849 format(//'Sampling of Designs'/'
* Mass=Masses of core, pressure vessel and reflector'/'
* Max delta p(Pa) acceptable=', el3.4//'
* I p/d Enr BU Mass(Kg) U5(Kg) DeltaP(Pa) coreR(cm)
*coreH(cm) ishape')/'
do 783 ipod = 1, npod
delpa = delp(ipod)
Rmass = GRea(ipod) / 1000.
enro = enrd(ipod)
buon = bual(ipod)
rdo = Rd(ipod)
Hdo = Hd(ipod)
U5m = U5md(ipod)
isha = isha(ipod)
write(8,855) ipod, podi(ipod), enro, buon, Rmass, U5m, delpa, Rdo, Hdo, isha
855 format(i3, 2f6.3, f6.2, 2f10.1, el3.4, 2f10.2, i3)
if (delpa.gt.delpr) go to 783
if (Rmass.lt.Rmref) ich = ipod
if (Rmass.lt.Rmref) Rmref = Rmass
continue

chosen design is ipod = ich
unless you had decided other thing

if (ichoode.ge.1.and.ichoode.le.5) ich = ichoode
R = Rd(ich)
H = Hd(ich)
dpv = dpvd(ich)
enr = enrd(ich)
pod = podi(ich)
dkbu = dkbup(ich)
dkp = dkpvd(ich)
rkre = rkbare(ich)
dkbeo = dkbe(ich)
Nbu = Nbun(ich)
bu = bual(ich)
Vcor = pce * R**2 * H
isha = isha(ich)
write(8,11) tit
write(8,51) Pow,D,Ereq,BU,drr,dra1,dra2,eps

format('/'INPUT TO THE PROGRAM'/', Power(Mw)',f8.2,' Core life',f8.3,' years',Energy Released(Mwday)',f10.2,' Burn-up(%)',f6.2//
'' Be reflector, radial thickness(cm)',f6.2/
'' top          ',f6.2/
'' bottom       ',f6.2/
'' The following design can produce that energy within the relative
''/numerical precision of',e12.4)

if(ishape.eq.1) write(8,317) xop
format('/'Minimum Core Volume Option Chosen: R/H=',fg.6/) 

if(ishape.eq.2) write(8,318) R
format('/'Core Radius Option Chosen: R(cm)=',f7.2/) 

if(ishape.eq.3) write(8,319) H
format('/'Core Height Option Chosen: H(cm)=',f7.2/) 

dkfp=dkbu
dkreq=dkfp+dkstr+dkeol+dkpv
dkbeo=dkbeo/100.
refec=rkre+dkbeo

c
c write(8,52) dkreq,dkfp,dkpv,dkstr,dkeol,refec,rkre,dkbeo

c format('/'And it has the following reactivity balance'/
'' Delta k required(%)',f6.2,' with components'/
'' Fission Products(%),f6.2/
'' Pressure Vessel(%),f6.2/
'' Structural(%),f6.2/
'' End of Life(%),f6.2/
'' keff at BOL(No structural mat)',f7.4,' Components'/
'' Bare Reactor',f7.4/
'' Reflector',f7.4/) 

write(8,521) enr,pod
format('/'Enrichment=',f8.4,' Pitch/Diameter=',f6.2)

Rad=R 
c call control to design control drums

dvp=dpv
Call Control 

c nrod=Nbu*nrodbu
Vcore=Vcor/1000.
c densities inside the pin
AU=enr*AU5+(1.-enr)*AU8
AUN=AU+AN
roN=roun*AN/AUN
roU=roun*AU/AUN
roU5=enr*AU5*roU/AU
roU8=(1.-enr)*AU8*roU/AU
CU5=roU5*Av/AU5
CU8=roU8*Av/AU8
Vact=nrod*pee*(drodc/2.)**2*H*fpin/1000.
u5m=Vact*roU5
u8m=Vact*roU8
Pum=0.
Fpm=0.
write(8,30) Vcore,Vact,R,H,nrod,nbu,nrodbu
format(‘ NUMBER DENSITIES AND MASSES OF FUEL PIN REACTOR’/
*’, ‘
GENERAL DESCRIPTION’/
*/‘Core Volume(L)’,f10.2,’ Active(UN) Volume(L)’,f10.2/
*’ Core Radius(cm)’,f10.2,’ Height(cm)’,f10.2/
*’ Number of rods’,i6,’ Bundles’,i6,’(’,i3,’rods per bundle’)//
see: 1.50 and dkbu are dummies

bup=0.01*bu
Call bupo(bup,1.50,cm5,cm8,dkbu)

rou5e=c5e*AU5/Av
rou8e=c8e*AU8/Av
roPue=c9e*APu/Av
U5me=rou5e*Vact
U8me=rou8e*Vact
Pume=roPue*Vact
Pup=(p9*APu/Av)*Vact
Fpme=roFpe*Vact
ftin=ftin*1.0e+24
fluxn=ftin/tiempo
write(8,5211)fluxn,D,ftin

format(’
*/Neutron Flux(1/cm2sec)(core and time average) ’,e12.4/
* ’ Fluence(1/cm2) ” after’,f6.2,’ years’,e12.4)

write(8,986) u5m,u5me,u8m,u8me,pum,pume,Pup,fpm,fpme
format(’
*/Masses(Kg) of Fissile Materials and Fission Products’//
*’ BOL EOL’/
*’ U-235’,2f10.3/
*’ U-238’,2f10.3/
*’ Pu-239’,3f10.3,’ Kg produced’/
*’Fiss Prod’,2f10.3)

write(8,40) drod,dc,dl,dHe,dpin
format(’
*/ Rod diameter(mm) is’,f7.4’/ Astar Alloy clad thickness,mm’,f7.4/
*/ W Liner,mm’,f7.4’/ He gap,mm’,f7.4’/ UN pin diameter,mm’,f7.4)

x=pod
pitch=x*drodc
fcool=1.-0.90689968*(1.+(x-1.)*x/3.)/x**2
frod=0.90689968/x**2
fwire=1.-fcool-frod
write(8,50)fcool,fwire,frod

format(’
*/ Volume fractions in Fuel Cell #1’/
*’/ Spacing Wire’,f7.4
*’/ Fuel Rod ’,f7.4)

Rco=0.52503757*pitch
ALi=ALi6*xLi6+ALi7*xLi7
coLi=roLi*Av/ALi
coLi6=coLi*xLi6
coLi7=coLi*xLi7
roTa=roAst*xTa
coTa=roTa*Av/ATa
coTun=roAst*xW
coTun=roAst*AV/AW
\[c W_2 c = c o T u n \times W_2\]
\[c W_3 c = c o T u n \times W_3\]
\[c W_4 c = c o T u n \times W_4\]
\[c W_6 c = c o T u n \times W_6\]
\[r o R e = r o A s t \times x R e\]
\[c o R e = r o R e \times A v / A R e\]
\[c R e_{185} = c o R e \times x R e_{5}\]
\[c R e_{187} = c o R e \times x R e_{7}\]
\[r o H f = r o A s t \times x H f\]
\[c H f = r o H f \times A v / A H f\]
\[f c l a c = (f c l a d + f w i r e) \times f r o d\]
\[R r o d w = R r o d \times \sqrt{1. + f w i r e / f r o d}\]
\[c o W = r o W \times A v / A W\]
\[c W_{21} = c o W \times x W_{2}\]
\[c W_{31} = c o W \times x W_{3}\]
\[c W_{41} = c o W \times x W_{4}\]
\[c W_{61} = c o W \times x W_{6}\]
\[f l i c = f l i n e r \times f r o d\]
\[p H e p = p H e \times 1000000.\]
\[r o H e = 0.001 \times r h o (p H e p , T H e)\]
\[c o H e = r o H e \times A v / A H e\]
\[f H e c = f H e \times f r o d\]
\[c N = r o N \times A v / A N\]
\[f p i n c = f p i n \times f r o d\]
\[w r i t e (8, 60) R c o , c o L i 6 , f c o o l , c o L i 7 , c \]
\[w r i t e (8, 1160) R l i n e r , c o H e , f H e c , c \]
\[w r i t e (8, 1160) c U 5 , f p i n c , c \]
\[w r i t e (8, 1160) c U 8 , c N \]

```
c 60  format(/'
   
   
   * Fuel Cell type 1 (Number Densities 10**24 atoms/cm^3)'/
   * Spacing Wire is diluted in clad'/
   * Region  Radius(cm) Isotope Concentration Volumetric Fraction'/
   * Coolant',f10.4,'  Li6',f12.8,f10.6/
   *   ',10x,'   Li7',f12.8/
   *  Clad',f10.4,' Ta181',f12.8,f10.6/
   *  ',f10.4,'(diluting spacing wire)'/
   *   ',10x,'   W182',f12.8/
   *   ',10x,'   W183',f12.8/
   *   ',10x,'   W184',f12.8/
   *   ',10x,'   W186',f12.8/
   *   ',10x,'   Re185',f12.8/
   *   ',10x,'   Re187',f12.8/
   *   ',10x,'   Hf',f12.8/
   * Liner',f10.4,' W182',f12.8,f10.6/
   *   ',10x,'   W183',f12.8/
   *   ',10x,'   W184',f12.8/
   *   ',10x,'   W186',f12.8/
   *   ',10x,'   N14',f12.8/)'

1160 format/
   
   *He Gap',f10.4,'  He',f12.8,f10.6/
   *Fuel Pin',f10.4,' U235',f12.8,f10.6/
   *   ',10x,'   U238',f12.8/
   *   ',10x,'   N14',f12.8)'/
```

c AVERAGES IN BUNDLE:
c

```
c Abu and Abund(cm2) area of 19 rods bundle with and without the duct
Abu=3.4641016*drodc**2*(pod*2.73205081-0.5+tduc/drod)**2
Abund=3.4641016*drodc**2*(pod*2.73205081-0.5)**2
```
c duct fraction
duct=(Abu-Abund)/Abu

c f1, 2, 3 are flow fractions for cell types 1, 2, 3 (with respect to cell)
f1 = 1 - 0.906900*(1. + (x-1.)**2/3.)/x**2
f2 = 2.30940*((x-5.)*x-.392699*(1.+.5*(x-1.)**2))/x**2
f3 = 2.30940*(.577350*(x-.5)**2-0.130900)/x**2

c area of cell(cm^2) is acell
pitch=pod*drodc
acell=0.433013*pitch**2

c a1, a2, a3 (cm^2) are area flow of cell types 1, 2, 3
a1 = f1*acell
a2 = f2*acell
a3 = f3*acell
At = 24.*a1+12.*a2+6.*a3

c flow fraction
fLi = At/Abu
Arod = pee*(drodc/2.)**2*19.

c rods fraction
frod = Arod/Abu

c spacing wire fraction
fwire = (Abund-Arod-At)/Abu

c core density, averaged within bundle, is rocore
rocore = duct*RoAst+fLi*roLi+frod*rorod+fwire*RoAst

c
fclw = fwire+frod*fclad+duct
flin = frod*fliner
fpinb = frod*fpin

Vact = Vcore*fpinb

coLi6 = coLi6*fLi
cLi7 = coLi7*fLi
cTa = coTa*fclw
cW2 = cW2c*fclw+cW2f*flin
cW3 = cW3c*fclw+cW3f*flin
cW4 = cW4c*fclw+cW4f*flin
cW6 = cW6c*fclw+cW6f*flin
cRe185 = cRe185*fclw
cRe187 = cRe187*fclw
chf = chf*fclw
cHe = coHe*frod*fHe
fHe = fHe*frod
cU5 = cU5*fpinb
cU8 = cU8*fpinb
cN = cN*fpinb

write(8,61) frod, fwire, fLi, fduct
write(8,65) coLi6, coLi7,
                 coTa,
                 cW2, cW3, cW4, cW6,
                 cRe185, cRe187,
                 chf,
                 coHe,
                 cU5,
                 cU8, cN

C

61 format('// AVERAGES IN BUNDLE (INCLUDING DUCT)'/
* 'Volumetric Fractions:  Rods', f7.4/
* ' Spacing Wire', f7.4/
* ' Li Coolant', f7.4/
* ' Duct', f7.4/)

65 format(
* ' Isotope Concentration '/
* '(Number Densities 10**24 atoms/cm^3)'/
* ' Li6', f12.8/
* ' Li7', f12.8/
* ' Ta181', f12.8/
* ' W182', f12.8/)
** compute masses and volumes inside the core

```fortran
Gcore = rocore * Vcore
Vrod = Vcore * frrod
Grod = Vrod * rorod
frodm = Grod / Gcore
VLi = Vcore * fLi
GLi = VLi / roLi
fLim = GLi / Gcore
Vduct = Vcore * fduct
Gduct = Vduct / roAst
fducm = Gduct / Gcore
Vwire = Vcore * fwire
Gwire = Vwire / roAst
fwim = Gwire / Gcore
write (8, 1093) Vrod, frod, Grod, frodm,
VLi, fLi, GLi, fLim,
Vduct, fduct, Gduct, fducm,
Vwire, fwire, Gwire, fwim,
Vcore, Gcore
```

** compute mass core+pressure vessel+reflector=Greactor

```fortran
Volpv = 2.*pee*(R+dpv)**2*dpv
Volpv = Volpv + pee*((R+dpv)**2-R**2)*H
Volpv = Volpv / 1000.
Gpv = Volpv / roAst
Rpv = R + dpv
Hpv = H + dpv*2.
Vref = pee*((Rpv+drr)**2-Rpv**2)*Hpv
Vref = Vref + pee*(Rpv+drr)**2*(dral+dra2)
Vref = Vref / 1000.
Gref = Vref / roOBe
Greactor = Gcore + Gpv + Gref
Vreactor = Vcore + Volpv + Vref
fvc = Vcore / Vreactor
fvpv = Volpv / Vreactor
fvr = Vref / Vreactor
fmc = Gcore / Greactor
fmpv = Gpv / Greactor
fmr = Gref / Greactor
write (8, 1095) Vcore, fvc, Gcore, fmc,
Volpv, fvpv, Gpv, fmpv,
Vref, fvr, Gref, fmr,
```
calculation of neutron shielding

compute fast source Sn

\[ Sn = \text{Pow} \cdot 1.0 \times 10^6 \cdot \text{rnu} / \text{wfi} \]

compute shielding by core, reflector and pressure vessel: fsh

concentrations smothered in Vol=Vcore+Volpv+Vref

\[ \text{coLi} = (\text{coLi}_6 + \text{coLi}_7) \cdot \text{fvc} \]
\[ \text{coTa} = \text{coTa} \cdot \text{fvc} \cdot x_{\text{Ta}} \cdot \text{fvpv} \cdot \text{roASt} \cdot \text{Av} / \text{ATa} \]
\[ \text{coW} = (\text{cW}_2 + \text{cW}_3 + \text{cW}_4 + \text{cW}_6) \cdot \text{fvc} \cdot x_{\text{W}} \cdot \text{fvpv} \cdot \text{roASt} \cdot \text{Av} / \text{AW} \]
\[ \text{coRe} = (\text{cRe}_185 + \text{cRe}_186) \cdot \text{fvc} \cdot x_{\text{Re}} \cdot \text{fvpv} \cdot \text{roASt} \cdot \text{Av} / \text{ARe} \]
\[ \text{coHf} = \text{coHf} \cdot \text{fvc} \cdot x_{\text{Hf}} \cdot \text{fvpv} \cdot \text{roASt} \cdot \text{Av} / \text{AHf} \]
\[ \text{coHe} = \text{coHe} \cdot \text{fvc} \]
\[ \text{coU5} = \text{coU5} \cdot \text{fvc} \]
\[ \text{coU8} = \text{coU8} \cdot \text{fvc} \]
\[ \text{coU} = \text{coU5} + \text{coU8} \]
\[ \text{coN} = \text{coN} \cdot \text{fvc} \]

\[ \text{robe} = \text{fvr} \cdot \text{roobe} \cdot \text{av} / (\text{AO} + \text{ABe}) \]
\[ \text{coO} = \text{robe} \]
\[ \text{coBe} = \text{robe} \]

\[ \text{sigre} = \text{coBe} \cdot \text{remBe} + \text{remW} \cdot (\text{coTa} + \text{coW} + \text{coRe} + \text{coHf}) + \text{coU} \cdot \text{remU} \]
\[ + \text{remLi} \cdot (\text{coLi} + \text{coHe}) + (\text{coN} + \text{coO}) \cdot \text{remO} \]

\[ \text{Reg} = (750. \cdot \text{Vreactor} / \text{pee}) \cdot 0.333 \times 10^3 \]

\[ \text{sire} = \text{sigre} \cdot \text{Reg} \cdot 2. \]
\[ \text{fsh} = 3. \cdot (0.5 - (1. - (1. + \text{sire}) \cdot \exp(-\text{sire})) / \text{sire})^2 / \text{sire} \]

\[ \text{Snsh} = \text{Sn} \cdot \text{fsh} \]

Fast fluence without shielding is flufa, at distance dist

\[ \text{dist} = 100. \cdot z_{\text{Load}} + 0.5 \cdot \text{Hrea} \]
\[ \text{flufa} = \text{Snsh} / (4. \cdot \text{pee} \cdot \text{dist}^2) \]
\[ \text{flufa} = \text{flufa} \cdot \text{tiempo} \]

Calculate Neutron Shield for zero gamma Shield

\[ \text{tne0} = \text{shieldn} (\text{flufa}, \text{fastf}, \text{ishn}, 0.00, \text{igam}) \]
\[ \text{if} (\text{ishin} . \text{eq} . 0) \text{ tne0=0.} \]

Now, Calculation Gamma Source Sogam()

\[ \text{Call Gamso} (\text{Sn}, \text{Sogam}, \text{PrU}, \text{fvr}) \]

First, Gamma Shield with no Neutron Shield

\[ \text{Call Shieldga} (\text{Sogam}, \text{Dose}, \text{Doses}, \text{Dosew}, \text{tiempo}, \text{tgam}0, 0., \text{igam1}, \text{ishn}, 0) \]

Now, Coupled with n Shield

\[ \text{Call Shieldga} (\text{Sogam}, \text{Dose}, \text{Doses}, \text{Dosew}, \text{tiempo}, \text{tgam}, \text{tne}, \text{igam2}, \text{ishn}, 1) \]

\[ \text{if} (\text{igam2} . \text{eq} . 0) \text{ tne=tne0} \]
\[ \text{if} (\text{igam2} . \text{eq} . 0) \text{ tgam=D.} \]

Volume and Masses of shieldings

\[ \text{Tgt} = \text{Tan} (100. \cdot r_{\text{load}} - \text{Rrea}) / (100. \cdot z_{\text{load}} + \text{Hrea}) \]
rr1=Hrea*Tgt+Rrea
rr2=(Hrea+tgam)*Tgt+Rrea
rr3=(Hrea+tgam+tne)*Tgt+Rrea
h1=rr1/Tgt
h2=rr2/Tgt
h3=rr3/Tgt
V1=pee*rr1**2*h1*0.33333333
V2=pee*rr2**2*h2*0.33333333
V3=pee*rr3**2*h2*0.33333333
Volg=(v2-v1)/1000.
Voln=(v3-v2)/1000.
Gg=RoW*Volg
if(ishn.eq.1) Ron=RoLiS
if(ishn.eq.2) Ron=RoBC
Gne=Voln*Ron
Vols=Vreactor+Voln+Volg
Gsis=Greactor+Gne+Gg
fresv=100.*Vreactor/Vols
fnev=100.*Voln/Vols
fvg=100.*Volg/Vols
fresg=100.*Greactor/Gsis
fneg=100.*Gne/Gsis
fgg=100.*Gg/Gsis

write(8,789) Vreactor,fresv,Voln,fnev
format(*' VOLUMES AND MASSES OF REACTOR AND SHIELDINGS'//
*' Volume(L) Fraction(%)'//
*' Reactor ',f10.2,f10.2/
*' N Shield',f10.2,f10.2)
write(8,796) Volg,fvg
format(*' G Shield',2f10.2)
write(8,797) Vols
format(*' Total ',f10.2//)
write(8,798) Greactor,fresg,Gne,fneg
format(*' Mass(Kg) Fraction(%)'//
*' Reactor ',f10.2,f10.2/
*' N Shield',f10.2,f10.2)
write(8,796) Gg,fgg
write(8,806) Gsis
format(*' Total ',f10.2//)
if(igam2.eq.0) write(8,808)
format(*' There were numerical problem with the calculation of'//
*' gamma shield, calculations skipped'//)
if(ishig.eq.0) write(8,809)
if(ishin.eq.0) write(8,810)
format(*' No need of gamma shield'//)
format(*' No need of neutron shield'//)
rr21 = rr2

write(8, 811) zload, rload, tgam, rr1, rr2, tne, rr21, rr3

format(811, ' DIMENSION OF THE SHIELDINGS'/
      ' LOAD AT Z(M)=', f8.2, ' WITH RADIUS(M)=', f8.2/
      ' G Shield Thickness(cm)=', f8.2, ' With Radius(cm)=', 2f8.2/

write(8, 758) tempv, pin, D

format(758, 'EVALUATION OF PRESSURE VESSEL'/
      'Evaluation at T(K)=', f8.2, ' PRESS(MPa)=', f8.2/
      ' and Full Power Life(y)=', f8.2//)

write(8, 1366) dpv

format('Pressure Vessel Thickness(cm)=', f6.2//)

if(ipresv.eq.0) write(8, 626)
format(' You have problems to contain your reactor, pressure Vesse
*1*/'calculations skipped, not included in shielding or balance'//)

flush = flufa
if(ishin.eq.1) flush = fastf
if(ishig.eq.1 and igam2.ne.0) flush = flufa*aten

write(8, 757) Sn, fsh, Req, sigre, D, flufa, flush, fastf, zload, tne, tne0

format(757, ' DETAILS OF THE SHIELDINGS'/
      ' Neutron Source(i/sec)=', e12.4/' Self Shielding by Reactor
      ' Materials', e12.4/' Equivalent R(cm)=', f8.2, ' Sigma Removal', f12.6/
      ' f6.2,' Years Fast Fluence(i/cm2) without Any Shielding', e12.4/
      ' Requested', e12.4
      ' All at', f6.2, ' meters'
      ' Neutron Shielding Thickness(cm)=', f10.2/
      ' Neutron Shielding Thickness if no W is present, cm', f10.2//)

if(ishn.eq.1) write(8, 767)
format(' NEUTRON SHIELDING: LiH-Stainless Steel Matrix'//)

if(ishn.eq.2) write(8, 768)
format(' NEUTRON SHIELDING: B4C'//)

write(8, 771)
format(' TOTAL PRODUCTION OF GAMMA RAYS(i/sec)'//
      ' GROUP  1  2  3  4  5  6
      7/
      0-1Mev  1  2  2  3  3  5  5  7  7  9
      >9'/)

write(8, 772) (sogam(i), i=1, 7)

format(1P7e10.3/)
write(8,*) ' % FRACTION PRODUCED BY U'
write(8,773) (PrU(i),i=1,7)
format(7f10.2)
write(8,*) ' Equivalent Z for Build up factors'
write(8,773) (Zeq(i),i=1,7)
write(8,*) ' Gamma Self shielding by Core, Reflector and PV'
write(8,774) (shg(i),i=1,7)
format(7f10.6)
write(8,*) ' The same but without Buildup factor'
write(8,774) (shgnb(i),i=1,7)
write(8,*)'Integrated Dose(Rad) without any shielding(n or gamma)'
write(8,772) (Dosew(i),i=1,7)
if(ishig.eq.0.and.ishin.eq.1)
  write(8,*)'Integrated Dose Neutrons Shieldings(and no W)'
  if(ishig.eq.0.and.ishin.eq.1) write(8,772) (DosenG(i),i=1,7)
if(ishig.eq.1.and.igam2.ne.0)
  write(8,*)'Integrated Dose with W and Neutrons Shieldings'
  if(ishig.eq.1.and.igam2.ne.0) write(8,772) (DoseG(i),i=1,7)
write(8,775) Dosew
format(' Integrated Dose without Any Shielding,Total(Rad)' ,e12.4)
if(ishig.eq.1.and.igam2.ne.0) Dosos=Doses
if(ishig.eq.0) Dosos=Dosen
write(8,776) Dosos,tgam,tgam0
format(' Integrated dose with Shieldings(W and Neutrons), Total (R
*ads)' ,e12.2/
  ' Tungsten Thickness(cm)' ,f10.2/
  ' Tungsten Thickness(cm)' ,f10.2,' if no Neutron Shield Present'//)
write(8,804) Dose,Zload
format(/' Requested Dose(Rad)' ,f10.2,' at ','f6.2,' meters'/)

SOLVE THERMALHYDRAULIC

Page B-23
c
podt=pod
Hact=H
write(8,2367) tout1
2367 format(//' THERMALHYDRAULICS CALCULATIONS'/
  * ' Average Temperature of the Coolant at Core Exit(K)',f10
  *'.2//)
c
c if(iboun.eq.1) write(8,3478)
3478 format(//' BOUNDARY CONDITION: INPUT FLOW'//)
c
c if(iboun.eq.2) write(8,3479)
3479 format(//' BOUNDARY CONDITION: OUTLET TEMPERATURE'//)
c check if this is a calculation assuming uniform power distribution
c
if(iopth.gt.2) go to 674
c here if 3D or 2D power density is constant
Pfacr=1.
Pfacaz=1.
Call Thermoli(0)
c program end
go to 677
674 continue
c here if we have uniform loading ie spacial dependent power density
if(iouth.eq.2) go to 671
c
Thermo at Max power density
c
Pfacaz=1.
c
write(8,687)
687 format(/***/PROFILE OF CHANNEL WITH MAXIMUM POWER DENSITY*/)
c
 calculation of Pfacr(radial power factor)MAX
nenrp=3
npodp=3
do 2577 j=1,npodp
do 2578 i=1,nenrp
2578 aux(i)=pfr(i,j)
call Inter(enrip,aux,nenrp,enr,rmm)
2577 bux(j)=rmm
call Inter(podip,bux,npodp,pod,Pfacr)
Call Thermoli(0)
671 continue
if(iouth.eq.1) go to 677
c
Thermo at Min power density
c
Pfacaz=1.-Ripple
c
write(8,697)
697 format(/***/PROFILE OF CHANNEL WITH MINIMUM POWER DENSITY*/)
c
calculation of min power radial profile
do 3577 j=1,npodp
do 3578 i=1,nenrp
3578 aux(i)=pfrm(i,j)
call Inter(enrip,aux,nenrp,enr,rmm)
3577  bux(j)=rm
         call Inter(podip,bux,npodp,pod,Pfacr)
         Call Thermoli(0)
       677  continue
         Stop
         End

He density(kg/m3) function of p(Pa) and t(K)
from page 405, ANS book "Thermal and Flow Design of Helium-Cooled
Reactors", G. Melese and R. Katz

Function rho(p,t)
   R=2077.22
   rho=p/(R*t+p*b(t))
   return
end

Function b(t)(used by rho)

Function b(t)
   data c1,c2,c3,c4,c5/9.489433e-4,9.528079e-4,3.420680e-2,
*    2.739470e-3,9.409120e-4/
   b=c1+c2/(1.-c3*t)+c4/(1.+c5*t)
   return
end

Compute available energy or
difference between available and requested energies
as function of S/F(other thing too)

Function Balance(ibu,enr,pod)
For input enr(ichment),pod(p/d) and when itest=0:
this function calculates 1) the volume of the core that satisfies the
reactivity balance; and then 2) the energy balance(Mwday)
Balance=Eavailable-Erequested. If ishape=2 or 3 (input R or H) the
function checks if R(or) H is compatible with reactivity balance
if not, set flag ibu=1 and RETURN
if itest=1 and for inputs enr and pod it calculates
available energy(for ishape=1,2 or 3),
c radius infinite core that satisfies reactivity balance if ishape=2
c height of infinite " " " " " " " =3

common /Bala/ Ereq,relr,relal,rela2,dkeol,dkstr,BU,Vc,
*U5m,dbu,dkbe,rkrem,dcr,sigma,pin,dpv,dkpv,tduc,
*eps,itest

common /MaBaSi/ R,H,ishape

dimension rm(5,5),enri(5),podii(5),bew(5,5)
*,ril(5,5),prv(5,5),aux(5),bux(5),dext(5)

data (rm(5,j),j=l,5)/7.695,8.762,9.841,10.927,12.010/
data (rm(4,j),j=l,5)/7.945,9.032,10.131,11.230,12.325/
data (rm(3,j),j=l,5)/8.149,9.248,10.357,11.470,12.571/
data (rm(2,j),j=l,5)/8.356,9.467,10.586,11.706,12.811/
data (rm(1,j),j=l,5)/8.563,9.681,10.805,11.929,13.037/
c rm(i,j) (cm) migration length of cell with enrichment i and p/d j
for the following enrichments and p/d

data(enri(i),i=1,5)/0.5,0.6,0.7,0.8,0.93/
data(podi(i),i=1,5)/1.1,1.2,1.3,1.4,1.5/

data(rki(5,j),j=1,5)/1.6953,1.6574,1.6194,1.5814,1.5432/
data(rki(4,j),j=1,5)/1.6127,1.5728,1.5333,1.4938,1.4544/
data(rki(3,j),j=1,5)/1.5366,1.4953,1.4545,1.4141,1.3740/
data(rki(2,j),j=1,5)/1.4460,1.4035,1.3618,1.3207,1.2802/
data(rki(1,j),j=1,5)/1.3364,1.2931,1.2510,1.2098,1.1695/

c rki k-infinite as function of i(enrichment) and j(p/d)

data(bew(5,j),j=1,5)/19.26,18.57,17.65,16.61,15.50/
data(bew(4,j),j=1,5)/17.26,16.30,15.18,13.99,12.76/
data(bew(3,j),j=1,5)/15.28,14.11,12.85,11.55,10.25/
data(bew(2,j),j=1,5)/12.78,11.40,10.02,8.65,7.32/
data(bew(1,j),j=1,5)/9.57,8.04,6.58,5.22,3.95/

c bew(i,j): % delta k; reactivity worth of 25 cm OBe radial reflector as
function of i(enr) and j(p/d)

data(prv(5,j),j=1,5)/5.69,5.39,5.12,4.77,4.41/
data(prv(4,j),j=1,5)/5.43,5.06,4.66,4.23,3.82/
data(prv(3,j),j=1,5)/5.10,4.63,4.14,3.67,3.22/
data(prv(2,j),j=1,5)/4.57,3.99,3.44,2.92,2.44/
data(prv(1,j),j=1,5)/3.73,3.05,2.45,1.91,1.43/
data(dref)/.

c prv(i,j): % delta k; reactivity worth Asas as pressure Vessel
function of i(enr) and j(p/d) at reference thickness dref

data(dext(j),j=1,5)/3.165,3.565,3.954,4.360,4.737/

c dext(j)(cm) extrapolation length for bare core(mainly function of p/d)

data xop,optimum shape for cylindrical reactors=Radius/Height

data pisq3=pi*sqrt(3)

data roun,drod,fpin,wfi/12.172,0.64,0.56861025,0.9501647/

c roun: density UN, fpin: fraction volume of pin inside rod, dpin=4.826mm
c drod=6.4mm, wfi=Mwd produced by the total fission of 1 g of U235
c at 200 Mev/fission

data AUS,AUB,AN,Av/235.044,238.0508,14.00307,0.602202/

c ibu=0
nenr=5
npod=5

c compute dexto(cm) extrapolated length

call Inter(podi,dext,npod,pod,dexto)

c compute kinf

do 1577 j=1,npod
do 1578 i=1,nenr
1578 aux(i)=rki(i,j)
call Inter(enri,aux,nnenr,fr,k)
1577 bux(j)=rkk
call Inter(podi, bux, npod, pod, rkin)

c compute migration length
c
    do 2577 j=1, npod
    do 2578 i=1, nenr
2578   aux(i)=rm(i, j)
    call Inter(enri, aux, nenr, enr, rmm)
2577   bux(j)=rmm
    call Inter(podi, bux, npod, pod, rmi)

c compute dk OBe reflector
c
    do 3577 j=1, npod
    do 3578 i=1, nenr
3578   aux(i)=bew(i, j)
    call Inter(enri, aux, nenr, enr, bmm)
3577   bux(j)=bmm
    call Inter(podi, bux, npod, pod, wbe)
    wber=wbe*relr
    wbeal=wbe*rela1
    wbea2=wbe*rela2
    dkbe=wber+wbeal+wbea2

c compute dk Astar pressure vessel (1. cm thick, reference value)
c
    do 4577 j=1, npod
    do 4578 i=1, nenr
4578   aux(i)=prv(i, j)
    call Inter(enri, aux, nenr, enr, bmm)
4577   bux(j)=bmm
    call Inter(podi, bux, npod, pod, wpv)
    drefp=Rref*(pin/sigma)*Rref*(dref/wpv)
    dcpv=(dref/pref)*relr*wpv

c compute delta k BU
c see: c50 and c80 are number densities inside the pin
c
    AU=enr*AU5+(1.-enr)*AU8
    AUN=AU+AN
    cu=roun*Av/AUN
    c50=cu*enr
    c80=cu*(1.-enr)
    bup=BU*0.01
    Call bupo(bup, rkin, c50, c80, dkbu)

c compute U235 density diluted in the core, rou5
c
    rkrm=1.+(DKBU+dkstr+dkeol-dkbe)/100.
    rkrem=rkrm+dkpv/100.
    go to (2001, 2002, 2003), ishape

c if ishape=1, optimum shape------>2001
2001   Rp=rmi*bo/sqrt(rkin/rkrem-1.)
    H=Rp-dexto
    dpv=(pin/sigma)*R
    H=hp-dexto*2.
    Vc=pee*R*2+H
    if(dpv.gt.0.4) go to 2004
    dpv=0.4
    aa=(rmi*bo)**2+rkin*apv*dexto/rkrm**2
    bb=0.5*apv*rkin/(rkrm**2*aa)
    cc=(rkin/rkrm-1.)/aa
    riv=-bb+sqrt(bb**2+cc)
rp=l./riv
hp=rp/xop
R=rp-dexto
H=hp-dexto*2.
Vc=pee*R**2*H
dkp=100.*apv/R
rkrem=rkrm+dkpv/100.
c write(8,1699) enr,pod,r,h,dpv,rkin,rmi,apv,rkrm,dexto,bo
1699 format('enr ',f6.3,' pod ',f6.3,' r ',f6.2,' h ',f6.2/)
*dpv ',f6.2,' rin ',f7.5,' m ',f6.2,/  
*apv ',e10.4,' rkrm ',f7.5,' dex ',f6.2,' bo ',f7.4/)
go to 2004
c
c go next if ishape=2----->input Radius of core
c 2002 continue
buck=sqrt(rkin/rkrem-1.)/rmi
Rcr=2.405/buck-dexto
dprs=Rcr*(pin/sigma)
if(dprs.gt.0.4) dcr=Rcr
if(dprs.gt.0.4) go to 1703
aa=(rmi*2.405)**2+rkin*apv*dexto/rkrm**2
bb=0.5*apv*rkin/(rkrm**2*aa)
cc=(rkin/rkrem-1.)/aa
riv=-bb+sqrt(bb**2+cc)
rp=l./riv
dcr=rp-dexto
1703 continue
if(R.lt.dcr) ibu=1
c
c set flag ibu=1 if R(input) is too small to satisfy reactivity balance
c
if(ibu.eq.1) return
dpv=(pin/sigma)*R
dpv=0.4
if(dpv.ge.0.4) go to 1823
dpv=100.*apv/R
1823 rkrem=rkrm+dkpv/100.
buca=(rkin/rkrem-1.)/rmi**2-(2.405/(R+dexto))**2
hp=pee/sqrt(buca)
H=hp-dexto*2.
Vc=pee*R**2*H
go to 2004
c
c go next if ishape=3--------input Height of the core
c 2003 dcr=pee*rmi/sqrt(rkin/rkrem-1.)-dexto*2.
if(H.le.dcr) ibu=1
c
c set flag ibu=1 if H(input) is too small to satisfy reactivity balance
c
if(ibu.eq.1) return
buca=rkin/rkrem-1.-(pee*rmi/(H+dexto*2.))**2
rp=rmi*2.405/sqrt(buca)
R=rp-dexto
dpv=(pin/sigma)*R
Vc=pee*R**2*H
dpv=0.4
if(dpv.gt.0.4) go to 2004
aa=(rmi*2.405)**2+rkin*apv*dexto/rkrm**2
bb=0.5*apv*rkin/(rkrm**2*aa)
cc=(rkin/rkrem-1.-rmi*pee/(H+dexto*2.))**2/aa
riv=-bb+sqrt(bb**2+cc)
rp=l./riv
R=rp-dexto
Vc=pee*R**2*H
dkp=100.*apv/R
rkrem=rkrm+dpv/100.

2004 continue

c Compute average density of U235

c Abu (cm2) area of 19 rods bundle with the duct
Abu=3.4641016+drodc**2*(pod*2.73205081-0.5+0.1*tduc/drodc)**2

c rods fraction
Arod=19.*pee*(drodc/2.)**2
frod=Arod/Abu
rouno=roun*frod*fpin
rou=roun*(AU/AUN)
rou5=enr*rou/AU


c check available energy

USm=Vc*rou5

Eavai(Mwd) is the total energy produced by the fission of U235, U238 and Pu239 at 200 Mev per fission. See, here BU=total fission/Initial number of U235 atoms; ie U5 at EOL is NOT BU*U5(BOL)

Eavai=USm*BU*wfi/100.
Balance=Eavai-Ereq
if(itest.eq.1) Balance=Eavai
return

end


c compute control drums

subroutine control

dimension cr(5,5),enri(5),podiri(5),aux(5),bux(5),bew(5,5),prv(5,5)
common /cont/R,dpv,drr,enr,pod,refec,ncr,dksu,dkstr,relr,dcd

c R:radius core, drr:thickness reflector; dref: reference reflector

c thickness(with which worths were calculated); raps:S/F element ratio

c refec:keff to control; ncr:number of control rods; dksu(%): subcriticality required for drums in.
c dkstr(%): dk structural part of reactor, relr: relative worth of reflector

data dref,dpvref,dcdref/25.,1.,2./
data (cr(5,j),j=1,5)/6.73,6.64,6.37,6.07,5.73/
data (cr(4,j),j=1,5)/5.98,5.74,5.43,5.08,4.69/
data (cr(3,j),j=1,5)/5.23,4.92,4.55,4.15,3.73/
data (cr(2,j),j=1,5)/4.29,3.91,3.50,3.06,2.63/
data (cr(1,j),j=1,5)/3.12,2.69,2.24,1.81,1.39/
data (bew(5,j),j=1,5)/19.26,18.57,17.65,16.61,15.50/
data (bew(4,j),j=1,5)/17.26,16.30,15.18,13.99,12.76/
data (bew(3,j),j=1,5)/15.28,14.11,12.85,11.55,10.25/
data (bew(2,j),j=1,5)/12.78,11.40,10.02,8.65,7.32/
data (bew(1,j),j=1,5)/9.57,8.04,6.58,5.22,3.95/
data (prv(5,j),j=1,5)/5.69,5.39,5.12,4.77,4.41/
data (prv(4,j),j=1,5)/5.43,5.06,4.66,4.23,3.82/
data (prv(3,j),j=1,5)/5.10,4.63,4.14,3.67,3.22/
data (prv(2,j), j=1,5)/4.57,3.99,3.44,2.92,2.44/
data (prv(1,j), j=1,5)/3.73,3.05,2.45,1.91,1.43/

prv(i,j): % delta k; reactivity worth Astar as pressure Vessel function of i(enr) and j(p/d) at reference thickness dref
data (enri(i), i=1,5)/0.5,0.6,0.7,0.8,0.93/
data (podi(j), j=1,5)/1.1,1.2,1.3,1.4,1.5/

if(ncr.eq.0) write(8,48)

48 format(' Your input for the number of control drums is zero'/' '* Subroutine Control bypassed'')

if(ncr.eq.0) return

pee=3.1415926
dcd(cm): thickness of B4C in Control drums
c

worth of drums for input enr,pod

c
npod=5
nenr=5
do 2577 j=1,npod
do 2578 i=1,nenr
2578 aux(i)=cr(i,j)
call Inter(enri,aux,nenr,enr,cr)
2577 bux(j)=cr
call Inter(podi,bux,npod,pod,cdr)
c

c worth of 2*pee sheet(cdr) is corrected because drr might not be =dref
c correction factor relative worth of reflector(with respect to dref) cdr, next, is for conditions: PV=1cm thick, B4C=2cm thick cdr=cd*relr
c
c Correction for PV.ne.1cm or B4C.ne.2cm:
c
c worth=AM*exp(-sigpv*dpv)*(1.-exp(-sigcd*dcd)
c where: sigpv and sigcd are removal cross section in PV and Drum
c
dpv,dcd are thicknesses of PV and B4C
c
c 1) Compute sigpv looking to worth of PV at "infinite" and dpvref=1.
c
c a) worth of reflector=worth of infinite thick PV=wpvi
c
do 3577 j=1,npod
do 3578 i=1,nenr
3578 aux(i)=bew(i,j)
call Inter(enri,aux,nenr,enr,cr)
3577 bux(j)=cr
call Inter(podi,bux,npod,pod,wpvi)
wpvi=wpvi*relr
c

c b) worth of dpvref cm thick PV=wpvl
c
do 4577 j=1,npod
do 4578 i=1,nenr
4578 aux(i)=prv(i,j)
call Inter(enri,aux,nenr,enr,cr)
4577 bux(j)=cr
call Inter(podi,bux,npod,pod,wpvl)
wpvl=wpvl*relr
c
c compute exponent of flux attenuation in PV
c

sigpv=-alog(1.-wpvl/wpvi)/dpvref
c

2) Compute sigcd and AM looking at worth of B4C at "infinite" and 2.cm
c worth of "infinite" thick B4C=wpvi(Reflector)-wpvl(PV)
wcdr=wpvi-wpvl
AM=wcdi*exp(sigpv*dpvref)
sigcd=-alog(1.-cdr/(AM*exp(-sigpv*dpvref)))/dcdref

c worth of 2 pi's sheet of B4C(thick=dcd) beside the PV(thick=dpv)
c
c cdr=AM*exp(-sigpv*dpv)*(1.-exp(-sigcd*dcd))

c rea(%) reactivity to control

c rea=(refec-1.)*100.+dksu-dkstr

c compute maximum number of drums=nmax

c Rpv=R+dpv
rd=0.5*drr
par=2.*asin(rd/(Rpv+rd))
pard=par*180./pee
write(8,23) rd,pard,dcd
23 format(//' From Control'/
*' Radius Drums(cm)',f8.2,' Central Parallax(degree)',f8.2/
*' Thickness B4C sheet on Control Drums,cm',f8.2/)c

c rd and par are the radius and the central parallax of the drums
c
nmax=2.*pee/par
cdrm=cdr*nmax*par/(2.*pee)
if(cdrm.ge.rea) go to 10
c pass to local parallax(seen from center of drum)--> dtcr,dtcd
bb=(Rpv+rd)*cos(0.5*par)
xx=bb
dtcr=2.*asin(xx*sin(0.5*par)/rd)
dtcd=180.*dtcr/pee
write(8,20) nmax,cdrm,rea,dtcd
20 format(//' You cannot control this reactor only with control'/
*' drums in the reflector'/
*' The reactivity worth of',i5,' drums(max value) is',f6.2,' %'/
*' and the reactivity to control is',f6.2,' %'/
*'Absorbing angle of each drum would be',f8.2,' degrees'//)
return

continue
if(ncr.gt.nmax) write(8,33) ncr,nmax
33 format(//' Your input for the number of drums is',i5/
*' larger than the max possible',i5,' continue with max'/)
if(ncr.gt.nmax) ncr=nmax
rcr=ncr
cdrm=cdrt*cr*par/(2.*pee)
if(cdrm.lt.rea) write(8,34) ncr,nmax
34 format(//' Your input for the number of drums',i5,' is too small'/
*(max possible is',i5,' program is going to increase it')
if(cdrm.lt.rea) then
101 ncr=ncr+1
if(cdrm.lt.rea) go to 101
else
endif
c c para is the central parallax of the absorbing part of one drum
c
c para=(rea/rcr)*(2.*pee/cdr)
c pass to local parallax(seen from center of drum)--> dtcr,dtcd
bb=(Rpv+rd)*cos(0.5*para)
cc=Rpvs+2+2.*Rpvs*rd
xx=bb-sqrt(bb**2-cc)
dtcr=2.*asin(xx*sin(0.5*para)/rd)
31  dtdc=180.*dcr/pee
   write(8,31) ncr,dtdc,rea
   format(/i5,' Drums with absorbing angle(d) ',f8.2,' each'/
*     ' Control dk(%)=',f8.2//)
   return
end

character*80 aln

Tsa(ps)=8143./(8.-alog10(ps/0.133322))
Psa(ts)=0.133322*10.**(8.00-8143./ts)

Tsa(ps) is saturation temperature of Li(in K) as function of ps(KPa)
Psa(ts) is " pressure of Li(in KPa)" of ts(K)

Tsa(ps)=8143./(8.-alog10(ps/0.133322))
Psa(ts)=0.133322*10.**(8.00-8143./ts)

Tsa(ps) is saturation temperature of Li(in K) as function of ps(KPa)
Psa(ts) is " pressure of Li(in KPa)" of ts(K)

nnodo: number of nodes;
iboun /1,2/ boundaries conditions : read flow or T outlet
ifri.ne.1 : switch off friction factor
c nclad: number nodes inside clad
c npin: number of nodes inside fuel
c icheck/0,1/ no,print some parameters to check them
c
pin(MPa), tin( K) inlet conditions
c pod=p/d,
c fact: factor to multiply the power
c total power; rjs(Kw/cm2) scale for plot heat rate
Vact(L) active volume of the core, ie Volume occupied by UN
tduc(mm) duct thickness; hod lead of the spacing wire(in unit of drod)

flowt(Kg/sec) : Total flow
flow1,2,(3(g/sec) : Channel flow for cell types 1,2,3

npu=nnodo+1
\[ \text{Abu} = 3.46410 \times \text{drod}^2 \times (\text{pod} \times 2.732051 - 0.5 + \text{tduc} / \text{drod})^2 \]
\[ \text{Abund} = 3.46410 \times \text{drod}^2 \times (\text{pod} \times 2.732051)^2 \]

\[ \text{flow per bundle} = \text{flow} / \text{Nbu} \]
\[ \text{d} = \text{drod} \times 0.01 \]

\[ \text{flow} = \text{flow} \times 24 \times \text{a1} / \text{At} \]
\[ \text{flow} = \text{flow} \times 12 \times \text{a2} / \text{At} \]
\[ \text{flow} = \text{flow} \times 6 \times \text{a3} / \text{At} \]

\[ \text{Gt} = 0.001 \times \text{flow} / \text{At} \]

\[ \text{p} = \text{pin} \times 1.1 \times 6 \]
\[ \text{call pli(h,p,tin,rhoi,visi,cp,pr,k,x,0)} \]
\[ \text{veln} = \text{Gt} / \text{rhoi} \]
\[ \text{call pli(h,p,tout,rhoo,viso,cp,pr,k,x,0)} \]
\[ \text{veout} = \text{Gt} / \text{rhoo} \]
\[ t = 0.5 \times (\text{tin} + \text{tout}) \]

\[ \text{Rea} = \text{Dt} \times \text{Gt} / \text{viso} \]
\[ \text{frica} = \text{afia} \]

\[ \text{deltapa} = \text{Gt} \times (\text{veout} - \text{veln}) + \text{facfra} \times \text{Hact} / \text{At} \]
c if iop=1 return after calculating 1 node estimation of delta P
c
dzet=Hact/nnodo
Vact=nrod*pee*rpin**2*Hact/1000.
roav=Powt*fact/Vact
write(8,12) aln
format(a80)
write(8,21) TLim,tin,drod,Powt,nrod,Nbu,nrodbu,flowt,Vact,fact
format('Thermodynamic profile of a liquid Li cooled channel'/

**'Remember Li melts at',f8.2,' K !!!!'
**'
**'Inlet temperature( K)=',f10.2/
**' Diameter Rod(cm)=',f7.2/
**' Total Power(Mw)=',f10.3,' No. Rods',i10,' No. Bundles',i5,'(',i3,'*rods/bundle)/'
**' Total Flow(Kg/sec)=',f10.3/
**' Factor that multiplies Power',f10.7/
write(8,162)roav,Hact
format('Average Power Density(Mw/L(UN))',f5.4,' Channel Length(cm)/

A1c=A1*10000.
A2c=A2*10000.
A3c=A3*10000.
Atc=At*10000.
A1cr=A1c/0.5
A2cr=A2c/0.5
A3cr=A3c*6.
Atcr=Atc/19.
pf1c=pf1*100.
pf2c=pf2*100.
pf3c=pf3*100.
pftc=pft*100.
d1c=d1*100.
d2c=d2*100.
d3c=d3*100.
dtc=dt*100.
ft=Atc/Abund

n1=24
n2=12
n3=6
write(8,190) pod,hod
format( 'FLOW CONDITIONS: '/

**'Pitch/drod',f8.3,' Lead wire spacer/drod',f8.3/
**'Cell Type (per bundle) ',1lx,'1lx,'2',1lx,'3',6x,'Bundle'''/
write(8,191) n1,n2,n3,flow1,flow2,flow3,flow,
* f1,f2,f3,ft, *
* A1c,A2c,A3c,Atc, *
* A1cr,A2cr,A3cr,Atcr, *
* pf1c,pf2c,pf3c,pftc, *
* d1c,d2c,d3c,dtc, *
* XX,drel

format( 'Number of Cells ',3i12/
**'Flow(g/s) Total ',4f12.4/
**'Flow Area (*) ',4f12.4/
**'Flow Area(cm2),per cell ',4f12.4/
**'Flow Area(cm2),per rod ',4f12.4/
**'Wet Perimeter(cm) Total ',4f12.4/
**'Effective Diameter(cm) ',4f12.4/
**'(*) 1,2,3 in units of cell 1 area '/
**'Parameters of the bundle for friction correlations:'
**'X=',f6.3, ' Delt/DT=',f6.3/
if(iboun.eq.1) write(8,237) tout
if(iboun.eq.2) write(8,238) tout
Boundary Condition: Fix coolant flow; Temp. outlet, f8.2
Boundary Condition: Fix outlet flow temperature, f8.2

\[ \text{flow} = 0.001 \times \text{flow} \]
\[ \text{Gt} = \text{flow}/\text{At} \]
\[ \text{flow1} = 0.001 \times \text{flow1}/24. \]
\[ \text{flow2} = 0.001 \times \text{flow2}/12. \]
\[ \text{flow3} = 0.001 \times \text{flow3}/6. \]

Pfraz : Power factor radial-azimuthal
Pfraz=1.
if(iopth.gt.2) Pfraz=Pfacr*Pfacaz

recompute flow according to option
if(iopth.eq.4) flow=flow*Pfraz

\[ \text{Hext} = \text{Hact} + 2 \times \text{Daxi} \]
\[ \text{we} = \text{Hext}/\text{Hact} \]
\[ \text{rij} = \text{pee}/\text{Hext} \]
\[ \text{Pfact} = \text{Pfraz} \times \text{pee}/(2 \times \text{we} \times \sin(0.5 \times \text{pee}/\text{we})) \]
do 182 i=1,npu
\[ \text{zzzz} = \text{Daxi} + (i-1) \times \text{dzet} \]
if(iopth.gt.1) pow(i)=roav*Pfact*sin(rij*zzzz)
if(iopth.eq.1) pow(i)=roav
z(i)=zzzz-Daxi

z(i) (cm) boundaries of the nodes
if(iopth.eq.1) write(8,1264)
1264 format( ' 3-D UNIFORM POWER DISTRIBUTION ASSUMED'/)
if(iopth.eq.2) write(8,1266)
1266 format( ' 2-D (R-THETA) UNIFORM POWER DISTRIBUTION ASSUMED'/)
if(iopth.ge.2) write(8,164) Pfact,Daxi
164 format( ' Cosine Axial Power Distribution=roav*Pfact*Cos(Pi*z/H)'/
          ' Pfact(Axial*Radial*Azim)=' f7.4,' Extrapolated Delta(cm)=' f7.2)
if(iopth.eq.4) write(8,1293)
1293 format( ' Coolant Flow Proportional to Power Density'/)
if(iopth.ne.4) write(8,1295)
1295 format( ' Uniform Coolant Flow Assumed'/)

End calculation coolant conditions

transform pow(i)(Mw/L) to power per unit length (watt/cm)
\[ \text{facto} = 1.0 \times 7 \times \text{pee} \times \text{Rp}^2 \]
do 123 i=1,npu
123 pow(i)=pow(i)*facto
z(i) (cm) boundaries of the nodes
if(ifri.ne.1) write(8,23)
format(’ friction was assumed zero’//)

write(8,253) pin

format(’/ AVERAGE CONDITIONS IN THE BUNDLE’//
"******************************************************************************’//
"************ Inlet Press(MPa), f9.6,”  **************************************************************************’//
"******************************************************************************’//
’//)

write(8,31)

format(’ Node  z(cm)Po(w/cm)  Pr(KPa)  T(K)  (Ts)  V(m/s)  Re’)

c for bundle
  pres(1)=pin*10.**6
  tbulk(1)=tin
  Tbuma(1)=tin
  p=pres(1)
  t=tbulk(1)
  call pli(h,p,t,rho,vis,cp,pr,k,x,O)

c Inlet conditions for cell types 1,2,3
  hi1=h
  hi2=h
  hi3=h

c Average conditions for bundle
  rhoi=rho
  Re=Dt*Gt/vis
  fri=fri(Re)
  ve(1)=Gt/rho

c remember for future use inlet conditions
  hin=h
  echannel=0.
  i=1
  pre=pres(1)*10.**(-3)
  Ts=Ts(pre)
  write(8,41) i,z(i),pow(1),pre,tbulk(i),Ts,ve(i),Re
  facfr=0.

c start analysis bulk conditions

c change units for the flow in each type of cell
  dt1m=0.
  dt2m=0.
  dt3m=0.
  isat=0
  coeRe=coerri

do 30 i=2,npu
  dz=z(i)-z(i-1)
  po= 0.5*(pow(i)+pow(i-1))*dz
  echannel=echannel+po*19.

c outlet of node for cell types 1,2,3 T1,T2,T3

c cell 1 1/2 rod
  h=hi1+po/(2.*flow1)
  p=pres(i-1)
  call pli(h,p,t,rho,vis,cp,pr,k,x,l)
  T1=t
  Tbuma(i)=T1
  hi1=h
  hout=24.*flow1*h

c cell 2 1/2 rod
  h=hi2+po/(2.*flow2)
call pli(h,p,t,rho,vis,cp,pr,k,x,l)
T2=t
hi2=h
hout=hout+12.*flow2*h

c cell 3 1/6 rod
h=hi3+po/(6.*flow3)
call pli(h,p,t,rho,vis,cp,pr,k,x,l)
T3=t
hi3=h
hout=hout+6.*flow3*h
hout=hout/flow

c compute average T in bundle
call pli(hout,p,t,rho,vis,cp,pr,k,x,l)
tbulk(i)=T

c remember max T of cells
dt1=T1-T
if(abs(dt1).gt.dtlm) ilm=i
if(abs(dt1).gt.dt1m) dt1m=dt1
dt2=T2-T
if(abs(dt2).gt.dt2m) i2m=i
if(abs(dt2).gt.dt2m) dt2m=dt2
dt3=T3-T
if(abs(dt3).gt.dt3m) i3m=i
if(abs(dt3).gt.dt3m) dt3m=dt3

c compute voutlet
ve(i)=ve(i-l)*rhoi/rho

c compute pressure
Re=Dt*Gt/vis
if(ifri.eq.0) go to 267
frico=fri(Re)
coeRe=coeRe+coefri
facfr=0.5*(rhoi*Ve(i-1)**2*frici+rho*ve(i)**2*frico)*Pft/2.
267 continue

continue


c end t bulk calculations

c format(i4,2f8.2,f10.2,f8.2,'(',f8.2,'')',f8.2,f8.0)
T1=T+dt1m
T2=T+dt2m
T3=T+dt3m
pl=psa(t1)
p2=psa(t2)
p3=psa(t3)
delp=pl-psa(T)
write(8,360) ilm,dt1m,t1,p1,i2m,dt2m,t2,p2,i3m,dt3m,t3,p3,delp,coe

30 continue

c Check If reactor is underpressurized ,isat=1

c * Re

If reactor is underpressurized ,isat=1

c, if yes write warning
if(isat.eq.0) go to 350
write(8,351) Ti,Ts

351 format('Although ,in a BULK sense, the pressurization is correct'/'
' * the temperature of cell type 1',f10.2/
' * reaches or passes boiling temperature',f10.2/
' * so some flushing is possible.'/
'You might:'/
'1) Increase p at inlet'/'
'2) Reduce T outlet(if iboun=2), or increase flow(if iboun=1)'/
'3) Reduce T inlet'/'
'4) Assume 2D uniform power distribution.'/
'5) Assume flow grading(iopth=4)'/
'6) Use larger bundle(not available yet)''/
if(ichoos==1) stop

2515 write(8,2516)
2516 format(//'************* WARNING *** WARNING *** WARNING *************'/'
'*********** WARNING *** WARNING *** WARNING ***********'/'
'**Despite previous caveats, Program continues with nominal values**'/'

350 continue

c calculation wall temperature and rod temperatures for MAX HEATED ROD
in bundle which is type 1 cell

c Initialization of function RNu
Dummy=RNu(Re,1.,1,pod)
dq=dHe*0.01
G1=flow/ll

...loop on z nodes...

have=0.
TTa=0.
TUN=0.
do 302 i=1,npu
p=pres(i)
t=tbuma(i)

...SEE: we have chosen the highest T (cell 1) Tbuma(i)...
call pli(h,p,t,rho,vis,cp,pr,k,x,0)
Re=G1*dl/vis
c define Peclet number
Pe=Re*Pr
RNu=RNu(Re,Pe,0,pod)
hco=RNu*k/Dt
have=have+hco

rjq=watt/m2
rjq=pow(i)*100./(pee*0.01*drod)
rj(i)=Kw/cm2
rj(i)=rjq*10**(-7)

Qh=watts/m3
Qh=100.*pow(i)/(pee*Rr**2)
Tw(i)=T+rjq/hco

From Twa to Tfuel

Clad=liner
cclad=Rkclad(Twa)
See only one node for the clad
c
Tclad(i)=Tw(i)+rjq*Rr*alog(Rr/Rcl)/cclad
Tclaa(i)=Tw(i)+rjq*(0.5-alog(Rr/Rcl)*Rc1**2/(Rr**2-Rcl**2))/
cclad
if(Tclad(i).gt.TTa) TTa=Tclad(i)
c
delta T across He gap
\begin{align*}
T_g &= T_{clad(i)} \\
T_{gap} &= r_{jq}/h_g \\
T_{gap} &= T_{clad(i)} + r_{jq}/h_g
\end{align*}

temperatures inside pin, npin nodes
\begin{align*}
\text{dr} &= R_p/\text{npin} \\
T_{inl} &= T_{gap} \\
T_{fa} &= 0. \\
\text{do} \ 3021 \ \text{in} = 1, \text{npin} \\
C_{fuel} &= R_k \text{UN}(T_{inl}) \\
\text{rout} &= \text{rnl} - \text{dr} \\
T_{out} &= T_{inl} + 0.25Q_h(r_{inl}^2 - r_{out}^2)/C_{fuel} \\
T_{fa} &= 0.5(T_{out} + T_{inl})*(r_{inl}^2 - r_{out}^2) \\
T_{inl} &= T_{out} \\
T_{rnl} &= T_{rout} \\
\text{3021 continue} \\
T_{fuel(i)} &= T_{out} \\
\text{if} (T_{out} > T_{UN}) \ T_{UN} &= T_{out} \\
T_{fa(i)} &= T_{fa}/R_p^2 \\
\text{302 continue} \\
\text{end loop on } z \text{ nodes pin} \\
\text{drd} &= 10. * \text{drod} \\
\text{dcl} &= (d_{clad} + d_{liner})*10. \\
\text{deHe} &= 1000. * d_g \\
\text{dpin} &= \text{drd} - (\text{dcl} + \text{deHe})*2. \\
\text{write}(8,978) \ \text{drd}, \ \text{dcl}, \ \text{deHe}, \ \text{dpin}
\end{align*}

\textbf{Conditions for Max Heated Rod of the Bundle (Type 1 cell)}
\begin{align*}
\text{write}(8,976) \\
\text{do} \ 2583 \ \text{i} = 1, \text{npu} \\
\text{write}(8,977) \ \text{i}, \ \text{z(i)}, \ \text{rj(i)}, \ \text{tw(i)}, \ \text{Tclad(i)}, \ \text{TcladAv} \\
\text{2583 continue} \\
\text{2977 format}(\text{i5, f10.2, f10.5, 5fi10.2}) \\
\text{calculation of axial averages} \\
\text{if}(\text{TTa} > \text{TmTa} \text{ or } \text{TUN} > \text{TmUN}) \text{ write}(8,2633) \ \text{TTa}, \ \text{TUN}, \ \text{TmTa}, \ \text{TmUN} \\
\text{2633 format} \\
**\text{Max. Temp(K) clad is ', f9.2,' Max. Temp(K) UN is ', f9.2/}
**\text{Ta melts at(K) ', f9.2,' UN melts at(K) ', f9.2/}
**\text{Relax inlet, outlet conditions or assume uniform power or/}
**\text{flow grading//}
\text{zav} = 0 \\
\text{thav} = 0. \\
\text{twa} = 0. \\
\text{tca} = 0. \\
\text{tfa} = 0. \\
\text{do} \ 1436 \ \text{i} = 2, \text{npu} \\
\text{dz} = z(i) - z(i-1) \\
\text{zav} = \text{zav} + \text{dz} \\
\text{phav} = \text{phav} + 0.5*(\text{pres(i)} + \text{pres(i-1)})*\text{dz} \\
\text{twa} = \text{twa} + 0.5*(\text{tw(i)} + \text{tw(i-1)})*\text{dz} \\
\text{tca} = \text{tca} + 0.5*(\text{Tclad(i)} + \text{Tclad(i-1)})*\text{dz} \\
\text{tfa} = \text{tfa} + 0.5*(\text{Tfa(i)} + \text{Tfa(i-1)})*\text{dz}
\end{align*}
thav = thav + 0.5*(tbulk(i) + tbulk(i-1))*dz
roin = roout
thav = thav/zav
phav = phav/zav
twa = twa/zav
tca = tca/zav
tfa = tfa/zav
pre = phav*0.000001

Write(8,1486) pre, thav, twa, have, tca, tfa

Format('// Axial Average Conditions in the Channel'//
* ' Coolant Pressure(MPa)',f8.3,' Temperature(K)',f9.3/
* ' Wall Temperature(K)',f9.3,' Heat Transfer(w/cm2K)',f8.2/
* ' Clad Temperature(K)',f9.3/
* ' Fuel Temperature(K)',f9.3)

dh = hout - hin
dq = echannel/flow
dkin = 0.5*(ve(npu)**2 - ve(1)**2)
rel = dkin/dq
bal = (dh + dkin)/dq
write(8,987) dq, dh, dkin, rel, bal

Format('// HEAT BALANCE FOR THE BUNDLE'//
* 'dQ: heat to coolant (joule/kg)',el4.5/'dH: change of enthalpy l(joule/kg)',el4.5/'dKin change kinetic energy(joule/kg)',el4.5/2' relative dKin/dQ',fl0.6/' Balance (dH+dKin)/dQ',fl4.7)

return
dend

c
friction factor for bundle cooled by liquid metal
function fri(Re)
common /fric/ pod, hod, xx, drel, coefri

c where Re is the Reynold's number

c Novendstern correlation, page 131 ANS book about LMFBR

if(Re.le.1000.) then
fri = 21./Re
coefri = 21./Re**0.75
else
coefri = (1.034/pod**.124+29.7*pod**6.94*Re**.086/hod**2.239)**.855
coefri = 0.079*coefri*xx**1.75/drel**1.25
fri = coefri/Re**0.25
endif
return
dend

c subroutine bisect(xl,x2,xav,fl,f2,fav,iwa)
if((fl*f2).le.0.) go to 11
write(8,1)
1 format('// f1*f2 > 0.//')
iwa = 1
return
11 iwa = 0
if((fav*f1).le.0.) go to 10
f1 = fav
xl = xav
return
10 f2 = fav
x2 = xav
return
dend

c
c Nussel Number for one Phase Flow of liquid metal along fuel elements
c  
function RNu(Re,Pe,ini,pod)
dimension B(4),x(4),cc(6),xx(6)
data (b(i),i=1,4)/7.25,10.65,12.,12.85/
data (x(i),i=1,4)/1.1,1.2,1.3,1.4/
data (cc(i),i=1,6)/.00293,.00253,.002078,.001607,.001194,.000862/
data (xx(i),i=1,6)/1.01,1.2,1.4,1.7,2.2,3.:/
c Where Re and Pe and Reynolds and Peclet numbers evaluated at bulk
c conditions,ini=1 initialize according pod and return. ini=0 compute
c Nussel number after the initialization. Correlation from page 189 ANS
c book about LMFBR's
if(ini.ne.1) go to 10
call Inter(xx,cc,6,pod,C)
if(pod.le.1.35) then
  al=0.80
  call Inter(x,b,4,pod,Cl)
c2=0.025
else
  al=0.86
  c1=6.66+3.126*pod+1.184*pod**2
  c2=0.0155
endif
10 Pr=Pe/Re
eon=C*Re**0.915
psi=1.82/(Pr*eon**1.4)
if(psi.lt.0.) psi=0.
RNu=C1+C2*(psi*Pe)**al
return
end

c Function: Thermal Conductivity of UN
c Source: Alkasys Manual
c  
Function RkUN(Te)
c  
T(K) RkUC (watt/mK)
c  
RkUN=24.
Return
End

c Function: Thermal Conductivity of He gap
c Source: Alkasys Manual
c  
Function Rkgap(T,d)
c  
T(K),d(m) Rkgap (watt/m2K)
c Rkgap=k(He)/d(He),k(He) from ANS book about gas cooled reactors
Rkgap=0.002774*T**0.701/d
Return
End

c Function: Thermal Conductivity of Astar clad and W liner
c Source: Alkasys Manual
c  
Function Rkclad(Te)
c  
T(K) RkUC (watt/cmK)
c Rkclad=57.
Return
End
Subroutine: Interpolate Table

Subroutine Inter(x,y,np,xi,yi)
Dimension x(20), y(20)

if (xi.lt.x(1)) go to 10
if (xi.ge.x(np)) go to 20
i=1
continue
if (x(i).gt.xi) go to 12
i=i+1
continue
go to 30
i=np
yi=y(i-1)+((y(i)-y(i-1))/(x(i)-x(i-1)))*(xi-x(i-1))
return
end

Properties of Li

Subroutine pli(h,p,t,rho,vis,cp,pr,rk,x,iflag)

Thermodynamic and Transport Properties of Lithium
from "Lithium Literature Review: Lithium’s Properties and Interactions"

SI units, T(K)
x=1.

go to 10 if iflag=1 (ie input is p,h)
if (iflag.ne.0) go to 10

Density rho
rho=0.515-0.000101*((T-273.15)-200.)
from g/cm3 to Kg/m3
rho=rho*1000.

Enthalpy h
h=-5.075+1.0008*(T-273.15)-5173./(T-273.15)
from cal/g to Joules/Kg
h=h*4186.8

Specific heat cp
cp=4186.8*(1.0008+5173./(T-273.15)**2)

Viscosity vis
vis=726.07/T-1.3380
vis=10.**(vis)
from centipoise to N/M2sec
vis=0.001*vis

Heat conductivity rk
rk=9.59+0.00455*(T-273.15)
from cal/sec-m-C
rk=rk*4.1868

Prandtl number
pr=vis*cp/rk
return
continue

find T from h

aa=4190.15
bb=-(h+21248.01)
cc=-21658316.
T=(-bb+sqrt(bb*bb-4.*aa*cc))/(2.*aa)
T = T + 273.15
    go to 1
end

***** DESIGN STRENGTH SUBROUTINE *****
Calculation of the Stress that Astar alloy can stand
subroutine from Alkasys

tt(K) Temperature, n=1 or 2 (it does not matter for sigpv)
fpl (years) power life, itma Max number iterations
ipr 1,0 OK, no Ok pressure vessel

subroutine desstr(tt, n, fpl, sigpv, sigrod, itma, ipr)

real tt, nr, tmat, fpl, sigpv, sigrod, rho
real b, c, v, sigma, theta, dtds

integer ii, n
ipr=1
if(tt.ne.0.) then
    if (tt.gt.tmat) then
        rho=.604
        b=67375.0
        c=3.548E9
        nr=1943
        v=.25875
    else
        rho=.31
        b=72614.8
        c=1.995E10
        nr=3768
        v=.03652
    endif
    do ll=1, n
        if (ll.eq.1) then
            theta=fpl*8766.139
        else
            theta=fpl*8766.139/2.
        endif
        sigma=1000
        theta=1/c*exp((b-nr*log(sigma)-v*sigma)/tt)
        ite=0
        dowhile ((abs((theta-theta)/theta)).gt.0.001)
            dtds=-theta*(nr+v*sigma)/sigma/tt
            sigma=sigma+(theta-theta)/dtds
            ite=ite+1
            if(ite.gt.itma) ipr=0
            if(ite.gt.itma) return
        if(sigma.lt.100) sigma=100
        theta=1/c*exp((b-nr*log(sigma)-v*sigma)/tt)
    enddo
    if (ll.eq.1) then
        sigpv=sigma*6.894757e-3
    else
        sigrod=sigma*6.894757e-3
    endif
enddo
sigpv=sigpv/1.5
endif
return
end

!SUBROUTINE DESSTR

*** function to compute thickness neutron shielding
Function Shieldn(fluin, fluout, ish, tw, igam)

common /cross/ AA, BB, signe, ishin, ishig

Fluin, fluout, fast fluxes in/out; ish=1, LiH+SS
  ish=2, B4C; tw(cm) gamma shielding (Tungstene) (if igam.ne.0)

data remLi, remH, remFe, remW, remBC
  * /1.01, 1.00, 1.98, 3.13, 5.1/

removal cross section for fast neutrons of Li, H, Fe, W, B4C

data Av, roLiH, roW, roBC, roFe, roLiss, ALiH, AFe, ABC, AW
  * /0.602202, 0.62, 19.3, 2.52, 7.874, 1.024, 7.95, 55.85, 55.26, 183.85/

sigW=remW*Av*roW/AW

ishin=1
go to(10, 20), ish

xLiH=(roLiss-roFe)/(roLiH-roFe)
xFe=1.-xLiH

sigre=(remLi+remH)*Av*roLiH*xLiH/ALiH+remFe*Av*roFe*xFe/AFe

go to 30

sigre=remBC*Av*roBC/ABC

aa=alog(fluin/fluout)/sigre

if(aa.le.0.) ishin=0

bb=sigW/sigre

signe=sigre

Shieldn=aa-bb*tw

return

end

Subroutine to calculate Gamma source

Subroutine Gamso(Sn, sogam, PrU, fvr)

common /Conce/ coBe, coTa, coU5, coU8, coLi, coW, coRe, coHf, coHe, coN, coO

Input: Sn(I/s): neutron production, fvr: volume fraction of reflector

Output:

sogam(1): Gamma source between "0" and 1 Mev
  (2):    1 and 2
  (3):    2 and 3
  (4):    3 and 5
  (5):    5 and 7
  (6):    7 and 9
  (7):    > around 9 Mev

and PrU(): fractions of gammas produced in U

Dimension Sogam(7), Pf(7), FP(7), GLi(7), GO(7), GTa(7), GBe(7),
  *GU(7), GRe(7), GHf(7), GW(7), GN(7), PrU(7)

Pf: Prompt Fission Gammas; FP: Fission Products Gammas (Both, Per Fiss)

GNI to GCr: Captures Gammas (per Event) for indicated Elements Ni,. . . Cr

Data from ANL-5800 page 631. For O: the 8 Mev released for the capture
  of one neutron was uniformly distributed in range 0-10 Mev.

See: capture in O is almost 0.0; Remember B10 has (n, alpha) rather (n,g)

Data(Pf(i), i=1,7) /3.1, 2.11, .73, .26, .0428, 0., 0./

Data(Fp(i), i=1,7) /9.03, 1.37, 4., 0., 0., 0., 0./

Data(GLi(i), i=1,7) /0., 0., 0., 0., 0., 0., 0./

Data(GTa(i), i=1,7) /1.37, 0.99, 0.66, 0.55, 0.05, 0., 0./

Data(GW(i), i=1,7) /0.68, 0.82, 0.59, 0.53, 0.15, 0.005, 0./

Data(GRe(i), i=1,7) /1.24, 0.88, 0.62, 0.51, 0.105, 0., 0./

Data(GHf(i), i=1,7) /1.37, 1.37, 0.85, 0.52, 0.12, 0.005, 0./

Data(GN(i), i=1,7) /0.0, 0., 0., 0., 0.54, 0.11, 0.15, 0.12/

Data(GO(i), i=1,7) /0.16, 0.16, 0.16, 0.32, 0.32, 0.32, 0.16/

Data(GBe(i), i=1,7) /0., 0., 54., 73., 0., 0./

Data(GU(i), i=1,7) /2.54, 1.78, 0.91, 0.34, 0., 0.0.41/

Data Rnu/2.52/

Data scLi, scTa, scW, scRe, scHf, scN, scO, scBe, scUS, scU8
See: Total number of Absorptions = Sn(Total production)

F: total number of fission
F5: ...... in U235
F8: ...... in U238

C5: total number of captures in U235
C8: ...... in U238

Ct: ...... captures (code assumes reactor is well reflected)
F = Sn/Rnu
sif = coU5*sfU5 + coU8*sfU8
F5 = F*coU5*sfU5/sif
F8 = F*coU8*sfU8/sif
C5 = F5*(scU5/sfU5)
C8 = F8*(scU8/sfU8)
Ct = Sn - F

distribute Ct in rest of materials
assume average flux in core, pressure vessel and half that flux for the reflector, then disadvantage factor are

disc = 1./(1-0.5*fVR)
disr = 0.5*disc
den = disc*(coLi*scLi+coTa*scTa+coW*scW+coRe*scRe+coHf*scHf+coN*scN+
* coU5*scU5+coU8*scU8)+disc*(coO*scO+coBe*scBe)
CLi = Ct*(coLi*scLi/den)
CTa = Ct*(coTa*scTa/den)
CW = Ct*(coW*scW/den)
CRe = Ct*(coRe*scRe/den)
CHf = Ct*(coHf*scHf/den)
CN = Ct*(coN*scN/den)
CO = Ct*(coO*scO/den)
CBe = Ct*(coBe*scBe/den)
Do 10 i = 1,7
GamU = F*(Pf(i)+Fp(i))+(C5+C8)*GU(i)
Sogam(i) = GamU + CLi*GLi(i) + CW*GW(i) + CTa*GTa(i) + CBe*GBe(i) + CRe*GRe(i) + CO*GO(i) + CHf*GHf(i) + CN*GN(i)
PrU(i) = 100.*GamU/Sogam(i)
continue
return
end

Subroutine Shieldga(Sogam,Dose,Dosea,Dosew,tiempo,tgam,ten,igam,
*ishn,iten)
Common /CROSS/ AA, BBB, signe, ishin, ishig

Shieldga: Computes gamma shielding
Sogam(i), i = 1, 7 Gamma Source (photons/sec); Dose(rad): Integrated
Dose at load area; Dosew(rad): Dose without the shielding
dosei: dose for tgam
igam: flag if = 1 problems with iterations
Tgam(cm): Thickness of Tungsten
ten(cm): thickness of n shielding, ishn = 1, LiH, ishn = 2, B4C
ten/0, 1/ if ten is input, ten isiterated by this subroutine/
tgam: iterated, if necessary, to have Dose = input
Index(1): Gamma Processes between "0" and 1 Mev
(2): 1 and 2
(3): 2 and 3
(4): 3 and 5
(5): 5 and 7
(6): 7 and 9
(7): > around 9 Mev
common /CROSS/ coBe, coTa, coU5, coU8, coLi, coW, coRe, coHf, coHe, coN, coO
**common /Gamsh/**

*dist,Reg,shg(7),shgnb(7),Zeq(7),Dosewg(7),Doseg(7),itmag,epsg*
*aten,Dosen,Doseng(7)*

dimension Sogam(7),GBe(7),GW(7),GO(7),GU(7),GH(7),GC(7),GFe(7),
*b(4,7),a3(4,7),a4(4,7),zb(4),a(4),al(4),a2(4),rh(7)*
*ega(7),sign(7),An(7),A1n(7),A2n(7)*

data (GH(i),i=1,7)/0.173,0.103,0.0876,0.0579,0.0446,0.0371,0.0321/
data (GC(i),i=1,7)/0.087,0.0518,0.0444,0.0304,0.0245,0.0213,0.0194/
data (GFe(i),i=1,7)/.087,0.0518,0.0445,0.0309,0.0254,0.0224,0.0206/
data (GBe(i),i=1,7)/.0773,.0459,.0394,.0266,.0211,.0180,.0161/
data (GW(i),i=1,7)/.125,.0492,.0437,.0402,.0418,.0438,.0465/
data (GO(i),i=1,7)/.087,.0518,.0445,.0309,.0254,.0224,.0206/
data (GU(i),i=1,7)/.176,.0548,.0484,.044,.0455,.0479,.0511/

c GBE...GU are the total mass attenuation coefficients(cm**2/g)
c for the 7 gamma groups. Li(Z=3) and B(Z=5) are lumped with Be(Z=4)
c Ta(Z=73),Re(Z=75) and Hf(Z=72) are lumped with W(Z=74)
c N(Z=7) is lumped with O(Z=8)

data (b(1,j),j=1,7)/8.,5.5,4.5,3.8,3.1,2.3,2.25/
data (b(2,j),j=1,7)/10.,8.,5.5,3.75,2.9,2.35,2.0/
data (b(3,j),j=1,7)/3.3,2.9,2.7,2.05,1.2,7,6/
data (b(4,j),j=1,7)/1.65,2.45,2.15,1.65,96,.67,5/

data (a3(1,j),j=1,7)/.11,.082,.074,.066,.064,.062,.060/
data (a3(2,j),j=1,7)/.0948,.0895,.0788,.075,.0825,.0833,.095/
data (a3(3,j),j=1,7)/.043,.069,.086,.118,.171,.205,.212/
data (a3(4,j),j=1,7)/.032,.045,.097,.123,.175,.204,.214/

data (a4(1,j),j=1,7)/.044,.093,.116,.130,.152,.150,.128/
data (a4(2,j),j=1,7)/.012,.04,.07,.082,.075,.0546,.0116/
data (a4(3,j),j=1,7)/.148,.188,.134,.070,.0,.052,.144/
data (a4(4,j),j=1,7)/.296,.178,.103,.064,.059,.067,.08/

data (zb(i),i=1,4)/13.,26.,74.,82./

c b(i,j),a2(i,j) and a4(i,j) are build up parameters for groups j
c and atomic number Z=Zb(i)

data (rh(i),i=1,7)/4.5e+5,5.5e+5,7.e+5,8.e+5,8.5e+5,9.e+5,1.e+6/

c rh(i) Gamma Flux Mev/cm2/sec that produces 1 Roentgen/hour

data (Ega(i),i=1,7)/0.5,1.5,2.5,4.,6.,8.,10./

c ega(i) Mev Average Energy of gamma group i

data ABe,ATa,AW,AHf,AUS,AUB,ALi,ARE,ANi,Av,RoW*
9.0122,180.948,183.85,15.9994,178.49,235.044,238.0508,6.939,186.2*
14.0067,0.602202,19.3/
data ZBE,ZTa,ZN,ZU,pee,ZLi,ZBo,ZRe,ZHf,ZN,ZO*
4./,73.,74.,92.,3.141593,3.5.,75.,72.,7.,8./

data roLiH,roBC,roSS,roLiS /0.82,2.92,7.874,1.024/igam=1
ishg=1
xLiH=(roLiS-roSS)/(roLiH-roSS)
xSS=1.-xLiH

c Attenuation*Build Up factor for N Shield(which also shield gammas)
c
do 101 j=1,7
go to(111,222),ishn
c ishn=1 LiH+SS
111 sig=roLiS*(xLiH*0.8732*GBe(j)+xLiH*0.1268*GH(j)+xSS*GFe(j))
sigZ = RoLiS * (ZLi * xLiH * 0.8732 * GBe(j) + ZH * xLiH * 0.1268 * GH(j) + ZFe * xSS * GF)
* e(j))
ZZ = sigZ / sig

222

sig = RoBC * (0.7826 * GBe(j) + 0.2174 * GC(j))
sigZ = RoBC * (ZBo * 0.7826 * GBe(j) + ZC * 0.2174 * GC(j))
ZZ = sigZ / sig

222 c ZZ is "equivalent Z for build up factor"
333 do 444 i = 1, 4
a(i) = b(i, j)
444 a2(i) = a4(i, j)
c interpolate in table as function of Z,
Call Inter(zb, a, 4, zz, am)
Call Inter(zb, a1, 4, zz, a3)
Call Inter(zb, a2, 4, zz, a12)
A(n)(j) = am
A1(n)(j) = a12
A2(n)(j) = a1
sign(j) = sig

101 continue

c end Calculation Attenuation/build up factor for n shield

c Start Calculation Self Shielding in Reactor

do 10 j = 1, 7

do 20 i = 1, 4
a(i) = b(i, j)
20 a1(i) = a3(i, j)
a2(i) = a4(i, j)
sig = coBe * ABe * GBe(j) + coTa * ATa * GW(j) + coO * AO * GO(j)
* + coHf * AHf * GW(j) + coU5 * AU5 * GU(j)
* + coRe * ARE * GW(j) + coLi * ALi * GBe(j) + coW * AW * GW(j)
* + coN * AN * GO(j)

sig = sig / Av
ZZ = coBe * ABe * GBe(j) * ZBe + coTa * ATa * GW(j) * ZTa + coO * AO * GO(j) * ZO
* + coHf * AHf * GW(j) * ZHf + coU5 * AU5 * GU(j) * ZU + coU8 * AU8 * GU(j) * ZU
* + coRe * ARE * GW(j) * ZRe + coLi * ALi * GBe(j) * ZLi + coW * AW * GW(j) * ZW
* + coN * AN * GO(j) * ZO
ZZ = ZZ / Av
zz = zz / sig
Call Inter(zb, a, 4, zz, am)
Call Inter(zb, a1, 4, zz, a3)
Call Inter(zb, a2, 4, zz, a12)
Zeq(j) = zz
b1 = 2. * sig * Req * (1. - a1)
b2 = 2. * sig * Req * (1. + a1)
exp1 = 0.
exp2 = 0.
if(b1.lt.50.) exp1 = exp(-b1)
if(b2.lt.50.) exp2 = exp(-b2)
shg(j) = 3. * Am * (0.5 - (1. - exp1 * (1. + b1)) / b1**2) / b1 +
* 3. * (1. - Am) * (0.5 - (1. - exp2 * (1. + b2)) / b2**2) / b2
bb = 2. * sig * Req
expo = 0.
if(bb.lt.50.) expo = exp(-bb)
shgnb(j) = 3. * (0.5 - (1. - expo * (1. + bb)) / bb**2) / bb

10 continue

c End Calculation Self shielding

c c Dosew and Dosewg() are the doses without any shield(n or gamma)
c Dosen and Doseng() are the doses without W(gamma shield) but inclu-
c ding the shielding effects of the neutron shield(either input or itera-
```fortran
     cted
     time=tiempo/3600.
     Dosew=0.
     Dosen=0.
     if(iten.eq.1) ten=AA
     if(iten.eq.1.and.ishin.eq.0) ten=0.
     do 30 i=1,7
     tsn=Sign(i)*ten
     Shin=exp(-tsn)*(An(i)*exp(-tsn*Aln(i))+(1.-An(i))*exp(-tsn*A2n(i))
     Dosewg(i)=time*Sogam(i)*shg(i)*Ega(i)/(4.*pee*dist**2*rh(i))
     Doseng(i)=Shin*Dosewg(i)
     Dosen=Dosen+Doseng(i)
     if(Dosen.le.Dose) ishig=0
     if(ishig.eq.0) tgam=0.
     if(ishig.eq.0) return
     30 continue
     c c Return if there is no need for gamma shield (thick W=0.)
     c
t1=0.
     Dosl=Dosen
     f1=Dosl-Dose
     c c Starts iteration on tgam:
     c c First look for
     c t2 such that Dose(t2) <Dose
     c
     it=0
     sig=GW(1)*RoW
     t2=alog(Dosewg(1)/Dose)/sig
     51 continue
     dose2=0.
     do 40 i=1,7
     am=b(3,i)
     all=-a3(3,i)
     al2=a4(3,i)
     sig=GW(i)*RoW
     BFA=am*exp(-all*sig*t2)+(1.-am)*exp(-al2*sig*t2)
     dose2=dose2+Dosewg(i)*exp(-sig*t2)*BFA
     if(dose2.1t.dose) go to 50
     t2=1.01*t2
     it=it+1
     if(it.le.itmag) go to 51
     igam=0
     write(8,*) ' Problem with Calculation of Gamma Shielding'
     continue
     f2=Dose2-Dose
     if(igam.eq.0) return
     it=0
     tgam=0.5*(t1+t2)
     dosea=0.
     do 41 i=1,7
     am=b(3,i)
     all=-a3(3,i)
     al2=a4(3,i)
     sig=GW(i)*RoW
     BFA=am*exp(-all*sig*tgam)+(1.-am)*exp(-al2*sig*tgam)
     40 continue
     f2=Dose2-Dose
     if(it2.eq.0) return
     it=0
     50 continue
     tgam=0.5*(t1+t2)
     dosea=0.
     do 41 i=1,7
     am=b(3,i)
     all=-a3(3,i)
     al2=a4(3,i)
     sig=GW(i)*RoW
     BFA=am*exp(-all*sig*tgam)+(1.-am)*exp(-al2*sig*tgam)
     c c recompute neutron shielding(ten) because W also shield neutrons
     c see: if ten<0. program set ten to 0.(ie no need of n shielding
     c because W is enough also if ishin=0(fluin it prescribed fluout)
     c
     if(iten.eq.1) ten=AA-BBB*tgam
     if(ten.lt.0.) ten=0.
     if(iten.eq.1.and.ishin.eq.0) ten=0.
     tsn=Sign(i)*ten
     Shin=exp(-tsn)*(An(i)*exp(-tsn*Aln(i))+(1.-An(i))*exp(-tsn*A2n(i))
```

Doseg(i) = Dosewg(i) * exp(-sig*tgam) * BFA * Shin

dosea = dosea + Doseg(i)

c recompute n shielding, because it might be smaller than input max flu-
ence

eco = (ten + BBB * tgam) * signe
aten = exp(-eco)
fa = Dosea - Dose
rel = abs(dosea - dose) / dose
if (rel .le. epsg) go to 60

! call Bisect(tl, t2, tgam, f1, f2, fa, iwa)
! it = it + 1
! if (it .le. itmag .and. iwa .ne. 1) go to 61
igam = 0
write(8, *) ' Problems with calculation of Gamma Shielding'
60 continue
return
end

C Compute the two solutions, d1 and d2, that produce energy E(Mwd)
C inputs: asymptotic(das) and optimum(dop) sizes for enrichment enr
C and p/d pod
C output: d1 and d2

Subroutine Size(das, dop, E, enr, pod, d1, d2)

common /Szoe/ its, epss
common /MaBaSi/ R, H, ishape

C left side limit
C
ri = 1.
it = 0
10 xl = das * (1. + 0.01 / ri)
   if (ishape .eq. 2) R = x1
   if (ishape .eq. 3) H = x1
   el = Balance(ibu, enr, pod) - E
   if (el .gt. 0.) go to 20
   ri = ri + 1.
   it = it + 1
   if (it .gt. its) go to 100
   go to 10
20 x2 = dop
   if (ishape .eq. 2) R = x2
   if (ishape .eq. 3) H = x2
   e2 = Balance(ibu, enr, pod) - e
   it = 0
35 xav = 0.5 * (xl + x2)
   if (ishape .eq. 2) R = xav
   if (ishape .eq. 3) H = xav
   Ea = Balance(ibu, enr, pod) - e
   test = abs(Ea) / E
   if (test .le. epss) go to 50
   call bisect(xl, x2, xav, E1, E2, Ea, iwa)
   it = it + 1
   if (iwa .eq. 1) go to 100
   if (it .gt. its) go to 50
   go to 35
50 dl = xav
C right side limit
C
xl = dop
   if (ishape .eq. 2) R = x1
if(ishape.eq.3) H=x1
E1=Balance(ibu,enr,pod)-e
it=0
x2=x1*(1.+0.10)**(it+1)
if(ishape.eq.2) R=x2
if(ishape.eq.3) H=x2
e2=Balance(ibu,enr,pod)-e
if(e2.gt.0.) go to 31
it=it+1
if(it.gt.its) go to 100
go to 41
31 it=0
36 xav=0.5*(x1+x2)
if(ishape.eq.2) R=xav
if(ishape.eq.3) H=xav
Ea=Balance(ibu,enr,pod)-e
test=abs(Ea)/E
if(test.le.epss) go to 51
call bisect(xl,x2,xav,E1,E2,Ea,iwa)
it=it+1
if(it.gt.its.or.iwa.eq.1) go to 100
go to 36
51 d2=xav
return
100 write(8,101) it
101 format(//' Program stop at subroutine Size'/'' iterations=',i0)
stop
end

c Subroutine bupo
c
Subroutine bupo(bup,rkin,c50,c80,dka)
common /mabu/ c5,c8,c9,p9,cfp,ftin
c
input: bup(burnup, fraction), rkin(k Infinity), c50,c80(1/cmbarn) initial
concentration of U235 and U238
c
output: dka(%, and modulus) reactivity effects of burnup
c
concentration(U235, and Fission Prod) at EOL
ftin: fluence at EOL, p9: total production of Pu239
dimension flutin(20),buta(20)
data rnu5,rnu8,rnu9/2.52,2.61,2.91/
data sa5,sa8,sa9,sa9/1.6646,0.2733,2.11,0.57/
data sf5,sf8,sf9/1.4400,0.11201,1.70/
data sc8/0.1613/
c compute table BU vs integrated flux
enr=c50/(c50+c80)
e5=sf5/sa5
e8=sf8/sa8
a8=e8*(1./enr-1.)
a9=sa8*(1./enr-1.)/(sa9-sa8)
a91=sf9/sa8
e9=sf9/sa9
nbu=20
dft=1./(sa5*19)
do 20 i=1,nbu
ftin=(i-1)*dft
flutin(i)=ftin
20 buta(i)=e5*(l.-exp(-sa5*ftin))+(A8+A9*A91)*(l.-exp(-sa8*ftin))- A9*e9*(l.-exp(-sa9*ftin))
call Inter(buta, flutin,nbu,bup,ftin)
srest=c50*(rnu5*e5/rkin-1.)*sa5+c80*(rnu8*e8/rkin-1.)*sa8
c5=c50*exp(-sa5*ftin)
c8=c80*exp(-sa8*ftin)
\[
c_9 = \left(\frac{c_8 c_{80}}{(s_{a9} - s_{a8})}\right) \left(\exp(-s_{a8} \cdot ftin) - \exp(-s_{a9} \cdot ftin)\right)
\]
\[
p_9 = (c_{80} - c_8) \frac{s_{c8}}{s_{a8}}
\]
\[
c_{fp} = 2 \cdot (c_{50} \cdot s_{f5} + c_{80} \cdot s_{f8}) \cdot ftin
\]
\[
c_{fp} = 2 \cdot (c_{50} - c_5) \cdot e_5 + (c_{80} - c_8) \cdot e_8 + (p_9 - c_9) \cdot e_9
\]
\[
r_{kinbu} = \frac{(rnu_5 \cdot c_5 \cdot s_{f5} + rnu_8 \cdot c_8 \cdot s_{f8} + rnu_9 \cdot c_9 \cdot s_{f9})}{(c_5 \cdot s_{a5} + c_8 \cdot s_{a8} + c_9 \cdot s_{a9} + c_{fp} \cdot s_{afp} + s_{rest})}
\]
\[
d_{ka} = \frac{r_{kinbu}}{r_{kin} - 1.}
\]
dka = -100 \cdot dka
return
end
### Title and Subtitle
Scoping Calculations of Power Sources for Nuclear Electric Propulsion

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### Abstract
This technical memorandum describes models and calculational procedures to fully characterize the nuclear island of power sources for nuclear electric propulsion. Two computer codes were written: one for the gas-cooled NERVA derivative reactor and the other for liquid metal-cooled fuel pin reactors. These codes are going to be interfaced by NASA with the balance of plant in order to making scoping calculations for mission analysis.

### Subject Terms
Nuclear electric propulsion, Reactor modeling, Liquid metal cooled reactor, Gas cooled reactor