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**OAK RIDGE
NATIONAL
LABORATORY**

MARTIN MARIETTA

Scoping Calculations of Power Sources for Nuclear Electric Propulsion

F. C. Difilippo

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CALCULATIONS OF POWER SOURCES FOR
NUCLEAR ELECTRIC PROPULSION (ORNL)
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Engineering Physics and Mathematics Division

**SCOPING CALCULATIONS OF POWER SOURCES
FOR NUCLEAR ELECTRIC PROPULSION**

F. C. Difilippo

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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_4C 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 pyrolytic 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 data base 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 XSDRNPM¹ 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}U) in the fuel element and the number of support-to-fuel-elements ratio. A plot of the critical mass of ^{235}U and the mass of the core plus the 24-cm reflector is presented in Fig. 1 showing that beyond ~ 500 g of ^{235}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 $^{235}\text{U}/\text{L}$ fuel; the database depends then on S/F alone.

4.1.1 Neutronic Properties of the Core

Multiplication constants, k_∞ , 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 $^{235}\text{U}/\text{L}$ of fuel.

4.1.3 Reactivity Worth of Burn-Up

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

Sheet	Δk (%)	$(\Delta k/\Delta k)_{\max}$
2 mm Nat B	21.0	0.70
2 mm 80% B	24.0	0.80
5 mm 90% B	25.9	0.86

*Core: S/F = 0, R_c = 59.25 cm, H_c = 109.11. Reflector: 30 cm Be $(\Delta k)_{\max}$ = 30.14% (removing the Be reflector).

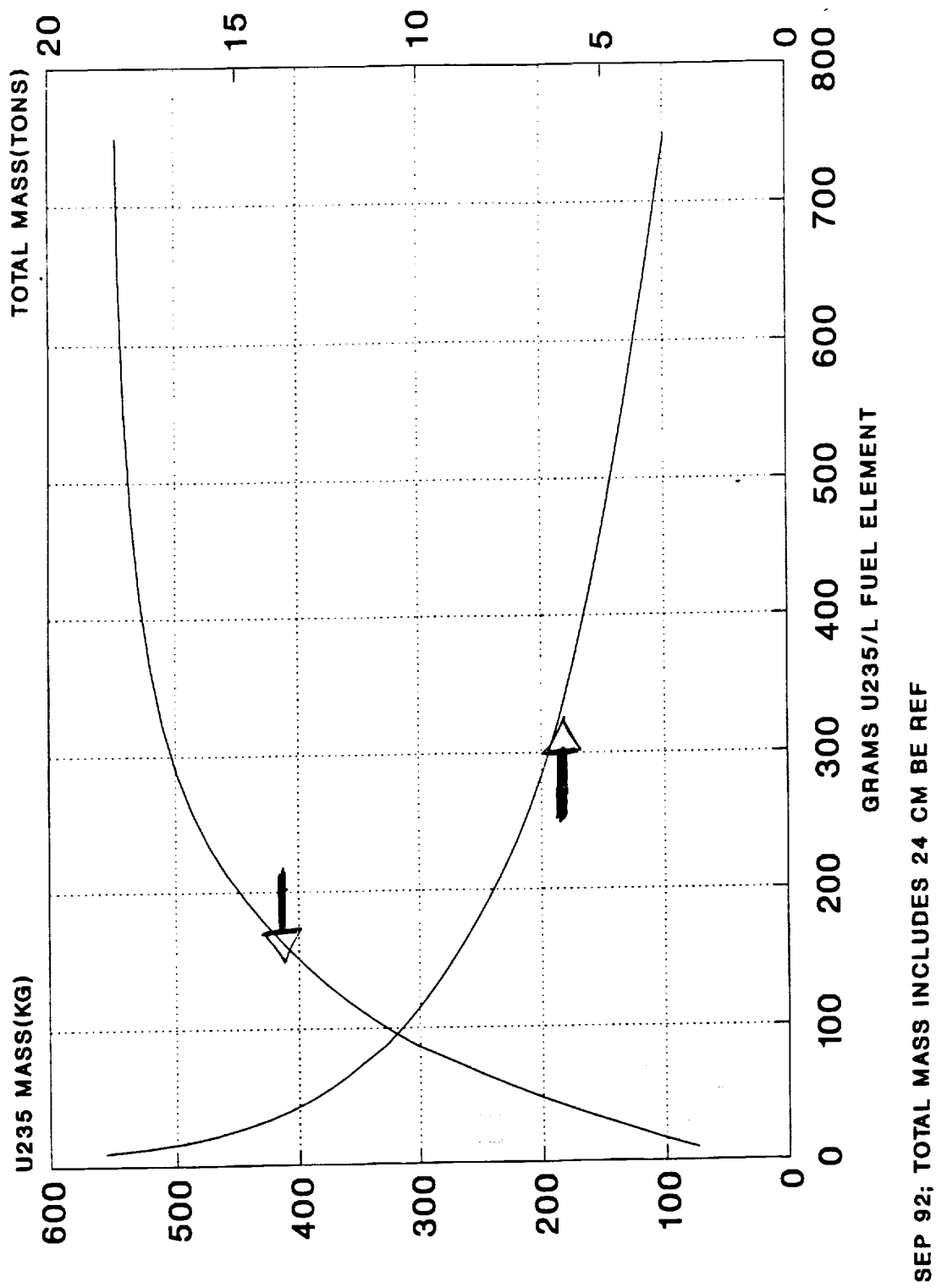


Fig. 1. ^{235}U critical mass of the core and mass of the core plus reflector for the NERVA derivative reactor.

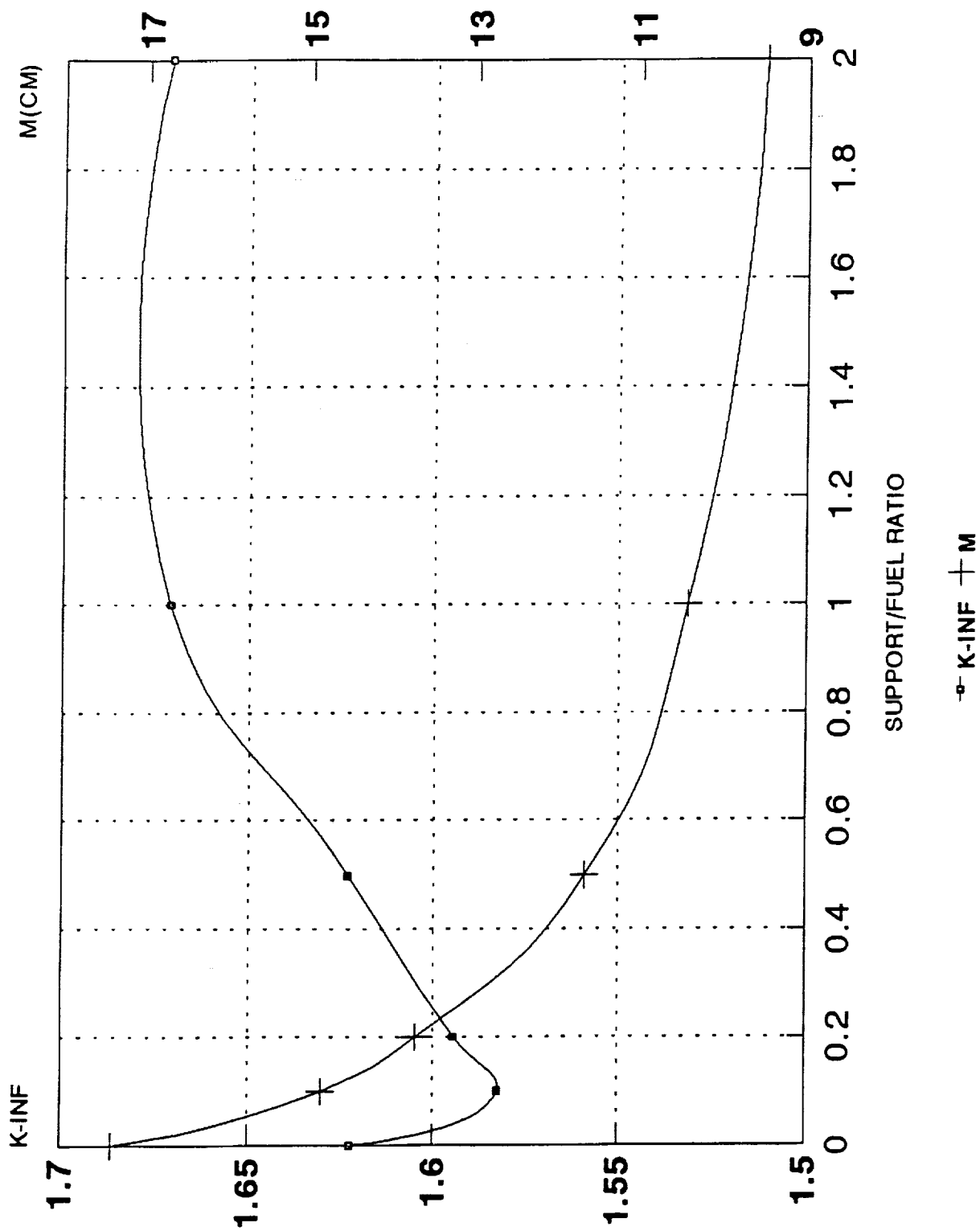
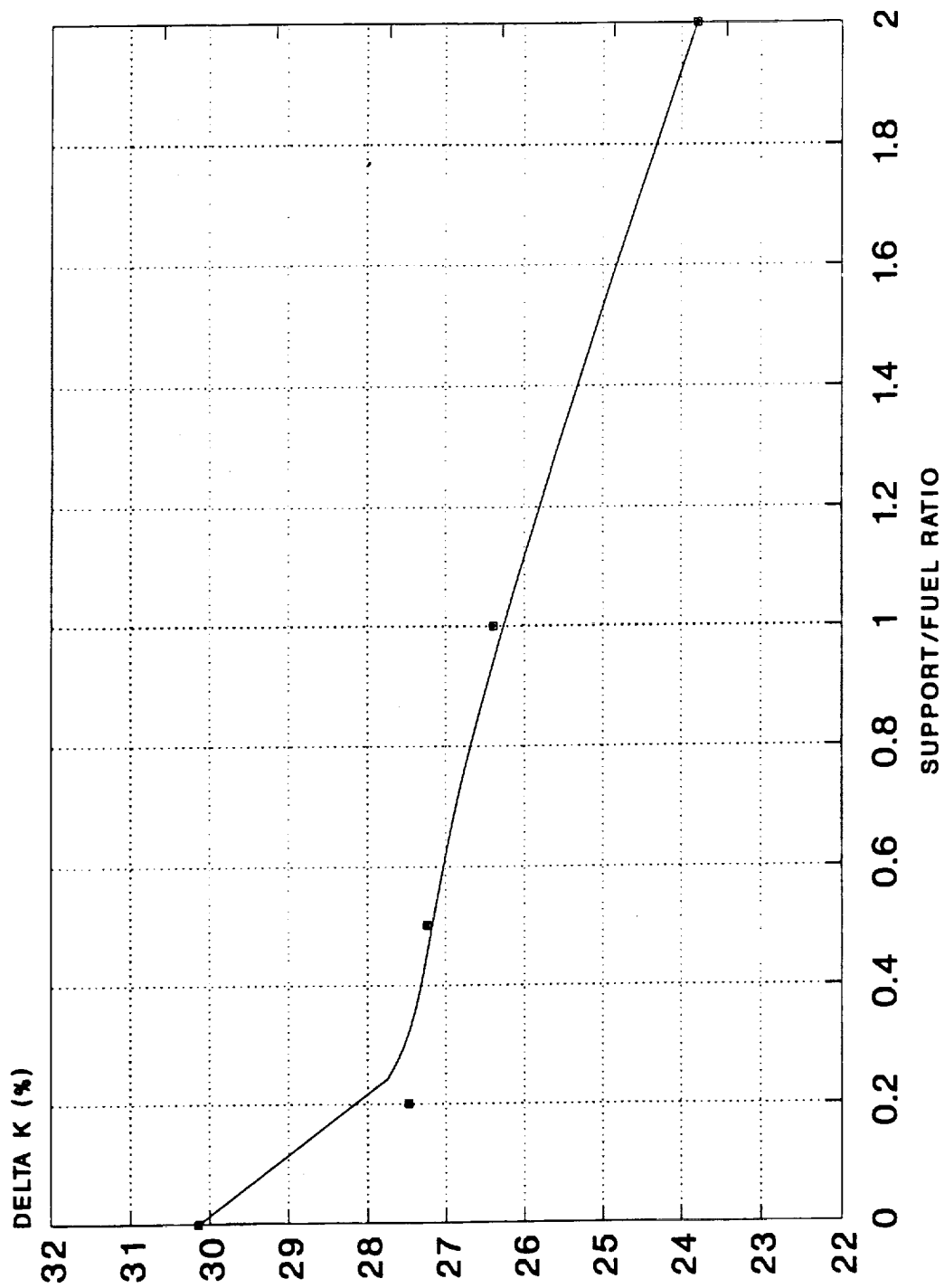


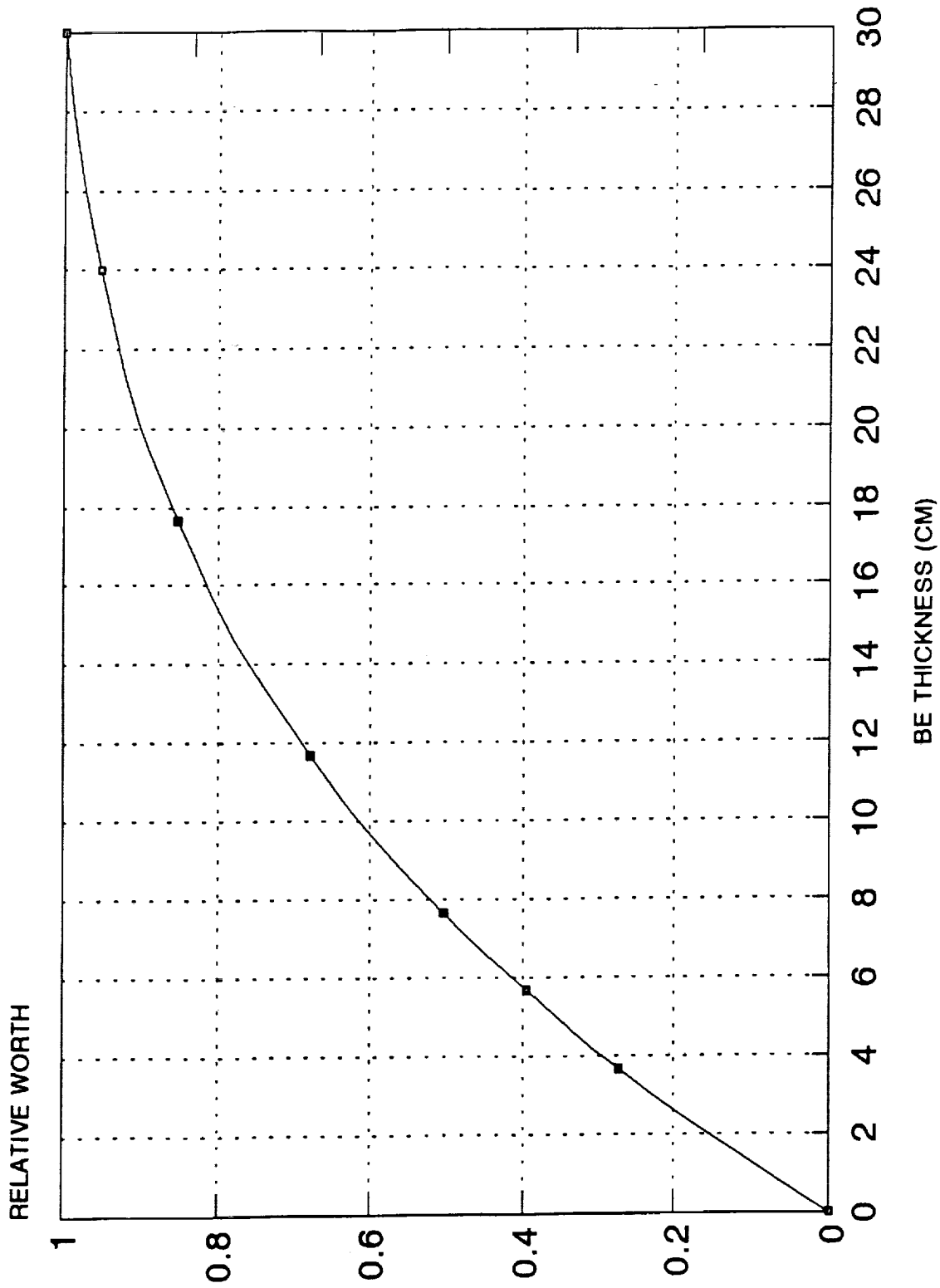
Fig. 2. k_{∞} and migration length for the NERVA derivative core.

500 GU5/L



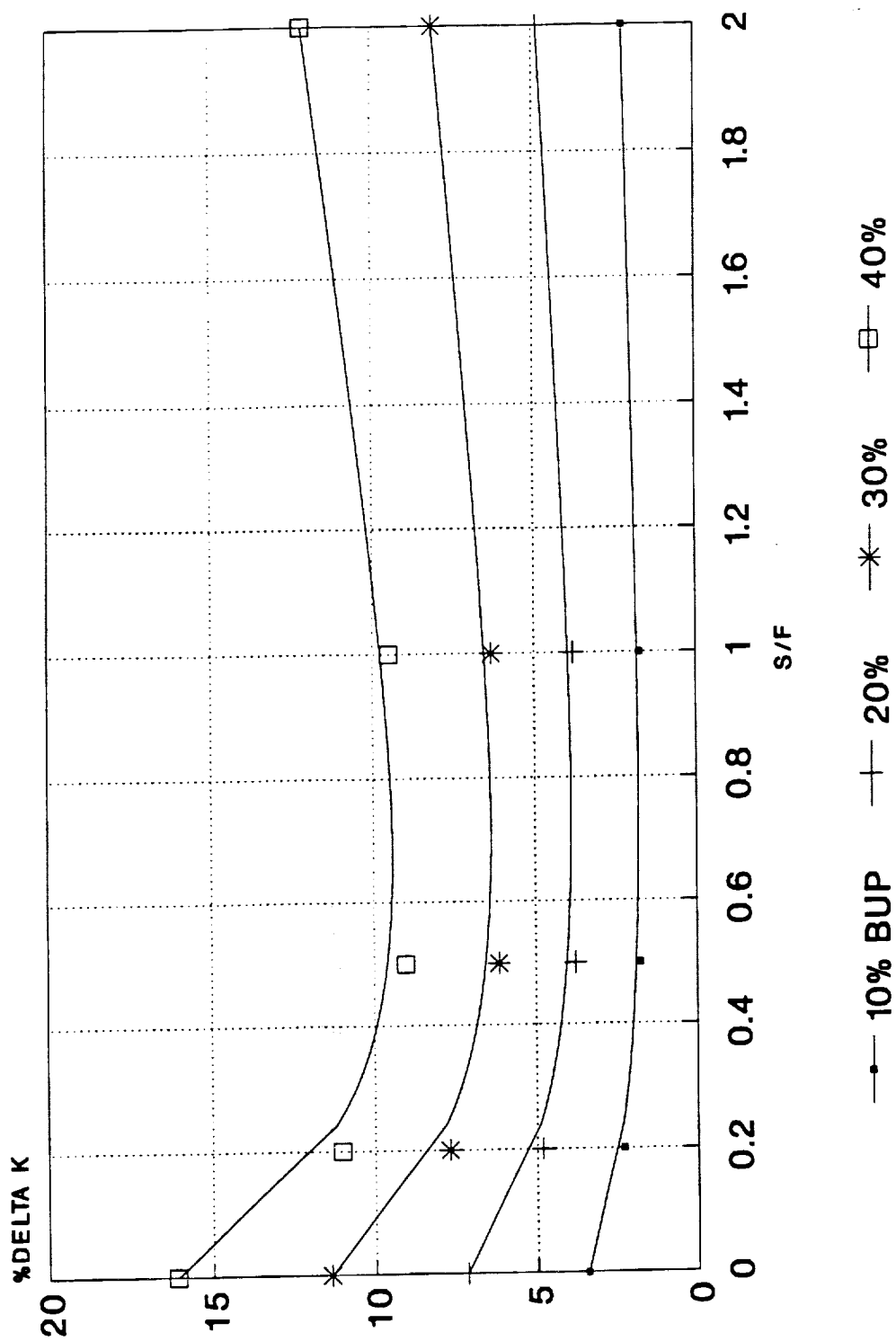
9-92

Fig. 3. Reactivity effects of a 30 cm thick radial Be reflector.



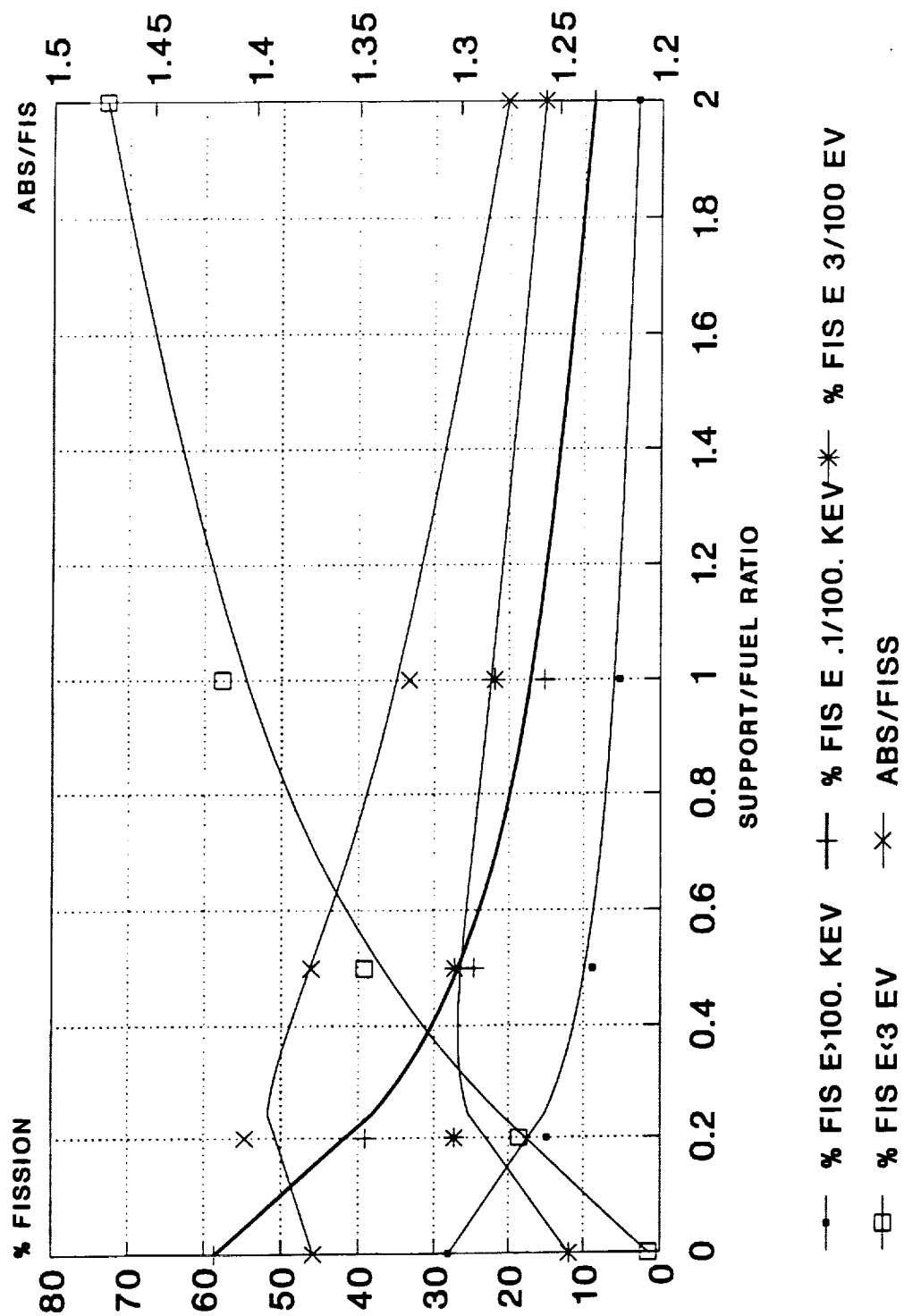
9-92; SUPP/FUEL ELEM=0.195; RCORE=48.33CM

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



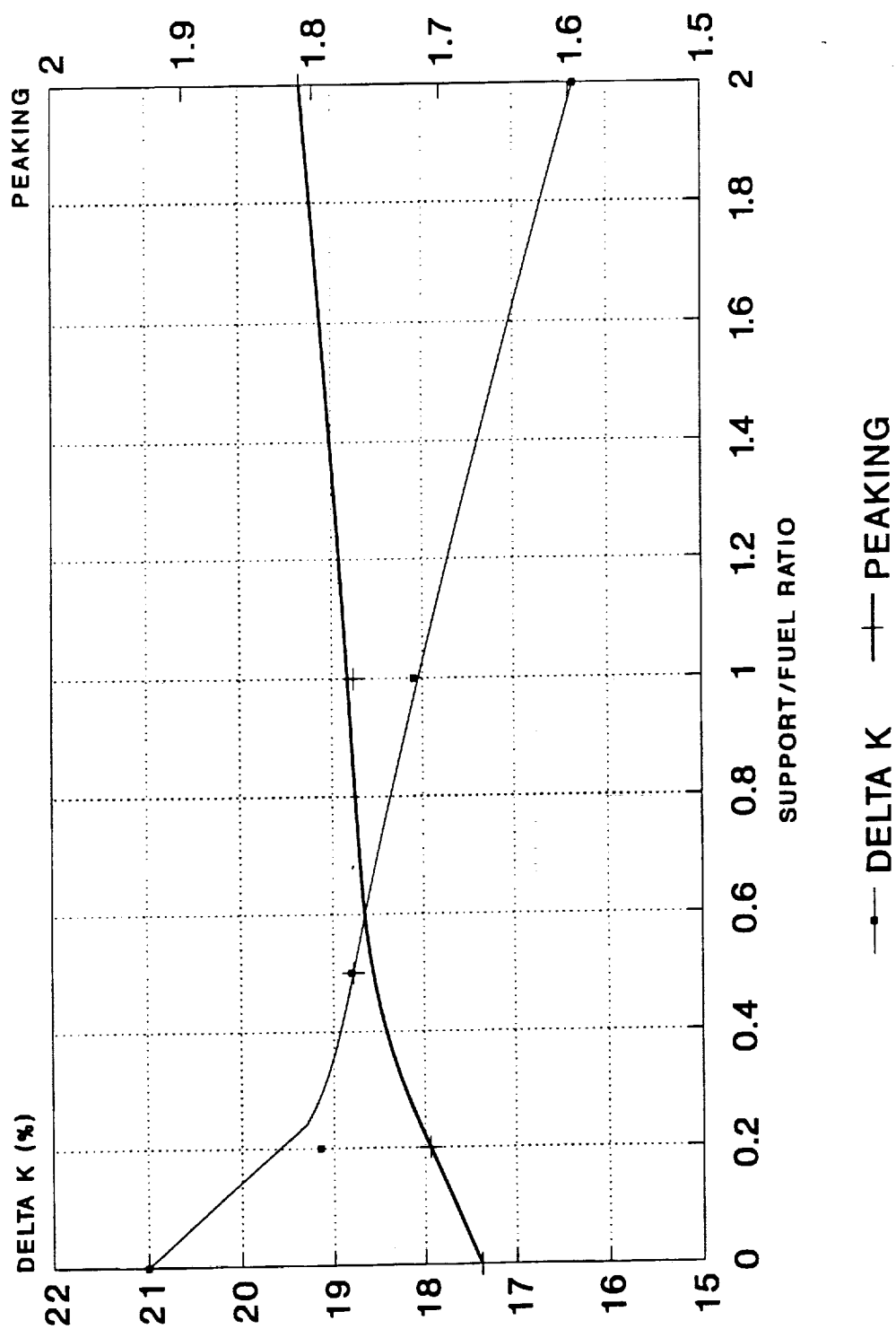
SEP 92; 500 G U235/L FUEL

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



500 GU5/L;30.CM BE; 2MM B4C

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



500 GU5/L;30.CM BE; 2MM B4C

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_{∞} 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 2. Reactivity worth (%) of 25 cm BeO reflector for the fuel pin core

P/d	Enrichment (%)				
	93.0	80.0	70.0	60.0	50.0
1.1	19.26	17.26	15.28	12.78	9.57
1.2	18.57	16.30	14.11	11.40	8.04
1.3	17.65	15.18	12.85	10.02	6.58
1.4	16.61	13.99	11.55	8.65	5.22
1.5	15.50	12.76	10.25	7.32	3.95

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:

$$\Delta k(BU) = k(BU) - k(0) = \frac{k_{\infty}(BU)}{k_{\infty}(0)} - 1 \quad (1)$$

NASA Parametrics K-infinity vs P/D

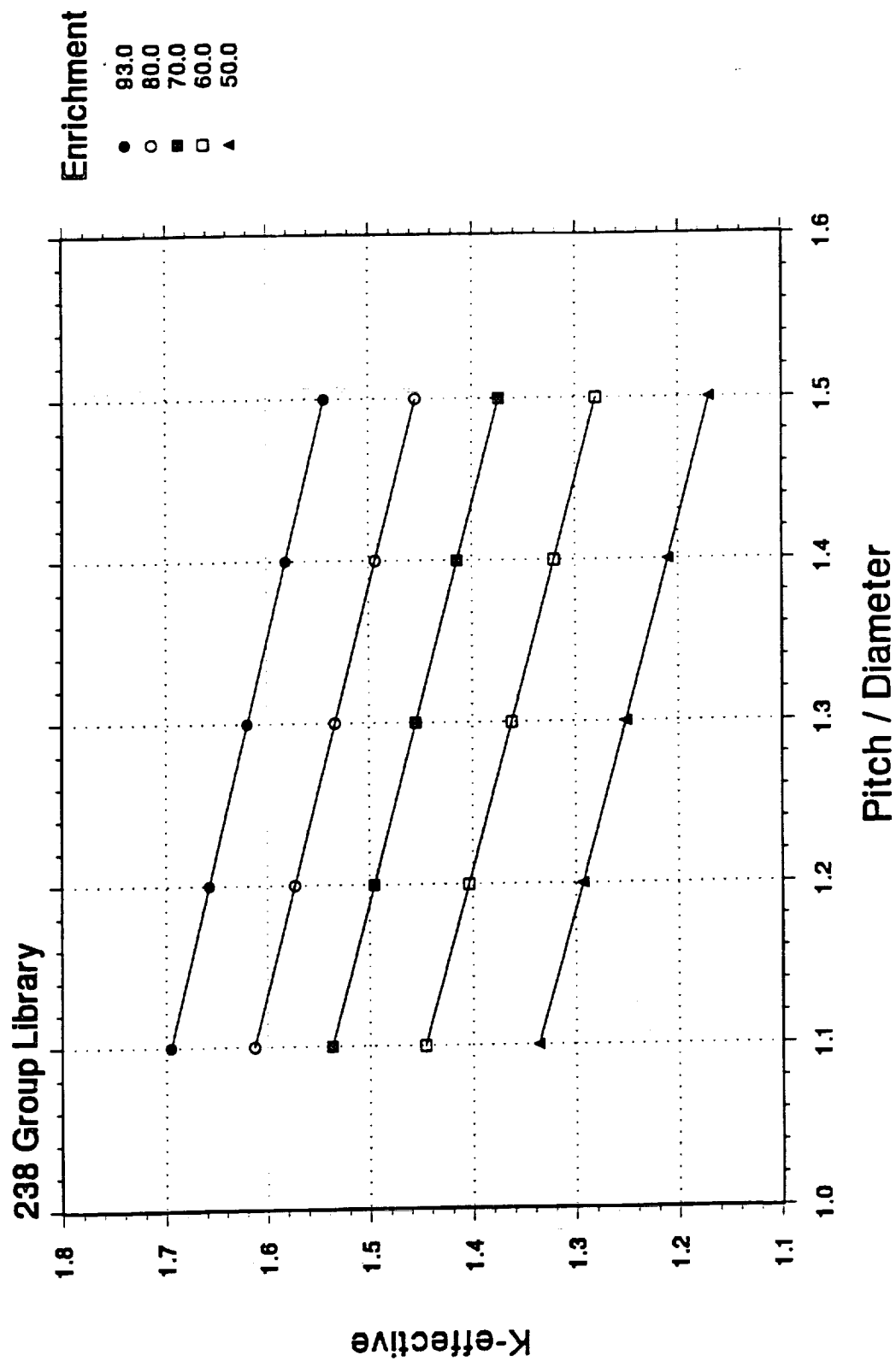


Fig. 8. Fuel pin reactor, k_{∞} as a function of pitch and enrichment.

NASA Parametrics B3 Buckling Calc. vs P/D

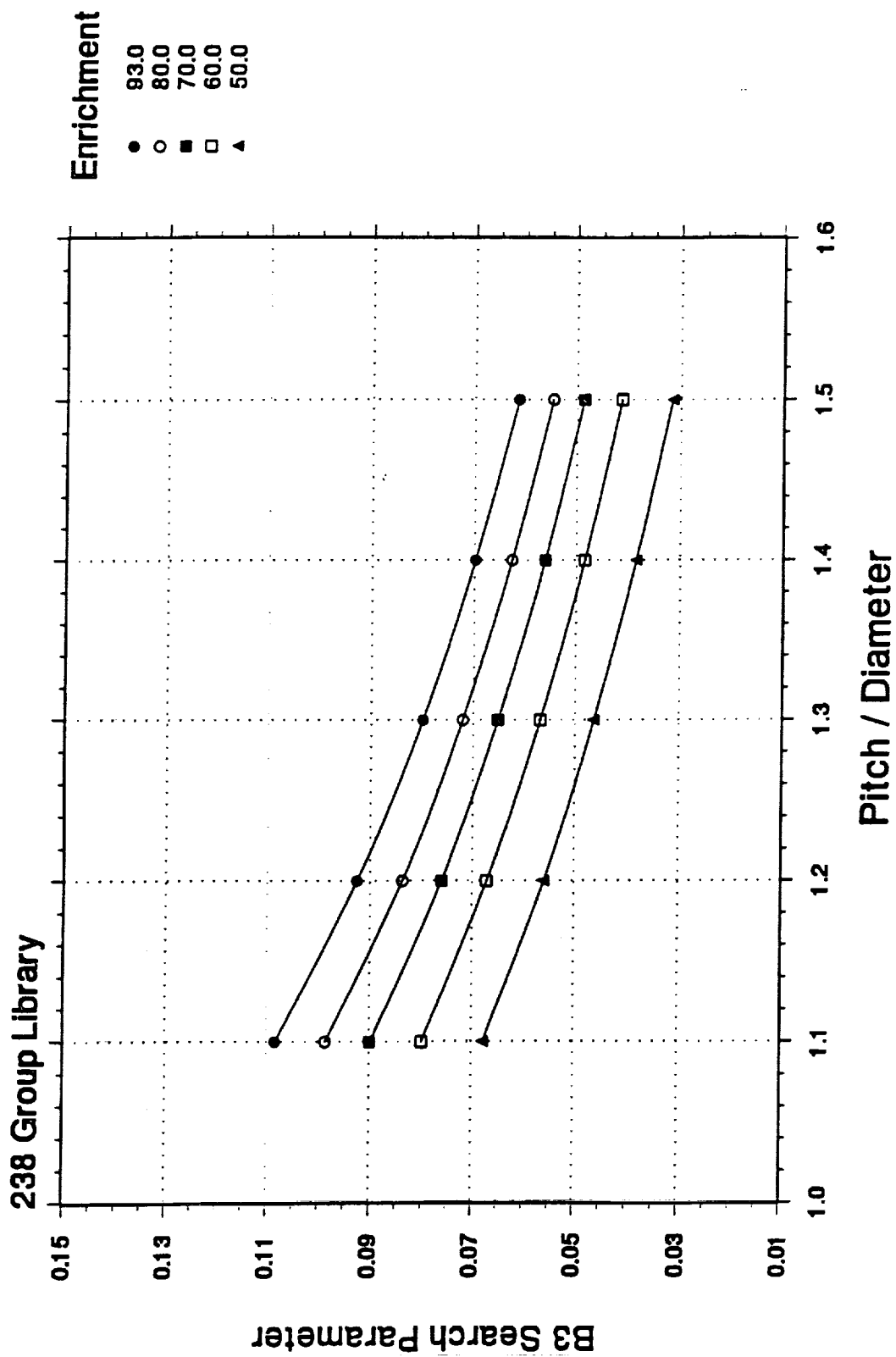
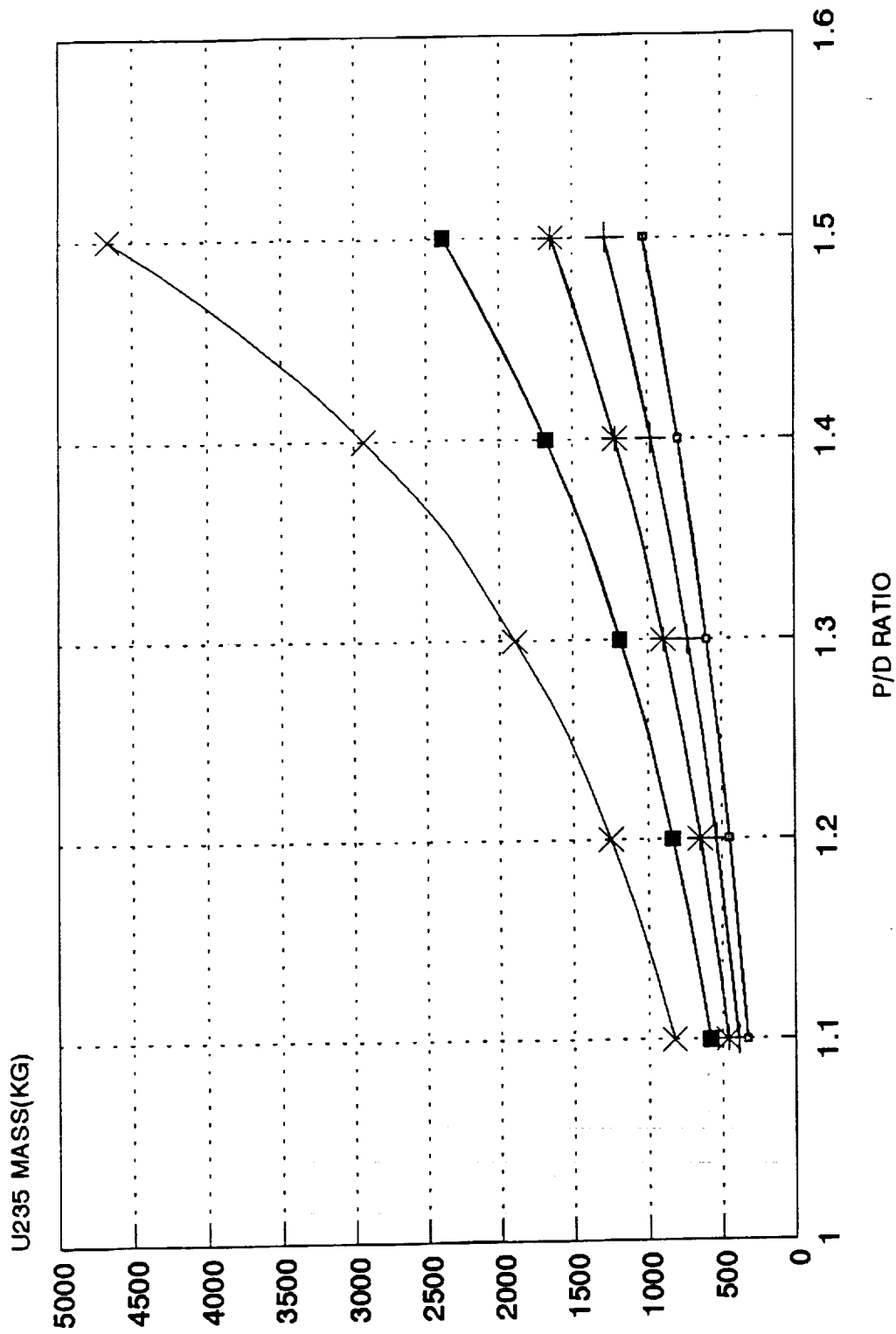


Fig. 9. Fuel pin reactor, critical buckling (cm^{-1}) as a function of pitch and enrichment.

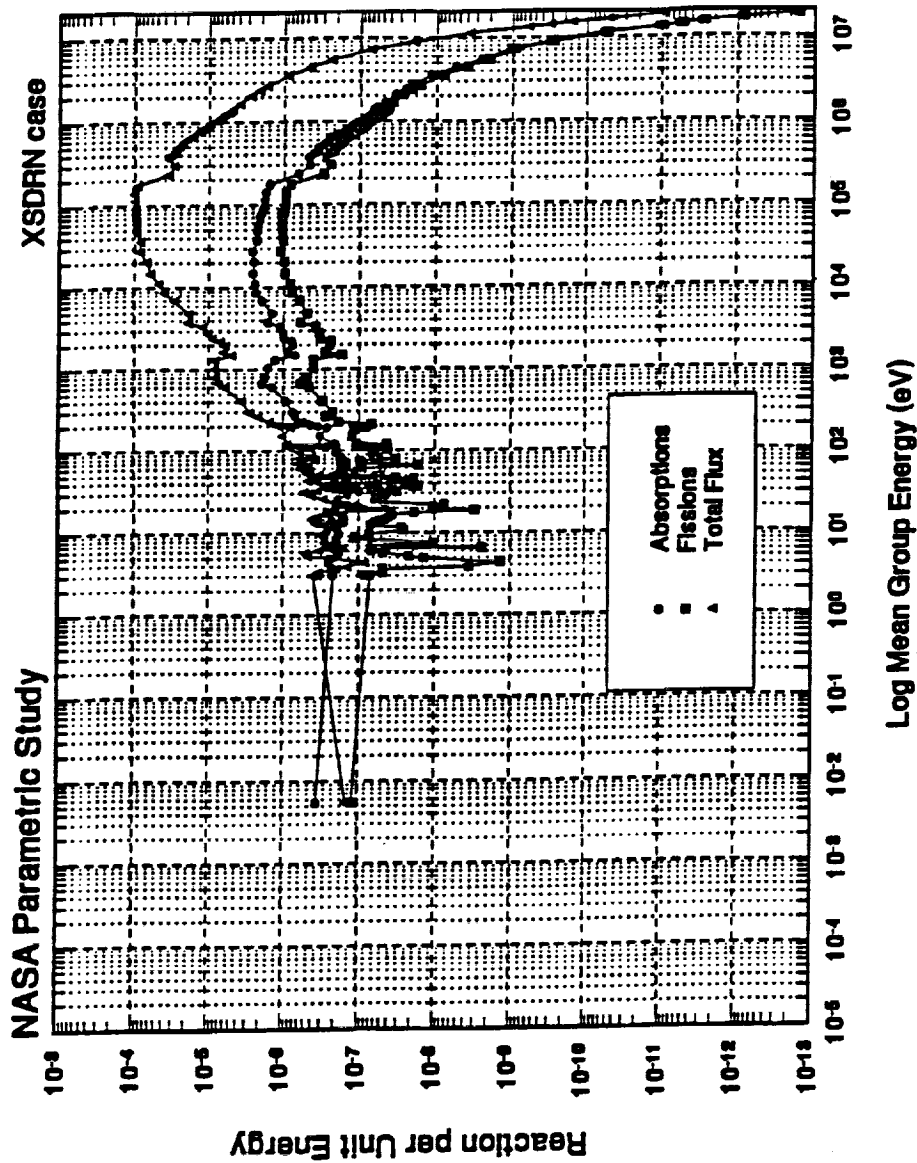


+ E=93% * E=80% * E=70% ■ E=60% * E=50%

1-93;0.64 CM FUEL RODS

Fig. 10. Fuel pin reactor, critical masses for spherical bare cores.

70 % Enriched P/D = 1.3
Reflected Sphere Zone 1 Results



e70pd13

JCT 1/07/93

Fig. 11. Fuel pin reactor, spectras averaged in the core for reflected spheres.

where the multiplication constant for the infinite lattice is

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

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 σ '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,

$$BU = \frac{f_5 + f_8 + f_9}{n_5(0)} \quad (3)$$

Note, that because of the way we compute the burnup this definition refers to depletion via fission only 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

$$BU = \frac{\sigma_{f5}}{\sigma_{a8}} (1 - e^{-\sigma_{a8} \phi t}) + \frac{\sigma_{f8}}{\sigma_{a8}} \left(\frac{1}{\epsilon} - 1 \right) (1 - e^{-\sigma_{a8} \phi t}) \quad (4)$$

$$+ \frac{\sigma_{c8}}{\sigma_{a9} - \sigma_{a8}} \left(\frac{1}{\epsilon} - 1 \right) \left[\frac{\sigma_{f9}}{\sigma_{a8}} (1 - e^{-\sigma_{a8} \phi t}) - \frac{\sigma_{f9}}{\sigma_{a8}} (1 - e^{-\sigma_{a9} \phi t}) \right]$$

where indices f, a, and c stand for fission, absorption and capture, ϵ is the initial enrichment, and the σ 's were taken from Ref. 4. For an input burnup, BU, Eq. 4 is solved for the fluence ϕt 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*

P/d	Enrichment (%)				
	93.0	80.0	70.0	60.0	50.0
1.1	5.69	5.43	5.10	4.57	3.73
1.2	5.39	5.06	4.63	3.99	3.05
1.3	5.12	4.66	4.14	3.44	2.45
1.4	4.77	4.23	3.67	2.92	1.91
1.5	4.41	3.82	3.22	2.44	1.43

*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 B₄C sheets

The reactivity worths of 360° 2 cm thick, 90% enriched B₄C 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 B₄C sheets*

P/d	Enrichment (%)				
	93.0	80.0	70.0	60.0	50.0
1.1	6.73	5.98	5.23	4.29	3.12
1.2	6.64	5.74	4.92	3.91	2.69
1.3	6.37	5.43	4.55	3.50	2.24
1.4	6.07	5.08	4.15	3.06	1.81
1.5	5.73	4.69	3.73	2.63	1.39

*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 B₄C 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 B₄C 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

$$f_s = \frac{3}{a} \left\{ \frac{1}{2} - \frac{1}{a^2} [1 - e^{-a}(1 + a)] \right\}, \quad (5)$$

where $a = 2\Sigma R$ and Σ 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

Case	Power distribution		Flow distribution	Comments
	r, θ	z	r, θ	
1	Uniform	Uniform	Uniform	3-D fuel grading
2	Uniform	Cosine	Uniform	2-D (r, θ) fuel grading
3	Not uniform	Cosine	Proportional to local power	Uniform fuel, flow conditioning
4	Not uniform	Cosine	Uniform	Uniform fuel

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

$$\rho_P = \bar{\rho}_P \frac{f_1}{f_2} F(r, \theta, z) \quad (6)$$

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,

$$F(r, \theta, z) = \frac{\pi R_c^2 H_c \psi(r, \theta, z)}{\int_{\text{core}} \psi(r, \theta, z) dV} \quad (7)$$

We assume the distribution Ψ can be written as

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

Consequently

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

where

$$f_z = \frac{Z(z)}{\frac{1}{H_c} \int_0^{H_c} Z(z) dz} \quad (10)$$

and

$$f_{r, \theta} = \frac{R(r, \theta)}{\frac{1}{\pi R_c^2} \int_0^{R_c} r dr \int_0^{2\pi} R(r, \theta) d\theta} \quad . \quad (11)$$

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

$$Z(z) = \sin \frac{\pi z}{H'_c} \quad , \quad (12)$$

where $H'_c = H_c + 2\delta$, with δ 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

$$f_z = \frac{\alpha}{\sin \alpha} \sin \frac{\pi z}{H'_c} \quad (13)$$

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

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 θ with period $\theta_d = 2\pi/N_d$ where N_d is the number of drums, $R(r, \theta)$ can then be expanded in Fourier series, resulting in

$$f_{r,\theta} = a_0(r) + \sum_{n=1}^{\infty} \left[a_n(r) \cos n2\pi \frac{\theta}{\theta_d} + b_n(r) \sin n2\pi \frac{\theta}{\theta_d} \right], \quad (14)$$

where

$$a_n = \frac{\bar{R}_n(r)}{\frac{1}{\pi R_c^2} \int_0^{R_c} \bar{R}_0(r) 2\pi r dr} \quad (15)$$

$$b_n = \frac{\bar{R}'_n(r)}{\frac{1}{\pi R_c^2} \int_0^{R_c} \bar{R}_0(r) 2\pi r dr} \quad (16)$$

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

and

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

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.,

$$f_{r,\theta}]_{\max} = a_0(r=0) \quad (19)$$

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

$$f_{r,\theta}]_{\min} = a_0(r=R_c) - \Delta_\theta \quad (20)$$

where $-\Delta_\theta$ is the sum of Eq. (14) evaluated at $r = R_c$ and the θ corresponding to the minimum, or

$$f_{r,\theta}]_{\min} = a_0(R_c) \left[1 - \frac{\Delta_\theta}{a_0(R_c)} \right] . \quad (21)$$

We had tabulated $a_0(r)$ by using the approximation of considering a continuous 360° 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

$$\rho v = \rho_i v_i \quad (22)$$

$$h + \frac{v^2}{2} = h_i + \frac{v_i^2}{2} + \frac{P_i}{w} \quad (23)$$

and

$$w \frac{dv}{dz} + A \frac{dp}{dz} + \frac{1}{2} \rho v^2 f P_f = 0 \quad (24)$$

where the channel was subdivided into nodes, subindex i refers to the inlet conditions and the unsubscripted variables refer to the outlet conditions. Variables ρ, 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

$$F(p,T) = h - h_i - \frac{P_i}{w} - \frac{v_i^2}{2} \left(1 - \frac{\rho_i^2}{\rho^2} \right) = 0 . \quad (25)$$

Using the equation of state, Eq. (24) can be written as

$$\frac{dp}{dz} \left[1 - \frac{v^2}{c^2} \right] + \frac{w^2}{A^2 p} \left[\frac{f P_f}{2A} - \frac{1}{\rho} \frac{\partial \rho}{\partial T} \frac{dT}{dz} \right] = 0 \quad (26)$$

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

$$G(p, T) \equiv p - p_i + \bar{F}_1 \Delta z + \bar{F}_2 (T - T_i) = 0 \quad (27)$$

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

$$F_1 = \frac{w^2 f P_f}{2 A^3 \rho} \left/ \left(1 - \frac{v^2}{c^2} \right) \right. \quad (28)$$

and

$$F_2 = \frac{w^2}{A^2 \rho^2} \frac{\partial \rho}{\partial T} \left/ \left(1 - \frac{v^2}{c^2} \right) \right. . \quad (29)$$

The averages are approximated by weighing the inlet and outlet conditions

$$\bar{F}_e \equiv \frac{1}{1+x} [F_e(p_i, T_i) + x F_e(p, T)], \quad e = 1, 2 \quad (30)$$

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, ($Re = 4w/\mu P_f$, μ viscosity),

$$f = \frac{16}{Re} , \quad (31)$$

and above $Re = 2000$ the Moody approximation to the Colebrook-White correlation was used

$$f = 0.001375 \left[1 + \left(20,000 \cdot \frac{\epsilon}{d} + \frac{10^6}{Re} \right)^{1/3} \right] , \quad (32)$$

which includes ϵ , 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 ρ 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

$$T_w = T_b + \frac{j}{h} , \quad (33)$$

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

$$F_R = \frac{T'_b - T_b}{T_s - T_b} , \quad (34)$$

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

$$h(T_s, p) = h(T_b, p) + v^2/2 . \quad (35)$$

The correlation of Mc Eligot et. al.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, Ψ , 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 $\partial T / \partial r|_{r=r_2} = 0$.

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, $k(\text{ZrC}) = 0.2077 \frac{\text{watt}}{\text{cmK}}$; the k of the mixture is calculated as

$$k(\text{mix}) = x(\text{UC}) k(\text{UC}) + x(\text{ZrC}) k(\text{ZrC}) + x(\text{graph}) k(\text{graph}) \quad (36)$$

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;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°K above the melting temperature of the $\text{UC} - \text{ZrC}$ 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 UN fuel pin to $r = r_p$, the He gap to $r = r_c$ and the tungsten liner and astar alloy clad up to $r = r_r$. 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 $T(r = r_p) = T_w$ (from Section 5.2.2) and $\partial T / \partial r|_{r=0} = 0$. Melting temperature of 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 equation¹²

$$d = \frac{pR}{\sigma} \quad (37)$$

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 σ is the maximum stress allowable for the pressure vessel. We have used a subroutine from the ALKASYS⁴ code to calculate σ , 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, δ_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 σ , the maximum stress for the astar 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 δ_R . The worth of axial reflectors, if any, are 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 σ 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:

$$k(EOL) \equiv 1 + \Delta k(EOL) = k_b + \Delta k(R) - \Delta k(BU) - \Delta k(PV) - \Delta k(SP) \quad (38)$$

where the multiplication constant of the bare core is:

$$k_b = \frac{k_{\infty}}{1 + M^2 B^2} \quad (39)$$

and the geometrical buckling is

$$B^2 = \left(\frac{\pi}{H_c} \right)^2 + \left(\frac{2.405}{R_c} \right)^2 \quad (40)$$

Equations (38) and (39) are then solved for the size of the core by specifying either ideal shape ($R_c/H_c = 0.54$), R_c or H_c ; in this process, some of the Δk '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 $E_r = PD$, the free parameters of each design are iterated until $E_a = E_r$. 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 (Ea, 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 Ea as function of R_c and H_c .

If the requested energy has a value, Er_1 , below the minimum of the E_o , $E_{o_{\min}}$, i.e., if Er 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 $E_{o_{\min}}$ is smaller than Er_1 and choosing the ideal shape disregarding any input R_c or H_c .

If the requested energy has a value, Er_2 , intermediate between the minimum and maximum of E_o , i.e., Er 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_c or H_c 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 Er_3 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 Er .

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 $n_{d(\max)} = \text{Integer}(2\pi / \Delta\theta)$ where $\Delta\theta = 2 \arcsin(r_d / (R_r + r_d))$ is the central parallax of the drums, r_d is the radius of the drums (1/2 of the reflector thickness) and R_r is the internal radius of the reflector; if larger the program continues with $n_d = n_{d(\max)}$. The reactivity worth per unit angle is calculated as $w_\theta = \Delta k(B_4C) / 2\pi$ where the numerator is read from tables as indicated in Sections 3.1.5 and 3.2.5; the maximum reactivity of the drums, $w_\theta \Delta\theta n_{d(\max)}$, is then compared with the reactivity to control $\Delta k_c = k(BOL) - 1 - \Delta k(SP) + \Delta k(SUB)$, where $\Delta k(SUB)$ is the desired subcriticality with the absorbers facing the core. If the maximum worth of the drums is smaller than Δk_c a warning message is printed and the program bypasses what follows.

The input number of drums is used to compute their maximum worth $\Delta k_d = w_\theta \Delta \theta n_d$ and if smaller than $\Delta k_c, n_d$ is increased to a value n'_d such that $\Delta k'_d = w_\theta \Delta \theta n'_d > \Delta k_c$. With n_d now fixed the central parallax of the absorbing part of the drum is computed as $\Delta k_c = w_\theta \Delta \theta_a n_d$ 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 Δk 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 δ_r , was parameterized as

$$\Delta k(PV) = \Delta k_n(PV) \left(\frac{d}{d_n} \right) \left(\frac{R_{cn}}{R_c} \right) f \left(\frac{\delta_r}{\delta_{rn}} \right) \quad (41)$$

where $\Delta k_n(PV)$ are the values quoted in Table 3 at nominal values, $d_n = 1 \text{ cm}$, R_{cn} and $\delta_{rn} = 25 \text{ cm}$. The values of the function $f \left(\frac{\delta_r}{\delta_{rn}} \right)$ 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_4C sheets a simple correlation was used to compute $\Delta k(B_4C)$ from the nominal values quoted in Table 4:

$$\Delta k(B_4C) = A e^{-\Sigma d} (1 - e^{-\Sigma_c d_c}) f \left(\frac{\delta_r}{\delta_{rn}} \right), \quad (42)$$

where the first exponential refers to the effects of pressure vessel of thickness d and the second to the B_4C 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 $d_c = 2 \text{ cm}$.

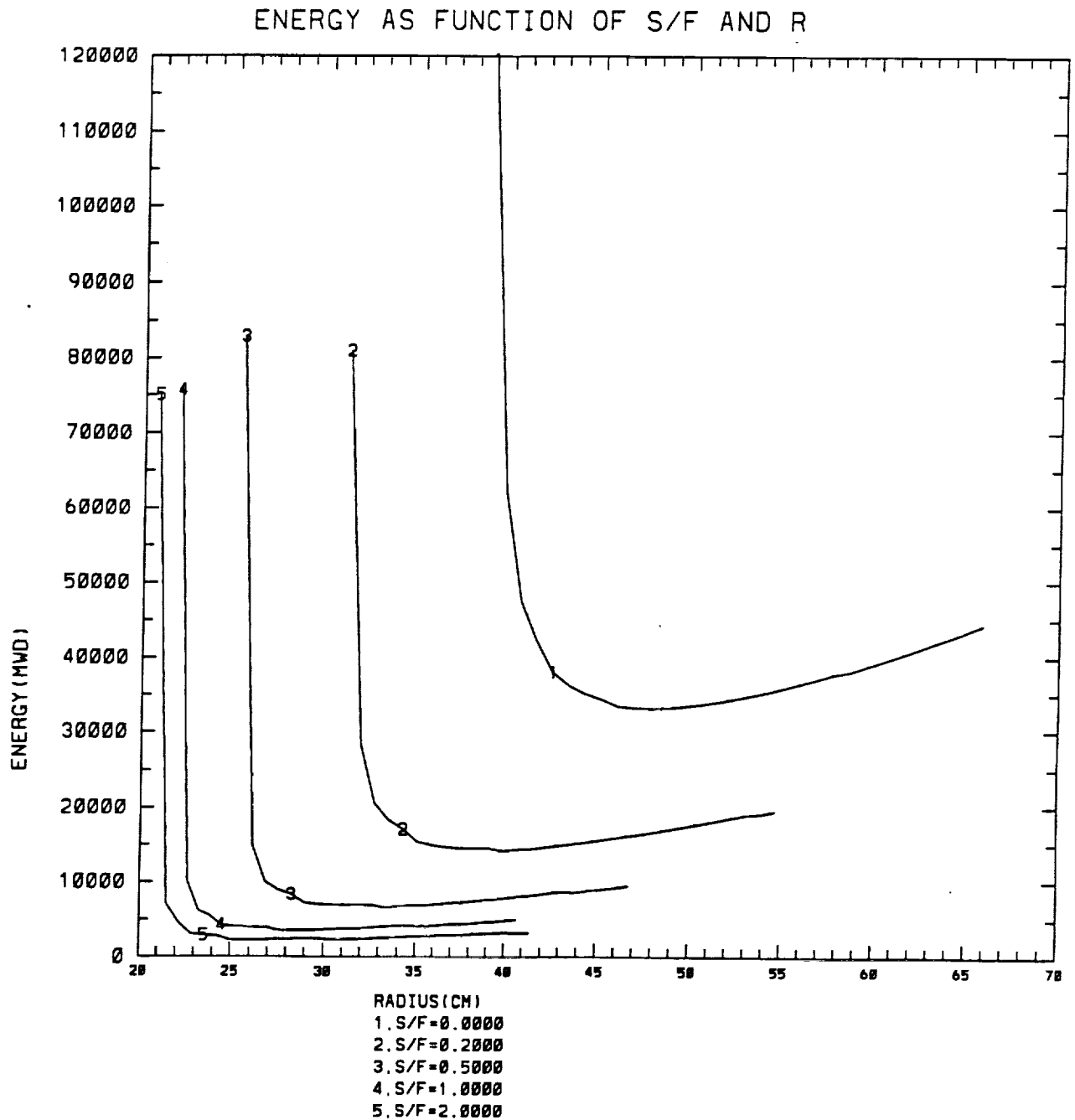


Fig. 12. Available energy in Mwd for the NERVA derivative reactor as a function of S/F, the radius of the core and for the following input conditions: 30 cm Be reflector, 2% reactivity worth for structural parts and desired end of life reactivity, and 15% burnup.

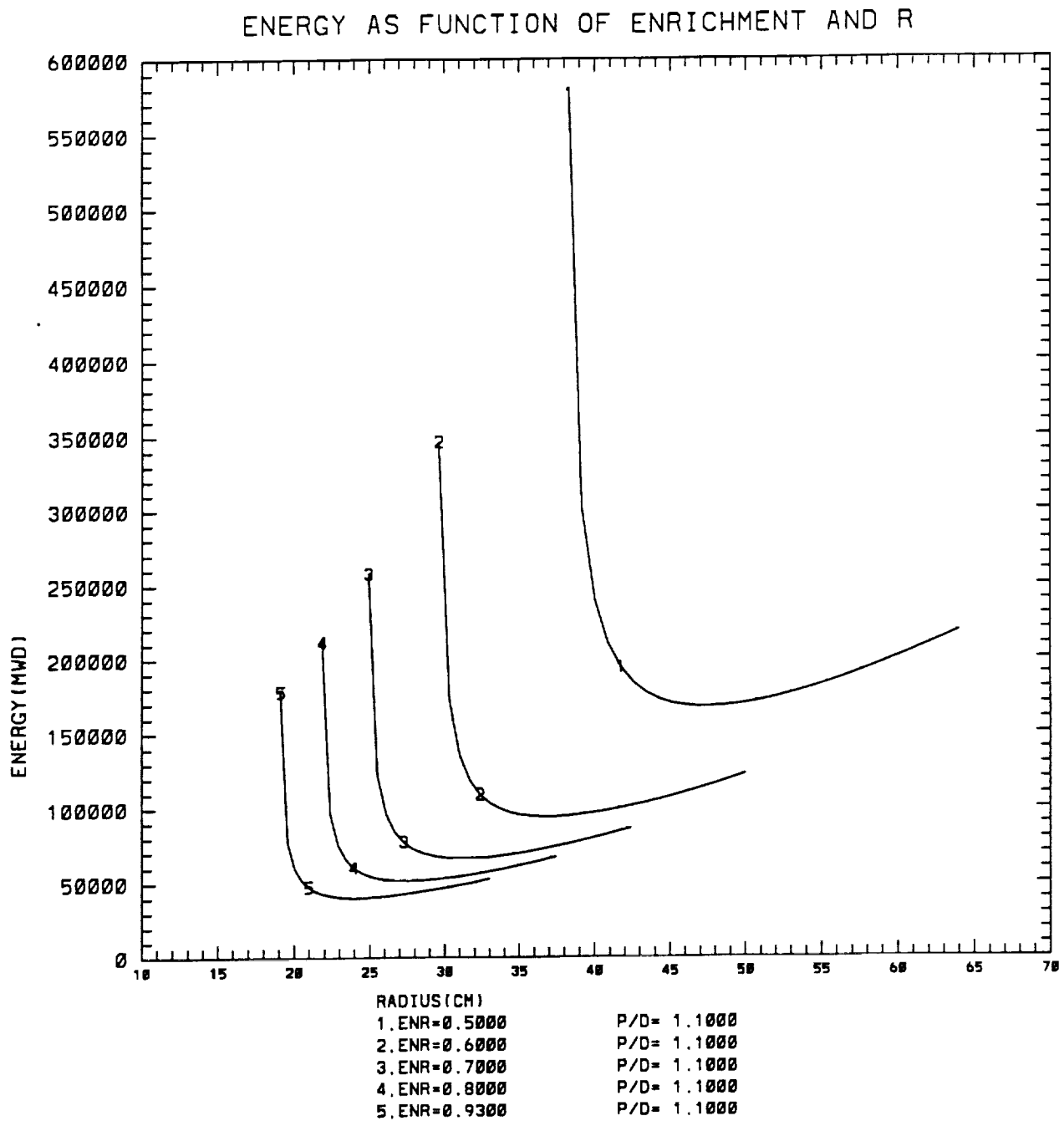


Fig. 13. Available energy in Mwd for the fuel pin reactor as a function of enrichment, the radius of the core and fixing $P/d = 1.1$. Other fixed input variables are 30 cm of BeO reflector, 2% reactivity worth for structural parts and end of life desired reactivity and 15% burnup.

Available Energy

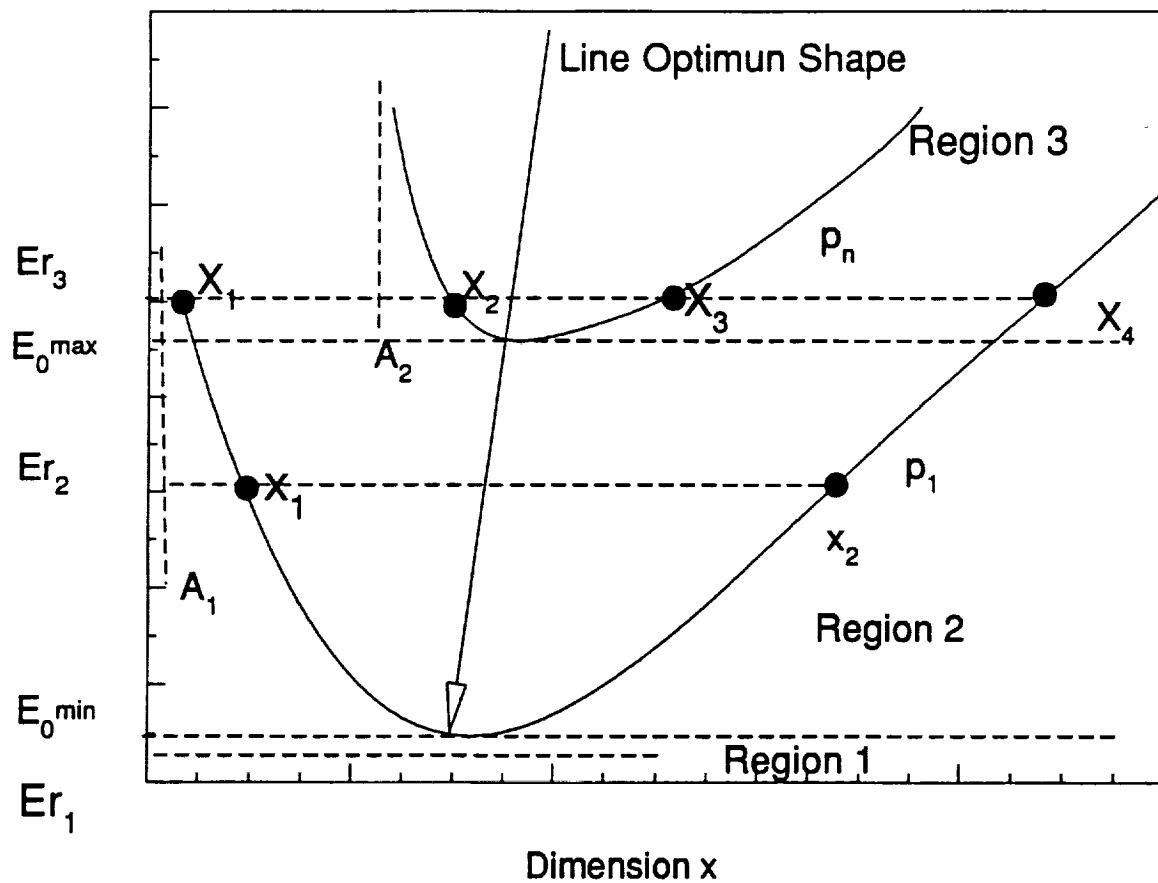


Fig. 14. Scheme for the exploration of possible designs, Ea is the available energy and x is one of the core dimensions (R_c or H_c).

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

itest/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_c or H_c , between the asymptotic and optimum values of R_c or H_c .

itmax: Maximum number of iterations.

icont/01/Do not/continue calculation after test.

nput: 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}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.

dra1 (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 ($R_c/H_c = 0.54$)

2: input R_c

3: input H_c

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

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

1: 3D uniform power distribution.

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

3: r,θ power distribution corresponding to uniform fuel load, cosine axial distribution and uniform flow distribution.

4: Like 3, but with (r,θ) 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
 iwrte/0,1/ No/Yes printing of iterations.
 ishm/1,2/ Selection of neutron shielding
 1: LiH stainless steel matrix
 2: B₄C
 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.
 toutl(°K): Outlet temperature of coolant if iboun = 1.
 ru: rugosity of the coolant channel.
 xi(1.): 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 toutl as the value of this
 variable.
 depvw(cm): Maximum allowed for pressure vessel thickness.
 fastf(1/cm²): 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

```

itest/# dR/itma/cont?/# of points in test      Format I5
    0   10  450    1   31
Pow(Mw)  /Life(y)  /Burnup(%) /Tolerance/Rel delta  E10.0
50.      2.       20.       0.001    1.01
Radial   /Top      /Bottom Reflector Thickness(cm)
30.      0.       0.
Struct.  /End Life /Subcrit    Reactivities(%)
2.       2.       2.
#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/ifri/idity/iprt/iouth/explicit,friction,Dittus,PrintDetails,Max,Min,Both?
    0    1    0    1    3
iwrte/Nshield/Ichoose/wrte its,LiH-SS or B4C?, Ichoose or Program?
    0    1    0
Pin(MPa) /Tin(K)   /Pin      /Tin/Inlet Conditions Fuel,Support Elements
2.       400.     5.       400.
iboun=0 input total coolant flow(Kg/s),iboun=1 input outlet T(K)
1700.
rugosity /Implicit /Fraction/P Ripple Angular Power
0.01     1.       0.97    0.1
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
1.       e+13 1000000. 15.0    5.
ishape/1,2,3/ (skip,input R,input H(cm))
60.

```

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

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 0.1591E-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

Coolant 0.3676
 Clad Coolant 0.0545
 Clad Fuel El 0.0208
 Fuel Mix 0.5571

Volumetric Fractions in Fuel Mix * Density(g/cm3)
 UC 0.07829 1.01545
 ZrC 0.06328 0.42394
 Graphite 0.85843 1.45934

Fuel microcell(Number Densities 10**24 atoms/cm3)
 Excludes outer cladding
 Coolant Radius(cm) 0.1397 He 0.00013774
 Clad Radius (cm) 0.1497 C 0.03908465 Zr 0.03908465
 Cell Radius (cm) 0.2280 C 0.00494617 Zr 0.00247308
 Graphite 0.07316656 U235 0.00229997
 U238 0.00017312

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

 Masses(kg) * Fractions(%)
 Graphite 431.466 38.353
 UC 300.228 26.688
 ZrC(in fuel) 125.343 11.142
 ZrC(in Clad) 267.757 23.801
 He(Coolant) 0.179 0.016

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

 Masses(Kg) * Fractions(%)
 He 0.028 0.031
 Inconel 10.430 11.368
 ZrH2 59.067 64.374
 Graphite 22.230 24.228

SUPERCELL CONFIGURATION(Number Densities 10**24atoms/cm3)

Support Element
 Coolant Radius(cm) 0.1500 He 0.00089003
 Inconel Radius(cm) 0.2500 Ni 0.06664123 Fe 0.00671785
 Cr 0.01546157 Ti 0.00279728
 Si 0.00477070
 ZrH2 Radius (cm) 0.6500 Zr 0.03616986 H 0.07233973
 Coolant Radius(cm) 0.7500 He 0.00089003
 Pyrographite R(cm) 0.8500 Gr 0.08523275
 Graphite Radii(cm) 1.0044 Gr 0.08523275

Ring of Fuel Elements. Average Densities
 Radius(cm) 4.3728 He 0.00005063 C 0.00569895
 Zr 0.00432113 Gr 0.04076312
 U5 0.00128138 U8 0.00009645

HOMOGENIZED DENSITIES IN CORE
 Radius(cm) 45.8626

From Fuel Elements

He	0.00004796	C	0.00539829
Zr	0.00409316	Gr	0.03861255
U5	0.00121377	U8	0.00009136

From Support Elements

He	0.00000756	Ni	0.00013941
Fe	0.00001405	Cr	0.00003234
Ti	0.00000585	Si	0.00000998
Zr	0.00068097	H	0.00136193
Gr	0.00198940		

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 " " " 75.22 " " 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

	Masses(Kg)	* Fractions(%)	Volume(L)	* Fraction(%)
Fuel Elem	1124.972	31.839	530.685	33.937
Support E	91.755	2.597	29.557	1.890
Reflector	1797.472	50.872	972.658	62.201
Pr Vessel	519.092	14.691	30.825	1.971

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)

GROUP	1	2	3	4	5	6	7
	0-1Mev	1-2	2-3	3-5	5-7	7-9	>9
	2.084E+19	6.404E+18	2.452E+18	9.606E+17	2.708E+17	1.207E+16	3.077E+16
% FRACTION PRODUCED BY U235							
	98.09	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)= 2.00000 Inlet temperature(K)= 400.00
 Diameter(cm)= 0.28 Rugosity= 0.01000 der parm=1.0100 eps= 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=roav*Pfact*Cos(Pi*z/H)
 Pfact(Axial*Radial*Azim)= 2.3949 Extrapolated Delta(cm) 5.00

Attention Implicit Calculation!! xi= 1.00000

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

Flow(g/s)= 0.191

Node	z(cm)	Po(w/cm)	Pr(MPa)	T(K)	V(m/s)	Re	Mach
1	0.00	6.02	2.00	400.00	13.06	3600.	0.011
2	1.70	8.04	2.00	411.99	13.46	3528.	0.011
3	3.39	10.02	2.00	427.39	13.97	3440.	0.011
4	5.09	11.98	2.00	446.15	14.59	3340.	0.012
5	6.78	13.90	2.00	468.21	15.31	3231.	0.012
6	8.48	15.77	1.99	493.51	16.15	3116.	0.012

7	10.17	17.60	1.99	521.97	17.08	2998.	0.013
8	11.87	19.37	1.99	553.49	18.13	2880.	0.013
9	13.57	21.07	1.99	587.97	19.27	2763.	0.013
10	15.26	22.72	1.99	625.31	20.50	2648.	0.014
11	16.96	24.29	1.98	665.39	21.84	2538.	0.014
12	18.65	25.78	1.98	708.08	23.26	2432.	0.015
13	20.35	27.19	1.98	753.24	24.77	2331.	0.015
14	22.04	28.52	1.98	800.74	26.36	2235.	0.016
15	23.74	29.75	1.97	850.42	28.04	2144.	0.016
16	25.43	30.89	1.97	902.13	29.79	2059.	0.017
17	27.13	31.94	1.97	955.70	31.58	1979.	0.017
18	28.83	32.88	1.97	1010.96	33.41	1904.	0.018
19	30.52	33.72	1.97	1067.74	35.28	1834.	0.018
20	32.22	34.45	1.97	1125.87	37.20	1768.	0.019
21	33.91	35.08	1.97	1185.14	39.16	1707.	0.019
22	35.61	35.59	1.97	1245.39	41.15	1650.	0.020
23	37.30	35.99	1.97	1306.41	43.16	1596.	0.020
24	39.00	36.28	1.97	1368.02	45.20	1547.	0.021
25	40.70	36.45	1.97	1430.03	47.25	1500.	0.021
26	42.39	36.51	1.97	1492.22	49.31	1457.	0.022
27	44.09	36.45	1.97	1554.42	51.37	1417.	0.022
28	45.78	36.28	1.97	1616.42	53.42	1379.	0.023
29	47.48	35.99	1.97	1678.02	55.46	1344.	0.023
30	49.17	35.59	1.96	1739.04	57.48	1312.	0.023
31	50.87	35.08	1.96	1799.27	59.48	1281.	0.024
32	52.57	34.45	1.96	1858.54	61.45	1253.	0.024
33	54.26	33.72	1.96	1916.65	63.38	1227.	0.025
34	55.96	32.88	1.96	1973.42	65.27	1203.	0.025
35	57.65	31.94	1.96	2028.66	67.11	1180.	0.025
36	59.35	30.89	1.96	2082.21	68.89	1159.	0.026
37	61.04	29.75	1.96	2133.90	70.61	1140.	0.026
38	62.74	28.52	1.96	2183.56	72.27	1122.	0.026
39	64.44	27.19	1.96	2231.04	73.86	1105.	0.027
40	66.13	25.78	1.96	2276.18	75.37	1090.	0.027
41	67.83	24.29	1.96	2318.85	76.80	1076.	0.027
42	69.52	22.72	1.96	2358.91	78.14	1064.	0.027
43	71.22	21.07	1.96	2396.23	79.40	1052.	0.028
44	72.91	19.37	1.96	2430.70	80.56	1042.	0.028
45	74.61	17.60	1.96	2462.20	81.62	1033.	0.028
46	76.30	15.77	1.96	2490.64	82.59	1025.	0.028
47	78.00	13.90	1.96	2515.92	83.45	1018.	0.028
48	79.70	11.98	1.96	2537.98	84.20	1012.	0.028
49	81.39	10.02	1.96	2556.73	84.85	1007.	0.029
50	83.09	8.04	1.96	2572.12	85.38	1002.	0.029
51	84.78	6.02	1.96	2584.10	85.80	999.	0.029

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

Node	z(cm)	J(Kw/cm2)	Twall(K)	Tclad(K)	TcladAv	Tfuel(K)	TfuelAv
1	0.00	0.00686	467.46	467.78	467.63	468.08	467.99
2	1.70	0.00915	506.76	507.19	506.98	507.62	507.49
3	3.39	0.01142	559.58	560.11	559.85	560.70	560.52
4	5.09	0.01365	613.05	613.69	613.37	614.41	614.20
5	6.78	0.01583	668.55	669.28	668.92	670.17	669.90
6	8.48	0.01797	725.73	726.56	726.15	727.62	727.31
7	10.17	0.02005	783.95	784.89	784.43	786.13	785.76

8	11.87	0.02206	843.70	844.73	844.22	846.17	845.74
9	13.57	0.02401	904.15	905.27	904.72	906.91	906.42
10	15.26	0.02588	965.39	966.60	966.00	968.44	967.89
11	16.96	0.02767	1027.10	1028.38	1027.75	1030.45	1029.83
12	18.65	0.02937	1088.90	1090.26	1089.59	1092.56	1091.88
13	20.35	0.03098	1151.59	1153.03	1152.32	1155.54	1154.79
14	22.04	0.03249	1214.34	1215.85	1215.11	1218.55	1217.74
15	23.74	0.03389	1277.39	1278.97	1278.19	1281.85	1280.99
16	25.43	0.03519	1339.86	1341.50	1340.69	1344.57	1343.65
17	27.13	0.03638	1402.55	1404.24	1403.40	1407.49	1406.52
18	28.83	0.03746	1465.89	1467.63	1466.77	1471.07	1470.05
19	30.52	0.03841	1527.71	1529.50	1528.62	1533.13	1532.05
20	32.22	0.03925	1589.96	1591.79	1590.89	1595.61	1594.47
21	33.91	0.03996	1651.84	1653.70	1652.78	1657.70	1656.51
22	35.61	0.04055	1712.36	1714.24	1713.31	1718.39	1717.15
23	37.30	0.04100	1772.70	1774.61	1773.66	1778.87	1777.60
24	39.00	0.04133	1831.93	1833.85	1832.91	1838.23	1836.92
25	40.70	0.04153	1891.09	1893.02	1892.07	1897.49	1896.16
26	42.39	0.04159	1948.17	1950.11	1949.15	1954.66	1953.30
27	44.09	0.04153	2004.33	2006.26	2005.30	2010.89	2009.51
28	45.78	0.04133	2059.27	2061.19	2060.24	2065.88	2064.48
29	47.48	0.04100	2112.38	2114.28	2113.34	2119.02	2117.60
30	49.17	0.04055	2164.50	2166.39	2165.46	2171.15	2169.73
31	50.87	0.03996	2214.32	2216.18	2215.26	2220.95	2219.53
32	52.57	0.03925	2262.11	2263.94	2263.03	2268.66	2267.25
33	54.26	0.03841	2308.21	2310.00	2309.12	2314.67	2313.27
34	55.96	0.03746	2351.81	2353.55	2352.69	2358.13	2356.77
35	57.65	0.03638	2392.75	2394.44	2393.61	2398.93	2397.59
36	59.35	0.03519	2431.68	2433.31	2432.50	2437.68	2436.38
37	61.04	0.03389	2467.61	2469.18	2468.41	2473.42	2472.16
38	62.74	0.03249	2500.68	2502.20	2501.45	2506.28	2505.06
39	64.44	0.03098	2531.06	2532.50	2531.79	2536.42	2535.25
40	66.13	0.02937	2558.25	2559.62	2558.94	2563.35	2562.24
41	67.83	0.02767	2582.57	2583.86	2583.22	2587.39	2586.34
42	69.52	0.02588	2603.95	2605.16	2604.56	2608.48	2607.49
43	71.22	0.02401	2621.93	2623.04	2622.49	2626.13	2625.21
44	72.91	0.02206	2636.83	2637.86	2637.35	2640.71	2639.86
45	74.61	0.02005	2648.22	2649.15	2648.69	2651.75	2650.97
46	76.30	0.01797	2656.46	2657.29	2656.88	2659.62	2658.93
47	78.00	0.01583	2661.10	2661.83	2661.47	2663.89	2663.27
48	79.70	0.01365	2662.12	2662.75	2662.44	2664.52	2663.99
49	81.39	0.01142	2659.92	2660.45	2660.19	2661.93	2661.49
50	83.09	0.00915	2654.09	2654.51	2654.30	2655.70	2655.34
51	84.78	0.00686	2644.94	2645.26	2645.10	2646.14	2645.88

Axial Average Conditions in the Channel

Coolant Pressure(MPa) 1.970 Temperature(K) 1056.332

Give Density(g/cm3) 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 0.50000 Melting Temperature(K) 3343.50

HEAT BALANCE FOR THE CHANNEL

dQ: heat to coolant (joule/kg) 0.11343E+08
dH: change of enthalpy (joule/kg) 0.11340E+08
dKin change kinetic energy(joule/kg) 0.35955E+04
relative dKin/dQ 0.000317
Balance (dH+dKin)/dQ 1.0000000

PROFILE OF CHANNEL WITH MINIMUM POWER DENSITY

Problem #1 Nerva Application to NEP

Thermodynamic profile of a He cooled channel
 Inlet pressure(MPa)= 2.00000 Inlet temperature(K)= 400.00
 Diameter(cm)= 0.28 Rugosity= 0.01000 der parm=1.0100 eps= 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=roav*Pfact*Cos(Pi*z/H)
 Pfact(Axial*Radial*Azim)= 0.6851 Extrapolated Delta(cm) 5.00

Attention Implicit Calculation!! xi= 1.00000

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

Flow(g/s)= 0.191

Node	z(cm)	Po(w/cm)	Pr(MPa)	T(K)	V(m/s)	Re	Mach
1	0.00	1.72	2.00	400.00	13.06	3600.	0.011
2	1.70	2.30	2.00	403.43	13.18	3579.	0.011
3	3.39	2.87	2.00	407.84	13.33	3552.	0.011
4	5.09	3.43	2.00	413.20	13.52	3520.	0.011
5	6.78	3.98	2.00	419.52	13.73	3484.	0.011
6	8.48	4.51	1.99	426.75	13.97	3443.	0.011
7	10.17	5.03	1.99	434.89	14.24	3399.	0.012
8	11.87	5.54	1.99	443.91	14.55	3351.	0.012
9	13.57	6.03	1.99	453.77	14.88	3301.	0.012
10	15.26	6.50	1.99	464.46	15.24	3249.	0.012
11	16.96	6.95	1.99	475.92	15.62	3195.	0.012
12	18.65	7.37	1.99	488.13	16.03	3140.	0.012
13	20.35	7.78	1.98	501.05	16.46	3084.	0.012
14	22.04	8.16	1.98	514.64	16.92	3028.	0.013
15	23.74	8.51	1.98	528.85	17.40	2972.	0.013
16	25.43	8.84	1.98	543.65	17.90	2916.	0.013
17	27.13	9.14	1.98	558.97	18.42	2861.	0.013
18	28.83	9.41	1.98	574.78	18.95	2806.	0.013
19	30.52	9.65	1.97	591.03	19.50	2753.	0.014
20	32.22	9.86	1.97	607.66	20.07	2701.	0.014
21	33.91	10.03	1.97	624.62	20.65	2650.	0.014
22	35.61	10.18	1.97	641.86	21.24	2601.	0.014
23	37.30	10.30	1.97	659.32	21.84	2554.	0.014
24	39.00	10.38	1.96	676.95	22.44	2508.	0.015
25	40.70	10.43	1.96	694.69	23.06	2464.	0.015
26	42.39	10.44	1.96	712.48	23.68	2421.	0.015
27	44.09	10.43	1.96	730.28	24.30	2381.	0.015
28	45.78	10.38	1.95	748.02	24.92	2342.	0.015
29	47.48	10.30	1.95	765.65	25.54	2305.	0.016
30	49.17	10.18	1.95	783.11	26.16	2269.	0.016
31	50.87	10.03	1.94	800.35	26.77	2235.	0.016
32	52.57	9.86	1.94	817.31	27.38	2203.	0.016
33	54.26	9.65	1.94	833.94	27.98	2173.	0.016
34	55.96	9.41	1.94	850.18	28.58	2145.	0.017
35	57.65	9.14	1.93	865.99	29.16	2118.	0.017
36	59.35	8.84	1.93	881.32	29.72	2092.	0.017
37	61.04	8.51	1.92	896.11	30.28	2068.	0.017
38	62.74	8.16	1.92	910.32	30.82	2046.	0.017
39	64.44	7.78	1.92	923.91	31.34	2025.	0.017
40	66.13	7.37	1.91	936.83	31.84	2006.	0.018
41	67.83	6.95	1.91	949.04	32.28	1988.	0.018
42	69.52	6.50	1.91	960.51	32.67	1972.	0.018
43	71.22	6.03	1.91	971.19	33.04	1957.	0.018
44	72.91	5.54	1.91	981.05	33.38	1944.	0.018

45	74.61	5.03	1.91	990.07	33.68	1931.	0.018
46	76.30	4.51	1.91	998.21	33.96	1921.	0.018
47	78.00	3.98	1.91	1005.44	34.21	1911.	0.018
48	79.70	3.43	1.91	1011.75	34.42	1903.	0.018
49	81.39	2.87	1.91	1017.12	34.61	1896.	0.018
50	83.09	2.30	1.91	1021.53	34.76	1890.	0.018
51	84.78	1.72	1.91	1024.95	34.88	1886.	0.018

From the Coolant Channel to the Uranium Carbide

Radius(cm) Orifices, 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

Node	z(cm)	J(Kw/cm2)	Twall(K)	Tclad(K)	TcladAv	Tfuel(K)	TfuelAv
1	0.00	0.00196	418.43	418.52	418.47	418.60	418.58
2	1.70	0.00262	428.86	428.98	428.92	429.09	429.06
3	3.39	0.00327	442.72	442.87	442.79	443.01	442.97
4	5.09	0.00390	456.75	456.93	456.84	457.10	457.05
5	6.78	0.00453	471.36	471.57	471.47	471.77	471.71
6	8.48	0.00514	486.64	486.88	486.76	487.11	487.04
7	10.17	0.00573	502.58	502.85	502.72	503.12	503.04
8	11.87	0.00631	519.20	519.49	519.35	519.79	519.70
9	13.57	0.00687	536.39	536.71	536.55	537.05	536.95
10	15.26	0.00740	553.97	554.32	554.15	554.69	554.58
11	16.96	0.00791	572.06	572.43	572.25	572.83	572.71
12	18.65	0.00840	590.41	590.81	590.61	591.24	591.11
13	20.35	0.00886	608.97	609.39	609.18	609.86	609.72
14	22.04	0.00929	627.86	628.29	628.08	628.79	628.64
15	23.74	0.00970	647.02	647.47	647.25	648.00	647.84
16	25.43	0.01007	666.19	666.66	666.43	667.22	667.06
17	27.13	0.01041	685.31	685.79	685.55	686.38	686.21
18	28.83	0.01072	704.51	705.01	704.77	705.63	705.45
19	30.52	0.01099	723.52	724.04	723.78	724.68	724.49
20	32.22	0.01123	742.50	743.02	742.76	743.69	743.49
21	33.91	0.01143	761.38	761.92	761.65	762.61	762.40
22	35.61	0.01160	779.88	780.42	780.15	781.14	780.92
23	37.30	0.01173	798.41	798.96	798.69	799.70	799.48
24	39.00	0.01182	816.44	816.99	816.72	817.75	817.52
25	40.70	0.01188	833.88	834.44	834.16	835.21	834.98
26	42.39	0.01190	851.21	851.76	851.49	852.55	852.31
27	44.09	0.01188	867.84	868.40	868.12	869.19	868.95
28	45.78	0.01182	884.27	884.82	884.54	885.61	885.38
29	47.48	0.01173	900.17	900.71	900.44	901.51	901.27
30	49.17	0.01160	915.21	915.75	915.48	916.55	916.31
31	50.87	0.01143	930.79	931.33	931.06	932.12	931.88
32	52.57	0.01123	944.52	945.04	944.78	945.83	945.59
33	54.26	0.01099	957.87	958.38	958.13	959.16	958.93
34	55.96	0.01072	970.33	970.83	970.58	971.59	971.36
35	57.65	0.01041	981.99	982.48	982.24	983.23	983.01
36	59.35	0.01007	992.99	993.46	993.23	994.19	993.97
37	61.04	0.00970	1003.13	1003.58	1003.36	1004.29	1004.08
38	62.74	0.00929	1012.38	1012.81	1012.59	1013.49	1013.29
39	64.44	0.00886	1020.71	1021.12	1020.92	1021.78	1021.58
40	66.13	0.00840	1028.09	1028.48	1028.29	1029.11	1028.92
41	67.83	0.00791	1034.51	1034.88	1034.69	1035.47	1035.29
42	69.52	0.00740	1040.09	1040.44	1040.27	1041.00	1040.83
43	71.22	0.00687	1044.67	1044.99	1044.83	1045.51	1045.36
44	72.91	0.00631	1048.23	1048.52	1048.38	1049.00	1048.86
45	74.61	0.00573	1050.91	1051.17	1051.04	1051.61	1051.48
46	76.30	0.00514	1052.46	1052.70	1052.58	1053.09	1052.97

47	78.00	0.00453	1053.04	1053.25	1053.15	1053.60	1053.49
48	79.70	0.00390	1052.65	1052.83	1052.74	1053.13	1053.04
49	81.39	0.00327	1051.20	1051.35	1051.27	1051.60	1051.52
50	83.09	0.00262	1048.73	1048.85	1048.79	1049.05	1048.99
51	84.78	0.00196	1045.25	1045.34	1045.29	1045.49	1045.44

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 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.

nput: 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.

dral(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.

tempv(°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 (≤ 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: Input R_c
- 3: Input H_c

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

- 1: 3D uniform power distributions.
- 2: 2D (r, θ) uniform power distribution, cosine axial distribution (1 and 2 with uniform flow distribution).
- 3: r, θ power distribution corresponding to uniform fuel load, cosine axial distribution and uniform flow distribution.
- 4: Like 3, but with (r, θ) flow distribution proportional to power distribution.

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

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.

iwrte/0,1/ No/Yes Printing of iterations.

ishn/1,2/ Selection of neutron shielding.

1: LiH in stainless steel matrix.

2: B₄C

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 Δp 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.

dcd(cm): Thickness of the B₄C control sheet.

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

fastf(1/cm²): 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 2 31

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)

30. 0. 0. 1.0

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

2. 2. 2.

Pin(MPa) /Tin(K) /PHe /THE(Inlet and He gap Conditions)/press vess 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 30 3 1 19

iopth/1:3D Unif Power;2:2D Unif Power;3:Unif Load and Flow;4:Unif Load Flow-Pow

3

ifri/iprth/iouth/friction Y/N;Print Details Y/N;Print Max,Min,Both?

1 1 3

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

0 1 0 0

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

0.97 0.1 10. 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.

8.4 OUTPUT FROM NEPPIN

The output from running the code with the input file of the previous section follow:

```
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

BU	Mwday
10.00	77233.00
9.00	66788.17

Sampling of Designs

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

I	p/d	Enr	BU	Mass(Kg)	U5(Kg)	DeltaP(Pa)	coreR(cm)	coreH(cm)	ishape
1	1.100	0.530	10.00	6424.6	769.0	0.1003E+04	39.96	73.27	1
2	1.200	0.615	10.00	6064.9	768.3	0.1199E+04	40.56	74.26	1
3	1.300	0.715	10.00	5750.4	768.2	0.1423E+04	40.90	75.01	1
4	1.400	0.829	10.00	5476.4	769.4	0.5433E+04	41.12	75.37	1
5	1.500	0.894	9.00	6010.7	854.8	0.6080E+04	43.70	79.94	1

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

Core Volume(L) 400.42 Active(UN) Volume(L) 80.94
 Core Radius(cm) 41.12 Height(cm) 75.37
 Number of rods 5871 Bundles 309(19rods per bundle)

Neutron Flux(1/cm2sec)(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

	BOL	EOL	
U-235	769.399	681.867	
U-238	160.488	157.337	
Pu-239	0.000	1.731	1.868 Kg produced
Fiss Prod	0.000	77.274	

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
Coolant	0.4704	Li6	0.00307001	0.512619
"		Li7	0.03830476	
Clad	0.3200	Ta181	0.05059388	0.176834
"	0.3284(diluting	spacing wire)		
"		W182	0.00117159	
"		W183	0.00063544	
"		W184	0.00135207	
"		W186	0.00125367	
"		Re185	0.00020190	
"		Re187	0.00034274	

"		Hf	0.00041192	
Liner	0.2565	W182	0.01617544	0.028710
"		W183	0.00877312	
"		W184	0.01866725	
"		W186	0.01730863	
He Gap	0.2438	He	0.00002413	0.005480
Fuel Pin	0.2413	U235	0.02435551	0.263098
"	"	U238	0.00501613	
"	"	N14	0.02937164	

AVERAGES IN BUNDLE(INCLUDING DUCT)

Volumetric Fractions:	Rods	0.3555
	Spacing Wire	0.0210
	Li Coolant	0.5358
	Duct	0.0878

Isotope Concentration (Number Densities 10**24 atoms/cm3)

Li6	0.00164494
Li7	0.02052410
Ta181	0.01192968
W182	0.00063304
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
N14	0.00593687

Moderation by Li, Li/U235= 4.5032

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

Part	Volume	Fraction	Masses	Fraction
Rods	142.34	0.355479	2006.38	0.706037
Coolant	214.55	0.535811	102.33	0.036009
Duct	35.14	0.087755	591.74	0.208232
Spacing	8.39	0.020955	141.30	0.049723
Total	400.42		2841.75	

VOLUME(L) AND MASSES(KG) OF REACTOR

Part	Volume	Fraction	Masses	Fraction
Core	400.42	0.327118	2841.75	0.517700
Press Ves	12.16	0.009935	204.79	0.037308
Reflector	811.51	0.662947	2442.64	0.444992
Total	1224.09		5489.18	

VOLUMES AND MASSES OF REACTOR AND SHIELDINGS

	Volume(L)	Fraction(%)
Reactor	1224.09	38.60
N Shield	1691.15	53.33
G Shield	255.87	8.07
Total	3171.11	

	Mass(Kg)	Fraction(%)
Reactor	5489.18	45.82
N Shield	1731.73	14.46
G Shield	4759.17	39.73
Total	11980.08	

DIMENSION OF THE SHIELDINGS

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 " " "	79.60	" " "	95.32	117.51

EVALUATION OF PRESSURE VESSEL

Evaluation at T(K)= 800.00 PRESS(MPa)= 2.00

and 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/cm²) 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)

GROUP	1	2	3	4	5	6	7
	0-1MeV	1-2	2-3	3-5	5-7	7-9	>9
	2.132E+19	7.140E+18	3.132E+18	1.474E+18	1.815E+17	1.493E+15	1.097E+16

% FRACTION PRODUCED BY U

	89.14	75.35	62.24	32.78	35.62	0.00	99.51
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Equivalent Z for Build up factors

	54.97	45.51	46.08	51.17	55.29	58.22	60.50
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Gamma Self shielding by Core, Reflector and PV

	0.040546	0.098502	0.095939	0.101189	0.097540	0.093919	0.089193
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The same but without Buildup factor

	0.022162	0.050059	0.057265	0.070490	0.074171	0.074878	0.073508
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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
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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
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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(19rods/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
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	9.2130
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 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 *****

Node	z(cm)	Po(w/cm)	Pr(KPa)	T(K)	(Tsat)	V(m/s)	Re
1	0.00	47.64	2000.00	500.00	(2129.52)	0.11	274.
2	2.51	71.06	2000.00	511.82	(2129.52)	0.11	296.
3	5.02	93.88	1999.99	528.40	(2129.52)	0.11	328.
4	7.54	115.90	1999.99	549.71	(2129.52)	0.11	371.
5	10.05	136.93	1999.99	575.68	(2129.52)	0.11	426.
6	12.56	156.79	1999.98	606.15	(2129.51)	0.11	493.

7	15.07	175.31	1999.98	640.90(	2129.51)	0.11	572.
8	17.59	192.33	1999.98	679.65(	2129.51)	0.11	664.
9	20.10	207.71	1999.97	722.07(	2129.51)	0.12	767.
10	22.61	221.31	1999.97	767.79(	2129.51)	0.12	880.
11	25.12	233.03	1999.97	816.40(	2129.51)	0.12	1002.
12	27.63	242.75	1999.97	867.47(	2129.51)	0.12	1130.
13	30.15	250.40	1999.96	920.54(	2129.51)	0.12	1263.
14	32.66	255.91	1999.96	975.13(	2129.51)	0.12	1399.
15	35.17	259.24	1999.95	1030.77(	2129.51)	0.12	1534.
16	37.68	260.35	1999.95	1086.96(	2129.51)	0.13	1668.
17	40.19	259.24	1999.95	1143.21(	2129.51)	0.13	1799.
18	42.71	255.91	1999.94	1199.03(	2129.51)	0.13	1926.
19	45.22	250.40	1999.94	1253.93(	2129.51)	0.13	2048.
20	47.73	242.75	1999.94	1307.44(	2129.51)	0.13	2162.
21	50.24	233.03	1999.93	1359.09(	2129.51)	0.13	2270.
22	52.76	221.31	1999.93	1408.42(	2129.51)	0.13	2370.
23	55.27	207.71	1999.93	1455.03(	2129.51)	0.14	2462.
24	57.78	192.33	1999.92	1498.50(	2129.51)	0.14	2545.
25	60.29	175.31	1999.92	1538.46(	2129.51)	0.14	2620.
26	62.80	156.79	1999.91	1574.56(	2129.51)	0.14	2686.
27	65.32	136.93	1999.91	1606.49(	2129.51)	0.14	2743.
28	67.83	115.90	1999.91	1633.99(	2129.51)	0.14	2792.
29	70.34	93.88	1999.90	1656.80(	2129.51)	0.14	2832.
30	72.85	71.06	1999.90	1674.74(	2129.50)	0.14	2862.
31	75.37	47.64	1999.90	1687.65(	2129.50)	0.14	2884.

Thermodynamics Conditions of Cells

Cell Type	z Node	Max(T-<T>)	T	Saturation P(kPa)
1	31	434.21	2121.87	1937.51
2	31	-351.02	1336.63	10.78
3	31	-497.75	1189.91	1.91

Delta pressure(KPa) because T1>T(average) 1738.05

<c> in $f=c/Re^{*0.25}$ is 0.25944

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)

Node	z(cm)	J(Kw/cm2)	Twall(K)	Tclad(K)	TcladAv	Tfuel(K)	TfuelAv
1	0.00	0.02369	502.51	506.13	504.15	549.07	541.17
2	2.51	0.03534	519.82	525.22	522.27	588.24	576.46
3	5.02	0.04669	543.62	550.75	546.87	632.31	616.75
4	7.54	0.05764	573.89	582.69	577.89	680.96	661.75
5	10.05	0.06810	610.48	620.88	615.22	733.91	711.21
6	12.56	0.07798	653.17	665.08	658.59	790.85	764.86
7	15.07	0.08719	701.62	714.94	707.68	851.49	822.42
8	17.59	0.09566	755.42	770.03	762.06	915.47	883.59
9	20.10	0.10330	814.09	829.86	821.27	982.43	948.00
10	22.61	0.11007	877.11	893.92	884.76	1051.95	1015.26
11	25.12	0.11590	943.92	961.62	951.97	1123.57	1084.94
12	27.63	0.12073	1013.93	1032.36	1022.32	1196.79	1156.55
13	30.15	0.12454	1086.52	1105.54	1095.17	1271.09	1229.57
14	32.66	0.12728	1161.06	1180.49	1169.90	1345.90	1303.47
15	35.17	0.12893	1236.89	1256.58	1245.85	1420.64	1377.66
16	37.68	0.12949	1313.37	1333.14	1322.36	1494.71	1451.55
17	40.19	0.12893	1389.82	1409.51	1398.78	1567.53	1524.55
18	42.71	0.12728	1465.60	1485.03	1474.44	1638.47	1596.04

19	45.22	0.12454	1540.05	1559.06	1548.70	1706.94	1665.43
20	47.73	0.12073	1612.52	1630.95	1620.91	1772.36	1732.12
21	50.24	0.11590	1682.40	1700.10	1690.45	1834.16	1795.53
22	52.76	0.11007	1749.08	1765.89	1756.73	1891.80	1855.11
23	55.27	0.10330	1812.00	1827.77	1819.17	1944.76	1910.33
24	57.78	0.09566	1870.60	1885.21	1877.24	1992.58	1960.69
25	60.29	0.08719	1924.39	1937.70	1930.44	2034.81	2005.75
26	62.80	0.07798	1972.89	1984.80	1978.31	2071.07	2045.08
27	65.32	0.06810	2015.70	2026.10	2020.43	2101.02	2078.32
28	67.83	0.05764	2052.44	2061.25	2056.45	2124.36	2105.14
29	70.34	0.04669	2082.80	2089.93	2086.04	2140.86	2125.29
30	72.85	0.03534	2106.50	2111.90	2108.96	2150.34	2138.56
31	75.37	0.02369	2123.35	2126.97	2124.99	2152.68	2144.79

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
 dH: change of enthalpy (joule/kg) 0.50566E+07
 dKin change kinetic energy(joule/kg) 0.43164E-02
 relative dKin/dQ 0.000000
 Balance (dH+dKin)/dQ 0.9999961

PROFILE OF CHANNEL WITH MINIMUM 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(19rods/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
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	9.2130
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 *****

Node	z (cm)	Po (w/cm)	Pr (KPa)	T (K)	(Tsat)	V (m/s)	Re
1	0.00	11.36	2000.00	500.00	(2129.52)	0.11	274.
2	2.51	16.94	2000.00	502.81	(2129.52)	0.11	279.
3	5.02	22.38	1999.99	506.72	(2129.52)	0.11	287.
4	7.54	27.63	1999.99	511.71	(2129.52)	0.11	296.
5	10.05	32.64	1999.99	517.75	(2129.52)	0.11	308.
6	12.56	37.38	1999.98	524.79	(2129.51)	0.11	321.
7	15.07	41.79	1999.98	532.79	(2129.51)	0.11	337.
8	17.59	45.85	1999.97	541.69	(2129.51)	0.11	355.
9	20.10	49.51	1999.97	551.42	(2129.51)	0.11	375.
10	22.61	52.76	1999.97	561.89	(2129.51)	0.11	396.
11	25.12	55.55	1999.96	573.04	(2129.51)	0.11	420.
12	27.63	57.87	1999.96	584.76	(2129.51)	0.11	445.
13	30.15	59.69	1999.96	596.96	(2129.51)	0.11	472.
14	32.66	61.01	1999.96	609.52	(2129.51)	0.11	500.
15	35.17	61.80	1999.95	622.35	(2129.51)	0.11	529.
16	37.68	62.06	1999.95	635.33	(2129.51)	0.11	559.
17	40.19	61.80	1999.95	648.34	(2129.51)	0.11	589.
18	42.71	61.01	1999.94	661.27	(2129.51)	0.11	620.
19	45.22	59.69	1999.94	674.01	(2129.51)	0.11	650.
20	47.73	57.87	1999.94	686.44	(2129.51)	0.11	680.
21	50.24	55.55	1999.94	698.46	(2129.51)	0.12	709.
22	52.76	52.76	1999.93	709.95	(2129.51)	0.12	737.
23	55.27	49.51	1999.93	720.82	(2129.51)	0.12	764.
24	57.78	45.85	1999.93	730.96	(2129.51)	0.12	789.
25	60.29	41.79	1999.92	740.29	(2129.51)	0.12	812.
26	62.80	37.38	1999.92	748.73	(2129.51)	0.12	833.
27	65.32	32.64	1999.92	756.20	(2129.51)	0.12	851.
28	67.83	27.63	1999.92	762.63	(2129.51)	0.12	867.
29	70.34	22.38	1999.91	767.97	(2129.51)	0.12	881.
30	72.85	16.94	1999.91	772.17	(2129.51)	0.12	891.
31	75.37	11.36	1999.91	775.19	(2129.51)	0.12	899.

Thermodynamics Conditions of Cells

Cell Type	z Node	Max(T-<T>)	T Saturation	P(kPa)
1	31	101.98	877.17	0.01
2	31	-81.96	693.23	0.00
3	31	-116.03	659.16	0.00

Delta pressure(KPa) because T1>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)

Node	z(cm)	J(Kw/cm2)	Twall(K)	Tclad(K)	TcladAv	Tfuel(K)	TfuelAv
1	0.00	0.00565	500.60	501.46	500.99	511.74	509.86
2	2.51	0.00843	504.71	506.00	505.30	521.27	518.46
3	5.02	0.01113	510.32	512.02	511.10	532.10	528.39
4	7.54	0.01374	517.40	519.50	518.35	544.12	539.54
5	10.05	0.01623	525.90	528.38	527.03	557.25	551.84
6	12.56	0.01859	535.77	538.61	537.06	571.39	565.19
7	15.07	0.02079	546.93	550.11	548.38	586.43	579.50
8	17.59	0.02280	559.32	562.80	560.90	602.26	594.66
9	20.10	0.02463	572.82	576.58	574.53	618.76	610.55
10	22.61	0.02624	587.34	591.35	589.17	635.80	627.06
11	25.12	0.02763	602.76	606.98	604.68	653.27	644.06
12	27.63	0.02878	618.94	623.34	620.94	671.03	661.43
13	30.15	0.02969	635.76	640.29	637.82	688.93	679.04
14	32.66	0.03034	653.05	657.68	655.16	706.85	696.73
15	35.17	0.03074	670.68	675.37	672.81	724.63	714.39
16	37.68	0.03087	688.48	693.19	690.62	742.14	731.85
17	40.19	0.03074	706.30	710.99	708.44	759.24	748.99
18	42.71	0.03034	723.99	728.62	726.09	775.78	765.67
19	45.22	0.02969	741.38	745.91	743.44	791.63	781.73
20	47.73	0.02878	758.32	762.72	760.32	806.65	797.05
21	50.24	0.02763	774.67	778.89	776.59	820.71	811.50
22	52.76	0.02624	790.28	794.28	792.10	833.70	824.95
23	55.27	0.02463	805.00	808.76	806.71	845.50	837.29
24	57.78	0.02280	818.72	822.20	820.30	856.00	848.40
25	60.29	0.02079	831.31	834.48	832.75	865.11	858.18
26	62.80	0.01859	842.65	845.49	843.94	872.75	866.55
27	65.32	0.01623	852.66	855.13	853.78	878.84	873.43
28	67.83	0.01374	861.23	863.33	862.18	883.32	878.74
29	70.34	0.01113	868.30	870.00	869.07	886.14	882.43
30	72.85	0.00843	873.80	875.09	874.39	887.28	884.47
31	75.37	0.00565	877.68	878.55	878.08	886.71	884.83

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

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APPENDIX A. LISTING OF CODE NEPNERVA

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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
c 2) support cell: He coolant, Inconel support for ZrH, coolant, Pyrolytic
c graphite and graphite (last two as thermal shield for ZrH)
c
c      character*80 tit, aldum
c
c      dimension buw(5,5), bup(5), aux(5), wbeth(8), th(8), pfr(5), sofl(5)
c      *, pfrm(5), Sogam(7), Pr5(7), Emin(5), Ras(5), Has(5), Rop(5), Hop(5)
c
c      common /Soze/ its, epss
c
c      common /MaBaSi/ R, H, ishape
c
c      common /Bala/ Ereq, buwo(5), relr, relal, rela2, dkeol, dkstr, BU, Vcor,
c      *U5m, dkbu, dkxes, dkxep, dksms, dksmp, dkbe, rkre, eps, itmax, dcr
c      *, itest, aofis
c
c      common /cont/ Rad, drr, dref, rasp, refec, ncr, dksu, dkest, relar
c
c      common /Fluxo/ Pow, Vc, sofr, fluxn(4), xedks, xedkt, tmax, smdks, smdkt,
c      *tsm, D, iwxe
c
c      common/thermo/ tit, nnodo, iexpl, ifri, imax, norif, iditus, nfu, pin, tin
c      *, dcm, ru, xi, der, epso, Powt, rjs, flowt, GU235, Vact, Enr, PUC, Rouc, RoZrC
c      *, RGraf, dclad, Hact, Pfacr, Daxi, fact, pf, tf, fe, iprth, iopth, iouth,
c      *Pfacz, iprob, flowal, iboun
c
c      common /fphe/ imaxt, epsi, dero
c
c      common /Gamsh/ coBe, coTa, coC, coZr, coU, coH, coNi, coFe, coCr, coTi, coSi
c      *, dist, Req, shg(7), shgnb(7), Zeq(7), Dosewg(7), Doseg(7), itmag, epsg
c      *, aten, Dosen, Doseng(7)
c
c      Common /CROSS/ AU, BBU, signe, ishin, ishig
c
c      open(unit=7, file='nepnerva3.i', status='old')
c      open(unit=8, file='nepnerva3.out', status='unknown')
c
c      read(7,11) tit
11  format(a80)
c
c      read(7,11) aldum
c      read(7,20) itest, ndt, itmax, icon, nput
c      read(7,11) aldum
c      read(7,10) Pow, D, BU, eps, der
c      read(7,11) aldum
c      read(7,10) drr, dral, dra2
c      read(7,11) aldum
c      read(7,10) dkstr, dkeol, dksu
c      dkest=dkstr
c      if(icon.eq.0) go to 2378
c      read(7,11) aldum
c      read(7,20) ncr, nnodo, nfu, ishape
c      read(7,11) aldum
c      read(7,20) iboun, iopth
c      read(7,11) aldum
c      read(7,20) iexpl, ifri, iditus, iprth, iouth
c      read(7,11) aldum
c      read(7,20) iwte, ishn, ichoose
c      read(7,11) aldum

```

```

      read(7,10) pin,tin,ps,ts
      read(7,11) aldum
      if(iboun.eq.0) read(7,10) flowt
      if(iboun.eq.1) read(7,10) toutl
      read(7,11) aldum
      read(7,10) ru,xi,fact,Ripple
      read(7,11) aldum
      read(7,10) tempv,depvw
      read(7,11) aldum
      read(7,10) fastf,Dose,zload,rload
      read(7,11) aldum
      if(ishape.eq.1) go to 2378
      if(ishape.eq.2) read(7,10) R
      if(ishape.eq.3) read(7,10) H
2378 continue
c
c
      epso=eps
      epsi=eps
      epsg=eps
      epss=eps
      dero=der
      Powt=Pow
      Daxi=5.
c
      Ereq=Pow*D*365.25
c
c
c      INPUT DESCRIPTION FOR REALS
c
c
c Pow(Mw): power; D(years): core life; BU(at%): percent U235 atoms
c burned;
c Inlet flow conditions:
c pin,tin(MPa,K)) pressure and temperature of the inlet coolant(fuel el
c ps,ts          pressure and temperature coolant(sup el), just for
c                book-keeping
c drr,dral,dra2 (cm) thickness of Be reflector:radial,top-bottom axial
c dkstr(%): reactivity structural materials(estimated)
c dkeol(%):      "      at end of life(desired)
c dksu (%):desired subcritical reactivity required at BOL with drums in
c eps: tolerance for iterations (like energy)
c ru: rugosity coolant channel; xi: /0., 1.0/ fully explicit to implicit
c der=1.01 (compute derivatives)
c fact:fraction fission energy/thermal
c flowr(kg/s)total coolant flow(applicable if iboun=0)
c Daxi(cm): extrapolation length axial cos power distribution
c Ripple:Relative amplitude of power distribution as function of angle
c at R=Rcore
c tempv(K): Temperature of Pressure Vessel; if <0. program chooses tout
c depvw(cm):Max thickness of the pressure vessel acceptable
c toutl(K): outlet temperature of coolant(applicable if iboun=1)
c fastf(1/cm2): fast fluence (during time D) at payload area
c zload(m) : axial distance from the base of reactor to payload plane
c rload(m) : radius of load area
c Dose(Rad): integrated gamma dose(during time D) required for payload
c ddt(cm): delta r and delta h for test curve Eavailable=f(R) or f(H)
c
10    format(7e10.0)
c
      imax=itmax
      imaxt=itmax
      itmag=itmax
      its=itmax
c
c
c      INPUT DESCRIPTION FOR INTEGERS

```

```

c
c
c itmax: 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 iwrte=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 iexpl/0,1/ implicit,explicit solution of coolant channel
c ifri/0,1/ no,yes friction factors;iditus/0,1/ no,yes Dittus Correlation
c nfu; number of nodes inside fuel mix
c iprth/0,1/no,yes print details cooling channel
c iopth=1 3-D uniform power density assumed
c      =2 2-D (r,theta) uniform power density assumed
c      =3 Uniform Fuel load/uniform coolant flow assumed
c      =4 Uniform Fuel load/Coolant flow proportional to power density
c      assumed
c iouth=1 Thermodynamic profile at Max power density channel is printed
c iouth=2      "      "      "      Min      "      "      "      "
c iouth=3      "      "      "      Max and Min      "      "      "
c iboun=0 Input Coolant Flow
c iboun=1 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 to compute Energy=f(R)
c or f(H), nput total number of points in tabulation
c ichoose=0,1 no,yes correction,by program,of incompatible request
c
c
c
c
20      format(14i5)
c
c      if(BU.gt.50.) write(8,32) BU
c
32      format(///' YOUR VALUE FOR BURN UP',f8.2,' IS TOO LARGE FOR'/
*          ' A REASONABLE EXTRAPOLATION OF THE DATA BASE'//
*          ' PROGRAM STOPS '///)
c
c      if(BU.gt.50.) stop
c
c      if(drr.gt.40..or.dra1.gt.40..or.dra2.gt.40.)
*write(8,31) drr,dra1,dra2
31      format(///' YOUR VALUE OF REFLECTOR THICKNESS(CM)',3f8.2/
*          ' ARE TOO LARGE FOR A REASONABLE EXTRAPOLATION'/
*          ' OF THE DATA BASE'//
*          ' PROGRAM STOPS '///)
c
c      if(drr.gt.40..or.dra1.gt.40..or.dra2.gt.40.) stop
c
c
c      data enr,ff,dh,dc,puc,dref,nh/.93,1.913,2.794,0.1,0.5,30.,19/
c
c enr: enrichment(at %);
c fuel element; ff(cm): flat to flat distance hexagonal element
c dh(mm) coolant hole; dc(mm) cladding thickness
c puc: mole fraction of UC in mix UC-ZrC
c dref(cm): thickness of Be reflector(for data base)
c nh number of coolant holes per fuel element(data base calculated,nh=19)
c
c      dcm=0.1*dh
c      dclad=0.1*dc
c      data r1,r2,r3,r4,r5/0.15,0.25,0.65,0.75,0.85/
c
c Support Element, radius of different regions(cm)
c r1,Coolant;r2,Inconel;r3,ZrH;r4,Coolant;r5,PyroGraphite
c data base calculated with these values
c

```

```

      data pee,Av,ABe,xop/3.1415926,0.602202,
      *          9.01219,0.541315/
c
c xop:optimum shape for cylindrical reactors; Av: Avogadro's number
c ABe: Be at-weight;pisq3=pi*sqrt(3)
c
      data au5,ah,ahe,azr,ac,ani,acr,afe,ati,asi,au8/235.044,1.00797,4.0
      *026,91.22,12.01115,58.71,51.996,55.847,47.90,28.086,238.0508/
c
c atomic weights
c au5:U235; ah:H; ahe:He; azr: Zr; ac: C; ani: Ni; acr: Cr; afe: Fe
c ati: Ti; asi: Si;au8: U238
c
      data xh1,xh2,xcl2,xcl3/.99985,0.00015,.9889,.0111/
c
c atomic fractions
c xh1,xh2: H and deuterium in nat H
c xcl2,xcl3: C12 and C13 in nat C (not used in present version)
c
      data rouc,rozrc,rgraf,rgrap,roin,rozrh/12.97,6.7,1.7,1.7,8.90,5.6/
c
c densities (g/cm3)
c rouc: UC; rozrc: ZrC; rgraf: Graphite; rgrap: pyrolytic Graphite;
c roin: inconel alloy; rozrh:ZrH2
c
      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/
c
c weight fraction inconel alloy
c xni: Ni; xcr: Cr; xfe: Fe; xTi: Ti;xsi: Si
c Densities(g/cm3): Ro...
c roBe: Be;RoAst: Astar Alloy ; RoLis:LiH+Stainless Steel N'Shield
c RoBC: B4C(N' Shield)
c
      data wfi,rnu,remH,remBe,remC,remFe,remNi,remZr,remU,remTa
      */3.2042e-11,2.44,1.,1.07,0.72,1.98,1.89,2.36,3.6,3./
c
c wfi: joules/fission(200Mev); rnu: number of neutrons per fission
c rem H,Be,C,Fe,Ni,Zr,U,Ta : removal cross sections(barns) for fast neut
c
      data (pfr(i),i=1,5)/1.67,1.71,1.77,1.77,1.81/
c
c pfr radial maximum power factor at BOL(These are number with control
c drums in, then at center line and for uniform load)
c
      data (pfrm(i),i=1,5)/0.577,0.423,0.311,0.311,0.257/
c
c pfrm minimum radial peaking factors at BOL( at border core)
c same restrictions as pfr
c
      data (buw(1,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.,10.,20.,30.,40./
c
c buw reactivity worth(% delta k) at bup(atom % burn up) for
c the following values of Support/Fuel elements
c
      data (sof1(i),i=1,5)/0.0,0.2,0.5,1.0,2.0/
c
c sof1: Support/Fuel ratio
c
c
      data (wbeth(i),i=1,8)/0.,0.2728,0.3947,0.5026,0.6778,0.8524,
      *          0.9517,1.000/

```

```

c wbeth: relative(to 30 cm) worth of Be as function of its thickness
c th(cm)(input next)
c
      data (th(i),i=1,8)/0.,3.67,5.67,7.67,11.67,17.67,24.,30./
c
c burn-up worths for input BU,stored at buwo()
c
      RoAst=RoAst/1000.
      isofl=5
      ibup=5
      icart=1
1274 continue
      do 101 i=1,isofl
      do 102 j=1,ibup
102   aux(j)=buw(j,i)
      call Inter(bup,aux,ibup,BU,y)
101   buwo(i)=y
c
c relative worth of Be reflectors: relr, radial;rela1,rela2:axial
c
      ibe=8
      call Inter(th,wbeth,ibe,drd,relr)
      relar=relr
      call Inter(th,wbeth,ibe,dra1,rela1)
      call Inter(th,wbeth,ibe,dra2,rela2)
      rela1=0.5*rela1
      rela2=rela2*0.5
c
c if itest=1 print your options:
c
c   TTTT EEEEE SSSSS TTTT      1) Energy available with optimum shape
c   T   E   S   T              2) Radius of infinite cylinder
c   T   EEE   S   T              3) Height of infinite "pancake"
c   T   E       S   T              4) Energy available as function of R and
c   T   EEEE SSSSS T              H
c                                   (2 or 3 would produce "infinite" energy)
c
c
c
c
c   ish=ishape
c   RRR=r
c   HHH=h
c
c
c   itpr=itest
c   if(itpr.eq.1)
c   *write(8,6133) Ereq,BU,drd,drl,dr2,dkeol,dkstr
6133 format(// ' INPUT'// ' You requested Mwdays',f10.2/
c   * ' And burn-up(%)',f5.2/
c   * ' With radial Be reflector thickness(cm)',f6.2/
c   * ' " top " " " " ',f6.2/
c   * ' " bottom " " " " ',f6.2/
c   * ' End of Life delta k(%) ',f6.2/
c   * ' Structural delta k(%) ',f6.2/)
c   if(itpr.eq.1)
c   *write(8,1632)
c
c   1632 format(' Run Test, Energy Available (Mwd) for Optimum Shape'/
c   * ' with corresponding Rop and Hop'/
c   * ' Critical Radius(cm) for Infinite Reactor'/
c   * ' Critical Height(cm) for Infinite Reactor'/
c   * ' For your input conditions'/
c   * 'S/F Energy Rop Hop Rc Hc'//)
c
c
c compute Energy available for ideal shape Emin()
c and asymptotic radius Ras() and height Has()

```

```

C      itest=1
      do 1633 is=1, isof1
        ishape=1
        sofac=sof1(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
C
C      if(itpr.eq.1)   write(8,1634) sofac,Ene,Ropo,Hopo,Rcri,Hcri
1633 continue
C
1634 format(f6.3,f12.1,4f12.2)
C
      itest=itpr
      if(itest.eq.0) go to 1631
C
C compute curves Eavailable as function of radius and Height of core and
C S/F in order to illustrate the user about the options.
C
      do 5782 is=1, isof1
        sofac=sof1(is)
C
C      write(8,5783) sofac,Ereq
C
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'//)
C
      Rs0=Ras(is)*der
      Hs0=Has(is)*der
      rnt=ndt
      ddr=(Rop(is)-Rs0)/rnt
      ddh=(Hop(is)-Hs0)/rnt
      ndtt=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
C
C      write(8,5784) idt, Rs, xra, Ener, Hs, xh, EneH
C
5784 format(i5,2(f9.2,f9.3,f12.0))
C

```



```

5782 continue
c
c
c      EEEEE  N  N  D      TTTTT EEEEE SSSSS TTTTT
c      E      NN  N  D D      T  E      S      T
c      EEE     N N N  D  D      T  EEE     S      T
c      E       N  NN  D  D      T  E       SS     T
c      EEEEE  N  N  D      T  EEEE  SSSSS  T
c
c 1631 bypass prints and some checks on energy
c
1631 continue
c
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
c check if you are requesting too little energy
c
      Emin=Emin(isof1)
      if(Ereq.ge.Emin) go to 337
      if(icart.eq.1)
*write(8,5133) Ereq,BU,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,Emin
1425 format(2f12.2)
      BUA=BU
      BU=BU-1.
      if(BU.le.0.) BU=BUA/2.
      go to 1274
337 continue
c
c check if there is enough energy for ideal shape(ishape=1)
c
      iwa=0
      if(Ereq.le.Emin(1)) go to 357
      iwa=1
c
c set the warning flag iwa=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
c

```

```

itest=1
ishape=2
sofac=sof1(isof1)
Das=Ras(isof1)
Dop=Rop(isof1)
call Size(Das,Dop,Ereq,sofac,R11,R41)
sfr14=sofac
hr4=h
hr1=Vcor/(pee*r11**2)
vr14=Vcor/1000.
sofac=sof1(1)
Das=Ras(1)
Dop=Rop(1)
call Size(Das,Dop,Ereq,sofac,R21,R31)
sfr23=sofac
hr3=h
hr2=Vcor/(pee*R21**2)
vr23=Vcor/1000.
ishape=3
sofac=sof1(isof1)
Das=Has(isof1)
Dop=Hop(isof1)
call Size(Das,Dop,Ereq,sofac,H1,H4)
sfh14=sofac
rh4=R
rh1=sqrt(Vcor/(pee*H1))
vh14=Vcor/1000.
sofac=sof1(1)
Das=Has(1)
Dop=Hop(1)
call Size(Das,Dop,Ereq,sofac,H2,H3)
sfh23=sofac
rh3=R
rh2=sqrt(Vcor/(pee*H2))
vh23=Vcor/1000.
write(8,369) Ereq,Emin(1),R11,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,drd,dr1,dr2,dkeol,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
357 continue
if(ishape.eq.1.or.iwae.eq.1) go to 434
c
c begin check of input R or H if E requested is not in bifurcation
c region
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
4551 format('/// I choose Flag=',i5,' Your R=',f8.2/
*      ' Outside Possible Range',2f10.2/
*      ' Program stop'//)
if(ichoose.eq.1) stop
Rin=R
R=0.5*(R11+R21)
write(8,4552) ichoose,Rin,R11,R21,R
4552 format('/// I choose Flag=',i5,' Your R=',f8.2/
*      ' Outside Possible Range',2f10.2/
*      ' Program continues with average, R=',f8.2//)

443 continue
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
4553 format('/// I choose Flag=',i5,' Your H=',f8.2/
*      ' Outside Possible Range',2f10.2/
*      ' Program stop'//)
if(ichoose.eq.1) stop
Hin=H
H=0.5*(H1+H2)
write(8,4554) ichoose,Hin,H1,H2,H
4554 format('/// I choose Flag=',i5,' Your H=',f8.2/
*      ' Outside Possible Range',2f10.2/
*      ' Program continues with average, H=',f8.2//)

454 continue
endif
itest=0
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
455 format('/// I choose Flag=',i3,' Not enough available energy'/

```

```

*                                     for ishape=1 option, program stop')
  if(ichoose.eq.1) stop
  ishape=2
  R=R31*1.01
  write(8,4555) R
4555 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
4556 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
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
c
c
  ibu=0
  sofal=sof1(1)
  ball=Balance(ibu,sofal)
  if(ibu.eq.1) write(8,597)
597 format(' Stop trying to bracket demand')
  if(ibu.eq.1) stop
  sofa2=sof1(isof1)
  bal2=Balance(ibu,sofa2)
  if(ibu.eq.1) write(8,597)
  if(ibu.eq.1) stop
c
c if we successfully arrived to this point,it means we bracket the demand
c Then:
c bisect Balance until Eavailable=Erequested
c
  it=0
145 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(iwrte.eq.1) write(8,219)
219 format(' it',7x,'sofal',8x,'sofa',7x,'sofa2',8x,'ball',7x,'Erem',
*8x,'bal2')

```

```

218   if(iwrte.eq.1) write(8,218)it,sofa1,sofa,sofa2,ball,Erema,bal2
      format(i4,3f12.6,3f12.3)
      call bisect(sofa1,sofa2,sofa,ball,bal2,Erema,iwa)
      if(it.le.itmax.and.iwa.eq.0) go to 145
144   continue
      if(it.gt.itmax.or.iwa.eq.1) then
        write(8,146) sofa1,ball,sofa2,bal2,it,iwa
146   format(////' Problems trying to bisect  Balance'/
*         ' sofa1=',e12.4,' ball=',e12.4/
*         ' sofa2=',e12.4,' bal2=',e12.4/
*         ' iteration=',i5/
*         ' iwa=',i5/)
      stop
      else
        continue
      endif

c
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=re/(1.+rasp)
        nf=rf
        nse=ne-nf
        rse=nse
      endif
1975  R=sqrt(ne*ae/pee)
      H=Vcor/(ne*ae)
      Hact=H

c
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, ac1 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.
      ac1=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-ac1-ac2-ac0

c
c  volumetric fractions
c

```

```

fe=aae/ae
fl=ac1/ae
f2=ac2/ae
fco=aco/ae
c
c radius of microcell: rml,coolant; rm2,clad; rm3 microcell
c
    rml=rh
    rm2=rh+dcc
    amicro=pee*rm2**2+aae/nh
    rm3=sqrt(amicro/pee)
c
c Calculate outlet condition, ie. if iboun=0(flow is input)>houtlet
c                                if iboun=1(tout is input)>flow
c See: 1) no velocities in energy conservation (see effects in detailed
c       of the channel)
c       2) tout=f(hout,pinlet) (reasonable approximation)
c       3) from 1) and 2) tout is reasonable.
c
    pino=pin*1.e+6
    call phe(hin,pino,tin,rhor,vis,cp,pr,a,rrk,xx,0)
    if(iboun.eq.0) go to 391
    call phe(hout,pino,toutl,rhor,vis,cp,pr,a,rrk,xx,0)
    flowt=fact*Pow*1.e+6/(hout-hin)
c
c alternative flow in case of problem in thermo
c
    call phe(hina,1.e+7,20.,rh,visa,cpa,pra,aa,rka,xxa,0)
    call phe(houta,1.e+7,toutl,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,rrk,xx,1)
c
c calculate maximum stress(sigma) for the Astar Pressure Vessel
c
    if(tempv.lt.0.) tempv=tout
    call desstr(tempv,l,D,sigma,sigrod,itmax,ipresv)
c
c number densities; for He: estimate taverage as the next statement
    tav=0.5*(tin+tout)
    rhe=rho(pino,tav)
    hen=0.001*rhe*Av/Ahe
    rf=nf
    ru5=1000.*u5m/(rf*aae*H)
    u5n=ru5*Av/Au5
    u8n=u5n*(1./enr-1.)
c
c 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=(u5n*au5+u8n*au8+un*ac)/av
c Volumetric fraction in UC-ZrC-Graphite mix
    xuc=rouca/rouc
    xzrc=rzrca/rozrc
    xgraf=1.-xuc-xzrc
    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)
    hena=hen*fco

```

```

cna=cn1*(f1+f2)+cn2*fe
zrna=zrn1*(f1+f2)+zrn2*fe
grafa=grafn*fe
u5na=u5n*fe
u8na=u8n*fe
Vcore=Vcor/1000.

c
c
c      write(8,11) tit
c
c      write(8,51) Pow,D,Ereq,BU,drd,dr1,dr2,test
c
51  format(// ' INPUT TO THE PROGRAM'// ' Power(Mw)',f8.2,' Core life',f
      *8.3,' 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)
c
c      if(ishape.eq.1) write(8,317) xop
317 format('/ Minimum Core Volume Chosen: R/H=',f9.6/)
c
c      if(ishape.eq.2) write(8,318) R
318 format('/ Core Radius Chosen: R(cm)=',f7.2/)
c
c      if(ishape.eq.3) write(8,319) H
319 format('/ Core Height Chosen: H(cm)=',f7.2/)
c
c      dkfp=dkbu+dkxep+dksm
      dkreq=dkfp+dkstr+dkeol
      dkbe=dkbe/100.
      refec=rkre+dkbe
c
c
c      write(8,52) dkreq,dkfp,dkbu,dkstr,dkeol,refec,rkre,dkbe
c
c
52  format(' And it has the following reactivity balance'//
      *' Delta k required(%)',f6.2,' with components'//
      *' Fission Products(%)',f6.2/
      *' " "(except Xe,Sm)(%)',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//)
c
c
c      write(8,521)sofr,xedks
c
c
521 format(' Support/Fuel Ratio=',f8.4,' Steady Xe reactivity(%)'f6.2)
      if(iwxe.eq.0) write(8,1521) xedkt,tmax
1521 format(
      *' Xe Reactivity after trip(%)',f6.2,' Peak at time(hr)',f6.2)
      if(iwxe.eq.1) write(8,1522)
1522 format(' No Xe peak after shutdown')
      write(8,5211)smdks,smdkt,tsm,(fluxn(i),i=1,4)
5211 format(
      *' Sm Reactivity (%) Steady',f6.2,' Peak after trip(%)',f6.2/
      *' Sm saturates at days',f8.2/
      *' Neutron Flux(1/cm2sec)(core average) >100.Kev',e12.4/
      *'           "           "           "           "           "           >100. ev',e12.4/
      *'           "           "           "           "           "           > 3. ev',e12.4/
      *'           "           "           "           "           "           < 3. ev',e12.4//)
c
c      Rad=R
c

```

```

c call control to design control drums
c
c      Call Control
c
c
c      write(8,30) u5m,enr,Vcore,rasp,R,H,ne,nse,nf,ff
c
30  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//)
c
c
c      write(8,40) puc,dc,nh,dh,pin,tav
c
40  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'/)
c
c
c      write(8,50) fco,f1,f2,fe
c
50  format(' Volume fractions in Fuel Element'/'          Coolant',f7.4/
*      '          ' Clad Coolant',f7.4
*      '          /' Clad Fuel El',f7.4
*      '          /' Fuel Mix      ',f7.4)
c
c
c      write(8,41) xuc,rouca,xzrc,rzrca,xgraf,rgraa
c
41  format('/' Volumetric Fractions in Fuel Mix * Density(g/cm3)'/
*      '          UC',f10.5,f13.5/
*      '          ZrC',f10.5,f13.5/
*      '          Graphite',f10.5,f13.5//)
c
c
c      write(8,60) rml,hen,rm2,cn1,zrn1,rm3,cn2,zrn2,grafn,u5n,u8n
c
60  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)
c
c Total mass of the fuel elements
Vact=rf*ae*H/1000.
Gfuel=Vact*(hena*ahe+cna*ac+zrna*azr+grafa*ac+u5na*au5+u8na*au8)/a
*v
Ggraf=Vact*grafa*ac/av
GZrCc=Vact*(f1+f2)*rozrc
GHe=Vact*hena*ahe/av
GZrCf=Vact*fe*rzrca
GUC=Vact*fe*rouca
wUC=GUC*100./Gfuel
wZrCf=GZrCf*100./Gfuel
wGraf=Ggraf*100./Gfuel
wZrCc=GZrCc*100./Gfuel
wHe=GHe*100./Gfuel
rou5=u5m*1000./Vact
c
c

```



```

        write(8,71) Vact,Gfuel,rou5,Ggraf,wGraf,GUC,wUC,GZrCf,wZrCf,GZrCc,
        *wZrCc,Ghe,wHe
c
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
c Number densities and masses of Support Element
c
      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*1.e6
      rhe=rho(p,ts)
      ches=0.001*rhe*av/ahe
      cni=roin*xni*av/ani
      cfe=roin*xfe*av/afe
      ccr=roin*xcr*av/acr
      cti=roin*xti*av/ati
      csi=roin*xsi*av/asi
      czr=rozrh*av/(azr+2.*ah)
      ch=2.*czr
      cgraf=rgraf*av/ac
      cgrap=rgrap*av/ac
c averages in support Elements
      chesa=(f1+f4)*ches
      cnisa=cnis*f2
      cfea=cfe*f2
      ccra=ccr*f2
      ctia=cti*f2
      csia=csi*f2
      czra=czr*f3
      cha=ch*f3
      cgras=f5*cgrap+f6*cgraf
c 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
      fhes=1.
      fInc=1.
      fZrh=1.
      fGras=1.
      if(rasp.eq.0.) go to 1763
      fhes=100.*Ghes/Gsup
      fInc=100.*GInc/Gsup
      fZrh=100.*GZrh/Gsup
      fGras=100.*Ggras/Gsup
c

```

```

c
1763 write(8,73) Vsup,Gsup
c
73   format('          SUPPORT ELEMENTS(ALL)'/
*      'Volume of Support Elements(L)',f10.3/
*      'Mass(Kg)',f10.3//)
c
c
      write(8,74) Ghes,fhes,GInc,fInc,GZrh,fZrh,Ggras,fgras
c
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//)
c
c
      write(8,636)
c
636  format(////' SUPERCELL CONFIGURATION(Number Densities 10**24atoms/c
*m3)')//)
c
      if(rasp.eq.0.) go to 1349
c
c
      write(8,72)r1,ches,r2,cni,cfe,ccr,cti,csi,r3,czr,ch,r4,ches,r5,cgr
*ap,r6,cgraf
c
72   format('Support Element'/
*      'Coolant Radius(cm)',f7.4,' He',f12.8/
*      'Inconel Radius(cm)',f7.4,' Ni',f12.8,' Fe',f12.8/
*      '          ',f7.4,' Cr',f12.8,' Ti',f12.8/
*      '          ',f7.4,' 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//)
c
      rsup=sqrt(r6**2+rf*ae/(pee*rse))
c
c
      write(8,70)rsup, hena,cna,zrna,grafa,u5na,u8na
c
70   format('Ring of Fuel Elements. Average Densities'/
*      'Radius(cm)',f7.4,' He',f12.8,' C',f12.8/
*      '          ',f7.4,' Zr',f12.8,' Gr',f12.8/
*      '          ',f7.4,' U5',f12.8,' U8',f12.8)
c
c Homogenized Densities in Supercell
1349 ff=rf/re
      fsup=rse/re
      hena=hena*ff
      cna=cna*ff
      zrna=zrna*ff
      grafa=grafa*ff
      u5na=u5na*ff
      u8na=u8na*ff
      ches=ches*(f1+f4)*fsup
      cni=cni*f2*fsup
      cfe=cfe*f2*fsup
      ccr=ccr*f2*fsup
      cti=cti*f2*fsup
      csi=csi*f2*fsup
      czr=czr*f3*fsup
      ch=ch*f3*fsup
      cgra=(f5*cgrap+f6*cgraf)*fsup
      cBe=roBe*Av/Abe

```

```

RBe=R+drd
C
C
write(8,91)R,hena,cna,zrna,grafa,u5na,u8na,ches,cni,cfe,ccr,cti,
*csi,czr,ch,cgra,RBe,cBe
C
91 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//
*' REFLECTOR'/
*'External Radius(cm)',f9.4/
*'
Be',f12.8)

C
rec=(grafa+cgra+cna)/u5na
reh=ch/u5na
C
C
write(8,92) rec,reh
C
92 format(////' Moderation by C. C/U235=',f10.4/
*'
Moderation by H. H/U235=',f10.4)
C
C Compute pressure vessel (if(ipresv.ne.0))
C
Volpv=0.
Gpv=0.
delpv=0.
Rcr=R+drd
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.
590 continue
Vref=pee*((R+drd)**2-R**2)*H/1000.
Vref=Vref+pee*(R+drd)**2*(dral+dra2)/1000.
Gref=Vref*roBe
Grea=Gsup+Gfuel+Gref+Gpv
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
C

```

```

c calculation of neutron shielding
c
c compute fast source Sn
c
      Sn=Pow*1.e+6*rnu/wfi
c
c compute shielding by core,reflector and pressure vessel: fsh
c concentrations smothered in Vol=Vsup+Vfuel+Vref+Vpv
c
      coBe=cBe*fre*0.01
      coTa=fvpv*Av*10.*RoAst/181.
      coC=fcore*(cna+grafa+cgra)
      coZr= fcore*(Zrna+cZr)
      coU=fcore*(U5na+U8na)
      coH=fcore*ch
      coNi=fcore*cni
      coFe=fcore*cfe
      coCr=fcore*ccr
      coTi=fcore*cTi
      coSi=fcore*cSi
      sigre=coBe*remBe+coTa*remTa+coC*remC+coZr*remZr+coU*remU+
      *      +coH*remH+(coNi+coCr)*remNi+(coFe+coTi+coSi)*remFe
      Req=(750.*Vres/pee)**0.33333333
      sire=sigre*Req*2.
      fsh=3.*(0.5-(1.-(1.+sire)*exp(-sire))/sire**2)/sire
      Snsh=Sn*fsh
c Fast fluence without shielding is flufa,at distance dist
      dist=100.*zLoad+0.5*Hrea
      flufa=Snsh/(4.*pee*dist**2)
c Multiply by core life, 1 julian year=31,557,600. sec
      tiempo=D*3.15576e+7
      flufa=flufa*tiempo
c
c Calculate Neutron Shield for zero gamma Shield
c
      tne0=shieldn(flufa,fastf,ishn,0.00,igam)
      if(ishin.eq.0) tne0=0.
c
c Now, Calculation Gamma Source Sogam()
c
      Call Gamso(Sn,aofis,sofr,Sogam,Pr5)
c
c First, Gamma Shield with no Neutron Shield
c
      Call Shieldga(Sogam,Dose,Doses,Dosew,tiempo,tgam0,0.,igam1,ishn,0)
c
c Now, Coupled with n Shield
c
      Call Shieldga(Sogam,Dose,Doses,Dosew,tiempo,tgam,tne,igam2,ishn,1)
c
      if(igam2.eq.0) tne=tne0
      if(igam2.eq.0) tgam=0.
c
c Volume and Masses of shieldings
c
      Tgt=Tan((100.*rload-Rrea)/(100.*zload+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=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

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

c
c
      write(8,796) Volg,fgv
796  format(' G Shield',2f10.2)
c
c
      write(8,797) Vols
c
797  format(' Total    ',f10.2//)
c
c
      write(8,798) Grea,fresg,Gne,fneg
c
798  format(
* '          Mass(Kg) Fraction(%)'//
* ' Reactor ',f10.2,f10.2/
* ' N Shield',f10.2,f10.2)

c
c
      write(8,796) Gg,fgg
c
c
      write(8,806) Gsis
c
806  format(' Total    ',f10.2//)
c
c
      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'//)
c
      rr21=rr2
c
c
      write(8,811) zload,rload,tgam,rr1,rr2,tne,rr21,rr3
c
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)
c

```

```

c
c      write(8,758) tempv,pin,D
c
758  format(
*' Pressure Vessel Evaluated at T(K)=' ,f8.2, ' PRESS(MPa)=' ,f8.2/
*'                                and Full Power Life(y)' ,f8.2//)
c
c
c      if(ipresv.eq.0) write(8,626)
626  format(' You have problems to contain your reactor, pressure Vesse
*'/'calculations skipped, not included in shielding or balance'//)
c
c
c      write(8,75) fcor,Gfuel,ffue,Vact,fvc,Gsup,fsup,Vsup,fvs,
*'Gref,fref,Vref, fre
c
c
75  format('DISTRIBUTION OF MASSES AND VOLUMES IN THE REACTOR'//
*' Fraction of Core Occupied by Fuel(%Vol)' ,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)
c
c
c      if(ipresv.ne.0) write(8,637) Gpv,fmpv,Volpv,fvpv,delpv
637  format('Pr Vessel' ,f10.3,f13.3,5x,f10.3,f13.3//
*' Pressure Vessel thickness(cm)' ,f8.2//)
c
c      flush=flufa
c      if(ishin.eq.1) flush=fastf
c      if(ishig.eq.1.and.igam2.ne.0) flush=flufa*aten
c
c
c      write(8,757) Sn,fsh,Req,sigre,D,flufa,flush,fastf,Zload,tne,tne0
c
757  format(
*'      DETAILS OF THE SHIELDINGS'//
*'      ' Neutron Source(1/sec)' ,e12.4/' Self Shielding by Reactor
*'Materials' ,e12.4/' 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//)
c
c
c      if(ishn.eq.1) write(8,767)
767  format(' NEUTRON SHIELDING: LiH-Stainless Steel Matrix'//)
c
c
c      if(ishn.eq.2) write(8,768)
768  format(' NEUTRON SHIELDING: B4C'//)
c
c
c      write(8,771)
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'//)
c
c
c      write(8,772) (sogam(i),i=1,7)
c
772  format(1P7e10.3/)
c

```

```

C      write(8,*) ' % FRACTION PRODUCED BY U235'
C
C      write(8,773) (Pr5(i),i=1,7)
C
773    format(7f10.2)
C
C      write(8,*) ' Equivalent Z for Build up factors'
C
C      write(8,773) (Zeq(i),i=1,7)
C
C      write(8,*) ' Gamma Self shielding by Core, Reflector and PV'
C
C      write(8,774) (shg(i),i=1,7)
774    format(7f10.6)
C
C      write(8,*) ' The same but without Buildup factor'
C
C      write(8,774) (shgnb(i),i=1,7)
C
C      write(8,*) 'Integrated Dose(Rad) without any shielding(n or gamma)'
C
C      write(8,772) (Dosewg(i),i=1,7)
C
C      if(ishig.eq.0.and.ishin.eq.1)
*write(8,*) 'Integrated Dose  Neutrons Shieldings(and no W)'
C
C      if(ishig.eq.0.and.ishin.eq.1) write(8,772) (DosenG(i),i=1,7)
C
C      if(ishig.eq.1.and.igam2.ne.0)
*write(8,*) 'Integrated Dose with W and Neutrons Shieldings'
C
C      if(ishig.eq.1.and.igam2.ne.0) write(8,772) (DoseG(i),i=1,7)
C
C      write(8,775) Dosew
775    Format(' Integrated Dose without Any Shielding,Total(Rad)',e12.4)
C
C      if(ishig.eq.1.and.igam2.ne.0) Dosos=Doses
      if(ishig.eq.0) Dosos=Dosen
      write(8,776) Dosos,tgam,tgam0
C
776    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'//)
C
C      write(8,804) Dose,Zload
C
804    format('/' Requested Dose(Rad)',f10.2,' at ',f6.2,' meters'/)
C
C      SOLVE THERMALHYDRAULIC

```

```

c      norif=nh*nf
c
c      write(8,2367) tout
c
2367  format(///' THERMALHYDRAULICS CALCULATIONS'/
*      ' Average Temperature of the Coolant at Core Exit(K)',f10
*.2//)
c
c
c      if(iboun.eq.0) write(8,3478)
3478  format('/' BOUNDARY CONDITION: INPUT FLOW'//)
c
c
c      if(iboun.eq.1) write(8,3479)
3479  format('/' BOUNDARY CONDITION: OUTLET TEMPERATURE'//)
c
c check if this is a calculation assuming uniform power distribution
c
c      if(iopth.gt.2) go to 674
c here if 3D or 2D power density is constant
c      Pfacr=1.
c      Pfacaz=1.
c      Call Thermohe
c program end
c      go to 677
674  continue
c here if we have uniform loading ie spacial dependent power density
c      if(iouth.eq.2) go to 671
c
c Thermo at Max power density
c
c      Pfacaz=1.
c
c
c      write(8,687)
c
687  format(' ****PROFILE OF CHANNEL WITH MAXIMUM POWER DENSITY****'//)
c
c      Call Inter(sof1,pfr,isof1,sofa,Pfacr)
c      Call Thermohe
c      if(iprob.eq.1) stop
671  continue
c      if(iouth.eq.1) go to 677
c
c Thermo at Min power density
c
c      Pfacaz=1.-Ripple
c
c
c      write(8,697)
c
697  format(///'***PROFILE OF CHANNEL WITH MINIMUM POWER DENSITY***'//)
c
c      Call Inter(sof1,pfrm,isof1,sofa,Pfacr)
c      Call Thermohe
677  continue
c      Stop
c      End
c
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
c Reactors",G. Melese and R. Katz
c
c      Function rho(p,t)
c      R=2077.22

```



```

        rho=p/(r*t+p*b(t))
        return
    end

c
c Function b(t)(used by rho)
c
    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

c
c Subroutine: Interpolate Table
c
    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
11  continue
    if(x(i).gt.xi) go to 12
    i=i+1
    go to 11
12  continue
    go to 30
10  i=2
    go to 30
20  i=np
30  yi=y(i-1)+((y(i)-y(i-1))/(x(i)-x(i-1)))*(xi-x(i-1))
    return
    end

c
c Compute available energy or
c difference between available and requested energies
c as function of S/F(other thing too)
c
    Function Balance(ibu,sofa)
c
c For input S/F=sofa and when itest=0:
c this function calculate the volume of the core that satisfies the
c reactivity balance; and then the energy balance(Mwday)
c Balance=Eavailable-Erequested. If ishape=2 or 3 (input R or H) the
c function checks if R(or) H is compatible with reactivity balance
c if not, set flag ibu=1 and RETURN
c
c if itest=1 and for input sofa calculate
c available energy
c radius infinite core that satisfies reactivity balance if ishape=2
c height of infinite " " " " " " " " =3
c
c
c      common /Bala/ Ereq,buwo(5),relr,rela1,rela2,dkeol,dkstr,BU,Vcor,
*U5m,dkbu,dkxes,dkxep,dksms,dksmpl,dkbe,rkre,eps,itmax,dcr
* ,itest,aofi
c
c      common /MaBaSi/ R,H,ishape
c
c      common /Fluxo/ Pow,Vc,sofr,fluxn(4),xedks,xedkt,tmax,smdks,smdkt
* ,tsm,D,iwxe
c
c      dimension rm(8),sof(8),sof1(5),aof(5),bew(5)
* ,rki(8)
c
c      data (rm(i),i=1,8)/17.40,14.86,13.71,11.65,10.41,9.499,8.958,8.76/
c
c rm (cm) migration length of mixture with 500 gU235/L fuel element

```

```

c for the following Support/Fuel element ratio
c
c   data (sof(i),i=1,8)/0.0,0.1,0.2,0.5,1.0,2.,3.,4./
c
c   data (rki(i),i=1,8)/1.62228,1.58272,1.59454,1.62315,1.67140,
*       1.67186,1.62773,1.56044/
c
c rki k-infinite as function of S/F
c
c   data (aof(i),i=1,5)/1.372,1.407,1.373,1.325,1.276/
c
c aof: absorption to fission ratio in U235 for the following S/F ratios
c
c   data (sof1(i),i=1,5)/0.0,0.2,0.5,1.0,2.0/
c
c sof1: Support/Fuel ratio
c
c   data (bew(i),i=1,5)/30.14,27.47,27.24,26.40,23.80/
c
c bew(): % delta k; reactivity worth of 30 cm Be radial reflector as
c function of S/F (sof1(i),i=1,5)
c
c   data dext,rofu /2.29,0.5/
c
c dext(cm) extrapolation length for bare core
c rofu (g/cm3) density of U235 corresponding to data base
c
c   data pee,xop,pisq3/3.1415926,0.541315,5.441398/
c
c xop:optimum shape for cylindrical reactors=Radius/Height
c pisq3=pi*sqrt(3)
c
c   sofr=sofa
c   ibu=0
c   isof=8
c   isof1=5
c   ibup=4
c   ibe=8
c   sofo=sofa
c
c compute kinf and migration length
c
c   call Inter(sof,rki,isof,sofo,rkin)
c   call Inter(sof,rm,isof,sofo,rmi)
c
c compute A/F for U235 at S/F=sofo
c
c   call Inter(sof1,aof,isof1,sofo,aofi)
c
c compute delta k BU
c
c   call Inter(sof1,buwo,isof1,sofo,dkbu)
c
c compute delta k of Be reflectors
c
c   call Inter(sof1,bew,isof1,sofo,wbe)
c   wber=wbe*relr
c   wbeal=wbe*rela1
c   wbea2=wbe*rela2
c   dkbe=wber+wbeal+wbea2
c
c Reactivity effects of Xe and Sm
c Simultaneous solution of dk(Xe,Sm)=g(Vc) and Vc=f(dk(Xe,Sm))
c bisect function h=g-h where h is inverse f
c
c   it=0
c   rkrem=1.+(DKBU+dkstr+dkeol-dkbe)/100.

```

```

c buck buck(0.Xe)
  buck=sqrt(rkin/rkrem-1.)/rmi
  go to (2001,2002,2003),ishape
c
c if ishape=1, optimum shape----->2001
2001  hp=pi*sq3/buck
      rp=xop*hp
      R=rp-dext
      H=hp-dext*2.
      Vc1=pee*R**2*H
      Vc=Vc1
      Call Flux
      Fu1=xedkt+smdkt
      Vc2=Vc1
728   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((Fu1*Fu2).gt.0..and.it.le.itmax) go to 728
      if(it.lt.itmax) go to 739
      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(Vc1,Vc2,Vca,Fu1,Fu2,Fua,iwa)
      test=abs(Vc1-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
c End iteration for the case optimum shape.RESULT: Volume of Core(Vc)
c that satisfies reactivity balance
c
  go to 2004
c
c go next if ishape=2----->input Radius of core
c
2002  buca=buck**2-(2.405/(R+dext))**2
      dcr=2.405/buck-dext
      if(buca.le.0.) ibu=1
c
c set flag ibu=1 if R(input) is too small to satisfy reactivity balance
c
  if(ibu.eq.1) return
  hp=pee/sqrt(buca)
  H=hp-2.*dext
  Vc1=pee*R**2*H
  Vc=Vc1
  Call Flux
  Fu1=xedkt+smdkt

```

```

      Vc2=Vc1
828  Vc2=Vc2+Vc1
      it=it+1
      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((Fu1*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+Vc1)*0.5
      it=it+1
      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(Vc1,Vc2,Vca,Fu1,Fu2,Fua,iwa)
      test=abs(Vc1-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
c End iteration for the case of input Radius.RESULT: Volume of Core(Vc)
c that satisfies reactivity balance
c
      go to 2004
c
c go next if ishape=3----->input Height of the core
c
2003  bucr=buck**2-(pee/(H+2.*dext))**2
      dcr=pee/buck-dext*2.
      if(bucr.le.0.) ibu=1
c
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
      Vc1=pee*R**2*H
      Vc=Vc1
      Call Flux
      Fu1=xedkt+smdkt
      Vc2=Vc1
928  Vc2=Vc2+Vc1
      it=it+1
      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((Fu1*Fu2).gt.0..and.it.le.itmax) go to 928
      if(it.lt.itmax) go to 939
      write(8,201)
      stop
939  continue

```

```

948  Vca=(Vc2+Vc1)*0.5
      it=it+1
      R=sqrt(Vca/(pee*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(Vc1,Vc2,Vca,Fu1,Fu2,Fua,iwa)
      test=abs(Vc1-Vca)/Vca
      if(test.gt.eps.and.iwa.eq.0) go to 948
      if(it.lt.itmax.and.iwa.eq.0) go to 949

c
c
      write(8,201)
c
201  format(/' stop in Balance, trying to compute Xe, Sm'/)
      stop

c
949  continue
c
c End iteration for the case of input Height.RESULT: Volume of Core(Vc)
c that satisfies reactivity balance
c
2004 continue
c
c End of iterations to obtain Volume of core that satisfies reactivity
c balance (that includes Xe and Sm reactivities)
c
      ibu=0
      dkxes=xedks
      dkxep=xedkt
      dksms=smdks
      dksmp=smdkt

c
c recompute required dk from bare core
c
      rkre=1.+(DKBU+dkxep+dksmp+dkstr+dkeol-dkbe)/100.

c
c check available energy
c
      Vcor=Vc
      Vact=Vcor/(1.+sofa)
      U5m=Vact*rofu

c
c for U235 at 200 Mev/fission
c
      Eavai=(U5m*BU)/(105.2*aofi)
      Balance=Eavai-Ereq
      if(itest.eq.1) Balance=Eavai
      return
      end

c
c
      subroutine bisect(x1,x2,xav,f1,f2,fav,iwa)
      if((f1*f2).le.0.) go to 11
      write(8,1)
      format(//' f1*f2 >0. '//)
      iwa=1
      return
11  iwa=0
      if((fav*f1).le.0.) go to 10
      f1=fav
      x1=xav
      return
10  f2=fav

```

```

        x2=xav
        return
    end

c
c compute control drums
c
    subroutine Control
    dimension cr(5),sof(5)
    common /cont/ R,drd,dref,rasp,refec,ncr,dksu,dkstr,relr
c
c 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(%):subcritical-
c lity required for drums in.
c dkstr(%): dk structural part of reactor,relr:relative worth of reflector
c
    data (cr(i),i=1,5)/21.0,19.15,18.8,18.1,16.35/
c
c cr: %delta k; max worth of control rods in Be reflector
c calculated with reflector thickness dref(reference)
c
    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
c
    pee=3.1415926
    isof=5
    Call Inter(sof,cr,isof,rasp,cdm)
c
c worth of 2*pee sheet(cdm) is corrected because drr might not be =dref
c correction factor relative worth of reflector(with respect to dref)
    cdm=cdm*relr
c rea(%) reactivity to control
    rea=(refec-1.)*100.+dksu-dkstr
c
c compute maximum number of drums=nmax
c
    rd=0.5*drr
    par=2.*asin(rd/(R+rd))
    pard=par*180./pee
c
c rd and par are the radius and the central parallax of the drums
c
    nmax=2.*pee/par
    cdrm=cdm*nmax*par/(2.*pee)
    if(cdrm.ge.rea) go to 10
    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
10    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=cdm*rcr*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

```

```

        cdrm=cdr*ncr*par/(2.*pee)
        if(cdrm.lt.rea) go to 101
        rcr=ncr
        else
        endif
c
c para is the central parallax of the absorbing part of one drum
c
        para=(rea/rcr)*(2.*pee/cdr)
c pass 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(%)=',f8.2//)
        return
        end
c
c Four groups cross section to compute fluxes,Xe and Sm Effects
c
        Subroutine Flux
        common /Fluxo/ Pow,Vc,sofr,fluxn(4),xedks,xedkt,tmax,smdks,smdkt,
        *tsm,D,iwxe
        dimension aux(5),spec(4,5),f5(4,5),sif(4),sp(4),sof(5)
c
        data (sof(i),i=1,5) /0.0,0.2,0.5,1.0,2.0/
c
c Neutron spectra as function of S/F and Neutron Energy
c
        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/
c
c U235 fission cross sections as function of S/f and Energy
c averaged in core volume(supp+fuel)
c
        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/
c
        data rou5,A5,Av,wfi,x23,x4,gi,gx,xel,rnu/0.5,235.044,0.602202,
        *3.2042e-11,623.,1.126e+6,0.061,0.003,2.09e-5,2.44/
c
c wfi: joules/fission, x23,x4: capture cross section Xe
c gi,gx: Yield I135 and Xe135 per fission, rnu=number neutrons/fission
c
        data rli,pml,sm23,sm4,gp/2.87e-5,3.56e-6,278.,29982.,0.0113/
c
c xel,rli,pml: decay constants Xe135,I135 and Pm149
c gp:Yield Pm149/fission, sm23,sm4: capture cross section Sm149
c
        Vact=Vc/(1.+sofr)
        ro5=rou5*Vact/Vc
c ro5 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
30    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*u5n
      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=xel*1.e+24/xec
      xedks=100.*(gi+gx)*flun/(rnu*(flun+fluxe))
c
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))/(rli-xel)
      xedkt=exp(-xel*tmax)*(gi+gx)*flun/(fluxe+flun)+
1      (exp(-xel*tmax)-exp(-rli*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
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
c solve thermalhydraulic
c
      subroutine thermohe
      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),Tfua(51)
c
c
      common/thermo/ aln,nnode,iexpl,ifri,itmax,norif,iditus,nfu,pin,tin
      *,d,ru,xi,der,eps,Powt,rjs,flowt,GU235,Vact,Enr,PUC,Rouc,RoZrC,
      *RoGraf,dclad,Hact,Pfacr,Daxi,fact,phav,thav,fe,iprth,iopth,iouth
      *,Pfcaaz,itry,flowal,iboun

```



```

common /fGu/ ifro,deri,pf,ar,dho,rug,dz
common /fphe/ imaxt,epsi,dero
data pee/3.1415926/,rgas/4124.2/
character*80 aln

c
c nnode: number of nodes; iexpl /0,1/ No, Yes explicit
c ifri.ne.1 : switch off friction factor
c itmax: max iters, norif: number of orifices, iditus/0,1/ no Dittus
c( means correction for Twall/Tbulk in Nussel correlation),1 Yes Dittus
c nfu: number of nodes inside fuel
c
      itry=0
      iexpl=iexpl
2013      dero=der
          ifro=ifri
          deri=der
          dho=d*0.01
          rug=ru
          imaxt=imaxt
          epsi=epsi

c
c pin(MPa), tin( K) inlet conditions
c d(cm), ru : channel diameter and rugosity
c xi /0.,1./ xi=0. fully explicit; xi=1. fully implicit
c der: factor to multiply variable to compute derivative numerically
c typical value 1.01; eps: tolerance to finish iterations; Powt(Mw)
c total power; rjs(Kw/cm2) scale for plot heat rate
c
c
c
c flowt(Kg/sec) : Total flow
c flow(g/sec)   : Channel flow
c
      flow=1000.*flowt/norif
      Vamix=Vact*fe

c
c Vact:Volume of fuel elements; Vamix: volume occupied by UC-ZrC mix in
c graphite matrix; exclude coolant holes and clads
c
c GU235 grams of U235 in active mix Volume Vamix(Liters) U is
c Enriched (at fraction), PUC mole fraction of UC in UC-ZrC mix
c RoUC, RoZrC and RoGraf (g/cm3) densities of UC, Zrc and Graphite
c 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
c 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(iopth.gt.2) Pfraz=Pfacr*Pfacaz

c
c recompute flow according to option
c
      if(iopth.eq.4) flow=flow*Pfraz
      Hext=Hact+2.*Daxi
      we=Hext/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
182    z(i)=zzzz-Daxi
c
c See: pow is power per unit volume of active mix(UC-ZrC-Graphite)
c transform pow(i) (Mw/L) to power per unit length (watt/cm)
c
      r0=d/2.
      r1=r0+dclad
      r2=sqrt(r1**2+Vamix*1000./ (pee*Hact*norif))
      facto=1000.*pee*(r2**2-r1**2)
      do 123 i=1,npu
123    pow(i)=pow(i)*facto
c
c z(i) (cm) boundaries of the nodes
c
      write(8,12) aln
12    format(a80)
      write(8,21) pin,tin,d,ru,der,eps,Powt,norif,flowt,fact
21    format(// ' Thermodynamic profile of a He cooled channel' /
* ' Inlet pressure(MPa)=',f10.5,' Inlet temperature( K)=',f10.2/
* ' Diameter(cm)=',f7.2,' Rugosity=',f8.5,' der parm=',f6.4,
* ' eps=',f10.7/ ' Total Power (Mw)',f10.3,' No. Orifices',i10/
* ' Total Flow(Kg/sec)',f10.3/
* ' Factor that multiplies Power',f10.7//)
      write(8,162)roav,Hact
162    format(' Average Power Density(Mw/L of active mix)',f8.4,
* ' Channel Length(cm)',f7.2//)
      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)
c
      if(iexpl.eq.1.or.xi.eq.0.) write(8,22)
22    format(// ' Attention Fully Explicit Calculation!!'//)
c
      if(iexpl.ne.1.and.xi.ne.0.) write(8,122) xi
122    format(// ' Attention Implicit Calculation!! xi=',f10.5//)
c
      if(ifi.ne.1) write(8,23)
23    format(' friction was assumed zero'//)
c
      if(iditus.eq.1) write(8,24)
24    format(' Dittus-Boelter Correlation for Nu (No Twall/Tbulk correct
*ion)')
      if(iditus.eq.0) write(8,376)
376    format(' Twall/Tbulk correction to Dittus-Boelter Correlation for
*Nu')
c
      pres(1)=pin*10.**6
      tbulk(1)=tin
      ar=pee*(dho/2.)**2
      pf=pee*dho
c
      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'//)
      write(8,31) flow
31    format(' Flow(g/s)=',f10.3//)

```

```

* 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(1)
     t=tbulk(1)
     call phe(h,p,t,rho,vis,cp,pr,a,k,x,0)
     pi=p
     ti=t
     rhoi=rho
     hi=h
     Re=dho*g/vis
     Rei=Re
     ve(1)=flow/(ar*rho)
c remember for future use inlet conditions
  hinlet=h
  echannel=0.
  rmach(1)=ve(1)/a
  i=1
  pre=pres(1)*10.**(-6)
  write(8,41) i,z(i),pow(1),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
    d1=drdp(pi,ti,der)
    d2=drdt(pi,ti,der)
    if(1fri.eq.1) f=fri(Rei,ru)
    f1=1.-d1*(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/f1-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) houtlet=h
    Re=dho*g/vis
    ve(i)=flow/(ar*rho)
    rmach(i)=ve(i)/a
    pre=pres(i)*10.**(-6)
    pi=p
    ti=t
    rhoi=rho
    hi=h
    Rei=Re
    if(1prth.eq.1.or.i.eq.npu)
      *write(8,41) i,z(i),pow(i),pre,tbulk(i),ve(i),Re,rmach(i)
30   continue
    gamma=cp/(cp-rgas)
41   format(i5,5f10.2,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)

```

```

        po= 0.5*(pow(i)+pow(i-1))*dz
        echannel=echannel+po
        po=po/flow
c
c First find an estimation of toutlet explicitly
c
        h=hi+po
        p=pi
        call phe(h,p,t,rho,vis,cp,pr,a,k,x,1)
c
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
43      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'//)
        iexpl=1
        go to 3001
        else
        endif
        it=0
c
c start bisect to find p at outlet node
c
45      pav=0.5*(pl+p2)
        Guav=Gu(pav,taprox,pi,ti,xi,g)
        test=abs(Guav)/p
        if(test.lt.eps) 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
44      continue
        if(it.gt.itmax.or.iwa.eq.1) then
        write(8,46) i,pl,Gu1,p2,Gu2,it,iwa
46      format('// implicit calculation, problem trying bisect Gu in node
        *,i3,' pl Gu1=',2e14.6//' p2 Gu2=',2e14.6,' its=',i4,' iwa=',i4/
        *,' go to explicit'//)
        iexpl=1
        go to 3001
        else
        endif
c
c 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)
        pprima=der*pav
        Fu2=Fu(pi,ti,pprima,taprox,po,vi)
        dfup=(Fu2-Fu1)/(pprima-pav)
        tprima=der*taprox
        Fu2=Fu(pi,ti,pav,tprima,po,vi)
        dfut=(Fu2-Fu1)/(tprima-taprox)
        Gu1=Gu(pav,taprox,pi,ti,xi,g)
        Gu2=Gu(pprima,taprox,pi,ti,xi,g)
        dgup=(Gu2-Gu1)/(pprima-pav)
        Gu2=Gu(pav,tprima,pi,ti,xi,g)

```

```

dgut=(Gu2-Gu1)/(tprima-taprox)
delta=dfup*dgut-dgup*dfut
delp=(-Ful*dgut+Gu1*dfut)/delta
delt=(-Gu1*dfup+Ful*dgup)/delta
c write(8,3478) ful,dfup,dfut,gu1,dgup,dgut,delta,delp,delt
3478 format(' Ful Df/Dp Df/dt',3e14.5/' Gu1 Dg/Dp Dg/Dt',3e14.5/
*' delta delp delt',3e14.5/)
p=pav+delp
t=taprox+delt
call phe(h,p,t,rho,vis,cp,pr,a,k,x,0)
if(i.eq.npu) houtlet=h
pre=p*10.**(-6)
pres(i)=p
tbulk(i)=t
ve(i)=flow/(ar*rho)
Re=dho*g/vis
rmach(i)=ve(i)/a
if(iprth.eq.1.or.i.eq.npu)
*write(8,41) i,z(i),pow(i),pre,tbulk(i),ve(i),Re,rmach(i)
hi=h
pi=p
ti=t
531 continue
4321 continue
c
c End calculation coolant conditions
c
c Check if we did not pass speed of sound anywhere , if yes change
c condition at inlet and set flag iprob=1
c
      iprob=0
      do 2297 i=2,npu
        if(pres(i).gt.pres(i-1).or.pres(i).lt.0.) iprob=1
2297 continue
      if(iprob.eq.0) go to 2303
c
c Hoping to fix the mess we change input conditions in order to relax
c thermalhydraulic
c
      if(itry.eq.1) write(8,2308)
2308 format(' No success with the change. Program Ends')
      if(itry.eq.1) return
      ifri=0
      Pfacr=1.
      Pfacaz=1.
      iopth=1
      pin=10.
      tin=20.
      itry=1
      iexpl=iexpl
      if(iboun.ne.0) flowt=flowal
      write(8,2314) pin,tin
2314 format(///' With previous power level and input conditions'/
*'flow velocities reach speed of sound. To relax thermalhydraulic'/
*'we change to following conditons:'/'
*'                                1) Uniform 3D power density.'/
*'                                2) Assume no friction in channel.'/
*'                                3) Inlet p(MPa)=' ,f8.2/
*'                                4) Inlet T(K)  =' ,f8.2//)
      go to 2013
c
c Beginning calculation wall temperature
c
2303 iwar=0
      do 302 i=1,npu
        p=pres(i)
        t=tbulk(i)

```

```

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,1)
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,1.,Zr)
hco=RNus*Rki
rjq=pow(i)*100./((pee*dho)
rj(i)=rjq*10.**(-7)
Twl=Tfa+rjq/hco
Tw(i)=Twl
if(iditus.eq.1) go to 3121
c write(8,143) Twl,rjq,hco,Rc,Tfa,Tfs
it=0
Trl=Twl/ti
Fq1=Fq(rjq,Zr,Rei,Pri,Rki,Tfa,Trl,Twl)
c write(8,144) Twl,Fq1
Tw2=Twl
422 Tw2=Tw2*der
Tr2=Tw2/ti
it=it+1
Fq2=Fq(rjq,Zr,Rei,Pri,Rki,Tfa,Tr2,Tw2)
c write(8,144) Tw2,Fq2
if((Fq1*Fq2).gt.0..and.it.le.itmax) go to 422
if(it.gt.itmax) then
write(8,431) i,Twl,Fq1,Tw2,Fq2
143 format(' first estimation, Twl=',f10.3,' Rjq hc',2e14.5/
*' Rc Tfa Tfs',3f14.3/12x,'Tw',12x,'Fq')
144 format(2e14.5)
431 format(' implicit calculation, problem trying to find Tw2 in node
*',i3,'Twl Fq1=',2e14.6//,'Tw2 Fq2=',2e14.6//,' bypass wall '///)
461 format(' implicit calculation, problem trying bisect Fq in node
*',i3,'Twl Fq1=',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
c start bisect to find T wall
c
452 Twa=0.5*(Twl+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+1
call bisect(Twl,Tw2,Twa,Fq1,Fq2,Fgav,iwa)
if(it.le.itmax.and.iwa.eq.0) go to 452
442 continue
if(it.gt.itmax.or.iwa.eq.1) then
write(8,461) i,Twl,Fq1,Tw2,Fq2,it,iwa
iditus=1
iwar=1
go to 3121
else
endif
endif

```

```

      Tw(i)=Twa
c From Twa to Tfuel
c
3121 continue
      if(xGraf.lt.0.) go to 302
      cclad=RkZrC(Twa)
      rjc=rjq*10.**(-4)
      Poa=rjc*2.*r0/r2**2
      Qh=Poa/(1.-(r1/r2)**2)
c See only one node for the clad
c
      Tclad(i)=Tw(i)+rjc*r0*alog(r1/r0)/cclad
      culo=1.+dclad/r0
      Tclaa(i)=Tw(i)+rjc*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
      Cfuel=(RaUC*RkUC(Tinl)+RaZrC*RkZrC(Tinl)+RaGraf*RkGraf(Tinl))/R
      *a
      rout=rinl+dr
      Tout=Tinl+(0.25*Qh*rinl**2/Cfuel)*(2.*(r2/rinl)**2*alog(rout/r
      *inl)+1.-(rout/rinl)**2)
      Tfa=Tfa+(Tout*rout+Tinl*rinl)*dr
      Tinl=Tout
      rinl=rout
3021 continue
      Tfuel(i)=Tout
      Tfua(i)=Tfa/(r2**2-r1**2)
302 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)',10x,' 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,npu
      if(iprth.eq.1.or.i.eq.npu)
      *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
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*(tclaa(i)+tclaa(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)
roout=rho
rohav=rohav+0.5*(roin+roout)*dz
thav=thav+0.5*(tbulk(i)*roout+tbulk(i-1)*roin)*dz
1436 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
1486 Format(/// ' Axial Average Conditions in the Channel' /
* ' Coolant Pressure(MPa)',f8.3, ' Temperature(K)',f9.3/ ' Give Den
*sity(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
384 format(/// ' Mol Fraction of UC in UC-ZrC mix',f7.5, ' Melting Temper
*ature(K)',f10.2)
dh=houtlet-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
987 format(/// ' HEAT BALANCE FOR THE CHANNEL' //
* 'dq: heat to coolant (joule/kg)',e14.5/'dh: change of enthalpy
1(joule/kg)',e14.5/'dKin change kinetic energy(joule/kg)',e14.5/
2' relative dKin/dQ',f10.6/ ' Balance (dH+dKin)/dQ',f14.7)

c
return
end

c
c friction factor for one phase flow
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
end

c
c calculate drho/dp

```



```

c
function drdp(pe,te,der)
p=pe
t=te
call phe(h,p,t,rho,vis,cp,pr,a,k,x,0)
p1=p
rho1=rho
p=der*p
call phe(h,p,t,rho,vis,cp,pr,a,k,x,0)
drdp=(rho1-rho)/(p1-p)
return
end

c
c calculate drho/dt
c
function drdt(pe,te,der)
p=pe
t=te
call phe(h,p,t,rho,vis,cp,pr,a,k,x,0)
t1=t
rho1=rho
t=der*t
call phe(h,p,t,rho,vis,cp,pr,a,k,x,0)
drdt=(rho1-rho)/(t1-t)
return
end

c
c function Fu to solve in order to find t outlet node
c
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
c function Gu to solve in order to find p outlet node
c
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
f3=-d2*(g/rho)**2
Re=d*g/vis
f=0
if(ifri.eq.1) f=fri(Re,ru)
f2=0.5*f*Pf*g*g/(rho*ar)
f1o=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

```

```

f3=-d2*(g/rho)**2
Re=d*g/vis
f=0
if(ifr1.eq.1) f=fri(Re,ru)
f2=0.5*f*Pf*g*g/(rho*ar)
f1i=f2/f1
f2i=f3/f1
fla=(f1i+xi*f1o)/(1.+xi)
f2a=(f2i+xi*f2o)/(1.+xi)
Gu=po-pi+fla*dz+f2a*(to-ti)
return
end

c
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.
      if(Zr.lt.5.) Zr=5.
      RNu=0.021*Re**0.8*Pr**0.4*Tr**(-0.5)*(1.+Zr**(-0.7))
      return
      end

c
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)
      return
      end

c
c Function: Thermal Conductivity of UC
c Source: Book El-Wakil
c
      Function RkUc(Te)
c 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
c Function: Thermal Conductivity of ZrC
c Source: Book Bussard-DeLauer
c
      Function RkZrC(Te)
c T(K) RkZrC(watt/cmK)
      RkZrC=0.2077
      Return
      End

c
c Function: Thermal Conductivity of Graphite
c Source: Book busaard-DeLauer
c
      Function RkGraf(Te)
c T(K) RkGraf (watt/cmK)
      Dimension      Tp(20),Rc(20)
      np=12

```

```

      Data (Tp(i),i=1,12)/277.8 ,416.7 ,555.5 ,833.3 ,1111.1 ,1388.9,
      *1666.7 ,1944.4 ,2222.2 ,2500. ,2777.8 ,3333.3/
      Data (Rc(i),i=1,12)/1.743, 1.414, 1.097, 0.817, 0.6339, 0.5485,
      *0.4632, 0.4145, 0.3657, 0.3413, 0.3169, 0.2926/
      call Inter(Tp,Rc,np,Te,Cond)
      RkGraf=Cond
      Return
      End

c
c Function: Melting Temperature of Uc-ZrC mix
c Source: Book busaard-DeLauer
c
      Function Tmelt(PUC)
c 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
c Properties of He
c
      subroutine phe(h,p,t,rho,vis,cp,pr,a,rk,x,iflag)
      common /fphe/ nit,eps,der
c Thermodynamic and Transport Properties of Helium
c from Appendix B, page 405, Thermal and Flow Design of Helium-Cooled
c Reactors by G. Melese and R.Katz American Nuclear Society, 1984.
      cp=5193.
      R=2077.22
      x=1.

c
c go to 10 if iflag=1 (ie input is p,h)
c
      if(iflag.ne.0) go to 10
1      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
c
c use bisect method to find t from p and h
c
      rc=der
      t1=h/cp
      en1=ent(h,p,t1)
      if(en1.lt.0.) rc=1./rc
      t2=t1
      it=0
30     t2=t2*rc
      it=it+1
      en2=ent(h,p,t2)
      if(en1*en2.lt.0) go to 20
      if(it.lt.nit) go to 30
      write(6,50) h,p
50     format(//'Program stop at phe(1). Unable to find T for input h=',
      *e14.5,' and p=',e14.5//)
      stop
20     continue
      it=0
      iwa=0

```

```

452  ta=0.5*(t1+t2)
     ena=ent(h,p,ta)
     test=abs(ena)/h
     if(test.lt.eps)go to 442
     it=it+1
     call bisect(t1,t2,ta,en1,en2,ena,iwa)
     if(it.le.nit.and.iwa.eq.0) go to 452
442  continue
     if(it.gt.nit.or.iwa.eq.1)
51    *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
     t=ta
     go to 1
     end
c
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
c
c
c ***** DESIGN STRENGTH SUBROUTINE *****
c Calculation of the Stress that Astar alloy can stand
c subroutine from Alkasys
c 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
c subroutine desstr(tt,n,fpl,sigpv,sigrod,itma,ipr)

real tt,nr,tmat,fpl,sigpv,sigrod,rho
real b,c,v,sigma,theta,thet,dt ds
  data tmat/1100./
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
  endif
do ll=1,n
  if (ll.eq.1) then
    thet=fpl*8766.139
  else
    thet=fpl*8766.139/2.
  endif
  sigma=1000

```

```

theta=1/c*exp((b-nr*log(sigma)-v*sigma)/tt)
  ite=0
dowhile ((abs((theta-thet)/thet)).gt.0.001)
  dtds=-theta*(nr+v*sigma)/sigma/tt
  sigma=sigma+(thet-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
c
c function to compute thickness neutron shielding
c
  Function Shieldn(fluin,fluout,ish,tw,igam)
  common /cross/ AA,BB,signe,ishin,ishig
c
c Fluin,fluout, fast fluxes in/out; ish=1, LiH+SS
c ish=2, B4C; tw(cm) gamma shielding (Tungstene)(if igam.ne.0)
c
  data remLi,remH,remFe,remW,remBC
  *      /1.01,1.00,1.98,3.13,5.1/
c removal cross section for fast neutrons of Li,H,Fe,W,B4C
c
  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/
  sigW=remW*Av*roW/AW
  ishin=1
  go to(10,20), ish
10  xLiH=(roLiss-roFe)/(roLiH-roFe)
  xFe=1.-xLiH
  sigre=(remLi+remH)*Av*roLiH*xLiH/ALiH+remFe*Av*roFe*xFe/AFe
  go to 30
20  sigre=remBC*Av*roBC/ABC
30  aa=log(fluin/fluout)/sigre
  if(aa.le.0.) ishin=0
  bb=sigW/sigre
  signe=sigre
  Shieldn=aa-bb*tw
  return
end
c
c Subroutine to calculate Gamma source
c
  Subroutine Gamso(Sn,aof,sof,sogam,Pr5)
c
c Input: Sn(1/s): neutron production; sof=S/F Elements
c aof=A/F in U235 for sof
c sogam(1): Gamma source between "0" and 1 Mev
c      (2):      1 and 2
c      (3):      2 and 3
c      (4):      3 and 5
c      (5):      5 and 7
c      (6):      7 and 9
c      (7):      > around 9 Mev
c      Dimension Sogam(7),Pf(7),Fp(7),GNi(7),GH(7),GZr(7),GBe(7),
c      *GU(7),GFe(7),GCr(7),Pr5(7)

```

```

c
c Pf: Prompt Fission Gammas; Fp: Fission Products Gammas(Both, Per Fiss)
c GNi to GCr: Captures Gammas(per Event) for indicated Elements Ni,...Cr
c
  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.,0.,1.,0.,0.,0.,0./
  Data(GZr(i),i=1,7)/0.,0.,0.,1.13,.35,.04,0./
  Data(GBe(i),i=1,7)/0.,0.,0.,.54,.73,.0,0./
  Data(GU(i),i=1,7)/2.54,1.78,.91,.34,.0,0,0.041/
  Data(GFe(i),i=1,7)/.75,.60,.27,.23,.25,.38,.02/
  Data(GCr(i),i=1,7)/.85,.41,.21,.12,.23,.39,.06/
  Data(FNi2,FH2,FZr2,FBe2,FU82,FFe2,FCr2
*   /.12,.083,.088,.051,.045,.016,.008/
  Data(FNi0,FH0,FZr0,FBe0,FU80,FFe0,FCr0
*   /0.,0.,.076,.087,.069,0.,0./
  Data Rnu/2.44/

c
c See: Total number of Absorptions= Sn(Total production)
c F: total number of fission
c A5: Total number of absorptions(capture+fission) in U235
c C5: total number of captures in U235
c Ct: " " captures
  F=Sn/Rnu
  A5=F*aof
  C5=A5-F
  Ct=Sn-F
  CNi=(FNi0+(FNi2-FNi0)*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

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

c
c Shieldga: Computes gamma shielding
c Sogam(i),i=1,7 Gamma Source (photons/sec); Dose(rad): Integrated
c Dose at load area; Dosew(rad): Dose without the shielding
c Dosea: dose for tgam
c igam: flag if =1 problems with iterations
c Tgam(cm): Thickness of Tungsten
c ten(cm) thickness of n shielding, ishn=1, LiH, ishn=2, B4C
c iten/0,1/ /ten input,ten iterated by this subroutine/
c tgam: iterated, if necessary, to have Dose=input
c Index(1): Gamma Processes between "0" and 1 Mev
c   (2): 1 and 2
c   (3): 2 and 3
c   (4): 3 and 5
c   (5): 5 and 7
c   (6): 7 and 9
c   (7): > around 9 Mev
c   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,epsq

```

```

*,aten,Dosen,Doseng(7)
dimension Sogam(7),GBe(7),GW(7),Gc(7),GZr(7),GU(7),GH(7),GFe(7),
*GTi(7),GSi(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),Aln(7),A2n(7)

c
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 (Gc(i),i=1,7) /.087,.0518,.0444,.0304,.0245,.0213,.0194/
data (GZr(i),i=1,7) /.0851,.0467,.0414,.0349,.0344,.0349,.0359/
data (GU(i),i=1,7) /.176,.0548,.0484,.044,.0455,.0479,.0511/
data (GH(i),i=1,7) /.173,.103,.0876,.0579,.0446,.0371,.0321/
data (GFe(i),i=1,7) /.0828,.0485,.0424,.033,.0304,.0295,.0294/
data (GTi(i),i=1,7) /.0876,.0518,.0451,.0338,.0302,.0285,.0280/
data (GSi(i),i=1,7) /.0869,.0517,.0447,.0323,.0277,.0254,.0243/

c
c GBE...GSi are the total mass attenuation coefficients(cm**2/g)
c for the 7 gamma groups. Fe(z=26),Ni(z=28) and Cr(z=24) can be lumped
c 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)

c
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/

c
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/

c
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/

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

c
c b(i,j),a2(i,j) and a4(i,j) are build up parameters for groups j
c and atomic number Z=2b(i)

c
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
c rh(i) Gamma Flux Mev/cm2sec that produces 1 Roentgen/hour

c
data (Ega(i),i=1,7)/0.5,1.5,2.5,4.,6.,8.,10./

c
c ega(i) Mev Average Energy of gamma group i

c
data ABe,ATa,AW,AC,AZr,AU,AH,ANi,AFe,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,ZC,ZZr,ZU,ZH,ZNi,ZFe,ZCr,ZTi,ZSi,pee,ZLi,ZBo
*/4.,73.,74.,6.,40.,92.,1.,28.,26.,24.,22.,14.,3.141593,3.,5./

c
data roLiH,roBC,roSS,roLiS /0.82,2.92,7.874,1.024/
igam=1
ishig=1
xLiH=(roLiS-roSS)/(roLiH-roSS)
xSS=1.-xLiH

c
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
      go to 333
c ish=2 B4C
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
c ZZ is "equivalent Z for buildup factor
333  do 444 i=1,4
      a(i)=b(i,j)
      al(i)=a3(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,al,4,zz,al1)
      Call Inter(zb,a2,4,zz,al2)
      An(j)=am
      Aln(j)=-al1
      A2n(j)=al2
      sign(j)=sig
101  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
      a(i)=b(i,j)
      al(i)=a3(i,j)
20  a2(i)=a4(i,j)
      sig=coBe*Abe*Gbe(j) +coTa*ATa*GW(j) +coC*AC*GC(j)
      * +coZr*AZr*GZr(j) +coU*AU*GU(j) +coH*AH*GH(j)
      * +coFe*AFe*GFe(j) +coNi*ANi*GFe(j) +coCr*ACr*GFe(j)
      * +coTi*ATi*GTi(j) +coSi*ASi*GSi(j)
      sig=sig/Av
      ZZ=coBe*Abe*Gbe(j)*ZBe +coTa*ATa*GW(j)*ZTa +coC*AC*GC(j)*ZC
      * +coZr*AZr*GZr(j)*ZZr +coU*AU*GU(j)*ZU +coH*AH*GH(j)*ZH
      * +coFe*AFe*GFe(j)*ZFe +coNi*ANi*GFe(j)*ZNi +coCr*ACr*GFe(j)*ZCr
      * +coTi*ATi*GTi(j)*ZTi +coSi*ASi*GSi(j)*ZSi
      ZZ=ZZ/Av
      zz=zz/sig
      Call Inter(zb,a,4,zz,am)
      Call Inter(zb,al,4,zz,al1)
      Call Inter(zb,a2,4,zz,al2)
      Zeq(j)=zz
      b1=2.*sig*Req*(1.-al1)
      b2=2.*sig*Req*(1.+al2)
      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
c End Calculation Self shielding
c
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-

```



```

c ted
  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*A1n(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)
  Dosew=Dosew+Dosewg(i)
30  Dosen=Dosen+Doseng(i)
    if(Dosen.le.Dose) ishig=0
    if(ishig.eq.0) tgam=0.
    if(ishig.eq.0) return

c
c Return if there is no need for gamma shield (thick W=0.)
c
  t1=0.
  Dose1=Dosen
  f1=Dose1-Dose

c
c Starts iteration on tgam:
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  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)
40  dose2=dose2+Dosewg(i)*exp(-sig*t2)*BFA
    if(dose2.lt.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'
50  continue
    f2=Dose2-Dose
    if(igam.eq.0) return
    it=0
61  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 lt 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*A1n(i))+(1.-An(i))*exp(-tsn*A2n(i))

```

```

      *
      Doseg(i)=Dosewg(i)*exp(-sig*tgam)*BFA*Shin
41  dosea=dosea+Doseg(i)
c  recompute n shielding, because it might be smaller than input max flu-
c  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(t1,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
c  Compute sizes for input Energy and S/F
c
      Subroutine Size(das,dop,E,sof,d1,d2)
c
      common /Soze/ its,epss
c
      common /MaBaSi/ R,H,ishape
c
      ri=1.
      it=0
10  x1=das*(1.+0.01/ri)
      if(ishape.eq.2) R=x1
      if(ishape.eq.3) H=x1
      e1=Balance(ibu,sof)-E
      if(e1.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,sof)-e
30  it=0
35  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
      go to 35
50  d1=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
21  it=0
41  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
31  it=0
36  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
51  d2=xav
    return
100 write(8,101) it
101 format(' Program stop at subroutine Size'// iterations=',i10/)
    stop
    end

```


APPENDIX B. LISTING OF CODE NEPPIN

```

c program to estimate preliminary design of fuel pin, liquid Li reactor
c for space applications.
c Assumptions
c 1) fuel cell: liquid Li(coolant), Astar alloy clad, W liner, He gap and
c   UN pellet.
c
c 2) Astar pressure vessel, OBe reflector and B4C(90%B10) drums in
c   reflector.
c
c 3) Gamma Shield: W; Neutron Shield: B4C or LiH in SS matrix
c
c 4) Data base parameters: Enrichment and pitch/drod for drod=6.4mm
c
c   character*80 tit, aldum
c
c   dimension aux(5), bux(5), wbeth(8), th(8), pfr(3,3), U5md(5), isha(5),
c   *pfrm(3,3), Sogam(7), PrU(7), Emin(5,5), Ras(5,5), Has(5,5), Rop(5,5)
c   *, Hop(5,5), enri(5), podi(5), BUal(5), Rd(5), Hd(5), dpvd(5), delp(5),
c   *GRea(5), dkbup(5), dkpvd(5), rkbare(5), enr(5), dkobe(5), Nbun(5),
c   *podip(3), enrip(3)
c
c   common /Soze/ its, epss
c
c   common /MaBaSi/ R, H, ishape
c
c   common /mabu/ c5e, c8e, c9e, p9, cfpe, ftin
c
c U5, U8, Pu9, FP concentrations at EOL (integrated fluence=ftin)
c all from subrou bupo. Per unit input volume
c
c   common /Bala/ Ereq, relr, relal, rela2, dkeol, dkstr, BU, Vcor,
c   *U5m, dkbu, dkbe, rkre, dcr, sigma, pin, dpv, dkpv, tduco,
c   *eps, itest
c
c   common /cont/ Rad, dvp, drr, enr, pod, refec, ncr, dksu, dkest, relar, dcd
c
c   common /thermo/ tit, nnodo, ifri, npin, pint, tin, toutl, deltapa
c   *, Pow, rjs, flowt, podt, tduc, Rc
c   *, Hact, Pfacr, Daxi, fact, iprth, iopth, ichoose
c   *, Pfacaz, iboun, nrod, nbu, nrodbu, hod
c
c   common /Conce/ coBe, coTa, coU5, coU8, coLi, coW, coRe, coHf, coHe, coN, coO
c   common /Gamsh/
c   *dist, Req, shg(7), shgnb(7), Zeq(7), Dosewg(7), Doseg(7), itmag, epsg
c   *, aten, Dosen, Doseng(7)
c
c   Common /CROSS/ AU, BBU, signe, ishin, ishig
c
c   Tsa(ps)=8143./(8.-alog10(ps/0.133322))
c   Psa(ts)=0.133322*10.** (8.00-8143./ts)
c
c Tsa(ps) is saturation temperature of Li(in K) as function of ps(KPa)
c Psa(ts) is " pressure of Li(in KPa)" " of ts(K)
c
c   open(unit=7, file='neppin1.i', status='old')
c   open(unit=8, file='neppin1.out', status='unknown')
c
c   TLim=453.7
c   read(7,11) tit
11  format(a80)
c

```

```

read(7,11) aldum
read(7,20) itest,ndt,itmax,icont,iboun,nput
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=dkstr
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,nnodo,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) iwrte,ishn,ichoose,ichoode
read(7,11) aldum
read(7,10) fact,Ripple,hod,dcd
read(7,11) aldum
read(7,10) delp
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
c
c check if T inlet>T melt Li
c
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
c
c compute flowt(Kg/s) or Toutlet according to option iboun
c
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)
333 continue
roLi=0.5*(rhoi+rhoo)/1000.
c
c check degree of subcooling at outlet
c
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 STOPS')
if(toutl.ge.Ts) stop
c

```

```

c      if(tempv.lt.0) tempv=toutl
c
c
c compute max stress (sigma) for pressure vessel
c call desstr(tempv,1,D,sigma,sigrod,itmax,ipresv)
c
c
c
c      epso=eps
c      epsi=eps
c      epsg=eps
c      epss=eps
c      dero=der
c      Daxi=5.
c      tduco=tduc
c
c      Ereq=Pow*D*365.25
c
c Core life in sec,multiply by 1 julian year=31,557,600. sec
c      tiempo=D*3.15576e+7
c
c
c      INPUT DESCRIPTION FOR REALS
c
c
c Pow(Mw): power; D(years): core life; BU(at%): percent U235 atoms
c burned;
c Inlet flow conditions:
c pin,tin(MPa,K)) pressure and temperature of the inlet coolant(fuel el
c pHe,THe(MPa,K) initial" " " of He gap in rod.
c drr,dral,dra2 (cm) thickness of Be reflector:radial,top-bottom axial
c dkstr(%): reactivity structural materials(estimated)
c dkeol(%): " at end of life(desired)
c dksu (%):desired subcritical reactivity required at BOL with drums in
c eps: tolerance for iterations (like energy)
c der=1.01 (compute derivatives)
c fact:fraction fission energy/thermal
c flowr(kg/s)total coolant flow(applicable if iboun=1)
c Daxi(cm): extrapolation length axial cos power distribution
c Ripple:Relative amplitude of power distribution as function of angle
c at R=Rcore
c tduc(mm): thickness of the duct of the bundle of fuel elements
c hod: led of the spacing wire of the fuel rod/rod diameter
c dcd(cm): thickness B4C sheet of control drums
c tempv(K): Temperature of Pressure Vessel; if <0. program chooses tout
c delpv(Pa): max delta pressure for core
c toutl(K): outlet temperature of coolant(applicable if iboun=2)
c fastf(1/cm2): fast fluence (during time D) at payload area
c zload(m) : axial distance from the base of reactor to payload plane
c rload(m) : radius of load area
c Dose(Rad): integrated gamma dose(during time D) required for payload
c ddt(cm): delta r and delta h for test curve Eavailable=f(R) or f(H)
c
10 format(7e10.0)
c
c      imax=itmax
c      imaxt=itmax
c      itmag=itmax
c      its=itmax
c
c
c      INPUT DESCRIPTION FOR INTEGERS
c
c
c itmax: 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 iwrte=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 Correlatio
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
c      =2 2-D (r,theta) uniform power density assumed
c      =3 Uniform Fuel load/uniform coolant flow assumed
c      =4 Uniform Fuel load/Coolant flow proportional to power density
c      assumed
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) nput is the number of points in tabulation
c ichoose=0,1 no,yes correction,by program,of incompatible request
c ichoode=/1,2,3,4,5/ choose design with p/d=1.1,1.2,1.3,1.4,1.5
c if different from /1,2,3,4,5/ program choose one for you
c
c
c
c
c      format(14i5)
c
c
c      if(drr.gt.40..or.dra1.gt.40..or.dra2.gt.40.)
*write(8,31) drr,dra1,dra2
31      format(// ' YOUR VALUE OF REFLECTOR THICKNESS(CM)',3f8.2/
*          ' ARE TOO LARGE FOR A REASONABLE EXTRAPOLATION'/
*          ' OF THE DATA BASE'//
*          ' PROGRAM STOPS '//)
c
c      if(drr.gt.40..or.dra1.gt.40..or.dra2.gt.40.) stop
c
c
c      data dc,dl,dhe,dpin,drod,dref/0.635,0.127,0.025,4.826,6.4,25./
c
c dc,dl,dhe(mm) cladding,liner and He gap thickness
c dpin(mm),drod pin rod diameters
c Tlim(K) melting temperature of Li
d dref(cm): thickness of Be reflector(for data base)
c
c      dclad=0.1*dc
c
c      data pee,Av,ABe,xop/3.1415926,0.602202,
*          9.01219,0.541315/
c
c xop:optimum shape for cylindrical reactors; Av: Avogadro's number
c ABe: Be at-weight;pisq3=pi*sqrt(3)
c
c      data AU5,AU8,APu,AN,AHe/235.044,238.0508,239.0522,14.00307,4.0026/
c      data AW2,AW3,AW4,AW6/181.9483,182.9503,183.9510,185.9543/
c      data ATa,ARe5,ARe7,ALi6,ALi7/180.9480,184.9530,186.9560,6.01513,
*7.01601/
c      data AW,ARe,AHf,AO/183.85,186.2,178.49,15.9994/
c
c atomic weights
c A+chemical symbol+1 digit for isotopes
c
c      data xLi6,xLi7,xRe5,xRe7/0.0742,0.9258,.3707,.6293/

```



```

      data xW2,xW3,xW4,xW6/0.2655,0.1440,0.3064,0.2841/
c
c atomic fractions
c x+chemical symbol+digit for isotope
c 0.37% of N15 ,0.0132% of Ta180 and 0.14% of W180 ignored
c
      data roun,row,roAst,roobe/12.172,18.6,16.84,3.01/
c
c densities (g/cm3)
c roun: UN; row: W; roAst: Astar alloy
c roobe: OBe
c
c Average 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
c
c
      data xTa,xW,xRe,XHf,RoLis,RoBC
      */0.90275,0.08,0.01,0.00725,1.024,2.92/
c
c weight fraction Astar alloy
c xTa: Ta; xW: W; xRe: Re; xHf: Hf
c Densities(g/cm3): Ro...
c RoLis:LiH+Stainless Steel N'Shield
c RoBC: B4C(N' Shield)
c
      data wfi,rnu,remLi,remBe,remO,remU,remW
      */3.2042e-11,2.44,1.01,1.07,0.92,3.6,3.13/
c
c wfi: joules/fission(200Mev); rnu: number of neutrons per fission
c rem Li,Be,O,U,Ta : removal cross sections(barns) for fast neutrons
c
      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/
c
c pfr(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,p/d j
c
      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/
c
c pfrm(i,j) minimum radial power factors at BOL( at border core)
c same restrictions as pfr
c
c pfr and pfrm are for enrip(i) and podip(j) bellow
      data (enrip(i),i=1,3)/0.5,0.70,0.93/
      data (podip(j),j=1,3)/1.1,1.3,1.5/
c
c
      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/
c
c enri(i): enrichment, podi(i) pitch/diameter of the data base
c
      data (wbeth(i),i=1,8)/0.,0.2728,0.3947,0.5026,0.6778,0.8524,
      * 0.9517,1.000/

```

```

c wbeth: relative(to 30 cm) worth of OBe as function of its thickness
c th(cm)(input next)
c
c   data (th(i),i=1,8)/0.,3.67,5.67,7.67,11.67,17.67,24.,30./
c
c   nenr=5
c   npod=5
c
c relative worth of OBe reflectors: relr, radial;relal,rela2:axial
c
c   ibe=8
c   call Inter(th,wbeth,ibe,dr,relr)
c   relar=relr
c   call Inter(th,wbeth,ibe,dral,relal)
c   call Inter(th,wbeth,ibe,dra2,rela2)
c   relal=0.5*relal
c   rela2=rela2*0.5
c
c if itest=1 print your options:
c
c   TTTT EEEEE SSSS TTTT      1) Energy available with optimum shape
c   T   E   S   T              2) Radius of infinite cylinder
c   T   EEE   S   T            3) Height of infinite "pancake"
c   T   E       S   T          4) Energy available as function of R and
c   T   EEEEE SSSS   T              H
c                                   (2 or 3 would produce "infinite" energy)
c
c
c   ish=ishape
c   RRR=r
c   HHH=h
c
c
c   itpr=itest
c   if(itpr.eq.1)
c     *write(8,6133) Ereq,BU,dr,dr1,dr2,dkeol,dkstr
6133   format(// ' INPUT'// ' You requested Mwdays',f10.2/
c     * ' And burn-up(%)',f5.2/
c     * ' With radial OBe reflector thickness(cm)',f6.2/
c     * ' " top " " " " ',f6.2/
c     * ' " bottom " " " " ',f6.2/
c     * ' End of Life delta k(%) ',f6.2/
c     * ' Structural delta k(%) ',f6.2/)
c   if(itpr.eq.1)
c     *write(8,1632)
c
c   1632   format(' Run Test, Energy Available (Mwd) for Optimum Shape'/
c     * ' with corresponding Rop and Hop'/
c     * ' Critical Radius(cm) for Infinite Reactor'/
c     * ' Critical Height(cm) for Infinite Reactor'/
c     * ' For your input conditions')
c   itest=1
c   do 299 ipod=1,npod
c     pod=podi(ipod)
c     if(itpr.eq.1) write(8,302) pod
302   format('/'p/d=',f6.4)
c     if(itpr.eq.1) write(8,301)
301   format(
c     * 'enr      Energy      Rop      dpv      Hop      Rc      dpv
c     *      Hcr')
c
c
c compute Energy available for ideal shape Emin()
c and asymptotic radius Ras() and height Has()
c
c   do 1633 ienr=1,nenr

```

```

        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
c
c
        if(itpr.eq.1) write(8,1634) enr,Ene,Ropo,dpvo,Hopo,Rcri,dpvc,Hcri
1633 continue
299 continue
c
1634 format(f5.3,f12.1,6f10.2)
c
        itest=itpr
        if(itest.eq.0) go to 1631
c
c compute curves Eavailable as function of radius and Height of core and
c enrichment and p/d in order to illustrate the user about the options.
c
        do 5682 ipod=1,npod
        pod=podi(ipod)
        do 5782 ienr=1,nenr
        enr=enri(ienr)
c
c
        write(8,5783) enr,pod,Ereq
c
5783 format(//
*' AVAILABLE ENERGY(MWDAYS) AS FUNCTION OF ENRICHMENT,P/D,R AND H'/
*/'ENR=',f6.4,10x,'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'//)
c
        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
c

```

```

c      write(8,5784) idt,rs,dpvr,xra,ener,hs,dpvh,xh,eneH
c
5784  format(i5,2(f9.2,f4.1,f5.2,f12.0))
c
5782  continue
5682  continue
c
c
c      EEEEE  N   N   D      TTTTT EEEEE SSSSS TTTTT
c      E      NN  N   D D      T   E   S      T
c      EEE     N N N   D  D      T   EEE   S      T
c      E       N  NN  D  D      T   E      SS     T
c      EEEEE  N   N   D      T   EEEE  SSSSS  T
c
c 1631 bypass prints and some checks on energy
c
1631  continue
c
c Stop here if your intentions are only to run the test
c
      if(iconf.eq.0) stop
c
      icart=1
c
c
      drodc=0.1*drod
c
c
      do 467 ipod=1,npod
        isha(ipod)=ish
467    bual(ipod)=bu
c
c
      do 1391 ipod=1,npod
c
c start loop of designs by fixing first p/d
c up to statement # 1391
c
      pod=podi(ipod)
      BU=bual(ipod)
      ishape=isha(ipod)
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
      fduct=(Abu-Abund)/Abu
c f1,2,3 are flow fractions for cell types 1,2,3(with respect to acell1)
      x=pod
      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(cm2) is acell
      pitch=pod*drodc
      acell=0.433013*pitch**2
c a1,a2,a3(cm2) 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*rrod**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=fduct*RoAst+fLi*roLi+frod*rorod+fwire*RoAst
c
        r=RRR
        h=HHH
        itest=0
c
c check if you are requesting too little energy
c
        iflamin=0
        Emin=Emin(nenr,ipod)
        if(Ereq.ge.Emin) go to 337
        iflamin=1
        write(8,5133) pod,Ereq,BU,drd,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.1) write(8,1424)
1424 format(// ' I choose=1, Program stops')
        if(ichoose.eq.1) 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
c
c Recompute Energy available for ideal shape Emin() by changing burnup
c
        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=BUA/2.
        BUal(ipod)=bu
        go to 4644
4633 continue
        itest=0
337 continue
c
c check if there is enough energy for ideal shape(ishape=1)
c
        iwa=0
        Emax=Emin(1,ipod)
        if(Ereq.le.Emax) go to 357
        iwa=1
c
c set the warning flag iwa=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

```

c
  itest=1
  ishape=2
  enr=enri(nenr)
  Das=Ras(nenr,ipod)
  Dop=Rop(nenr,ipod)
  call Size(Das,Dop,Ereq,enr,pod,R1,R4)
  enr14=enr
  hr4=h
  hr1=Vcor/(pee*r1**2)
  vr14=Vcor/1000.
  enr=enri(1)
  Das=Ras(1,ipod)
  Dop=Rop(1,ipod)
  call Size(Das,Dop,Ereq,enr,pod,R2,R3)
  enr23=enr
  hr3=h
  hr2=Vcor/(pee*R2**2)
  vr23=Vcor/1000.
  ishape=3
  enr=enri(nenr)
  Das=Has(nenr,ipod)
  Dop=Hop(nenr,ipod)
  call Size(Das,Dop,Ereq,enr,pod,H1,H4)
  enr14=enr
  rh4=R
  rh1=sqrt(Vcor/(pee*H1))
  vh14=Vcor/1000.
  enr=enri(1)
  Das=Has(1,ipod)
  Dop=Hop(1,ipod)
  call Size(Das,Dop,Ereq,enr,pod,H2,H3)
  enr23=enr
  rh3=R
  rh2=sqrt(Vcor/(pee*H2))
  vh23=Vcor/1000.
  write(8,369)pod,Ereq,Emaxo,R1,R2,R3,R4,enr14,vr14,hr1,hr4,enr23
  *,vr23,hr2,hr3
369  format(// ' ATTENTION: '//
  *' Designs with p/d=',f8.5/
  *' 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/
  *'                                     or R(cm) between'//
  *'                                     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,enr14,vh14,rh1,rh4,enr23,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 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,drd,dr1,dr2,dkeol,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
357 continue
if(ishape.eq.1.or.iwae.eq.1) go to 434
c
c begin check of input R or H if E requested is not in bifurcation
c region
c
itest=1
if(ishape.eq.2) then
enr=enri(nenr)
Das=Ras(nenr,ipod)
Dop=Rop(nenr,ipod)
call Size(Das,Dop,Ereq,enr,pod,R1,R2)
R=RRR
if(R1.lt.R.and.R.lt.R2) go to 443
if(ichoose.eq.1) write(8,4551)pod,ichoose,R,R1,R2
4551 format(///' Sampling p/d=',f6.3/
*///' I choose Flag=',i5,' Your R=',f8.2/
* ' Outside Possible Range',2f10.2/
* ' Program stop'//)
if(ichoose.eq.1) stop
Rin=R
R=0.5*(R1+R2)
write(8,4552) pod,ichoose,Rin,R1,R2,R
4552 format(///' Sampling p/d=',f6.3
*///' I choose Flag=',i5,' Your R=',f8.2/
* ' Outside Possible Range',2f10.2/
* ' Program continues with average, R=',f8.2//)
443 continue
else
enr=enri(nenr)
Das=Has(nenr,ipod)
Dop=Hop(nenr,ipod)
call Size(Das,Dop,Ereq,enr,pod,H1,H2)
H=HHH
if(H1.lt.H.and.H.lt.H2) go to 454
if(ichoose.eq.1) write(8,4553) pod,ichoose,H,H1,H2
4553 format(///' Sampling p/d=',f6.3
*///' I choose Flag=',i5,' Your H=',f8.2/
* ' Outside Possible Range',2f10.2/
* ' Program stop'//)
if(ichoose.eq.1) stop
Hin=H
H=0.5*(H1+H2)
write(8,4554) pod,ichoose,Hin,H1,H2,H
4554 format(///' Sampling p/d=',f6.3
*///' I choose Flag=',i5,' Your H=',f8.2/
* ' Outside Possible Range',2f10.2/
* ' Program continues with average, H=',f8.2//)
454 continue
endif
itest=0

```

```

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
455  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
4555  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
c
c
c enr1 (higher enrichment) has balance<0.
    ibu=0
    enr1=enri(nenr)
    bal1=Balance(ibu,enr1,pod)
    if(ibu.eq.1) write(8,597)
597  format(' Stop trying to bracket demand')
    if(ibu.eq.1) stop
c loock for enrichment that produces balance>0.
    if(ishape.eq.1.or.iwae.eq.1) then
        enr2=enri(1)
        bal2=Balance(ibu,enr2,pod)
        if(ibu.eq.1) write(8,597)
        if(ibu.eq.1) stop
    else
        it=0
        enr2=enr1
790  enr2=enr2/der
        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
794   format(' stop trying to find Bal>0. iterations=',i5,' enr=',f10.3/
        *'p/d=',f10.3)
        stop
890   continue
        endif

c
c if we successfully arrived to this point,it means we bracket the demand
c Then:
c bisection Balance until Eavailable=Erequested
c
        it=0
145   enra=0.5*(enr1+enr2)
        Erema=Balance(ibu,enra,pod)
        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(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,' enr1',8x,' enra',7x,' enr2',8x,' bal1',7x,' Erem',
        *8x,' bal2')
        if(iwrte.eq.1) write(8,218) it,enr1,enra,enr2,bal1,Erema,bal2
218   format(i4,3f12.6,3f12.3)
        call bisection(enr1,enr2,enra,bal1,bal2,Erema,iwa)
        if(it.le.itmax.and.iwa.eq.0) go to 145
144   continue
        if(it.gt.itmax.or.iwa.eq.1) then
        write(8,146) enr1,bal1,enr2,bal2,it,iwa
146   format(///' Problems trying to bisection Balance'/
        *' enr1=',e12.4,' bal1=',e12.4/
        *' enr2=',e12.4,' bal2=',e12.4/
        *' iteration=',i5/
        *' iwa=',i5/)
        stop
        else
        continue
        endif

c
c successful end of reactor search, calculate masses
c change R such area fit integer number of bundles
        Nbu=pee*R**2/Abu
        Rbu=pee*R**2/Abu
        Rnbu=nbu
        if((Rbu-Rnbu).gt.0.5) Nbu=Nbu+1
        R=sqrt(Nbu*Abu/pee)

c
c recompute H
        H=Vcor/(pee*R**2)

c
c compute mass core+pressure vessel+reflector=Greactor
c
        Volpv=0.
        Gpv=0.
        Volpv=2.*pee*(R+dpv)**2*dpv
        Volpv=Volpv+pee*((R+dpv)**2-R**2)*H
        Gpv=Volpv*RoAst
        Rpv=R+dpv
        Hpv=H+dpv
        Vref=pee*((Rpv+drd)**2-Rpv**2)*Hpv
        Vref=Vref+pee*(Rpv+drd)**2*(dra1+dra2)
        Gref=Vref*roOBe

```

```

      GReactor=Vcor*rocore+Gpv+Gref
c
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
      dpvd(ipod)=dpv
      GRea(ipod)=GReactor
      delp(ipod)=deltapa
      dkbup(ipod)=dkbu
      dkpvd(ipod)=dkpv
      rkbare(ipod)=rkre
      dkobe(ipod)=dkbe
      Nbun(ipod)=Nbu
      u5md(ipod)=U5m/1000.
      isha(ipod)=ishape
1391 continue
c
c at 1391 end of loop on p/d
c
c Now choose design using Greactor and delta p as criteria
c
      ich=1
      Rmref=GRea(1)/1000.
      write(8,849) delp
849   format(// 'Sampling of Designs' /
* 'Mass=Masses of core,pressure vessel and reflector' /
* ' Max delta p(Pa) acceptable=',e13.4//
* ' 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)
      ishu=isha(ipod)
      write(8,855) ipod,podi(ipod),enro,buon,Rmass,U5m,delpa,Rdo,Hdo,ishu
855   format(i3,2f6.3,f6.2,2f10.1,e13.4,2f10.2,i3)
      if(delpa.gt.delp) go to 783
      if(Rmass.lt.Rmref) ich=ipod
      if(Rmass.lt.Rmref) Rmref=Rmass
783   continue
c
c chosen design is ipod=ich
c 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)
      dkbup(ipod)=dkbu
      dkpvd(ipod)=dkpv
      rkre=rkbare(ich)
      dkbeo=dkobe(ich)
      Nbu=Nbun(ich)
      bu=bual(ich)
      Vcor=pee*R**2*H
      ishape=isha(ich)
      write(8,11) tit

```

```

c      write(8,51) Pow,D,Ereq,BU,drd,dr1,dr2,eps
c
51      format(// ' INPUT TO THE PROGRAM'// ' Power(Mw)',f8.2,' Core life',f
*8.3,' 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)
c
      if(ishape.eq.1) write(8,317) xop
317      format(// ' Minimum Core Volume Option Chosen: R/H=',f9.6/)
c
      if(ishape.eq.2) write(8,318) R
318      format(// ' Core Radius Option Chosen: R(cm)=',f7.2/)
c
      if(ishape.eq.3) write(8,319) H
319      format(// ' Core Height Option Chosen: H(cm)=',f7.2/)
c
      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
52      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//)
c
c
      write(8,521) enr,pod
c
521      format(' Enrichment=',f8.4,' Pitch/Diameter=',f6.2)
c
      Rad=R
c
c call control to design control drums
c
      dvp=dpv
      Call Control
c
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
c
30  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)')//)
c
c
      bup=0.01*bu
      Call bupo(bup,1.50,cu5,cu8,dkbu)
c
c see: 1.50 and dkbu are dummies
c
      rou5e=c5e*AU5/Av
      rou8e=c8e*AU8/Av
      roPue=c9e*APu/Av
      roFpe=cfpe*0.5*AU/Av
      U5me=rou5e*Vact
      U8me=rou8e*Vact
      Pume=roPue*Vact
      Pup=(p9*APu/Av)*Vact
      Fpme=roFpe*Vact
      ftin=ftin*1.e+24
      fluxn=ftin/tiempo
      write(8,5211)fluxn,D,ftin
5211 format(
      */'Neutron Flux(1/cm2sec)(core and time average)          ',e12.4/
      * ' " Fluence(1/cm2) " " after',f6.2,' years',e12.4)
c
      write(8,986) u5m,u5me,u8m,u8me,pum,pume,Pup,fpm,fpme
986  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)
c
      write(8,40) drod,dc,dl,dHe,dpin
c
40  format('          FUEL RODS'/
      */'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)
c
c
      x=pod
      pitch=x*drodc
      fcool=1.-0.90689968*(1.+(x-1.)**2/3.)/x**2
      frod=0.90689968/x**2
      fwire=1.-fcool-frod
      write(8,50) fcool,fwire,frod
c
50  format(//'Volume fractions in Fuel Cell #1'/
      *      'Coolant',f7.4
      *      'Spacing Wire',f7.4
      *      'Fuel Rod',f7.4)
c
c
c
      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
      roTun=roAst*xW
      coTun=roTun*Av/AW

```

```

cW2c=coTun*xW2
cW3c=coTun*xW3
cW4c=coTun*xW4
cW6c=coTun*xW6
roRe=roAst*xRe
coRe=roRe*Av/ARe
cRe185=coRe*xRe5
cRe187=coRe*xRe7
roHf=roAst*xHf
cHf=roHf*Av/AHf
fclac=(fclad+fwire)*frod
Rrodw=Rrod*sqrt(1.+fwire/frod)
coW=roW*Av/AW
cW21=coW*xW2
cW31=coW*xW3
cW41=coW*xW4
cW61=coW*xW6
flic=fliner*frod
pHep=pHe*1000000.
roHe=0.001*rho(pHep,THE)
coHe=roHe*Av/AHe
fHec=fHe*frod
cN=roN*Av/AN
fpinc=fpin*frod
write(8,60) Rco,coLi6,fcool,coLi7,
*           Rrod,coTa,fclac,
*           Rrodw,
*           cW2c,cW3c,cW4c,cW6c,
*           cRe185,cRe187,
*           cHf,
*           Rclad,cW21,flic,
*           cW31,cW41,cW61
write(8,1160)
*           Rliner,coHe,fHec,
*           Rpin,cU5,fpinc,
*           cU8,cN
c
60  format(//
*' Fuel Cell type 1 (Number Densities 10**24 atoms/cm3)'/
*' Spacing Wire is diluted in clad'//
*'Region   Radius(cm) Isotope Concentration Volumetric Fraction'//
*'Coolant  ',f10.4,',      Li6',f12.8,f10.6/
*' "       ',f10x,',      Li7',f12.8/
*'Clad     ',f10.4,',      Ta181',f12.8,f10.6/
*' "       ',f10.4,',(diluting spacing wire)'/
*' "       ',f10x,',      W182',f12.8/
*' "       ',f10x,',      W183',f12.8/
*' "       ',f10x,',      W184',f12.8/
*' "       ',f10x,',      W186',f12.8/
*' "       ',f10x,',      Re185',f12.8/
*' "       ',f10x,',      Re187',f12.8/
*' "       ',f10x,',      Hf',f12.8/
*'Liner    ',f10.4,',      W182',f12.8,f10.6/
*' "       ',f10x,',      W183',f12.8/
*' "       ',f10x,',      W184',f12.8/
*' "       ',f10x,',      W186',f12.8)
1160 format(
*'He Gap   ',f10.4,',      He',f12.8,f10.6/
*'Fuel Pin ',f10.4,',      U235',f12.8,f10.6/
*' "       ',f10x,',      U238',f12.8/
*' "       ',f10x,',      N14',f12.8//)
c
c AVERAGES IN BUNDLE:
c
c Abu and Abund(cm2) area of 19 rods bundle with and without the duct
Abu=3.4641016*drod**2*(pod*2.73205081-0.5+tduc/drod)**2
Abund=3.4641016*drod**2*(pod*2.73205081-0.5)**2

```

```

c duct fraction
  fduct=(Abu-Abund)/Abu
c f1,2,3 are flow fractions for cell types 1,2,3(with respect to acell1)
  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(cm2) is acell
  pitch=pod*drodc
  acell=0.433013*pitch**2
c a1,a2,a3(cm2) 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=fduct*RoAst+fLi*roLi+frod*rorod+fwire*RoAst
c
  fclw=fwire+frod*fclad+fduct
  flin=frod*fliner
  fpinb=frod*fpin
c
  Vact=Vcore*fpinb
c
  coLi6=coLi6*fLi
  coLi7=coLi7*fLi
  coTa=coTa*fclw
  cW2=cW2c*fclw+cW2l*flin
  cW3=cW3c*fclw+cW3l*flin
  cW4=cW4c*fclw+cW4l*flin
  cW6=cW6c*fclw+cW6l*flin
  cRel85=cRel85*fclw
  cRel87=cRel87*fclw
  cHf=cHf*fclw
  coHe=coHe*frod*fHe
  fHec=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,
    *          cRel85,cRel87,
    *          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/cm3)'//
    * '   Li6',f12.8/
    * '   Li7',f12.8/
    * '   Ta181',f12.8/
    * '   W182',f12.8/

```

```

*'      W183',f12.8/
*'      W184',f12.8/
*'      W186',f12.8/
*'      Re185',f12.8/
*'      Re186',f12.8/
*'      Hf',f12.8/
*'      He',f12.8/
*'      U235',f12.8/
*'      U238',f12.8/
*'      N14',f12.8//)
rLi=(coLi6+coLi7)/cU5
write(8,92) rLi
c
92      format(////' Moderation by Li, Li/U235=',f10.4)
c
c compute masses and volumes inside the core
c
      Gcore=rocore*Vcore
      Vrod=Vcore*frod
      Grod=Vrod*rorod
      frodm=Grod/Gcore
      VLi=Vcore*fLi
      GLi=VLi*roLi
      fLim=GLi/Gcore
      Vduct=Vcore*fduct
      Gduct=Vduct*roAst
      fduc=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
1093      format(//
*' VOLUME(L) AND MASSES(KG) INSIDE THE CORE'//
*'Part      Volume      Fraction      Masses      Fraction'//
*'Rods      ',2(f10.2,f10.6)/
*'Coolant    ',2(f10.2,f10.6)/
*'Duct       ',2(f10.2,f10.6)/
*'Spacing    ',2(f10.2,f10.6)/
*'Total      ',2(f10.2,10x))
c
c compute mass core+pressure vessel+reflector=Greactor
c
      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+drd)**2-Rpv**2)*Hpv
      Vref=Vref+pee*(Rpv+drd)**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,

```

```

*          VReactor,GReactor
1095 format(//
*' VOLUME(L) AND MASSES(KG) OF REACTOR'//
*'Part      Volume      Fraction  Masses      Fraction'//
*'Core      ',2(f10.2,f10.6)/
*'Press Ves',2(f10.2,f10.6)/
*'Reflector',2(f10.2,f10.6)/
*'Total     ',2(f10.2,10x))
      Hrea=Hpv+dra1+dra2
      Rrea=Rpv+drd
c
c calculation of neutron shielding
c
c compute fast source Sn
c
      Sn=Pow*1.e+6*rnu/wfi
c
c compute shielding by core,reflector and pressure vessel: fsh
c concentrations smothered in Vol=Vcore+Volpv+Vref
c
      coLi=(coLi6+coLi7)*fvc
      coTa=coTa*fvc+xTa*fvpv*roAst*Av/ATa
      coW=(cW2+cW3+cW4+cW6)*fvc+xW*fvpv*roAst*Av/AW
      coRe=(cRe185+cRe186)*fvc+xRe*fvpv*roAst*Av/ARE
      coHf=cHf*fvc+          xHf*fvpv*roAst*Av/AHf
      coHe=coHe*fvc
      coU5=cU5*fvc
      coU8=cU8*fvc
      coU=coU5+coU8
      coN=cN*fvc
      robe=fvr*roobe*av/(AO+ABe)
      coO=robe
      coBe=robe
      sigre=coBe*remBe+remW*(coTa+coW+coRe+coHf)+coU*remU+
*'      +remLi*(coLi+coHe)+(coN+coO)*remO
      Req=(750.*Vreactor/pee)**0.33333333
      sire=sigre*Req*2.
      fsh=3.*(0.5-(1.-(1.+sire)*exp(-sire))/sire**2)/sire
      Snsh=Sn*fsh
c Fast fluence without shielding is flufa,at distance dist
      dist=100.*zLoad+0.5*Hrea
      flufa=Snsh/(4.*pee*dist**2)
      flufa=flufa*tiempo
c
c Calculate Neutron Shield for zero gamma Shield
c
      tne0=shieldn(flufa,fastf,ishn,0.00,igam)
      if(ishin.eq.0) tne0=0.
c
c Now, Calculation Gamma Source Sogam()
c
      Call Gamso(Sn,Sogam,PrU,fvr)
c
c First, Gamma Shield with no Neutron Shield
c
      Call Shieldga(Sogam,Dose,Doses,Dosew,tiempo,tgam0,0.,igam1,ishn,0)
c
c Now, Coupled with n Shield
c
      Call Shieldga(Sogam,Dose,Doses,Dosew,tiempo,tgam,tne,igam2,ishn,1)
c
      if(igam2.eq.0) tne=tne0
      if(igam2.eq.0) tgam=0.
c
c Volume and Masses of shieldings
c
      Tgt=Tan((100.*rload-Rrea)/(100.*zload+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
fgv=100.*Volg/Vols
fresg=100.*Greactor/Gsis
fneg=100.*Gne/Gsis
fgg=100.*Gg/Gsis

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

C
C
      write(8,796) Volg,fgv
796  format(' G Shield',2f10.2)
C
C
      write(8,797) Vols
C
797  format(' Total   ',f10.2//)
C
C
      write(8,798) Greactor,fresg,Gne,fneg
C
798  format(
      *'          Mass(Kg) Fraction(%)'//
      *' Reactor ',f10.2,f10.2/
      *' N Shield',f10.2,f10.2)

C
C
      write(8,796) Gg,fgg
C
C
      write(8,806) Gsis
C
806  format(' Total   ',f10.2//)
C
C
      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'//)
C

```



```

write(8,*) ' % FRACTION PRODUCED BY U'
c
c
write(8,773) (PrU(i),i=1,7)
c
773 format(7f10.2)
c
c
write(8,*) ' Equivalent Z for Build up factors'
c
c
write(8,773) (Zeq(i),i=1,7)
c
c
write(8,*) ' Gamma Self shielding by Core, Reflector and PV'
c
c
write(8,774) (shg(i),i=1,7)
774 format(7f10.6)
c
c
write(8,*) ' The same but without Buildup factor'
c
c
write(8,774) (shgnb(i),i=1,7)
c
c
write(8,*) 'Integrated Dose(Rad) without any shielding(n or gamma)'
c
c
write(8,772) (Dosewg(i),i=1,7)
c
c
if(ishig.eq.0.and.ishin.eq.1)
*write(8,*) 'Integrated Dose Neutrons Shieldings(and no W)'
c
c
if(ishig.eq.0.and.ishin.eq.1) write(8,772) (DosenG(i),i=1,7)
c
c
if(ishig.eq.1.and.igam2.ne.0)
*write(8,*) 'Integrated Dose with W and Neutrons Shieldings'
c
c
if(ishig.eq.1.and.igam2.ne.0) write(8,772) (DoseG(i),i=1,7)
c
c
write(8,775) Dosew
c
775 Format(' Integrated Dose without Any Shielding,Total(Rad)',e12.4)
c
c
if(ishig.eq.1.and.igam2.ne.0) Dosos=Doses
if(ishig.eq.0) Dosos=Dosen
write(8,776) Dosos,tgam,tgam0
c
776 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'//)
c
c
write(8,804) Dose,Zload
c
804 format('/ Requested Dose(Rad)',f10.2,' at ',f6.2,' meters'//)
c
c SOLVE THERMALHYDRAULIC
c

```

```

c
c      podt=pod
      Hact=H
      write(8,2367) tout1
c
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
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
c Thermo at Max power density
c
      Pfacaz=1.
c
c      write(8,687)
c
687  format(' ****PROFILE OF CHANNEL WITH MAXIMUM POWER DENSITY****'//)
c
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
c Thermo at Min power density
c
      Pfacaz=1.-Ripple
c
c      write(8,697)
c
697  format(///' ***PROFILE OF CHANNEL WITH MINIMUM POWER DENSITY***'//)
c
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)=rmm
      call Inter(podip,bux,npodp,pod,Pfacr)
      Call Thermoli(0)
677   continue
      Stop
      End

c
c
c
c
c
c
c
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
c Reactors",G. Melese and R. Katz
c
      Function rho(p,t)
      R=2077.22
      rho=p/(r*t+p*b(t))
      return
      end

c
c Function b(t)(used by rho)
c
      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

c
c Compute available energy or
c difference between available and requested energies
c as function of S/F(other thing too)
c
      Function Balance(ibu,enr,pod)
c
c For input enr(ichment),pod(p/d) and when itest=0:
c this function calculates 1) the volume of the core that satisfies the
c reactivity balance; and then 2)the energy balance(Mwday)
c Balance=Eavailable-Erequested. If ishape=2 or 3 (input R or H) the
c function checks if R(or) H is compatible with reactivity balance
c if not, set flag ibu=1 and RETURN
c
c if itest=1 and for inputs enr and pod it calculates
c available energy(for ishape=1,2 or 3),
c radius infinite core that satisfies reactivity balance if ishape=2
c height of infinite " " " " " " " " =3
c
      common /Bala/ Ereq,relr,relal,rela2,dkeol,dkstr,BU,Vc,
*U5m,dkbu,dkbe,rkrem,dcr,sigma,pin,dpv,dkpv,tduc,
*eps,itest
c
      common /MaBaSi/ R,H,ishape
c
      dimension rm(5,5),enri(5),podi(5),bew(5,5)
* ,rki(5,5),prv(5,5),aux(5),bux(5),dext(5)
c
      data (rm(5,j),j=1,5)/7.695,8.762,9.841,10.927,12.010/
      data (rm(4,j),j=1,5)/7.945,9.032,10.131,11.230,12.325/
      data (rm(3,j),j=1,5)/8.149,9.248,10.357,11.470,12.571/
      data (rm(2,j),j=1,5)/8.356,9.467,10.586,11.706,12.811/
      data (rm(1,j),j=1,5)/8.563,9.681,10.805,11.929,13.037/
c

```

```

c rm(i,j) (cm) migration length of cell with enrichment i and p/d j
c for the following enrichments and p/d
c
  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/
c
  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
c rki k-infinite as function of i(enrichment) and j(p/d)
c
c
  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
c bew(i,j): % delta k; reactivity worth of 25 cm OBe radial reflector as
c function of i(enr) and j(p/d)
c
  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/1./
c
c prv(i,j): % delta k; reactivity worth Astar as pressure Vessel
c function of i(enr) and j(p/d) at reference thickness dref
c
  data (dext(j),j=1,5) /3.165,3.565,3.954,4.360,4.737/
c
c dext(j)(cm) extrapolation length for bare core(mainly function of p/d)
c
  data pee,xop,pisq3,bo/3.1415926,0.541315,5.441398,2.945511/
c
c xop:optimum shape for cylindrical reactors=Radius/Height
c pisq3=pi*sqrt(3)
c
  data roun,drodc,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 drodc=6.4mm, wfi=Mwd produced by the total fission of 1 g of U235
c at 200 Mev/fission
  data AU5,AU8,AN,Av/235.044,238.0508,14.00307,0.602202/
c
c
c
c
  ibu=0
  nenr=5
  npod=5
c
c compute dexto(cm) extrapolated length
c
  call Inter(podi,dext,npod,pod,dexto)
c
c compute kinf
c
  do 1577 j=1,npod
  do 1578 i=1,nenr
1578   aux(i)=rki(i,j)
      call Inter(enri,aux,nenr,enr,rkk)
1577   bux(j)=rkk

```

```

      call Inter(podi,bux,npod,pod,rkin)
c
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
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
cb 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)
      Rref=bo*rmi/sqrt(rkin-1.)-dexto
      drefp=Rref*(pin/sigma)
      apv=relr*0.01*wpv*(0.4/dref)*Rref
      dkpv=(drefp/dref)*relr*wpv
c
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
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
c if ishape=1, optimum shape----->2001
2001   Rp=rmi*bo/sqrt(rkin/rkrem-1.)
      Hp=Rp/xop
      R=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=1./riv
hp=rp/xop
R=rp-dexto
H=hp-dexto*2.
Vc=pee*R**2*H
dkpv=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/rkrm-1.)/aa
riv=-bb+sqrt(bb**2+cc)
rp=1./riv
dcr=rp-dexto
1703 continue
if(R.le.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
if(dpv.ge.0.4) go to 1823
dpv=0.4
dkpv=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
if(dpv.gt.0.4) go to 2004
dpv=0.4
aa=(rmi*2.405)**2+rkin*apv*dexto/rkrm**2
bb=0.5*apv*rkin/(rkrm**2*aa)
cc=(rkin/rkrm-1.-(rmi*pee/(H+dexto*2.))**2)/aa
riv=-bb+sqrt(bb**2+cc)
rp=1./riv
R=rp-dexto
Vc=pee*R**2*H
dkpv=100.*apv/R

```



```

      rkrem=rkrm+dkpv/100.
2004 continue
c
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=rouno*(AU/AUN)
      rou5=enr*rou*AU5/AU
c
c check available energy
c
      U5m=Vc*rou5
c
c Eavai(Mwd) is the total energy produced by the fission of U235,U238and
c Pu239 at 200 Mev per fission. See,here BU=Total fission/Initial number
c of U235 atoms; ie U5 at EOL is NOT BU*U5(BOL)
c
      Eavai=U5m*BU*wfi/100.
      Balance=Eavai-Ereq
      if(itest.eq.1) Balance=Eavai
      return
      end

c
c
c compute control drums
c
      subroutine Control
      dimension cr(5,5),enri(5),podi(5),aux(5),bux(5),bew(5,5),prv(5,5)
      common /cont/ R,dpv,drd,enr,pod,refec,ncr,dksu,dkstr,relr,dcd
c
c R:radius core, drd: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(%):subcritica-
c lity required for drums in.
c dkstr(%): dk structural part of reactor,relr:relative worth of reflecto
c
      data dref,dpvref,dcdref/25.,1.,2./
c
c dref,dpvref,dcdref:reference values for calculation worth of reflector
c PV and B4C in Control drums(cd)
      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/
c Cr(i,j)
c %delta k; max worth of control rods in OBe reflector
c for enrichment i and p/d j and
c calculated with reflector thickness dref(reference)
c
      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
c bew(i,j): % delta k; reactivity worth of 25 cm OBe radial reflector as
c function of i(enr) and j(p/d)
c
      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/
c
c prv(i,j): % delta k; reactivity worth Astar as pressure Vessel
c function of i(enr) and j(p/d) at reference thickness dref
c
      data (enri(i),i=1,5)/0.5,0.6,0.7,0.8,0.93/
      data (pod(i),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
c
      pee=3.1415926
c dcd(cm): thickness of B4C in Control drums
c
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,crr)
2577      bux(j)=crr
      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)
c cdr,next, is for conditions: PV=1cm thick,B4C=2cm thick
      cdr=cdr*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,crr)
3577      bux(j)=crr
      call Inter(podi,bux,npod,pod,wpvi)
      wpvi=wpvi*relr
c
c b)worth of dpvref cm thick PV=wpv1
c
      do 4577 j=1,npod
      do 4578 i=1,nenr
4578      aux(i)=prv(i,j)
      call Inter(enri,aux,nenr,enr,crr)
4577      bux(j)=crr
      call Inter(podi,bux,npod,pod,wpv1)
      wpv1=wpv1*relr
c
c compute exponent of flux attenuation in PV
c
      sigpv=-alog(1.-wpv1/wpvi)/dpvref
c
c 2) Compute sigcd and AM looking at worth of B4C at "infinite" and 2.cm
c worth of "infinite" thick B4C=wpvi(Reflector)-wpv1(PV)
      wcdi=wpvi-wpv1

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```

      AM=wcdi*exp(sigpv*dpvref)
      sigcd=-alog(1.-cdr/(AM*exp(-sigpv*dpvref)))/dcdref
c
c worth of 2 pi's sheet of B4C(thick=dcd) beside the PV(thick=dpv)
c
      cdr=AM*exp(-sigpv*dpv)*(1.-exp(-sigcd*dcd))
c
c
c rea(%) reactivity to control
c
c
      rea=(refec-1.)*100.+dksu-dkstr
c
c compute maximum number of drums=nmax
c
      Rpv=R+dpv
      rd=0.5*dr
      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
10  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)
      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
      cdrm=cdr*ncr*par/(2.*pee)
      if(cdrm.lt.rea) go to 101
      rcr=ncr
      else
      endif
c
c para is the central parallax of the absorbing part of one drum
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=Rpv**2+2.*Rpv*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(%)=' ,f8.2//)
        return
    end

c
c solve thermalhydraulic
c
    subroutine thermoli(iop)
    real*4 k
    dimension pow(51),pres(51),tbulk(51),ve(51),z(51),rj(51)
    *,tw(51),Tclad(51),Tfuel(51),Tclaa(51),Tfua(51),Tbuma(51)
c
    common/thermo/ aln,nnodo,ifri,npin,pin,tin,tout,deltapa
    *,Powt,rjs,flowt,pod,tduc,Rc
    *,Hact,Pfacr,Daxi,fact,iprth,iopth,ichoose
    *,Pfacaz,iboun,nrod,nbu,nrodbu,hodo
c
    common /fric/ podf,hod,xx,drel,coefri
c
    character*80 aln
c
c
    Tsa(ps)=8143./(8.-alog10(ps/0.133322))
    Psa(ts)=0.133322*10.**((8.00-8143.)/ts)
c
c Tsa(ps) is saturation temperature of Li(in K) as function of ps(KPa)
c Psa(ts) is      "      pressure      of Li(in KPa)"      "      of ts(K)
c
    data pee/3.1415926/
c
    data drod,dclad,dliner,dHe,TLim /0.64,0.0635,0.0127,0.0025,453.7/
    data rpin/0.2413/
    data TmTa,TmUN/3269.,2903./
c
c cm diameter rod,clad,liner,He thickness
c
c
c
c nnode: number of nodes;
c iboun /1,2/ boundaries conditions : read flow or T outlet
c 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
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
c Vact(L) active volume of the core, ie Volume occupied by UN
c tduc(mm) duct thickness; hod lead of the spacing wire(in unit of drod)
c
c
c
c flowt(Kg/sec) : Total flow
c flow1,2,3(g/sec) : Channel flow for cell types 1,2,3
c
c
c pin(MPa), tin( K) inlet conditions
c total power; rjs(Kw/cm2) scale for plot heat rate
c
c
    npu=nnodo+1

```

```

        hod=hodo
        podf=pod
c
c Hact(cm):active length; Pfact:Radial Peaking factor at r position
c assume cos in z and Daxi(cm) axial extrapol.
c
        Abu=3.46410*drod**2*(pod*2.732051-0.5+.1*tduc/drod)**2
        Abund=3.46410*drod**2*(pod*2.732051-0.5)**2
c flow per bundle flow(g/s)
        flow=1000.*flowt/Nbu
        d=drod*0.01
c f1,2,3 are flow fractions for cell types 1,2,3(with respect to acell1)
        x=pod
        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(m2) is acell
        pitch=pod*d
        acell=0.433013*pitch**2
c a1,a2,a3(m2) are area flow of cell types 1,2,3
        a1=f1*acell
        a2=f2*acell
        a3=f3*acell
c wet perimeters (m) are pf1,2,3
        pf1=pee*d*(2.+x)/6.
        pf2=.25*d*(pee+x*(pee+4.))
        pf3=d*(pee+6.92820*(x-.5))/6.
c d1,2,3 are the equivalent diameters(m) for cell types 1,2,3
        d1=4.*a1/pf1
        d2=4.*a2/pf2
        d3=4.*a3/pf3
c total area flow,At and equivalent diameter for 19 rods bundle
        At=24.*a1+12.*a2+6.*a3
        pft=24.*pf1+12.*pf2+6.*pf3
        dt=4.*At/pft
        drel=D1/Dt
c XX factor for bundle pressure correlation
        XX=At/(24.*A1+12.*A2*(D2/D1)**0.714+6.*A3*(D3/D1)**0.714)
c geometry of fuel rod:
        Rr=0.01*drod/2.
        Rcl=Rr-(dclad+dliner)*0.01
        Rp=Rcl-0.01*dHe
c
c d,Rr,Rc,Rp(meter) are diameter and radius of rod,internal radius of
c clad+liner and radius of pin
c
c distribute flow in cell types according to area
        flow1=flow*24.*A1/At
        flow2=flow*12.*A2/At
        flow3=flow*6.*A3/At
c estimation of delta p across bundle
c
        Gt=0.001*flow/At
c viscosity at average conditions
        p=pin*1.e+6
        call pli(h,p,tin,rhoi,visi,cp,pr,k,x,0)
        vein=Gt/rhoi
        call pli(h,p,tout,rhoo,viso,cp,pr,k,x,0)
        veout=Gt/rhoo
        t=0.5*(tin+tout)
        call pli(h,p,t,rhoa,visa,cp,pr,k,x,0)
        Rea=Dt*Gt/visa
        frica=fri(Rea)
        vea=Gt/rhoa
        facfra=rhoa*Vea**2*frica*Pft/2.
        deltapa=Gt*(veout-vein)+facfra*Hact/At
        if(iop.eq.1) return

```

```

c
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
12    format(a80)
    write(8,21) TLim,tin,drod,Powt,nrod,Nbu,nrodbu,flowt,Vact,fact
21    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/
* 'Active Volume(L of UN)',f10.3/
* ' Factor that multiplies Power',f10.7//)
    write(8,162)roav,Hact
162    format('Average Power Density(Mw/L(UN))',f8.4,' Channel Length(cm)
* ',f7.2/)
    Alc=A1*10000.
    A2c=A2*10000.
    A3c=A3*10000.
    Atc=At*10000.
    Alcr=Alc/0.5
    A2cr=A2c/0.5
    A3cr=A3c*6.
    Atcr=Atc/19.
    pflc=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
190    format(// 'FLOW CONDITIONS:' //
* ' Pitch/drod',f8.3,' Lead wire spacer/drod',f8.3//
* 'Cell Type (per bundle) ',11x,'1',11x,'2',11x,'3',6x,'Bundle'//)
    write(8,191) n1,n2,n3,flow1,flow2,flow3,flow,
*      f1,f2,f3,ft,
*      Alc,A2c,A3c,Atc,
*      Alcr,A2cr,A3cr,Atcr,
*      pflc,pf2c,pf3c,pftc,
*      d1c,d2c,d3c,dtc,
*      XX,drel
191    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,' Del/DT=',f6.3//)
    if(iboun.eq.1) write(8,237) tout
    if(iboun.eq.2) write(8,238) tout

```

```

237  format(' Boundary Condition: Fix coolant flow; Temp. outlet',f8.2)
238  format(' Boundary Condition: Fix outlet flow temperature',f8.2)
    flow=0.001*flow
    Gt=flow/At
    flow1=0.001*flow1/24.
    flow2=0.001*flow2/12.
    flow3=0.001*flow3/6.

c
c
c Pfraz : Power factor radial-azimuthal
    Pfraz=1.
    if(iopth.gt.2) Pfraz=Pfacr*Pfacaz
c
c recompute flow according to option
c
    if(iopth.eq.4) flow=flow*Pfraz
c.
c
    Hext=Hact+2.*Daxi
    we=Hext/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
182  z(i)=zzzz-Daxi
c
c
c z(i) (cm) boundaries of the nodes
c
c
    if(iopth.eq.1) write(8,1264)
1264 format(' 3-D UNIFORM POWER DISTRIBUTION ASSUMED'//)
c
    if(iopth.eq.2) write(8,1266)
1266 format(' 2-D (R-THETA) UNIFORM POWER DISTRIBUTION ASSUMED'//)
c
    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)
c
c
c
    if(iopth.eq.4) write(8,1293)
1293 format(' Coolant Flow Proportional to Power Density'//)
c
    if(iopth.ne.4) write(8,1295)
1295 format(' Uniform Coolant Flow Assumed'//)
c
c
c
c End calculation coolant conditions
c
c
c transform pow(i) (Mw/L) to power per unit length (watt/cm)
c PER ROD
    facto=1.e+7*pee*Rp**2
    do 123 i=1,npu
123  pow(i)=pow(i)*facto
c
c z(i) (cm) boundaries of the nodes
ci
c
c
    if(ifri.ne.1) write(8,23)

```

```

23   format('  friction was assumed zero'//)
c
c
c
c
      write(8,253) pin
253  format('// AVERAGE CONDITIONS IN THE BUNDLE'/
      '*****'
      '***** Inlet Press(MPa)',f9.6,' *****'/
      '*****'
      '////)
      write(8,31)
31   format(
      ' Node      z(cm) Po(w/cm)    Pr(KPa)    T(K)    (Tsat)    V(m/s)    Re')
c
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,0)
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
      frici=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=Tsa(pre)
      write(8,41) i,z(i),pow(1),pre,tbulk(i),Ts,ve(i),Re
      facfr=0.
c
c
c start analysis bulk conditions
c
c
c change units for the flow in each type of cell
      dt1m=0.
      dt2m=0.
      dt3m=0.
      isat=0
      coeRe=coefri
c
      do 30 i=2,npu
      dz=z(i)-z(i-1)
c po is # of watts per rod in dz
      po= 0.5*(pow(i)+pow(i-1))*dz
      echannel=echannel+po*19.
c toutlet 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,1)
      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,1)
      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,1)
      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,1)
      tbulk(i)=T
c remember max T of cells
      dt1=T1-T
      if(abs(dt1).gt.dt1m) i1m=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-1)*rhoi/rho
c compute pressure
      Re=Dt*Gt/vis
      if(ifr1.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
      dz=0.01*dz
      pres(i)=pres(i-1)-Gt*(ve(i)-ve(i-1))-facfr*dz/At
      rhoi=rho
      frico=frici
      pre=pres(i)*1.e-03
      Ts=Tsa(pre)
      if(i.eq.npu.or.iprth.eq.1)
*write(8,41) i,z(i),pow(i),pre,tbulk(i),Ts,ve(i),Re
      if(Ts.le.T1) isat=1
30   continue
      coeRe=coeRe/npu
c
c end t bulk calculations
c
41   format(i4,2f8.2,f10.2,f8.2,'(',f8.2,')',f8.2,f8.0)
      T1=T+dt1m
      T2=T+dt2m
      T3=T+dt3m
      p1=psa(t1)
      p2=psa(t2)
      p3=psa(t3)
      delp=p1-psa(T)
      write(8,360) i1m,dt1m,t1,p1,i2m,dt2m,t2,p2,i3m,dt3m,t3,p3,delp,coe
*Re
360  format(' Thermodynamics Conditions of Cells'/
*      'Cell Type      z Node      Max(T-<T>)      T Saturation P(kPa)'/
*      '      '      1',i9,3f12.2/
*      '      '      2',i9,3f12.2/
*      '      '      3',i9,3f12.2//
*      ' Delta pressure(KPa) because T1>T(average)',f10.2//
*      ' <c> in f=c/Re**0.25 is',f10.5//)
c
c Check If reactor is underpressurized ,isat=1
c , if yes write warning

```

```

c      if(isat.eq.0) go to 350
      write(8,351) T1,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(ichoose.eq.1) stop
2515  write(8,2516)
2516  format(//
*   *****
*   ***** WARNING *** WARNING *** WARNING *****
*   *****
*   Despite previous caveats, Program continues with nominal values'//
*)
350  continue
c
c calculation wall temperature and rod temperatures for MAX HEATED ROD
c IN bundle which is type 1 cell
c
c Initialization of function RNu
      Dummy=RNu(Re,1.,1,pod)
      dg=dHe*0.01
      G1=flow1/a1
c
c loop on z nodes
c
      have=0.
      TTa=0.
      TUN=0.
      do 302 i=1,npu
      p=pres(i)
      t=tbuma(i)
c
c SEE: we have chosen the highest T (cell 1) Tbuma(i)
c
      call pli(h,p,t,rho,vis,cp,pr,k,x,0)
      Re=G1*D1/vis
c define Peclet number
      Pe=Re*Pr
      RNus=RNu(Re,Pe,0,pod)
      hco=RNus*k/Dt
      have=have+hco
c rjq=watt/m2
      rjq=pow(i)*100./((pee*0.01*drod)
c rj(i)=Kw/cm2
      rj(i)=rjq*10.**(-7)
c Qh=watts/m3
      Qh=100.*pow(i)/((pee*Rp**2)
      Tw(i)=T+rjq/hco
c From Twa to Tfuel
c Clad+liner
      cclad=Rkclad(Twa)
c See only one node for the clad
c
      Tclad(i)=Tw(i)+rjq*Rr*alog(Rr/Rcl)/cclad
      Tclaa(i)=Tw(i)+rjq*Rr*(0.5-alog(Rr/Rcl)*Rcl**2/(Rr**2-Rcl**2))/
      *cclad
      if(Tclad(i).gt.TTa) TTa=Tclad(i)
c delta T across He gap

```

```

      Tg=Tclad(i)
      hg=Rkgap(Tg,dg)
      Tgap=Tclad(i)+rjq/hg
c temperatures inside pin , npin nodes
      dr=Rp/npin
      Tinl=Tgap
      rinl=Rp
      Tfa=0.
      do 3021 in=1, npin
      Cfuel=RkUN(Tinl)
      rout=rinl-dr
      Tout=Tinl+0.25*Qh*(rinl**2-rout**2)/Cfuel
      Tfa=Tfa+0.5*(Tout+Tinl)*(rinl**2-rout**2)
      Tinl=Tout
      rinl=rout
3021 continue
      Tfuel(i)=Tout
      if(Tout.gt.TUN) TUN=Tout
      Tfua(i)=Tfa/Rp**2
302 continue
      have=have/(10000.*npu)
c
c end loop on z nodes pin
      drd=10.*drod
      dcl=(dclad+dliner)*10.
      deHe=1000.*dg
      dpin=drd-(dcl+deHe)*2.
      write(8,978) drd,dcl,deHe,dpin
978 format(/// ' From the Coolant Channel to fuel pin temperature' /
      *' Rod Diameter(mm):',f8.4/
      *' Clad+Liner Thickness( "):',f8.4/
      *' He gap " ( "):',f8.4/
      *' Fuel Pin Diameter ( "):',f8.4//
      *' CONDITIONS FOR MAX HEATED ROD OF THE BUNDLE(Type 1 cell)')
      write(8,976)
976 format(/// ' Node z(cm) J(Kw/cm2) Twall(K) Tclad(K) TcladAv
      * Tfuel(K) TfuaAv '///)
      do 2583 i=1,npu
      if(i.eq.1.or.i.eq.npu.or.iprth.eq.1)
      *write(8,977)i,z(i),rj(i),tw(i),Tclad(i),Tclaa(i),Tfuel(i),Tfua(i)
2583 continue
977 format(i5,f10.2,f10.5,5f10.2)
c
c calculation of axial averages
c
      if(TTa.ge.TmTa.or.TUN.ge.TmUN) write(8,2633) TTA,TUN,TmTa,TmUN
2633 format(
      *'*****WARNING*****WARNING*****WARNING*****' /
      *'*****WARNING*****WARNING*****WARNING*****' /
      *'*****WARNING*****WARNING*****WARNING*****' //
      *'Max. Temp(K) clad is',f9.2,' Max. Temp(K) UN is',f9.2/
      *' Ta melts at(K) ',f9.2,' UN melts at(K) ',f9.2/
      *' Relax inlet, outlet conditions or assume uniform power or' /
      *' flow grading'//)
      zav=0
      thav=0.
      phav=0.
      twa=0.
      tca=0.
      tfa=0.
      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=tw+0.5*(tw(i)+tw(i-1))*dz
      tca=tca+0.5*(tclaa(i)+tclaa(i-1))*dz
      tfa=tfa+0.5*(Tfua(i)+Tfua(i-1))*dz

```

```

thav=thav+0.5*(tbulk(i)+tbulk(i-1))*dz
1436 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
1486 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
987 format(// ' HEAT BALANCE FOR THE BUNDLE' //
* ' dq: heat to coolant (joule/kg)',e14.5/' dH: change of enthalpy
1(joule/kg)',e14.5/' dKin change kinetic energy(joule/kg)',e14.5/
2' relative dKin/dQ',f10.6/' Balance (dH+dKin)/dQ',f14.7)
return
end

```

```

c
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
end

```

```

c
c
subroutine bisect(x1,x2,xav,f1,f2,fav,iwa)
if((f1*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
x1=xav
return
10 f2=fav
x2=xav
return
end

```

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,C1)
      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.-1.82/(Pr*eon**1.4)
    if(psi.lt.0.) psi=0.
    RNu=C1+C2*(psi*Pe)**al
    return
  end

c
c Function: Thermal Conductivity of UN
c Source: Alkasys Manual
c
  Function RkUN(Te)
c
c T(K) RkUC (watt/mK)
c
  RkUN=24.
  Return
  End

c
c
c Function: Thermal Conductivity of He gap
c Source: Alkasys Manual
c
  Function Rkgap(T,d)
c
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
c
c Function: Thermal Conductivity of Astar clad and W liner
c Source: Alkasys Manual
c
  Function Rkclad(Te)
c
c T(K) RkUC (watt/cmK)
c
  Rkclad=57.
  Return
  End

```

```

c Subroutine: Interpolate Table
c
      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
11    continue
      if(x(i).gt.xi) go to 12
      i=i+1
      go to 11
12    continue
      go to 30
10    i=2
      go to 30
20    i=np
30    yi=y(i-1)+((y(i)-y(i-1))/(x(i)-x(i-1)))*(xi-x(i-1))
      return
      end

c
c Properties of Li
c
      subroutine pli(h,p,t,rho,vis,cp,pr,rk,x,iflag)
c2345678901234567890123456789012345678901234567890123456789012
c Thermodynamic and Transport Properties of Lithium
c from "Lithium Literature Review:Lithium's Properties and Interactions"
c HEDL-TME 78-15, April 1978.
c
c SI units, T(K)
      x=1.
c
c go to 10 if iflag=1 (ie input is p,h)
c
      if(iflag.ne.0) go to 10
c density rho
1    rho=0.515-0.000101*((T-273.15)-200.)
c from g/cm3 to Kg/m3
      rho=rho*1000.
c enthalpy h
      h=-5.075+1.0008*(T-273.15)-5173./(T-273.15)
c from cal/g to Joules/Kg
      h=h*4186.8
c specific heat cp
      cp=4186.8*(1.0008+5173./(T-273.15)**2)
c viscosity vis
      vis=726.07/T-1.3380
      vis=10.**(vis)
c from centipoise to N/M2sec
      vis=0.001*vis
c heat conductivity rk
      rk=9.59+0.00455*(T-273.15)
c from cal/sec-m-C
      rk=rk*4.1868
c Prandtl number
      pr=vis*cp/rk
      return
10    continue
c
c find T from h
c
      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

```

```

c
c ***** DESIGN STRENGTH SUBROUTINE *****
c Calculation of the Stress that Astar alloy can stand
c subroutine from Alkasys
c 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
c subroutine desstr(tt,n,fpl,sigpv,sigrod,itma,ipr)

real tt,nr,tmat,fpl,sigpv,sigrod,rho
real b,c,v,sigma,theta,thet,dtds
data tmat/1100./
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
do ll=1,n
if (ll.eq.1) then
thet=fpl*8766.139
else
thet=fpl*8766.139/2.
endif
sigma=1000
theta=1/c*exp((b-nr*log(sigma)-v*sigma)/tt)
ite=0
dowhile ((abs((theta-thet)/thet)).gt.0.001)
dtds=-theta*(nr+v*sigma)/sigma/tt
sigma=sigma+(thet-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

```

```

c
c function to compute thickness neutron shielding

```

```

c      Function Shieldn(fluin,fluout,ish,tw,igam)
c      common /cross/ AA,BB,signe,ishin,ishig
c
c      Fluin,fluout, fast fluxes in/out; ish=1, LiH+SS
c      ish=2, B4C; tw(cm) gamma shielding (Tungstene)(if igam.ne.0)
c
c      data remLi,remH,remFe,remW,remBC
c      *      /1.01,1.00,1.98,3.13,5.1/
c      removal cross section for fast neutrons of Li,H,Fe,W,B4C
c
c      data Av,roLiH,roW,roBC,roFe,roLiss,ALiH,AFe,ABC,AW
c      *      /0.602202,0.82,19.3,2.52,7.874,1.024,7.95,55.85,55.26,183.85/
c      sigW=remW*Av*roW/AW
c      ishin=1
c      go to(10,20),ish
10     xLiH=(roLiss-roFe)/(roLiH-roFe)
c      xFe=1.-xLiH
c      sigre=(remLi+remH)*Av*roLiH*xLiH/ALiH+remFe*Av*roFe*xFe/AFe
c      go to 30
20     sigre=remBC*Av*roBC/ABC
30     aa=log(fluin/fluout)/sigre
c      if(aa.le.0.) ishin=0
c      bb=sigW/sigre
c      signe=sigre
c      Shieldn=aa-bb*tw
c      return
c      end

c
c      Subroutine to calculate Gamma source
c
c      Subroutine Gamso(Sn,sogam,PrU,fvr)
c      common /Conce/ coBe,coTa,coU5,coU8,coLi,coW,coRe,coHf,coHe,coN,coO
c
c      Input: Sn(1/s): neutron production,fvr: volume fraction of reflector
c      Output:
c      sogam(1): Gamma source between "0" and 1 Mev
c      (2): 1 and 2
c      (3): 2 and 3
c      (4): 3 and 5
c      (5): 5 and 7
c      (6): 7 and 9
c      (7): > around 9 Mev
c      and PrU(): fractions of gammas produced in U
c      Dimension Sogam(7),Pf(7),Fp(7),GLi(7),GO(7),GTa(7),GBe(7),
c      *GU(7),GRe(7),GHf(7),GW(7),GN(7),PrU(7)
c
c      Pf: Prompt Fission Gammas; Fp: Fission Products Gammas(Both, Per Fiss)
c      GNi to GCr:Captures Gammas(per Event) for indicated Elements Ni,..Cr
c      Data from ANL-5800 page 631. For O: the 8 Mev released for the capture
c      of one neutron was uniformly distributed in range 0-10 Mev.
c      See:capture in O is almost 0.0; Remember B10 has (n,alpha) rather(n,g)
c      Data(Pf(i),i=1,7)/3.1,2.11,.73,.26,.0428,0.,0./
c      Data(Fp(i),i=1,7)/9.03,1.137,.4,0.,0.,0.,0./
c      Data(GLi(i),i=1,7)/0.,0.,0.,0.,0.4,0.6,0./
c      Data(GTa(i),i=1,7)/1.37,0.99,0.66,0.55,0.05,0.,0./
c      Data(GW(i),i=1,7)/0.68,0.82,0.59,0.53,0.15,0.005,0./
c      Data(GRe(i),i=1,7)/1.24,0.88,0.62,0.51,0.105,0.,0./
c      Data(GHf(i),i=1,7)/1.37,1.37,0.85,0.52,0.12,0.005,0./
c      Data(GN(i),i=1,7)/0.0,0.,0.,0.54,0.11,0.15,0.12/
c      Data(GO(i),i=1,7)/0.16,0.16,0.16,0.32,0.32,0.32,0.16/
c      Data(GBe(i),i=1,7)/0.,0.,0.,.54,.73,.0,.0/
c      Data(GU(i),i=1,7)/2.54,1.78,.91,.34,.0,.0,0.041/
c      Data Rnu/2.52/
c      Data scLi,scTa,scW,scRe,scHf,scN,scO,scBe,scU5,scU8

```



```

      */0.000024,0.3,0.25,0.5,0.5,0.0002,0.0,0.0,0.2246,0.1613/
      Data sfU5,sfU8/1.4400,0.11201/

c
c See: Total number of Absorptions= Sn(Total production)
c F: total number of fission
c F5: " " " in U235
c F8: " " " in U238
c C5: total number of captures in U235
c C8: " " " in U238
c 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

c
c distribute Ct in rest of materials
c assume average flux in core,pressure vessel and half that flux for the
c reflector, then disadvantage factor are
c
      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)+disr*(coO*scO+coBe*scBe)
      CLi=Ct*(coLi*scLi*disc/den)
      CTa=Ct*(coTa*scTa*disc/den)
      CW=Ct*(coW*scW*disc/den)
      CRE=Ct*(coRe*scRe*disc/den)
      CHf=Ct*(coHf*scHf*disc/den)
      CN=Ct*(coN*scN*disc/den)
      CO=Ct*(coO*scO*disr/den)
      CBe=Ct*(coBe*scBe*disr/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)
10  continue
      return
      end

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

c
c Shieldga: Computes gamma shielding
c Sogam(i),i=1,7 Gamma Source (photons/sec); Dose(rad): Integrated
c Dose at load area; Dosew(rad): Dose without the shielding
c Dosea: dose for tgam
c igam:flag if =1 problems with iterations
c Tgam(cm): Thickness of Tungsten
c ten(cm) thickness of n shielding, ishn=1, LiH, ishn=2, B4C
c iten/0,1/ /ten is input,ten is iterated by this subroutine/
c tgam:iterated,if necessary,to have Dose=input
c Index(1): Gamma Processes between "0" and 1 Mev
c (2): 1 and 2
c (3): 2 and 3
c (4): 3 and 5
c (5): 5 and 7
c (6): 7 and 9
c (7): > around 9 Mev
      common /Conce/ coBe,coTa,coU5,coU8,coLi,coW,coRe,coHf,coHe,coN,coO

```

```

common /Gamsh/
*dist,Req,shg(7),shgnb(7),Zeq(7),Dosewg(7),Doseg(7),itmag,epsq
*,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),a1(4),a2(4),rh(7)
*,ega(7),sign(7),An(7),Aln(7),A2n(7)

c
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,.0194/
data (GFe(i),i=1,7)/.0828,.0485,.0424,.033,.0304,.0295,.0294/
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
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)

c
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/

c
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/

c
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/

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

c
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)

c
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
c rh(i) Gamma Flux Mev/cm2sec that produces 1 Roentgen/hour

c
data (Ega(i),i=1,7)/0.5,1.5,2.5,4.,6.,8.,10./

c
c ega(i) Mev Average Energy of gamma group i

c
data ABe,ATa,AW,AO,AHf,AU5,AU8,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,ZW,ZU,pee,ZLi,ZBo,ZRe,ZHf,ZN,ZO
*/4.,73.,74.,92.,3.141593,3.,5.,75.,72.,7.,8./

c
data roLiH,roBC,roSS,roLiS /0.82,2.92,7.874,1.024/
igam=1
ishig=1
xLiH=(roLiS-roSS)/(roLiH-roSS)
xSS=1.-xLiH

c
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
        go to 333
c ish=2 B4C
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
c ZZ is "equivalent Z for buildup factor
333  do 444 i=1,4
        a(i)=b(i,j)
        al(i)=a3(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,al,4,zz,al1)
        Call Inter(zb,a2,4,zz,al2)
        An(j)=am
        Aln(j)=-al1
        A2n(j)=al2
        sign(j)=sig
101  continue
c end Calculation Attenuation/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
        a(i)=b(i,j)
        al(i)=a3(i,j)
20  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)          +coU8*AU8*GU(j)
        * +coRe*ARE*GW(j)          +coLi*ALi*GBe(j)          +coW*AW*GW(j)
        * +coN*ANi*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*ANi*GO(j)*ZO
        ZZ=ZZ/Av
        zz=zz/sig
        Call Inter(zb,a,4,zz,am)
        Call Inter(zb,al,4,zz,al1)
        Call Inter(zb,a2,4,zz,al2)
        Zeq(j)=zz
        b1=2.*sig*Req*(1.-al1)
        b2=2.*sig*Req*(1.+al2)
        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
c End Calculation Self shielding
c
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-

```

```

c ted
  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)
    Dosew=Dosew+Dosewg(i)
30   Dosen=Dosen+Doseng(i)
    if(Dosen.le.Dose) ishig=0
    if(ishig.eq.0) tgam=0.
    if(ishig.eq.0) return
c
c Return if there is no need for gamma shield (thick W=0.)
c
  t1=0.
  Dose1=Dosen
  f1=Dose1-Dose
c
c Starts iteration on tgam:
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  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(-al1*sig*t2)+(1.-am)*exp(-al2*sig*t2)
40  dose2=dose2+Dosewg(i)*exp(-sig*t2)*BFA
    if(dose2.lt.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'
50  continue
    f2=Dose2-Dose
    if(igam.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(-al1*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 lt 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
41  dosea=dosea+Doseg(i)
c  recompute n shielding, because it might be smaller than input max flu-
c  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(t1,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

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
c
      Subroutine Size(das,dop,E,enr,pod,d1,d2)
c
      common /Soze/ its,epss
c
      common /MaBaSi/ R,H,ishape
c
c  left side limit
c
      ri=1.
      it=0
10  x1=das*(1.+0.01/ri)
      if(ishape.eq.2) R=x1
      if(ishape.eq.3) H=x1
      e1=Balance(ibu,enr,pod)-E
      if(e1.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
30  it=0
35  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 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
      go to 35
50  d1=xav
c
c  right side limit
c
      x1=dop
      if(ishape.eq.2) R=x1

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        if(ishape.eq.3) H=x1
        E1=Balance(ibu,enr,pod)-e
21      it=0
41      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(x1,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=',i10/)
        stop
        end

c
c Subroutine bupo
c
c      Subroutine bupo(bup,rkin,c50,c80,dka)
c      common /mabu/ c5,c8,c9,p9,cfp,ftin
c
c input: bup(burnup,fraction),rkin(k Infinity),c50,c80(1/cmbarn) initial
c concentration of U235 and U238
c
c output: dka(% , and modulus) reactivity effects of burnup
c
c c5,c8,c9,cfp, concentrations(U235,U238,Pu239 and Fission Prod) at EOL
c ftin: fluence at EOL, p9: total production of Pu239
c      dimension flutin(20),buta(20)
c      data rnu5,rnu8,rnu9/2.52,2.61,2.91/
c      data sa5,sa8,sa9,safp/1.6646,0.2733,2.11,0.57/
c      data sf5,sf8,sf9/1.4400,0.11201,1.70/
c      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=sc8*(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*(1.-exp(-sa5*ftin))+(A8+A9*A91)*(1.-exp(-sa8*ftin))-
        *      A9*e9*(1.-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)

```

```

c9=(sc8*c80/(sa9-sa8))*(exp(-sa8*ftin)-exp(-sa9*ftin))
p9=(c80-c8)*sc8/sa8
c
cfp=2.*(c50*sf5+c80*sf8)*ftin
cfp=2.*((c50-c5)*e5+(c80-c8)*e8+(p9-c9)*e9)
rkinbu=(rnu5*c5*sf5+rnu8*c8*sf8+rnu9*c9*sf9)/
*      (c5*sa5+c8*sa8+c9*sa9+cfp*safp+srest)
dka=rkinbu/rkin-1.
dka=-100.*dka
return
end

```


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