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**CALIOP
A MULTICHANNEL DESIGN CODE FOR GAS-COOLED
FAST REACTORS
CODE DESCRIPTION AND USER'S GUIDE**

**by
W. I. THOMPSON**

**Work prepared under
Contract DE-AT03-76SF71023
for the San Francisco Operations Office
Department of Energy**

DATE PUBLISHED: OCTOBER 1980

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Pirt Royal Road
Springfield, Virginia 22161
NTIS Price Code: Printed Copy A06; Microfiche A01

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GENERAL ATOMIC PROJECT 6113
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ABSTRACT

CALIOP is a design code for fluid-cooled reactors composed of parallel fuel tubes in hexagonal or cylindrical ducts. It may be used with gaseous or liquid coolants. It has been used chiefly for design of a helium-cooled fast breeder reactor and has built-in cross section information to permit calculations of fuel loading, breeding ratio, and doubling time. Optional cross-section input allows the code to be used with moderated cores and with other fuels.

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1. GENERAL DESCRIPTION

The CALIOP program is a generalization of the GAZELLE code (Ref. 1-1), which was written originally for rapid exploration of fast gas-cooled reactors. In its present form, the program may specify a reactor in terms of number of fuel elements, rod diameter, number of rods per element, core length, blanket thickness, and reflector thickness. The following principal options are available:

1. Determine maximum power level with fixed input geometry and core pressure drop.
2. Determine pressure drop required for a fixed geometry and power level.
3. With fixed pressure drop, determine lattice spacing and outlet temperature for a given power level.
4. With fixed pressure drop and fixed outlet temperature, determine lattice spacing and core length for a given power level.
5. With fixed pressure drop and fixed rod rating (kW/ft), determine lattice spacing and core length for a given power level.
6. With fixed pumping power, determine lattice spacing for a given power level.

Radial power distribution and fuel element flux tilts in the core can be calculated by the code, or they can be directly entered as input based on physics information. Fuel enrichment at beginning of equilibrium cycle and

burnout during the cycle are calculated by the code with the input requirement of end of cycle reactivity. This makes possible a calculation of breeding ratio (including Pu-241 decay and other losses) and doubling time.

CALIOP is used, like the original GAZELLE code, to screen many design proposals to arrive at a reference design basis. Sufficient information is available from a CALIOP run, including operating and room temperature dimensions, to form a basis for detailed mechanical and thermal design and neutronic performance analysis. Gas flows, temperatures, and pressure drops are used as a basis for detailed balance of plant studies.

It is possible to make a follow-on run with CALIOP with element powers representing the end of equilibrium cycle conditions, but holding orifice settings at the initial values. Under this condition, if total core power and outlet temperatures are maintained at initial values, some of the element maximum cladding temperatures will be higher than initial values and some will be lower. These results can be used to set individual element maximum temperatures at the start so that none will exceed this limit at the end.

The reliability of the CALIOP code depends on the use of well-established design methods for thermal-hydraulic analysis (COBRA) and for neutronic analysis. Results from COBRA calculations for a single fuel element have been used to correct for the effect of multichannel treatment of flow distribution and cross flow. The physics treatment is straight-forward but depends on input values of one-group cross sections. Since these numbers depend on the core geometry and composition, it is necessary to derive them from 2DB (Ref. 1-2) calculations of similar systems. Preliminary results indicate that CALIOP and 2DB yield similar results if the one-group cross sections are equal.

REFERENCES

- 1-1. Fortescue, P., "GAZELLE-V - A Code for the Thermal Design of Homogeneous Gas-Cooled Reactors (Particularly Fast Reactors)," USAEC Report GAMD-6754, General Atomic Company, December 1, 1965.
- 1-2. Little, W. W., Jr., and R. W. Hardie, "2DB User's Manual - Revision 1," Battelle Northwest Laboratory Report BNWL-831, Rev. 1, 1968.

2. CRITICALITY CALCULATIONS

The subroutine VFRAC (Ref. 2-1) is used to calculate the critical core enrichment for a given core geometry or to calculate the critical multiplication factor (CAYDES) for a given enrichment. The calculation is activated by the option ICRIT:

ICRIT

2	Modify fuel enrichment
3	Modify value of CAYDES

Subroutines VFRAC1 and VFRAC2 carry out the calculations for ICRIT = 2 and 3.

With the aid of subroutine BURNUP, CALIOP will determine the core critical loading and reactivity change during burnup. The code proceeds by making two runs. The first run determines the beginning of equilibrium cycle (BOEC) fission product content and approximate reactivity changes during the cycle. The second run uses an adjusted beginning of cycle K, chosen to make the final K-effective equal to the desired value (CAYSTR on card 6). The blanket content of fissionable material is also corrected for breeding and burnout, and the content is adjusted to BOEC conditions. Equilibrium cycle conditions are based on replacing a fixed fraction of the core (FPROC on card C) and a fixed fraction of the blanket (FPROC* RECYC, card D) at each refueling interval.

Cross-section information for the nuclear calculations is provided on cards 33 and 34. Numerical values for one group cross sections may be obtained by 2DB runs on the same geometry or by MICROX-2 runs (Ref. 2-2) with the same lattice configuration, or the code built-in values may be used by setting ICROSS = 0 on card 30.

The information from the nuclear calculations is used in subroutine CYC2 to calculate the doubling time and the ratio of total power (including blankets) to core-only power.

The accumulation and burnup of Pu-239 in the blanket can be ignored by setting LAST (card 10) equal to 5. This option was included to analyze the calculation method. The effect on nuclear performance is small because of counterbalancing features. Recognizing the extra fissionable material in the blanket reduces the critical mass slightly. Accounting for the burnup reduces the net production of Pu-239.

REFERENCES

- 2-1. Davison, W., "VFRAC, A Self-Contained, Monoenergetic, Two-Dimensional Diffusion Theory Subroutine," General Atomic Company, unpublished data, August 1969.
- 2-2. Mathews, D., and P. Koch, "MICROX-2, An Improved Two-Region Flux Spectrum Code for the Efficient Calculation of Group Cross Section," DOE Report GA-A15009, General Atomic Company, December 1979.

3. RADIAL BLANKET CALCULATIONS

The subroutine BLANKT has been modified to perform a parallel flow design, using option IBLANK = 2 (card 10ab). Rod powers are calculated using the input TILTB tilt factor on flux. However, gas temperature rise (without hot channel factor) uses a modified tilt factor, TILTBE (card 11a), to account for flow cross mixing. Input is also provided (card 11a) for blanket hot channel and hot film factors. The degree of overcooling of the blanket element is set by RISEF (card 10ab), which is the ratio of radial blanket mixed-mean temperature rise to core mixed-mean temperature rise. This information is used in subroutine OUTPTB to correct the reactor outlet temperature for this overcooling.

The thermal constants for the blanket are input as follows:

<u>Names</u>	<u>Card No.</u>	
RATIOP	8	Ratio of total power to core-only power
POWRAT	13	Ratio of power in maximum-powered blanket element to average blanket element power in first blanket row
TILTB	13	Flux maximum to average across blanket element
FCB	16	Blanket hot channel factor (parallel flow)
FFB	16	Blanket hot film factor (parallel flow)
TILTBE	16	TILT corrected for cross-mixing
AXRAT	16	Ratio of axial blanket power to radial blanket power
EPSAB	16	Blanket axial maximum to average flux
FRACT	12	Fraction of blanket heat released in first rows.

The value of TILTB is used to estimate the fraction of the radial blanket power which is developed in the first row of elements. The performance of the plant is computed for BOEC blanket power. The extra temperature degradation at the start because of low initial blanket power is printed as a footnote in the first page of output.

4. HEAT TRANSFER AND PRESSURE DROP DESIGN

The general treatment of hydraulics and heat transfer is described in Appendices A through E.

The CALIOP code is constantly updated to use the best current information. Benchmark studies in cooperation with the Nuclear Research Center in Karlsruhe and the Swiss Federal Institute for Reactor Research are used as a basis for selecting Stanton numbers and friction factors in the roughened region of the core. Since the code treats a complete fuel element as a single passage, corrections are applied for pressure drop and cross-flow mixing based on COBRA multi-subchannel calculations. Detailed information on element geometry beyond the core and blanket (e.g., shielding, traps) is incorporated by the use of corrected values for inlet and outlet losses (CINL and COUTL on card 5).

5. RADIAL PEAKING FACTOR

The radial power peaking distribution is handled in different ways, depending on options.

The normal method is to use the flux distribution produced by the nuclear calculations (VFRAC) together with the radial fissile density distribution (as optimized by VFRAC) to produce the local power density and power tilt across an element.

This method may be improved by specifying the loading sequence for each channel and the equilibrium cycle change in fissile density for each channel. This detailed difference in local power density is used to modify the homogeneous distribution.

Finally, an input parameter, FPEAK, can be used to exaggerate the individual differences between the local power and the core average power.

The above methods are used in the absence of detailed power and tilt information from physics codes, such as GAUGE. If such information is available, the radial powers and flux tilts may be input directly to the code and will not be modified.

6. RUNNING FOLLOW-ON CASES

By means of extra cards placed at the end of the input deck, extra cases can be run with selected parameters changed. For each extra case, there should be one data card for each parameter being changed. A blank card ends the data input for each extra case. Each data card has a two-digit number indicating the variable to be modified and the new value of the variable. Format is I2, E18.2. Any number of variables can be changed from one run to the next. The variables are given in Table 6-1.

TABLE 6-1
UPDATED VARIABLES

<u>No.</u>	<u>Variable</u>
1	Q, core cladding o.d./i.d. ratio
2	XM, core reflector savings, cm
3	XB, core blockage ratio
4	PO, pressure, atm
5	XLf, axial blanket length, each end, cm
6	V, core volume, liters
7	Z, core L/D ratio
8	TO, core inlet temperature, °C
9	DT, core temperature rise, °C
10	PDR, core pressure drop ratio
11	RATIOp, ratio of total power including blanket to core-only power
12	ETA1, core Stanton multiplier
13	ETA2, core friction multiplier
14	TMAXL, core maximum mid-cladding temperature, °C
15	BLKTK, blanket thickness, cm
16	CYADES, core neutron multiplication constant
17	VFB, fuel volume fraction in blanket
18	ROWB, number of rows of rods in blanket element
19	QB, blanket rod o.d./i.d. ratio
20	PASS, number of flow reversals in blanket (for cross flow)
21	POWRAT, ratio of maximum power to beginning of cycle power in blanket
22	XBB, blanket blockage fraction (reset in subroutine HEXX)
23	TILTB, flux tilt across blanket element (maximum to average)
24	DEAD, number of structural rods per element
25	RISEF, ratio of blanket temperature rise to core mixed-mean temperature rise
26	CRN, number of control rods
27	ROWS, number of rows of rods in a fuel element

TABLE 6-1 (Continued)

<u>No.</u>	<u>Variable</u>
28	FCB, blanket hot channel factor
29	FFB, blanket hot film factor
30	TILTBE, blanket flux tilt factor corrected for bundle cross mixing
31	CDV, fuel rod o.d., cm (hot)
32	DRAT, multiplier to be applied to input fuel fissionable density
33	VOLIN, core fuel volume fraction
34	FCIN, hot channel factor
35	FFIN, hot film factor
36	FPIN, fuel peaking factor
37	EPS, fuel rod roughening height, cm
38	ICRIT
39	TPS, thermal power, MW
40	EFFX, thermal efficiency fraction
41	QKWF, rod maximum, kW/ft
42	SHIFT, fractional displacement of axial symmetry
43	AXRAT, ratio of total to core power
44	IGEOM, performance option (see Table 8-1)
45	INDENT, roughening geometry option
46	EL, core length
47	IORIF, orifice option
48	TT2, desired reactor outlet temperature, °C
49	IBURN, burnup option
50	IPCHAN, channel data punching option
51	ITML, option to specify individual channel maximum clad temperature
52	IPRINT, output printing option
53	BGAPR, ratio box gap to box o.d. across flats
54	RPITCH, rod pitch, cm
55	CP, coolant heat capacity
56	XMW, coolant molecular weight
57	SKEW, peaking due to control rod motion

TABLE 6-1 (Continued)

<u>No.</u>	<u>Variable</u>
58	IFRACP, option to input FRACP
59	ITILT, option to input TILT
60	TI, reactor inlet temperature, °C

7. REACTOR GEOMETRY

Reactor geometry is completely specified by the following parameters:

Core and Axial Blanket

CDD(I)	Rod o.d. (for diameters for volume fraction zoning), cm
ROWS	Number of rows of rods per fuel element
GBR	Ratio of rod-wall spacing to rod-rod spacing for fuel
RPITCH	Fuel rod pitch, cm
DEAD	Number of structural rods per element
DISPL	Number of fuel rods displaced by control rods in a control element
EL	Active core length, cm
XLF	Axial blanket length, each end, cm
BOXI	Number of core elements, fuel and control
CRN	Number of core elements
ELEM(I)	Number of elements in each channel
CONTR(I)	Logic variable indicating T = control element

Radial Blanket

BLANK	Number of rows of radial blanket elements
VFB	Fuel volume fraction in radial blanket
ROWB	Number of rows of rods per radial blanket element
GBRB	Ratio rod-wall spacing to rod-rod spacing for radial blanket element

All of these parameters are given by input quantities. The only parameters varied by the code are EL, core length, and RPITCH, rod pitch. (In the case of volume fraction zoning, the rod diameters of all channels, except the first channel, are calculated by the code.)

8. INPUT DESCRIPTION

The required input to the code is listed in Table 8-1.

TABLE 8-1
INPUT TO CALIOP

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
1	1-72	12A6	TITLE	Any number or title cards followed by a blank card
2	1-72	12A6	TITLE	Subtitle
3	1-10	E10	Q	Fuel rod o.d./i.d.
	11-20	E10	QM	Stanton number smooth (trial value)
	21-30	E10	XM	Reflector savings, cm (trial value)
	31-40	E10	XB	Core blockage fraction (trial value)
	41-50	E10	PO	Entry pressure, atm
	51-60	E10	CP	Coolant specific heat, joules/GM/°C
	61-70	E10	SPAN	Distance between spacers divided by rod diameter
	71-80	E10	TRAD	Radial steel reflector, cm
4	1-10	E10	XMW	Coolant molecular weight
	11-20	E10	PF	Fuel fissile density, GM/cm ³ (trial value)
	21-30	E10	AL	Radial max./avg. power (enter 1.0)
	31-40	E10	XLF	Axial reflector length (each), cm
	41-50	E10	AKF	Fuel thermal conductivity, W/cm-°C
	51-60	E10	AKC	Cladding thermal conductivity, W/cm-°C
	61-70	E10	PKFX	Fuel peaking factor (not used)
	71-80	E10	TAX	Axial steel reflector, cm
5	1-10	E10	CINL	Inlet loss - velocity heads
	11-20	E10	COUT	Outlet loss - velocity heads
	21-30	E10	ENSPAC	Number of spacers
	31-40	E10	CSLD	Spacer solidity constant (not used)
	41-50	E10	WRAT	Ratio spacer thickness to rod diameter
	51-60	E10	DRGA	Ratio box wall area to rod area (not used)
	61-70	E10	XLAM	Spacer pressure drop constant (not used)
	71-80	I10	I235	0-Treat U-235 as fertile 1-Treat U-235 as fissile
6	1-10	E10	FCX	Hot channel factor (not used)
	11-20	E10	FFX	Hot film factor (not used)
	21-30	E10	DENS	Fuel fraction of theoretical density
	31-40	E10	SCOND	Fuel-clad conductance, Btu/ft ² -hr-°F
	41-50	I10	KOPT	Fuel conductivity option 0-Oak Ridge function 1-GE function
	51-60	I10	KWOPT	kW/ft option (not used)
	61-70	E10	QKWF	Desired kW/ft
	71-80	E10	CAYSTR	Desired end of cycle reactivity

TABLE 8-1 (Continued)

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
7	1-72	12A6	TITLE	Title
8	1-10	E10	V	Core volume, liters (not used)
	11-20	E10	Z	Core L/D ratio (not used)
	21-30	E10	T1	Reactor inlet temperature, °C
	31-40	E10	DT	Core temperature rise, °C (trial value)
	41-50	E10	PDR	Reactor pressure drop ratio
	51-60	E10	XF	Fuel volume fraction (enter 0)
	61-70	E10	RATIO	Ratio total to core power
	71-80	I10	IMAT	Two-digit number, first clad, second structure 0-HT-9 (ferritic steel) 1-316 (austenitic stainless) 2-PE-16 (high-nickel alloy)
9	1-10	E10	TMAX	Nominal maximum clad, °C (initial value)
	11-20	I10	KORE	Fraction rough = KORE/10,000 For KORE=0, use optimum roughening
	21-30	I10	KON	1-Use input multipliers ETA1 and ETA2 0-Code will recalculate multipliers
	31-40	E10	H	Fuel pellet hole diam. to rod i.d. ratio
	41-50	I10	LIP	Rod axial temperature distribution 0-Do not calculate N-Calculate for channel N
	51-60	I10	LOP	Shell layout option 0-Hexagonal shells 1-Rounded shells
	61-70	E10	EFFX	Plant thermal efficiency (fraction)
	71-80	I10	ICIRC	Rod pattern option 0-Hexagonal element 1-Circular element
10	1-10	E10	DELTX	Length fraction increment for temp. distribution
	11-20	I10	LAST	If LAST=5, Pu buildup in blankets is ignored (both reactivity effect and burnout)
	21-30	E10	ETA1	Heat transfer multiplier
	31-40	E10	ETA2	Friction multiplier
	41-50	E10	ETA3	Ratio Stanton/friction (trial value)
	51-60	E10	AMU	Coolant viscosity, poises (trial value)
	61-70	E10	TMAXL	Mid-cladding hot spot, °C

TABLE 8-1 (Continued)

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
10	71-80	I10	IBURN	0-No burnup 1-Do 1/3 cycle burnup, adjust PFX 2-Same as 1 plus punch channel input 3-Same as 1, but reset fission products to 0 and set Pu composition to fresh feed values (for repeat runs) 4-Modify CAYDES based on final reactivity, adjust fission products to BOEC for following run
11	1-10	E10	YN	Ratio loop ΔP to reactor ΔP
	11-20	E10	EFFB	Circulator efficiency (not used)
	21-30	E10	G	Fuel volume factor (not used)
	31-40	I10	IBOX	Calculate box geometry 0-No 1-Short output (HEXVOL) 2-Long output (HEXX)
	41-50	I10	IHOT	Calculate hot spot factors 0-No 1-Yes
	51-60	I10	IKWF	Iterate for kW/ft (not used, enter 0)
	61-70	I10	ICRIT	Nuclear criticality calculation (VFRAC) 0-No 2-Adjust fuel enrichment 3-Calculate reactivity (CAYDES)
	71-80	I10	IPCHAN	0-Ignore 1-Punch channel input cards (not used)
	1-10	E10	BLKTK	Radial blanket thickness, cm (initial value)
	11-20	E10	CAYDES	Effective core multiplication factor
12	21-30	E10	RORAT	Volume fraction ratio, blanket to core (initial value)
	31-40	E10	VFB	Fuel volume fraction in radial blanket
	41-50	E10	BLANK	Number of radial blanket rows
	51-60	E10	ROWB	Rod rows per blanket element
	61-70	E10	QB	Blanket rod o.d./i.d. ratio
	71-80	E10	FRACT	Fraction of radial blanket heat released in first row (if blank, code supplies .72)
	1-10	E10	PASS	Number of cross-flow passes in blanket
	11-20	E10	POWRAT	Ratio of maximum power per element to average element in first blanket row

TABLE 8-1 (Continued)

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
13	21-30	E10	XBB	Blanket blockage fraction (initial value)
	31-40	E10	TILTB	Maximum to average flux across first row blanket element
	41-50	E10	HB	Ratio hole diam. to rod i.d., blanket
	51-60	E10	BAF	Ratio baffle leak to total blanket flow in cross-flow blanket element
	61-70	E10	AREA	Fraction of blanket flow area blocked by baffle in cross-flow blanket element
	71-80	I10	NTHOR	Fuel-fertile material option 0-All uranium fertile 1-U Core, U AB, Th RB 2-U Core, Th AB, Th RB 3-All thorium fertile 4-All thorium fertile, U-233 - U-238 instead of Pu isotopes
14	1-10	E10	GBRG	Blanket, ratio rod to wall gap to rod to rod gap
	11-20	E10	COEFF	Blanket cross flow, velocity heads per parallel flow region
	21-30	E10	PEAK	Blanket flow peaking ratio
	31-40	E10	DEAD	Number of structural pins per fuel element
	41-50	E10	RISEF	Blanket temp. rise divided by core temp. rise
	51-60	I10	IBLANK	Blanket flow option 1-Cross flow 2-Parallel flow
	61-70	I10	KLUST	Heat transfer enhancement for rod cluster 0-No enhancement 1-Use cluster correction (Markoczy)
	71-80	I10	INDENT	Roughening geometry option 0-Root diam. at inlet, rough o.d. at outlet 1-Rough o.d. at both inlet and outlet 2-Root diam. at both inlet and outlet Rod diam. (CD) always means smooth inlet diam.
15	1-10	E10	CRN	Number of control rods
	11-20	E10	DISP	Number of fuel rods displaced per control rod (=number of active rods for dedicated control rod)

TABLE 8-1 (Continued)

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
15	21-30	E10	GCF	Fuel to clad diametral gap, cm
	31-40	E10	GBR	Fuel, ratio rod to wall gap to rod to rod gap
	41-50	E10	BWT	Box wall thickness, divided by i.d. across flats
	51-60	E10	ROWS	Rows of rods per fuel element
	61-70	E10	SHIGH	Spacer length, cm
	71-80	I10	IPRINT	0-Print full output
				1-Hold back most output
16	1-10	E10	FCB	Blanket hot channel factor
	11-20	E10	FFB	Blanket hot film factor
	21-30	E10	TILTBE	Blanket tilt factor corrected for cross flow
	31-40	E10	AXRAT	Ratio axial blanket heat to radial blanket heat (initial value)
	41-50	E10	EPS	Fuel rod roughening height, cm
	51-60	E10	EPSAB	Blanket axial maximum to average flux over active core length
	61-70	E10	SHIFT	Fractional displacement of axial symmetry
	71-80	E10	PITRAT	Roughening pitch to width ratio (if zero, code supplies 3.47).
17	1-10	2I1	NTP1	Internal iteration options. Use NTP1=1, NTP2=4.
			NTP2	
	11-20	E10	CONVTO	Fuel rod diameter, cm. For volume fraction zoning enter first channel rod diameter
	21-30	I10	TOLER	Convergence tolerance. If zero code supplies .001
	31-40	I10	IPNTR	Enter 5 for volume fraction zoning, otherwise leave blank
	41-50	I10	ICYC	0-No fuel cost
				1-Do fuel cost
				2-Do fuel cost including DISCO
	51-60	I10	NTP3	0-Calculate thermal efficiency
18	61-70	I10	MULT	1-Use input thermal efficiency
	71-80	I10	IPCH	Multiple channel option - enter 4
				Not used
	1-10	I10	NCHAN	Number of channels
	11-20	I10	IFRACP	0-Ignore
				1-Input FRCP values (see card 35)

TABLE 8-1 (Continued)

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
18	21-30	I10	ITILT	0-Ignore 1-Input TLT values (see card 36)
	31-40	I10	IBIAS	0-Ignore 1-Input BIAS values (see card 21)
19		7E10	ELEM	Number of elements per channel, 7 per card
20		7E10	PFX	Fissile density (GM/cm ³) in region between hole and rod i.d. for each channel, 7 per card
21		7E10	BIAS	Relative maximum power for each enrichment zone. Include this card if IBIAS=1 (card 18).
22	1-10	E10	VOLIN	Fuel volume fraction in core (trial value)
	11-20	E10	FCIN	Core hot channel factor
	21-30	E10	FFIN	Core hot film factor
	31-40	E10	FPIN	Core peaking factor (applied only to max. kW/ft)
	41-50	E10	DRAT	Modifying ratio for input PFX (card 20)
	51-60	I10	IPFX	Option to modify input PFX by zone (see card 28) 0-Ignore 1-Modify
	61-70	I10	ITML	Option to specify different maximum cladding temperatures for each channel (see card 32)
	71-80	E10	SKEW	Correction to maximum flux for control rod insertion
23		70L1	CONTR	Control rod channel designation. Enter T for each control element.
24	1-10	I10	NZ1	Last channel number for first enrichment zone
	11-20	I10	NZ2	Last channel number for second enrichment zone
	21-30	I10	NZ3	Last channel number for third enrichment zone
	31-40	I10	NZ4	Last channel number for fourth enrichment zone (with 3 zones, NZ3=NZ4, etc.)
	41-50	I10	IORIF	Orifice option 0-Set orifices for desired mid-cladding maximum temperatures

TABLE 8-1 (Continued)

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
24				<p>4-Use input orifice diameters, card 29. The orifice diameters calculated in a run with IORIF=0 may be used in a follow-on run by setting IORIF=4 (see card "EXTRA", at end of input listing). For example, the performance at end of cycle can be determined after a beginning of cycle calculation by adding the following "EXTRA" cards:</p> <p>44 1.0 (IGEOM) 47 4.1 (IORIF) 48 Blank (TT2) 11 New value (RATIO) 25 New value (RISEF) 49 .1 (IBURN) 38 3.1 (ICRIT) 51 .1 (ITML)</p> <p>The second run will have the same reactor geometry, power level, and outlet temperature, but will use total/core power (RATIO) and relative radial blanket temperature rise (RISEF) appropriate for end of cycle. The principal result will be the set of maximum cladding temperatures.</p> <p>51-60 E10 TT2 Desired outlet gas temperature, °C 61-70 I10 IBRN Option to input ratio of BOEC to EOEC Fissile density. See cards 25 and 26. 0-No 1-Input ratios</p> <p>71-80 E10 FISMEV MEV per fission. If blank code supplies 200.</p>
25		7E10	BRN	Burnup ratios. See card 24, 7 per card.
26		72I1	LOAD	Loading sequence (1, 2, or 3) for each channel. Include cards 25 and 26 if IBRN=1 (card 24).
27	1-10	E10	FPEAK	Modifier for radial peaking. Increases difference between channel power and average by the fraction FPEAK.
	11-20	E10	SLEAK	Effective unheated core bypass (in addition to flow through radial blanket), fraction

TABLE 8-1 (Continued)

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
27	21-30	E10	ADDTM	Modifier of individual channel hotspot limits, in the case where they are specified (ITML-1, card 22)
	31-40	E10	COMP	Modifier of gas constant for non-perfect gas
28	1-10	E10	X ₁	Multipliers for individual enrichment zone fissile densities. Include this card if IPFX=1, card 22.
	11-20	E10	X ₂	
	21-30	E10	X ₃	
	31-40	E10	X ₄	
29		7E10	DORIF	Orifice diameters, cm, 7 per card. Include this card if IORIF=4 on card 24.
30	1-10	E10	IGEOM	Code performance option 1-Hold input dimensions and ΔP , calculate power 2-Hold input ΔP , vary rod pitch for power and core length for kW/ft 3-Hold input ΔP , vary rod pitch for power and core length for outlet temperature 4-Hold input ΔP , vary rod pitch for power 5-Hold input dimensions, vary ΔP for power 6-Hold core length, vary rod pitch for power and ΔP for circulator power
	11-20	E10	RPITCH	Fuel rod to rod pitch, cm (at temperature)
	21-30	E10	BOXI	Number of core elements including control
	31-40	E10	EL	Core length, cm
	41-50	E10	BGAPR	Ratio of box gap to outside box diameter across flats
	51-60	E10	TPS	Reactor thermal power, MW
	61-70	I10	INPLUT	0-Ignore 1-Input plutonium isotope composition and U-235 Mol fraction in uranium. See card 31.
	71-80	I10	ICROSS	0-Ignore 1-Input one group cross sections. See cards 33 and 34.
	1-40	4E10	XP	Plutonium Mol fractions (49, 40, 41, 42)
	41-50	E10	X235	Mol fraction U-235 in uranium. Include this card if IPLUT=1 on card 30.

TABLE 8-1 (Continued)

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
32		7E10	TML	Hot spot limits for individual channels, 7 per card. Include if ITML=1, card 22.
33	1-10	E10	SIGA49	Pu-239 absorption cross section
	11-20	E10	SIGA40	Pu-240 absorption cross section
	21-30	E10	SIGA41	Pu-241 absorption cross section
	31-40	E10	SIGA42	Pu-242 absorption cross section
	41-50	E10	SGNU49	(Fission cross section)*n/fission, Pu-239
	51-60	E10	SGNU40	(Fission cross section)*n/fission, Pu-240
	61-70	E10	SGNU41	(Fission cross section)*n/fission, Pu-241
	71-80	E10	SGNU42	(Fission cross section)*n/fission, Pu-242
34	1-10	E10	SIGAFP	Fission product absorption cross section (2 per fission)
	11-20	E10	SGNUBL	(Fission cross section)*n/fission for blanket uranium
	21-30	E10	SIGA25	U-235 absorption cross section
	31-40	E10	SGNU25	(Fission cross section)*n/fission, U-235 in core
	41-50	E10	SIGA28	U-238 absorption cross section
	51-60	E10	SGNU28	(Fission cross section)*n/fission, U-238 in core
	61-70	E10	SIGC28	U-238 capture cross section (to Pu-239) Include cards 33 and 34 if ICROSS=1, card 30
35		8E10	FRCP	Channel powers, from physics data, 7 per card. Include if IFRACP=1, card 18.
36		8E10	TLT	Channel tilt factors from physics data, 7 per card. Include if ITLT=1, card 18.
A(a)	1-4	14	IOPT1	Is this first CYCOST problem? 0 = No 1 = Yes (input of all cards required)
	5-8	14	IOPT2	Will CYCOST repeat 0 = No 1 = Yes
	9-12	14	IOPT3	Read new card B: 0 = No 1 = Yes

(a)
Cards A through G should be included if ICYC = 1 or 2 on card 17.

TABLE 8-1 (Continued)

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
A	13-16	14	IOPT4	Read new card C: 0 = No 1 = Yes
	17-20	14	IOPT5	Read new card D: 0 = No 1 = Yes
	21-24	14	IOPT6	Read new card E: 0 = No 1 = Yes
	25-28	14	IOPT7	Read new card F: 0 = No 1 = Yes
	29-32	14	IOPT8	Read new card G: 0 = No 1 = Yes
B	1-12	E12	B1	Ratio of total to core fissions
	13-24	E12	EMAX	Maximum burnup, MWd/tone fuel metal
	25-36	E12	EFIS	MW-hr(t)/kg fissioned, usually 23,300
	37-48	E12	ZETA	Fast fission factor (total fissions per fissionable fission), trial value
	49-50	E12	ALFA	Capture to fission ratio for average fissionable isotope, trial value
	61-72	E12	FCTOR	Correction factor for fuel fabrication cost
C	1-12	E12	FPROC	Fraction of core reloaded per cycle
	13-24	E12	FACTOR	Ratio peak/avg. burnup to peak/avg. power
	25-36	E12	XLDFAC	Reactor load factor
	37-48	E12	RHOMET	Density of metal in fuel, g/cm ³
	49-60	E12	ELCAP	Electrical capacity served by fabrication plant [MW(e)]
	61-72	E12	XXXM	Reprocessing plant capacity scaling factor
D	1-12	E12	BLKTHK	Radial blanket thickness, cm
	13-24	E12	OVERLAP	Ratio of corner blanket length to axial blanket length
	25-36	E12	RHORAT	Ratio of radial blanket fuel atom density to core fuel atom density
	37-48	E12	RECYC	Fraction of radial blanket reprocessed for each total core reload

TABLE 8-1 (Continued)

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
D	49-60	E12	BD	Radial blanket pin o.d., cm, trial value
	61-72	E12	XLOSS	Total fabrication and reprocessing loss fraction
E	1-12	E12	P9	Fissile fuel value, \$/kg
	13-24	E12	PR	Reprocessing plant basic charge, \$/kg
	25-36	E12	PHFR	Fresh fuel shipping charge, \$/kg
	37-48	E12	PHSP	Spent fuel shipping charge, \$/kg
	49-60	E12	CAPF	Fuel item interest rate
	61-72	E12	CAPW	Non-fuel item interest rate
F	1-12	E12	T1	Pre-reactor holdup, yr
	13-24	E12	T3	Post-reactor holdup, yr
	25-36	E12	RPLDFC	Reprocessing plant load factor
	37-48	E12	AAC	Fabrication constant - core
	49-60	E12	AAA	Fabrication constant - axial blankets
	61-70	E12	AAR	Fabrication constant - radial blankets
G	1-12	E12	XXNC	Fabrication throughput factor - core
	13-24	E12	XXNA	Fabrication throughput factor - axial blanket
	25-36	E12	XXNR	Fabrication scale factor for mass of fuel per pin - core
	37-48	E12	XXKC	Fabrication scale factor for mass of fuel per pin - axial blanket
	49-60	E12	XXKA	Fabrication scale factor for mass of fuel per pin - axial blanket
	61-72	E12	XXKR	Fabrication scale factor for mass of fuel per pin - radial blanket
DISCO-1(a)		12A6	TITLE	Title for DISCO fuel cycle cost
DISCO-2	1-4	I4	N2M	Longest leveling period to do (≤ 30); all periods (0-1) through (0-N2M) are calculated and printed
	5-8	I4	NDF	Number of optional discount rates to use (in order, but if NDF=1, only IDF1=1 option will perform), where IDF=0, for rate=(RE + FLAT) IDF=1, for rate=after tax required Rate of return, where before - Tax rate=working capital rate $= (1-BF) \cdot (RE + FLAT) + BF \cdot (1-TAU) \cdot (RB + FLAT) = RAT = (1-TAU) \cdot RBT$ IDF=2, for rate=(RE + LAMB) for fuel only

(a) DISCO input is needed if ICYC=2 on card 7

TABLE 8-1 (Continued)

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
DISCO-2	9-12	14	IDF1	Option to get values of IDF=1 0=Calculate 1=Read in as in GA-cost. If to be read in, values will be: bFR=DFRIN (DISCO-5)=discount rate=RAT RBT=RBTIN (DISCO-5)=working capital rate=RBT
DISCO-3	1-12	E12	BF	Fraction of capital stock debt (bond) financed
	13-24	E12	RB	Interest paid to bond holders with no inflation (fraction)
	25-36	E12	RE	No-inflation rate of return to stock holders (fraction)
	37-48	E12	TAU	Effective corporate tax rate on ordinary income (fraction)
	49-60	E12	GAMMA	Fraction of TAU at which capital gains are taxed if long term, i.e., GC tax rate = GAMMA*TAU
	61-72	E12	FLAT	General price inflation (fraction/yr)
DISCO-4	1-12	E12	LAMB	Specific additional price escalation for investments in fuel capital stock (fraction)
DISCO-5	1-12	E12	DFRIN	Discount rate (fraction)
	13-24	E12	RBTIN	Working capital rate (fraction)
DISCO-6	1-12	E12	TSU	Year of startup
	13-24	E12	TESC	Year escalation begins
EXTRA(a)	1-2	I2	N	Follow-on case parameter number (Table 6-1)
	3-28	E18	B	Follow-on case parameter value, one card per variable
LAST(a)				Blank card

(a) Include for follow-on run. If FRCP and TLT are to be respecified, IFRACP and ITILT should be set to 1 (Table 6-1) and the new values should be placed after the blank card.

9. PRINCIPAL SUBROUTINES

9.1. CALIOP

Figure 9-1 is a flowsheet of the main program, CALIOP (formerly GAZELLE). After reading the data [CHANEL(1) inputs the multichannel information], CHANEL(2) is called to set options for operation of the code. From here until the end of a channel calculation (statement 913), the code is practically the same as the original GAZELLE program. At this point, CHANEL(3) is called to carry out a number of iterations for various options. Following these iterations, each of which returns the program to statement 37 or 38, the core design is completely specified. A series of subroutines then operates to give further details of the design as follows:

PROFIL - prints point temperatures for a channel selected by LIP.

HEXX - calculates core geometry based on a hexagonal lattice.

BLANKT - calculates performance of the maximum-powered radial blanket element, with options for baffled cross flow or parallel flow of coolant.

CYCOST - performs fuel cycle cost estimate.

9.2. COMPUT

The COMPUT subroutine carries out the thermohydraulic calculations for the core. The method and equations are given in Appendices A, B, and C, and Fig. 9-2 is a flowchart of the subroutine. The design equations are used in arrangements dictated by the performance options NTP1 and NTP2. CHANEL(6) sets these options at the beginning of COMPUT, and CHANEL(8) resets them at the end. Within COMPUT, the options are always NTP1=2, NTP2=4.

Fig. 9-1. CALIOP main routine

Fig. 9-2. Subroutine COMPUT

The COMPUT subroutine operates almost the same as in the original GAZELLE, with one principal exception. In the GAZELLE code, the pumping power fraction (ratio of theoretical pumping power to core thermal power) was specified and the pressure drop was computed. With a multichannel code, the overall pressure drop (including orifices) is the same for all channels, so the pumping power fractions will be different. Therefore, the code was changed to input the pressure drop ratio. With variable volume fraction zoning (IPNTR=5), it is assumed that the pressure drop will be the same in all zones. With variable enrichment zoning (IPNTR=0), the input pressure drop ratio is taken to be the pressure drop for the element which contains the highest-rated fuel rod. All other channels will be orificed for constant maximum midwall cladding temperature.

9.3. CHANEL(3)

The CHANEL(3) subroutine collects the results of COMPUT calculations and arranges various iterations in accordance with design options. Figure 9-3 is a simplified flowsheet for the most important steps.

After the first channel is calculated, the total power can be derived. In all IGEOM options except 1, this step is iterated until the power is satisfactory. Then the remaining channels are computed.

With IORIF=4, the pressure drop ratio is modified to provide the correct allowance for the fixed orifice diameter. The calculation is iterated several times for each channel.

At this point, the maximum pressure drop ratio and the circulator power requirement are available. With IGEOM options from 1 through 4, the initial value of PDR is modified to suit the maximum pressure drop available. With IGEOM=6, the initial PDR value is modified to obtain the desired circulator power.

Fig. 9-3. Subroutine CHANEL(3)

The final iteration modifies the core length, EL, to achieve the desired rod rating (IGEOM=2) or reactor outlet temperature (IGEOM=3). Successful exit from this step completes the design.

In any iteration return where the rod pitch (RPITCH) or core length (EL) has been changed, the nuclear calculation (VFRAC) is repeated (I=38).

10. OUTPUT PRINTING

This section contains output from a typical CALIOP run. The first page lists the input card images. The next two pages list the input with FORTRAN names. The next page gives diagnostics from the VFRAC2 subroutine, concluding with an estimate of the end of initial cycle reactivity.

A condensed summary of the principal results of the design is followed by a detailed neutron balance, a listing of heavy atom density (atoms per barn-cm) characteristics for each channel (three pages), axial temperature distributions for the selected channel, plots of axial temperature distributions and radial neutron flux distribution, detailed core and blanket geometry (three pages), blanket thermal-hydraulic analysis, fuel cycle cost, and breeding ratio analysis including doubling time. At the end, the final reactivity (CAYDES) after one equilibrium cycle burnup is printed. This may be compared with the initial reactivity (the first summary page) to obtain an estimate of burnup reactivity change. The three values labelled BURN are the fission product atoms per initial fissile atom at the end of an equilibrium cycle for each of the three enrichment zones. There are assumed to be two fission product atoms per fission.

@ELT,LID CARDS

ELT 8R1 S74Q1C 04/03/80 09:45:42 (->0)

1.	00	@XQT,Q	6CFR3*CALIOP.CALA							
2.	00									
3.	00	BENCH1	- COMMERCIAL PLANT	- 100 BAR	- 3600 MWT					
4.	00	1.121	.002	33.27	.147412	98.55	5.2	25.8	20.	
5.	00	4.	1.123	1.	60.	.019	.208	1.127	20.	
6.	00	1.68	.5	5.0	4.26	.0318	.1	1.0		
7.	00	1.206	1.115	.8931	2000.		1	15.	1.01	
8.	00	3600 MWT								
9.	00	4000.	.5	301.67	200.	.01774		1.120		22
10.	00	640.		0	0.001		1	.36		
11.	00	.05		02.2615	4.9509	.6236	.364	-03730.		4
12.	00	1.333	.77	1.065		2	0		2	
13.	00	56.	1.04	1.666	.45	3.	6.	1.0419	.84	
14.	00	20.	1.14	.155	1.74	0.	.3	.7		0
15.	00	1.	1.	1.127	7.	.46		2		1
16.	00	19.	264.	.014	.46	.0168	10.	1.3		1
17.	00	1.3	2.045	1.5	1.	.013	1.2	0.		
18.	00	14	.8068	.001			1	1	4	
19.	00		18	0	0	0				
20.	00	1.	1.	5.	12.	12.	6.	24.		
21.	00	6.	24.	6.	30.	30.	12.	48.		
22.	00	54.	60.	66.	72.					
23.	00	1.	1.	1.	1.	1.	1.	1.		
24.	00	1.	1.	1.	1.	1.	1.	1.		
25.	00	1.	1.	1.	1.	1.	1.	1.		
26.	00	.3	1.152	1.248	1.153	1.		0	1.0	
27.	00	T	T T T							
28.	00		13	16	18	18	554.44		0210.	
29.	00	.0	.02	0.	1.02					
30.	00		11.11229	469.	121.02	.06794	3600.		1	1
31.	00	.6727	.2021	.1013	.0239	.002				
32.	00	2.13	.811	2.67	.578	5.1	1.2	6.89	.921	
33.	00	.2014	.066	2.21	4.28	.306	.144	.256		
34.	00	1								
35.	00	1.0705	100000.	23300.	1.25	.2237	.5			
36.	00	.3333	1.	.75	.52	15000.	.53			
37.	00	60.	1.	1.526	.75	1.176	.02			
38.	00	25000.	310.	10.	30.	.14	.14			
39.	00	.5	.5	0.7123	112.	6.0	75.0			
40.	00	.25	.25	.25	.35	.35	.35			
41.	00	52	.1							
42.	00									
43.	00	@PMD,BDER								

END ELT. ERRORS: NONE. TIME: 0.267 SEC. IMAGE COUNT: 43

@ADD,P CARDS

@XQT,Q GCFR3*CALIOP.CALA

TYPE 14 ITERATION FOR FOLLOWING CASE

ITERATE FOR GIVEN CAN DIAMETER (CD)
BY VARYING TEMPERATURE RISE (DT)

* * * I N P U T * * *

BENCH1 - COMMERCIAL PLANT - 100 BAR - 3500 MWT

Q	QH	XM	XB	PO	CP	SPAN	TRAD
1.121	.304761-02	.31830+02	.232858+00	98.55	5.200	25.800	20.00
XHW	PF	AL	XLF	AKF	AKC	PKFX	TAX
4.00	1.044	1.000	60.000	.01900	.20800	1.15300	20.00
CINL	COUT	ENSPAC	CSLD	WRAT	DRGA	XLAM	I235
1.6600	.5000	13.000	4.2630	.03180	.1322	.351	0
FCX	FFX	DENS	SCOND	KOPT	KWOPT	QKWF	CAYSTR
1.2040	1.2480	.8931	2000.00	1	0	15.000	1.0100
3600 MWT							
V	Z	T1	DT	PDR	XF	RATIO	IMAT
.203356+05	.261656+00	301.670	273.846	.01774	.00000000	1.1200	22
THAX	KORE	KON	H	LIP	LOP	EFFX	ICIRC
595.637	0	0	.0010	1	0	.3600	0
DELIX	LAST	ETA1	ETA2	ETA3	AMU	TMAXL	IBURN
.0500	0	1.6777	3.4378	.6113	.00038304	730.0	4
YN	EFFB	G	I80X	IHOT	IKWF	ICRIT	IPCHAN
1.3330	.7700	1.0650	2	0	0	2	0
BLKTK	CAYDES	RORAT	VFB	BLANK	ROWB	QB	FRACT
55.48	1.0321	1.6660	.4500	3.0000	6.0000	1.0419	.8400
PASS	POWRAT	XBB	TILTB	HB	BAF	AREA	NTHOR
20.00	1.1400	.1793	1.7400	.0000	.3000	.7000	0
GRRB	COEFF	PEAK	DEAD	RISEF	IBLANK	KLUST	INDENT
1.0000	1.0000	1.1270	7.0000	.4600	2	0	1
CRN	DISP	GCF	GBR	BWT	ROWS	SHIGH	IPRINT
19.	264.	.01400	.4600	.01680	10.	1.300	0
FCB	FFB	TILTBE	AXRAT	EPS	EPSAB	SHIFT	PITRAT
1.30000	2.04500	1.50000	1.66168	.01300	1.20000	.00000	3.47000
NTP1-NTP2	CONVTO	TOLER	IPNTR	ICYC	NTP3	MULT	IPCH
14	.806800+00	.100000-02	0	1	1	4	0

*** CHANNEL INPUT ***

NCHAN,IFRACP,ITILT,IBIAS= 18 0 0 0

ELEM(I),I=1,NCHAN

1.00000	1.00000	5.00000	12.00000	12.00000	6.00000	24.00000
6.00000	24.00000	6.00000	30.00000	30.00000	12.00000	48.00000
54.00000	60.00000	66.00000	72.00000			

TOTAL NUMBER OF ELEMENTS = 469. (0. 469. 0.)

PFX(I),I=1,NCHAN

.94235	.94235	.94235	.94235	.94235	.94235	.94235
.94235	.94235	.94235	.94235	.94235	.94235	.99110
.99110	.99110	1.21684	1.21684			

CDD(I),I=1,NCHAN

.80680	.80680	.80680	.80680	.80680	.80680	.80680
.80680	.80680	.80680	.80680	.80680	.80680	.80680
.80680	.80680	.80680	.80680			

VOLIN	FCIN	FFIN	FPIN	DRAT	IPFX	ITML	SKEW
.30000	1.15200	1.24800	1.15300	1.00000	0	0	1.00000

CONTR(I),I=1,NCHAN

F T F F F T F T F T F F F F F F F

NZ1	NZ2	NZ3	NZ4	IORIF	TT2	IBRN	FISMEV
13	16	18	18	0	554.44	0	210.0

FPEAK, SLEAK, ADDTH, COMP .0030 .0200 .0000 1.0200

IGEOM	RPITCH	BOXI	EL	3GAPR	TPS	IPLUT	ICROSS
1	1.112290	469.0	121.02	.6734-01	3600.0	1	1

PLUTONIUM ATOM FRACTIONS .6727 .2021 .1013 .0239 .0020

SIGA49	SIGA40	SIGA41	SIGA42	SGNU49	SGNU40	SGNU41	SGNU42
2.1300	.8110	2.6700	.5780	5.1000	1.2000	6.8900	.9210

SIGA49	SGNU41	SIGA25	SGNU25	SIGA28	SGNU28	SIGC28
.2014	.0660	2.2100	4.2800	.3060	.1440	.2560

HEAVY METAL BY ZONES, KG

FISSILE PLUTONIUM	1837.3	2086.9	2182.6	.0
NON-FISSILE PLUTONIUM	536.5	609.4	637.3	.0
URANIUM	13731.5	14702.4	12021.3	.0

TOTAL TIME IN COMPUT .914 TOTAL CALLS TO COMPUT 82
TOTAL TIME IN VFRAC 4.399 TOTAL CALLS TO VFRAC 21

AK	PHN(I)	SU(I)	UTOP(I)	SPU(I)	PU40C	TIM2	XP(1)	XP(3)	AKPH
.4075-16	.3345+16	.2769+00	.5785+01	.1721+01	.4862-01	.4001+01	.6727+00	.1013+00	-.1291-01
.4075-16	.3344+16	.2769+00	.5785+01	.1721+01	.4862-01	.4001+01	.6727+00	.1013+00	-.1290-01
.4075-16	.3344+16	.2769+00	.5785+01	.1721+01	.4862-01	.4001+01	.6727+00	.1013+00	-.1290-01
.4075-16	.3341+16	.2769+00	.5785+01	.1721+01	.4862-01	.4001+01	.6727+00	.1013+00	-.1290-01
.4075-16	.3336+16	.2769+00	.5785+01	.1721+01	.4862-01	.4001+01	.6727+00	.1013+00	-.1289-01

.4075-16	.3336+16	.2769+00	.5785+01	.1721+01	.4862-01	.4001+01	.6727+00	.1013+00	-.1289-01
.4075-16	.3328+16	.2769+00	.5785+01	.1721+01	.4862-01	.4001+01	.6727+00	.1013+00	-.1288-01
.4075-16	.3318+16	.2769+00	.5785+01	.1721+01	.4862-01	.4001+01	.6727+00	.1013+00	-.1287-01
.4075-16	.3318+16	.2769+00	.5785+01	.1721+01	.4862-01	.4001+01	.6727+00	.1013+00	-.1287-01
.4075-16	.3305+16	.2769+00	.5785+01	.1721+01	.4862-01	.4001+01	.6727+00	.1013+00	-.1285-01
.4075-16	.3305+16	.2769+00	.5785+01	.1721+01	.4862-01	.4001+01	.6727+00	.1013+00	-.1285-01
.4075-16	.3289+16	.2769+00	.5785+01	.1721+01	.4862-01	.4001+01	.6727+00	.1013+00	-.1282-01
.4075-16	.3289+16	.2769+00	.5785+01	.1721+01	.4862-01	.4001+01	.6727+00	.1013+00	-.1282-01
.4075-16	.3247+16	.2743+00	.5453+01	.1716+01	.4862-01	.4001+01	.6727+00	.1013+00	-.2619-01
.4075-16	.3080+16	.2743+00	.5453+01	.1716+01	.4862-01	.4001+01	.6727+00	.1013+00	-.2526-01
.4075-16	.2792+16	.2743+00	.5453+01	.1716+01	.4862-01	.4001+01	.6727+00	.1013+00	-.2365-01
.4075-16	.2374+16	.2654+00	.4263+01	.1706+01	.4862-01	.4001+01	.6727+00	.1013+00	-.5562-01
.4075-16	.1714+16	.2654+00	.4263+01	.1706+01	.4862-01	.4001+01	.6727+00	.1013+00	-.4239-01

VFRAC2 - CAYDES 1.01774									
BURN	.3674+00	.3329+00	.2177+00	.0000	.0000	.0000	.0000	.0000	.0000

UPDATED ITEMS FOR NEXT CASE													
52	0	0	0	0	0	0	0	0	0	0	0	0	0
IPRINT													

A1	.9487	A2	.9744	A3	1.0874	A4	.0000	ER	.08739	IFLUX	1	M	3	ERR	-.00002
A1	.9772	A2	.9766	A3	1.0497	A4	.0000	ER	.04969	IFLUX	2	M	3	ERR	.00001
A1	.9886	A2	.9805	A3	1.0325	A4	.0000	ER	.03247	IFLUX	3	M	3	ERR	.00001

REVISED VALUES FOR FRACP AND FTILT

CHANNEL	FRACP	FTILT	FLUX	OUTER RADIUS	CD
1	1.00000	1.00000	1.24306	10.68	.8068
2	.99954	1.00048	1.24249	28.26	.8068
3	.99954	1.00048	1.24249	28.26	.8068
4	.99825	1.00095	1.24088	46.55	.8068
5	.99607	1.00144	1.23816	64.96	.8068
6	.99607	1.00144	1.23816	64.96	.8068
7	.99296	1.00203	1.23427	83.41	.8068
8	.98883	1.00261	1.22913	101.88	.8068
9	.98883	1.00261	1.22913	101.88	.8068
10	.98363	1.00325	1.22264	120.36	.8068
11	.98363	1.00325	1.22264	120.36	.8068
12	.97726	1.00393	1.21469	138.84	.8068
13	.97726	1.00393	1.21469	138.84	.8068
14	.99779	1.01653	1.19772	157.32	.8068
15	.94813	1.03953	1.13705	175.81	.8068
16	.86383	1.06389	1.03428	194.30	.8068
17	.87972	1.11890	.88537	212.79	.8068
18	.64902	1.23490	.64460	231.29	.8068
NUMBER OF POWER ITERATIONS			0	POWER	3586.7 MWT

HEAVY METAL BY ZONES, KG

FISSILE PLUTONIUM	1843.6	2077.1	2180.1	.0
NON-FISSILE PLUTONIUM	582.5	656.3	688.8	.0
URANIUM	13488.0	14463.6	11811.9	.0
TOTAL TIME IN COMPUT	1.848	TOTAL CALLS TO COMPUT	164	
TOTAL TIME IN VFRAC	6.463	TOTAL CALLS TO VFRAC	31	

FERTILE MATERIAL ALL URANIUM
CLADDING MATERIAL 316SS DUCT MATERIAL 316SS

BENCH1 - COMMERCIAL PLANT - 100 BAR - 3600 MW

CASE 2 1.0

OUTSIDE/INSIDE CAN DIAM.=	1.1210	REFLECTOR SAVINGS =	32.612				
STANTON NO.SMOOTH SURFS.=	.003030	BLOCKAGE FRACTION =	.23286				
ENTRY PRESSURE(ATMOSPH.)=	98.55	MOLECULAR WEIGHT =	4.00				
TOTAL/CORE POWER (RATIO)=	1.1200	AXRAT =	1.5776				
SPEC.HEAT(JLS/GM/DEG.C)=	5.200	RADIAL MAX/MEAN =	1.1304				
FISSILE DENSITY(GM/CM*3)=	1.0430	AXIAL BLANKET CM	60.00				
FUEL COND. (WS/CM/DEG.C)=	.01900	CLAD. (WS/CM/DEG.C)=	.20800				
INLET LOSS-VEL HEADS =	1.680	OUTLET LOSS, V4 =	.500				
NUMBER OF SPACERS =	13.0	SOLIDITY CONSTANT =	4.260				
RATIO WIRE-ROD DIAM. =	.03180	BOX FRACT DRAG AREA=	.13219				
SPACER PRESS DROP CONST =	.35063	SPACER SOLIDITY =	.17860				
FUEL FRACT. THEO. DENS. =	.8931	FUEL-CLAD COND. =	2000.00 BTU/SQ FT-HR-DEG F				
RADIAL STEEL REFLECTOR,CM	20.00	AXIAL REFLECTOR, CM	20.00				
FINAL CAYDES =	1.03209	BREEDING RATIO	CORE .9790	RADIAL .1809	AXIAL .3618	CORNER .0485	TOTAL 1.4702
RADIAL BLANKET THICKNESS	55.48	CORE FUEL DENSITIES					
REACTOR CAVITY DIA4-FT	30.73	PLUTONIUM ATOM DENSITIES	.000834	.000980	.001207	.000000	
REACTOR CAVITY HEIGHT-FT	47.52	URANIUM TO PLUTONIUM RATIO	5.5594	5.2915	4.1173	.0000	

3600 MW

MAX.SURF.TEMP.(DEG.C) =	596.66	CORE VOLUME(LITRES)=	20335.57	
L/D RATIO OF CORE =	.26166	FUEL VOL. FRACTION =	.28763	
GAS TEMP.RISE (DEG.C) =	261.17	ENTRY TEMPERATURE C=	311.26	
REACTOR INLET TEMP. =	301.67	REACTOR OUT TEMP. =,	563.63	1046.54 DEG-F **
ROUGHNING H.T. FACTOR =	1.6809	ROUGHNING FRICTION =	3.4619	
STANTON/FRICTION RATIO =	.6118	VISCOSITY =	.000383	
HOLE DIAM./FUEL DIAM. =	.001000	OPT. ROUGH		
HOT CLAD TEMP (DEG-C) =	730.20	HOT FUEL TEMP =	2016.48	*

	NEUTRON BALANCE CONSUMED	PRODUCED
PU239-241	1.0000	2.5872
HIGH ACTINIDES	.0782	
FERTILE CAPT	1.4702	(PU40C .0527)
FERTILE FISS	.2141	.5780
STRUCTURE	.1396	
RADIAL LEAK	.0089	
AXIAL LEAK	.0378	
REFLECTOR	.0212	
F PRODUCTS	.0363	
BALANCE	.1589	
TOTAL	3.1652	3.1652

ACTIVE CORE LENGTH(CMS) =	121.02	OPT.SMOOTH FRACTION=	.4729	
REYNOLDS NUMBER =	80038.	REA. RATING(MW/KG) =	.58792	
COOLANT VOID FRACT.(BOX)=	.52285	CAN DIAMETER(CMS) =	.80680	
MAX.LINEAR RATING(KW/FT)=	10.59	NO.OF RODS =	118800.	
POWER DENSITY(KW/LITRE) =	157.48	PRESSURE DROP RATIO=	.17740-01	25.70 PSI
AVE VEL HEAD MAX CHAN,AT=	.10980	MAX/MEAN POWER RATIO=	1.35352	
POWER TO FLOW (W-HR/LB) =	171.8	TRIANGULAR PITCH =	1.11229	
PUMP-HEAT RATIO	.02077	AVE FUELTEMP(DEG.C)=	1066.8	
MASS FLOW TOTAL (LB/SEC)=	5799.6	VOLUME FLOW (CFS)=	11283.4	
RADIAL BLANKET =	489.7	ZONE FISSILE DENSITIES	.94560	.98643 1.21539 .00000
BYPASS LEAKAGE =	116.0	ZONE FUEL VOLUME FRACTIONS	.26607	.29977 .29977 .00000
TOTAL REACTOR POWER(MWT)=	3586.74	EFFICIENCY =	.3600	

* BASED ON AVERAGE FUEL CONDUCTIVITY (INPUT ABOVE)

** CORRECTED FOR PARALLEL FLOW BLANKET TEMPERATURE DEGRADATION OF 12.78 DEG-C

REACTOR PRESSURE DROP IN MEAN VELOCITY HEADS

INLET	IN-BLANK	SMOOTH	ROUGH	OUT-BLANK	SPACERS	ACCEL	OUTLET	TOTAL
1.3652	1.0315	1.0842	5.4587	1.5073	4.5581	.3748	.5937	15.9736

DETAILED NEUTRON BALANCE

	CORE		RADIAL BLANKET		AXIAL BLANKET		CORNER		TOTAL	
	CONS	PROD	CONS	PROD	CONS	PROD	CONS	PROD		
PU239-241	1.0000	2.5872							1.0000	2.5872
HIGH ACTINIDES	.0782								.0782	
FERTILE CAPTURE	.8790		.1809		.3619		.0485		1.4702	
FERTILE FISSION	.1493	.4032	.0190	.0514	.0405	.1096	.0051	.0138	.2141	.5780
STRUCTURE	.0977		.0077		.0321		.0021		.1396	
RADIAL LEAK			.0089						.0089	
AXIAL LEAK					.0378				.0378	
REFLECTOR ABS			.0063		.0149				.0212	
FISS PRODUCTS	.0363								.0363	
BALANCE	.1589								.1589	
TOTAL	2.3995	2.9904	.2228	.0514	.4872	.1096	.0556	.0138	3.1652	3.1652

HIGH ACTINIDES INCLUDE PU240 FISSION AND PU242 DESTRUCTION
FISSION NEUTRONS ARE INCLUDED IN FIRST ITEM

FERTILE CAPTURE (BREEDING RATIO) INCLUDES U238, TH232 AND PU240 CAPTUPE

FERTILE FISSION INCLUDES U238 AND U235 FISSION OR TH232 FISSION

WHEN U233 IS THE FUEL THE U238 MIXED WITH IT IS TREATED AS
FERTILE COMPONENT OF THE FUEL, ANALOGOUS TO THE TREATMENT OF
PU240 IN PLUTONIUM FUEL. IN THIS CASE THE FIRST TWO PLUTONIUM
ATOM FRACTIONS REPRESENT U233 AND U238

CHANNEL	HEAVY METAL DENSITIES, ATOMS PER BARN CM								
	U235	U238	PU239	PU240	PU241	PU242	FISSP	UTOP	ENPLU
1	.10443-04	.52111-02	.63853-03	.20067-03	.75038-04	.24790-04	.34832-03	.55605+01	.93903-03
2=	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.56097+01	.00000
3	.10443-04	.52111-02	.63853-03	.20067-03	.75038-04	.24790-04	.34821-03	.55606+01	.93904-03
4	.10443-04	.52112-02	.63854-03	.20068-03	.75038-04	.24790-04	.34789-03	.55606+01	.93904-03
5	.10443-04	.52112-02	.63854-03	.20068-03	.75039-04	.24790-04	.34735-03	.55606+01	.93905-03
6=	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.56097+01	.00000
7	.10443-04	.52112-02	.63855-03	.20068-03	.75040-04	.24791-04	.34656-03	.55605+01	.93906-03
8=	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.56097+01	.00000
9	.10444-04	.52113-02	.63856-03	.20068-03	.75041-04	.24791-04	.34550-03	.55605+01	.93907-03
10=	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.56096+01	.00000
11	.10444-04	.52114-02	.63857-03	.20069-03	.75042-04	.24791-04	.34414-03	.55605+01	.93909-03
12	.10444-04	.52115-02	.63859-03	.20069-03	.75044-04	.24792-04	.34245-03	.55605+01	.93911-03
13	.10444-04	.52115-02	.63859-03	.20069-03	.75044-04	.24792-04	.34245-03	.55605+01	.93911-03
14	.10366-04	.51725-02	.66530-03	.20909-03	.78184-04	.25829-04	.34984-03	.52973+01	.97840-03
15	.10368-04	.51738-02	.66592-03	.20928-03	.78257-04	.25853-04	.33215-03	.52937+01	.97932-03
16	.10372-04	.51754-02	.66700-03	.20962-03	.78383-04	.25895-04	.30154-03	.52868+01	.98090-03
17	.99455-05	.49628-02	.81508-03	.25616-03	.95785-04	.31644-04	.30528-03	.41486+01	.11987-02
18	.99360-05	.49581-02	.82594-03	.25957-03	.97062-04	.32066-04	.22326-03	.40901+01	.12146-02

*** CHANNEL INPUT ***

CHANNEL NUMBER ICHAN	RELATIVE FLUX FRACP	ORIFICE VEL HEADS VH	***** CHANNEL FCI	HOT SPOT FACTORS FILM FFI	***** POWER FPI	POWER MWE POWZ	FISSILE DENSITY PFX	FLOW KGM/SEC FLO	CAN DIAMETER COD
1	1.0000	.28814	1.20400	1.24800	1.15300	3.19761	.94556	5.57915	.80680
2*	.9995	.00000	1.20389	1.24800	1.15300	.00000	.94556	.00000	.80680
3	.9995	.27376	1.20389	1.24800	1.15300	15.98076	.94556	27.89734	.80680
4	.9982	.30037	1.20379	1.24800	1.15300	38.30414	.94556	66.88984	.80680
5	.9961	.37656	1.20369	1.24800	1.15300	38.22056	.94557	66.73393	.80680
6*	.9961	.00000	1.20368	1.24800	1.15300	.00000	.94557	.00000	.80680
7	.9930	.46403	1.20354	1.24800	1.15300	76.20195	.94558	133.02927	.80680
8*	.9888	.00000	1.20341	1.24800	1.15300	.00000	.94559	.00000	.80680
9	.9888	.56969	1.20341	1.24800	1.15300	75.88557	.94559	132.52159	.80680
10*	.9836	.00000	1.20327	1.24800	1.15300	.00000	.94561	.00000	.80680
11	.9836	.70908	1.20327	1.24800	1.15300	94.35767	.94561	164.82084	.80680
12	.9773	.88575	1.20312	1.24800	1.15300	93.74680	.94563	163.78446	.80680
13	.9773	.89185	1.20312	1.24800	1.15300	37.49872	.94563	65.51264	.80680
14	.9978	.00026	1.20029	1.24800	1.15300	153.14650	.98520	271.04529	.80680
15	.9481	.96057	1.19511	1.24800	1.15300	163.71501	.98612	294.96923	.80680
16	.8638	3.43439	1.18962	1.24800	1.15300	165.73107	.98771	303.05515	.80680
17	.8797	1.52938	1.17725	1.24800	1.15300	185.65807	1.20700	355.56156	.80680
18	.6490	10.89891	1.15115	1.24800	1.15300	149.42151	1.22308	306.35763	.80680

*** CHANNEL OUTPUT ***

CHANNEL	VOLUME ZONE VV	RADIUS ZONE RAD	NUMBER RODS XNN	ORIFICE DIAMETER DORIF	FUEL ENRICHMENT ENRCH	TEMP. RISE DIT	** SURFACE NOMINAL TMAXX	MAX HOTSPOT TMAXLX	*** REYNOLDS NUMBER REE	KW PER FT XKWF	PRESSURE DROP PDRX
1	43.359	10.679	264.00	13.388	.11599	273.36	650.3	729.8	84442.	10.44	.017366
2*	43.359	15.103	.00	.000	.11513	.00	.0	.0	0.	.00	.000000
3	216.797	28.254	1320.00	13.404	.11599	273.22	650.1	729.8	84500.	10.44	.017385
4	520.313	46.549	3168.01	13.375	.11599	273.13	650.0	729.8	84425.	10.43	.017351
5	520.313	59.459	3168.01	13.293	.11600	273.17	650.0	730.0	84184.	10.41	.017255
6*	260.157	64.959	.00	.000	.11514	.00	.0	.0	0.	.00	.000000
7	1040.626	83.407	6336.01	13.203	.11600	273.21	650.0	730.1	83911.	10.39	.017146
8*	260.157	87.413	.00	.000	.11514	.00	.0	.0	0.	.00	.000000
9	1040.626	101.373	6336.01	13.097	.11600	273.12	649.8	730.1	83598.	10.35	.017016
10*	260.157	105.178	.00	.000	.11514	.00	.0	.0	0.	.00	.000000
11	1300.783	120.348	7920.01	12.964	.11600	273.05	649.6	730.1	83186.	10.30	.016848
12	1300.783	133.810	7920.01	12.805	.11600	273.00	649.5	730.1	82669.	10.24	.016640
13	520.313	138.829	3168.01	12.800	.11600	273.00	649.5	730.1	82651.	10.24	.016633
14	2081.253	157.314	12672.02	13.722	.12082	269.49	645.7	730.1	85708.	10.59	.017740
15	2341.409	175.802	14256.02	12.740	.12091	264.72	639.3	729.9	83204.	10.29	.016558
16	2601.566	194.291	15840.02	11.221	.12109	260.83	633.4	729.8	77157.	9.59	.014142
17	2861.723	212.781	17424.03	12.297	.14775	249.04	619.8	730.2	83024.	10.27	.015943
18	3121.879	231.273	19008.03	9.212	.14964	232.63	596.7	729.8	66430.	8.37	.009900

CHANNEL	M	LOCATION OF HOT SPOTS		ROUGH CONSTANTS		THEAN	GG	SMOOTH FRACTION
		NOMINAL	WITH HOT SPOT FACTORS	STANTON	FRICITION			
1	.76966	.94814	.9229	.00484	.06876	1138.	37.72	.4722
2*	.00000	.00000	.0000	.00000	.00000	0.	.00	.0000
3	.76981	.94809	.9228	.00484	.06876	1137.	37.75	.4721
4	.76967	.94814	.9228	.00484	.06876	1137.	37.71	.4722
5	.76915	.94830	.9230	.00485	.06876	1135.	37.60	.4724
6*	.00000	.00000	.0000	.00000	.00000	0.	.00	.0000
7	.76860	.94847	.9232	.00485	.06876	1133.	37.48	.4725
8*	.00000	.00000	.0000	.00000	.00000	0.	.00	.0000
9	.76798	.94866	.9234	.00486	.06876	1131.	37.34	.4728
10*	.00000	.00000	.0000	.00000	.00000	0.	.00	.0000
11	.76716	.94891	.9237	.00486	.06875	1128.	37.15	.4731
12	.76612	.94923	.9241	.00487	.06875	1124.	36.92	.4735
13	.76606	.94925	.9241	.00487	.06875	1124.	36.91	.4735
14	.77187	.94746	.9213	.00483	.06877	1133.	38.18	.4701
15	.76737	.94885	.9221	.00486	.06875	1100.	36.94	.4704
16	.75539	.95256	.9257	.00494	.06870	1049.	34.15	.4740
17	.76630	.94918	.9190	.00486	.06875	1047.	36.43	.4651
18	.73202	.95993	.9274	.00509	.06858	900.	28.78	.4729
		.9510	.9234	1.6783	3.6169	1067.		.4713

AXIAL TEMPERATURE DISTRIBUTION FOR CHANNEL 1

RELATIVE DISTANCE	WITHOUT HOT SPOT FACTORS				WITH HOT SPOT FACTORS				FLUX
	SURFACE TEMPERATURE DEG.C	FUEL AVERAGE TEMPERATURE* DEG.C	GAS TEMPERATURE DEG.C	*	SURFACE TEMPERATURE DEG.C	CENTERLINE TEMPERATURE* DEG.C	GAS TEMPERATURE DEG.C	CLAD INSIDE DEG.C	
.00000	419.59	687.50	311.26	*	446.46	1024.86	311.26	462.12	.52266
.05000	446.25	781.01	320.51	*	479.32	1205.60	322.40	497.49	.60682
.10000	472.92	872.59	331.09	*	512.14	1378.38	335.14	532.64	.68466
.15000	499.33	959.37	342.89	*	544.58	1537.55	349.34	567.21	.75537
.20000	525.21	1039.33	355.77	*	576.31	1679.73	364.85	600.81	.81822
.25000	550.28	1111.07	369.62	*	606.99	1803.26	381.53	633.12	.87254
.30000	574.29	1173.75	384.28	*	636.31	1907.56	399.18	663.80	.91779
.35000	596.98	1226.87	399.61	*	663.96	1992.70	417.63	692.52	.95347
.40000	618.13	1270.19	415.44	*	689.65	2059.06	436.69	718.98	.97923
.45000	637.50	1303.58	431.60	*	713.12	2107.11	456.15	742.92	.99479
.47224	645.50	1315.23	438.86	*	722.78	2122.72	464.89	752.68	.99839
.47224	562.07	1217.72	438.86	*	618.65	2001.47	464.89	648.56	.99839
.50000	571.34	1230.03	447.94	*	629.83	2017.48	475.82	659.78	1.00000
.55000	587.03	1244.93	464.28	*	648.69	2032.88	495.49	678.49	.99479
.60000	601.27	1250.51	480.44	*	665.75	2031.23	514.96	695.08	.97923
.65000	613.92	1246.79	496.27	*	680.83	2012.71	534.01	709.39	.95347
.70000	624.84	1233.82	511.60	*	693.79	1977.41	552.47	721.28	.91779
.75000	633.92	1211.72	526.26	*	704.48	1925.42	570.12	730.61	.87254
.80000	641.06	1180.67	540.11	*	712.79	1856.83	586.79	737.30	.81822
.85000	646.20	1140.97	553.00	*	718.63	1771.90	602.31	741.26	.75537
.90000	649.28	1093.13	564.79	*	721.95	1671.16	616.51	742.46	.68466
.95000	650.26	1037.87	575.37	*	722.71	1555.62	629.25	740.89	.60682
1.00000	649.14	976.23	584.62	*	720.91	1426.97	640.38	736.57	.52266

* USING ASAMOTO FUEL CONDUCTIVITY FORMULA

MAXIMUM FUEL TEMPERATURE BEFORE DENSIFICATION - 2034.5 DEG C
 MAXIMUM FUEL TEMPERATURE AFTER DENSIFICATION - 1920.4 DEG C
 FINAL FUEL PELLETT HOLE DIAMETER = .12642 CM

CLADDING MAXIMUM THERMAL STRESS - 10473.4 PSI

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 327.8 I
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 307.8 I*

* .000 * .100 * .200 * .300 * .400 * .500 * .600 * .700 * .800 * .900 * 1.000
 FRACT LENGTH

10-15

NEUTRON FLUX

GAZELLE INPUT VALUES

Q	H	XB	CD	XN	CV	XF	PF
1.121	.0010	.2329	.8068	*****	.5228	.2876	1.0430
EL	V	ENSPAC	WRAT	TO	DT	TMAX	
121.020	20336.	13.0	.0318	311.3	261.2	596.7	

HEXVOL SUBROUTINE INPUT

CRN	DISP	GCF	GBR	BWT	ROWS	SHIGH		
19.	264.	.01400	.4600	.0168	10.	1.300		
TEXPC	DTCL	TASS	PLTOD	TDPUD	TDUO	FTD		
.186-04	20.0	24.0	1.000	11.46	10.97	.893		
FP39	FP40	FP41	FP42	FU35	FU38	F02		
.680	.214	.080	.026	.003	.998	1.000		
S316C	S316MN	S316P	S316S	S316SI	S316CR	S316NI	S316MO	S316FE
.00080	.02000	.00045	.00030	.01000	.17000	.12000	.02500	.65000
TOL	TS16CR	TS16NI	TS16MO	TS16FE	S316D	SS316		
MAX	.0100	.0200	.0050	.0300	.290	316 SS		
ATWTC	ATWTMN	ATWTP	ATWTS	ATWTSI	ATWTCR	ATWTNI	ATWTMO	ATWTFE
12.01	54.93	30.98	32.07	28.09	52.01	58.69	95.95	55.85

CORE GEOMETRY AND COMPOSITION FOR GCFR CASE -

GCFR CORE GEOMETRY AT AVERAGE OPERATING TEMPERATURE

FUEL ROD

* = GAZELLE INPUT VALUE
 ** = SUBROUTINE INPUT VALUE

OUTPUT VALUES

* FUEL ROD OD = .80680 CM.(.31764 IN)
 * INFINITE LATTICE ROD PITCH = 1.11229 CM.(.43791 IN)
 ** BOX WALL TO ROD GAP/INTER ROD GAP = .46000
 * OUTSIDE/INSIDE FUEL CLAD DIAMETER = 1.12100
 * RATIO OF HOLE TO CLAD ID = .00100
 ** DIAMETRAL GAP, FUEL TO CLAD = .01400 CM.(.00551 IN)
 ** CORE LENGTH = 121.020 CM.(47.646 IN)

FUEL ROD PITCH (TRIANGULAR) = 1.11229 CM.(.43791 IN)
 BOX WALL TO ROD GAP = .14053 CM.(.05532 IN)
 FUEL CLAD THICKNESS = .04354 CM.(.01714 IN)
 DIAMETER OF CENTER HOLE IN FUEL PELLET = .00072 CM.(.00028 IN)

HEXAGONAL FUEL ELEMENT

** ROWS OF RODS IN BOX = 10.0
 ** FUEL RODS DISPLACED BY A CONTROL ROD = 264.

NUMBER OF FUEL RODS IN AN ELEMENT = 264.
 HEX INSIDE DIAM. ACROSS FLATS = 18.427 CM.(7.255 IN.)
 INSIDE HEX BOX SIDE LENGTH = 10.63868 CM.(4.188 IN)
 OUTSIDE HEX ACROSS FLATS = 19.04587 CM.(7.498 IN)
 GAP BETWEEN ELEMENTS = 1.29398 CM.(.5094 IN)
 FUEL ELEMENT PITCH = 20.33985 CM.(8.0078 IN)

** BOX WALL THICKNESS = .30957 CM.(.12188 IN)

CORE COMPOSITION

** NUMBER OF BOXES WITH CONTROL RODS = 19.
 * FUEL RODS SET BY HEAT TRANSFER = 118800.

NUMBER OF FUEL ONLY BOXES = 450.
 NUMBER OF CORE BOXES = 469.
 FUEL RODS ADDED TO FILL LAST BOX = 0.
 TOTAL RODS TO FILL BOXES = 118800.

VOLUME AND VOLUME FRACTIONS FOR THE CORE

	VOLUME,CC	VOLUME FRACTION	GAZELLE VOL. FR.	FUEL ELEMENT	CONTROL ELEMENT
CENTER FUEL PELLET HOLE	6.	.00000		.00000	.00000
COOLANT WITHIN BOXES	8162293.	.40155		.41832	.00000
FUEL EXCLUDING CENTER HOLE	5623709.	.27666	.28763	.28822	.00000
FUEL TO CLAD GAP	225340.	.01109		.01155	.00000
CLADDING	1501108.	.07385	(VFRAC VALUE= .06149)	.07693	.00000
BLOCKAGE COMPONENTS					
CONTROL RODS	(667651.)	(.03285)		(.00000)	(.81041)
BOX WALL INCLUDING CONTROL SHROUDS	(1316938.)	(.06479)	(XSTEEL= .06481)	(.06513)	(.05608)
SUPPORT PIN VOIDS	(325032.)	(.01599)		(.01666)	(.00000)
INTER BOX GAP	(2505109.)	(.12324)		(.12324)	(.12324)
BLOCKAGE	4814730.T	.23686	.23286	.20502	.98973
SPACERS(INCLUDED IN BOX WALL)	(93106.)	(.00458)		(.00477)	(.00000)
TOTALS					
SUMMATION	20327185.	1.00000		1.00004	.98973
OVERALL DIMENSIONS	20335875.		20336. (IN LITERS)		
() NOT INCLUDED IN SUM					

CORE GEOMETRY AND COMPOSITION FOR GCFR CASE -

GCFR CORE GEOMETRY AT ROOM TEMPERATURE, 24C (75F)

AVERAGE OPERATING TEMPERATURE OF STRUCTURE = 441.8 C.
AVERAGE OPERATING TEMPERATURE OF CLAD = 486.1 C.
CORE INLET TEMPERATURE = 311.3 C.
CORE AVERAGE OUTLET TEMPERATURE = 572.4 C.

MEAN COEFFICIENT OF THERMAL EXPANSION = .186000-04 1/C

AGV. LINEAR DIMENSION CHANGE (OPERATING TO ASSEMBLY)

-CORE STRUCTURE = -.771 %
-FUEL CLAD = -.852 %
-CORE INLET = -.531 %
-CORE OUTLET = -1.010 %

FUEL ROD

FUEL ROD OD = .79993 CM. (.31493 IN)
FUEL ROD PITCH (TRIANGULAR) = 1.10371 CM. (.43453 IN)
MINIMUM GAP BETWEEN RODS = .30379 CM. (.11960 IN)
MINIMUM GAP BETWEEN ROD AND BOX WALL = .13977 CM. (.05503 IN)
CLAD WALL THICKNESS = .04317 CM. (.01700 IN)
FUEL ROD ID = .71358 CM. (.28094 IN)
DIAMETRAL FUEL PELLET CLEARANCE = .01400 CM. (.00551 IN)
COLD FUEL PELLET OD = .69958 CM. (.27543 IN.)
DIAMETER OF CENTER HOLE IN FUEL PELLET = .00072 CM. (.00028 IN)
CONTRACTION OF HOLE FROM OPERATING TEMPERATURE NEGLECTED
FUEL PELLET LENGTH = .69958 CM. (.27543 IN)
CORE LENGTH = 119.989 CM. (47.240 IN)

FUEL ELEMENT

FUEL ELEMENT PITCH (EXPANSION CONTROL BY TOP CORE SUPPORT) = 20.23175 CM. (7.96524 IN)
INSIDE HEX ACROSS FLATS = 18.28463 CM. (7.19866 IN)
OUTSIDE HEX ACROSS FLATS = 18.89899 CM. (7.44053 IN)
BOX WALL THICKNESS = .30718 CM. (.12094 IN)
GAP BETWEEN ELEMENTS = 1.33276 CM. (.52471 IN)

FIRST ROW MAXIMUM POWERED BLANKET ELEMENT

PARALLEL FLOW OF COOLANT - HOT CHANNEL ANALYSIS

CV .3870 DH .8594 APAR 96.47 GP 39.36

ROWS 6.0 RODS 91.0 BPITCH 20.340 GBR 1.00000 V/F .45000 XB .17927 XT 1.18222 Q 1.04190 EL 121.02 RATIO 1.12000 GCF .01400

FRACT .8400 POWRAT 1.1400 TILT 1.7400 WTPCC 212.198 RISEF .4500 FC 1.3000 FF 2.0450 PEAK 1.1270 CV .3870 TILTEF 1.5000

CD 1.5881 SIDE 10.6387 FLAT 18.4267 PASS 20.0000 HV 54.9788 EPSA 1.2000 B1 78.0 B2 84.0 B3 90.0 VFSTL .09573 W 3797.4

H	TA	T	PPAR	P	REAVE	TMAX	HA	TFUEL	XKL
		.3017+03		.9855+02					
.6139+05	.3259+03	.3229+03	.0000	.0000	.1068+05	.4376+03	.6558+00	.1242+04	.5809+01
.7029+05	.3324+03	.3289+03	.0000	.0000	.1060+06	.4601+03	.6566+00	.1381+04	.6650+01
.7845+05	.3397+03	.3358+03	.0000	.0000	.1052+06	.4821+03	.6575+00	.1510+04	.7422+01
.8578+05	.3478+03	.3436+03	.0000	.0000	.1043+06	.5033+03	.6585+00	.1627+04	.8116+01
.9222+05	.3566+03	.3520+03	.0000	.0000	.1033+06	.5235+03	.6595+00	.1732+04	.8725+01
.9769+05	.3659+03	.3611+03	.0000	.0000	.1022+06	.5425+03	.6606+00	.1822+04	.9243+01
.1021+06	.3758+03	.3708+03	.0000	.0000	.1012+06	.5601+03	.6618+00	.1898+04	.9664+01
.1055+06	.3860+03	.3808+03	.0000	.0000	.1001+06	.5761+03	.6630+00	.1958+04	.9983+01
.1078+06	.3966+03	.3912+03	.0000	.0000	.9906+05	.5903+03	.6642+00	.2002+04	.1020+02
.1089+06	.4072+03	.4019+03	.0000	.0000	.9800+05	.6027+03	.6654+00	.2030+04	.1031+02
.1089+06	.4180+03	.4126+03	.0000	.0000	.9697+05	.6131+03	.6666+00	.2040+04	.1031+02
.1078+06	.4287+03	.4234+03	.0000	.0000	.9597+05	.6215+03	.6678+00	.2033+04	.1020+02
.1055+06	.4392+03	.4340+03	.0000	.0000	.9501+05	.6276+03	.6689+00	.2010+04	.9983+01
.1021+06	.4494+03	.4444+03	.0000	.0000	.9409+05	.6315+03	.6700+00	.1969+04	.9664+01
.9769+05	.4593+03	.4545+03	.0000	.0000	.9324+05	.6332+03	.6710+00	.1913+04	.9243+01
.9222+05	.4686+03	.4641+03	.0000	.0000	.9244+05	.6326+03	.6720+00	.1841+04	.8725+01
.8578+05	.4774+03	.4732+03	.0000	.0000	.9171+05	.6298+03	.6729+00	.1753+04	.8116+01
.7845+05	.4855+03	.4816+03	.0000	.0000	.9104+05	.6247+03	.6737+00	.1652+04	.7422+01
.7029+05	.4929+03	.4894+03	.0000	.0000	.9045+05	.6174+03	.6745+00	.1538+04	.6650+01
.6139+05	.4993+03	.4963+03	.0000	.0000	.8994+05	.6080+03	.6751+00	.1412+04	.5809+01
		.5024+03		.0000					
		.5367+03		.9786+02					

TOTAL PRESSURE DROP= .686 ATM, (69.482 KPA) (10.080 PSI)

RE1 FM1 RE2 FM2 RE3 FM3
.10984+06 .13215+01 .10268+06 .13198+01 .96574+05 .13182+01

THIS VERSION OF CYCOST, THE FUEL CYCLE COST CODE, IS BASED ON MEMO BY R SHANSTROM 12/9/67

OPTIONS SELECTED

OPT 1= 1 OPT 2= 0 OPT 3= 0 OPT 4= 0 OPT 5= 0 OPT 6= 0 OPT 7= 0 OPT 8= 0

TOTAL TO CORE FISSIONS	1.1200+00	B1
TOTAL TO CORE POWER	1.1200+00	B2
MAX BURNUP (MWD/T)	1.0000+05	EMAX
MWHR(SITH)/KG FISSIONED	2.3520+04	EFIS
TOTAL/FISSION FISSIONS	1.2366+00	ZETA
FISSION CAPTURE/FISSION	2.1988-01	ALFA
FABRICATION COST FACTOR	.5000	FCR
FRACTION CORE PER CYCLE	.3333+00	FPROC
PK/AVG BURNUP/ PK/AVG PWR	1.0000+00	FACTOR
REACTOR LOAD FACTOR	.750	XLDFAC
METAL DENSITY IN FUEL GM/CC	8.3377+00	RHOMET
ELECT CAP SERVED BY FAB PLT	1.5000+04	ELCAP
REP PLT CAP SCALE FACTOR	5.3000-01	XXXM
RAD BLK THICKNESS CM	5.5479+01	BLKTHK
CORNER BLK LGTH/AX BLK LGTH	1.0000+00	OVERLP
RAD BLK/CORE FUEL MET A.D.	1.5260+00	RHORAT
RAD BLK REPROCESSING FRACT	7.5000-01	RECYC
RAD BLK PIN O.D. (CM)	1.5881+00	BD
TOTAL FAB + REP LOSS FRACT.	2.0000-02	XLOSS
FISSION VALUE \$/KG	2.5000+04	P9
REP. PLANT CHG. \$/KG	3.1000+02	PR
SHIPPING, FRESH FUEL \$/KG	1.0000+01	PHFR
SHIPPING, SPENT FUEL \$/KG	3.0000+01	PHSP
INTEREST RATE, FUEL ITEMS	1.4000-01	CAPF
INTEREST RATE, NON FUEL	1.4000-01	CAPW
PRE REACTOR HOLDUP , YRS.	5.0000-01	T1
POST REACTOR HOLDUP, YRS.	5.0000-01	T3
REPROCESSING PLT. LOAD FACT	7.1230-01	RPLDFC

FABRICATION COST CONSTANTS

CORE FUEL FACTOR	1.1200+02	AAC
AX BLK FUEL FACTOR	6.0000+00	AAA
RAD BLK FUEL FACTOR	7.5000+01	AAR
THROUGHPUT FACTOR, CORE	2.5000-01	XXNC
THROUGHPUT FACTOR, AX BLK	2.5000-01	XXNA
THROUGHPUT FACTOR, RAD BLK	2.5000-01	XXNR
FUEL PIN MASS FACTOR, CORE	3.5000-01	XXKC
FUEL PIN MASS FACTOR,AX BLK	3.5000-01	XXKA
FUEL PIN MASS FACTOR,RD BLK	3.5000-01	XXKR

BREAKDOWN OF CORE AND BLANKET FABRICATION COST

DOLLARS/KG CORE FUEL

	CORE	AXIAL BLANKET	RADIAL BLANKET
GEOMETRY PER KG CORE FUEL			
KG FISSILE	.1230	*****	*****
NO. PELLETS	.4096+03	.4061+03	.2718+02
NO. RODS	.2436+01	.0000	.3424+00
NO. ELEMENTS	.9617-02	*****	.3876-02
NO. SPACER HOLES	.3167+02	*****	.1696+01
LENGTH OF ROD, CM	.5871+03	.0000	.8253+02

FABRICATION COST, DOLLARS/KG FUEL

PELLETS	487.2	235.3	54.4
ELEMENT ASSEMBLY	682.1	101.5	57.5
MATERIALS	.0	.0	.0
TOTAL	1169.3	336.8	111.9

FABRICATION COST OF ONE CORE ASSEMBLY 156611. DOLLARS

FABRICATION COST OF ONE RADIAL BLANKET ASSEMBLY 28871. DOLLARS

CALCULATION OF BREEDING RATIO AND DOUBLING TIME

INITIAL FISSILE INVENTORY,KG	6100.76	FBOC	
OUT OF REACTOR FACTOR	1.2490	ORF	
FISSILE PRODUCED (GROSS),KG	1736.38	FPROD	(PLUTONIUM 1736.38 U-233 .001
RELOAD CYCLES PER YEAR	.7472	CYC	
FRACTION OF CORE RELOADED PER CYCLE	.3333	FPROC	
REACTOR FISSILE DESTR. (EX PU41 DECAY),KG	1181.03	FDEST	
IN REACTOR PU241 DECAY,KG	39.67	P41C	
FINAL REACTOR FISSILE INVENTORY,KG	5918.25	FEOC	
FISSILE GAIN,KG	515.69	FGAIN	
BREEDING RATIO WITH LOSSES	1.4225	BR	
OUT OF REACTOR REPROCESSING LOSS,KG	40.06	OUTLOS	
OUT OF REACTOR PU241 DECAY,KG	9.73	P41L	
COMPOUND INVENTORY DOUBLING TIME, YEARS	14.942	DUBTIM	

RAD28	FR49R	P49R	U25R	FISINR	AX28	FR49A	P49A	U25A	FISINA
.8519+05	.1003-01	.1071+02	.0000	.3205+03	.5046+05	.2541-01	.5426+02	.0000	.4274+03

ROUGH ESTIMATE OF BLANKET HEAT RATES

RATIO-BOEC	1.07359
RATIO-EOEC	1.09418
AXRAT	1.57756

OUTPUT EDIT

FUEL CYCLE COST DERIVED PARAMETERS

TOT MWD PER TONNE OF CORE FUEL	32747.1992
ELECTRICAL ENERGY TERM (KG/MW-HR(E))	.0013987
THERMAL ENERGY YIELD TERM (MW-HR(T)/KG)	26703.2021
DESTRUCTIONS OF FISSILE/ INITIAL FISSILE ATOM	.1936
RATIO OF FINAL TO INITIAL FISSILE	1.2700
BREEDING RATIO CORRECTED FOR PU241 DECAY	1.4225

RADIAL PEAK/AVG POWER (IN CORE)	1.1304
AXIAL PEAK/AVG POWER (IN CORE)	1.1973
PEAK/AVG BURNUP IN CORE	1.3535
MID CYCLE CORE FISSILE INVENTORY, KG	6009.5
MID CYCLE AXIAL BLANKET FISSILE INVENTORY	641.1
MID CYCLE RADIAL BLANKET FISSILE INVENTORY	427.3
NET FISSILE GAIN PER YEAR	348.1

SPECIFIC POWER (MW/KG)	.5879
INITIAL ENRICHMENT	.1280
ELECTRICAL OUTPUT (MW)	1291.2278
EFFICIENCY	.3600

FUEL SHEAR DENSITY, FRACTION THEO.	.8587
PRE REACTOR HOLDUP TIME (YRS) (**)	.5000
IN CORE TIME (YRS)	4.0153
POST REACTOR HOLDUP TIME (YRS (**)	.5000
DOUBLING TIME (YRS)	14.9423
MAXIMUM NEUTRON FLUX (OVER .1 MEV)	2.5666+15
MAXIMUM NEUTRON FLUENCE (OVER .1 MEV)	2.4379+23

** INDICATES INPUT QUANTITY

FUEL CYCLE COSTS FOR 20335 LITER (1291 MW(E)) REACTOR

	S/KG FUEL IN CORE		MILLS PER KW-HR						
DEPLETION									
BUY FISSILE	3233.1		4.522						
SELL FISSILE	-4024.9		-5.630						
SUBTOTAL	-791.7		-1.107						
FABRICATION									
CORE	OLD	NEW	OLD	NEW					
AXIAL BLANKET	234.1	1169.3	.327	1.636					
RADIAL BLANKET	12.5	336.8	.018	.471					
SUBTOTAL	29.4	111.9	.041	.157					
	276.1	1618.0	.386	2.263					
REPROCESSING	682.6		.955						
SHIPPING									
FRESH FUEL	26.2		.037						
SPENT FUEL	78.7		.110						
SUBTOTAL	104.9		.147						
NON WORKING CAPITAL	271.8	1613.8	.380	2.257					
WORKING CAPITAL COSTS									
NON FUEL ITEMS									
FABRICATION	96.9	568.0	.136	.795					
REPROCESSING	-239.6		-.335						
SHIPPING	-36.8		-.052						
FUEL ITEMS									
BOUGHT FUEL									
PRE-REACTOR	226.3		.317						
REACTOR	908.7		1.271						
SUBTOTAL	1135.1		1.588						
SOLD FUEL									
REACTOR	1131.3		1.582						
POST- REACTOR	281.7		.394						
SUBTOTAL	1413.0		1.976						
					WORKING CAPITAL BY CASH FLOW METHOD				
WORKING CAPITAL SUBTOTAL	2368.5	2839.7	3.313	3.972	2.835				
NET FUEL CYCLE COST	2640.3	4453.5	3.693	6.229	3.215				
AK	PHM(1)	SU(1)	UTOP(1)	SPU(1)	PU40C	TIM2	XP(1)	XP(3)	AKPH
.4166-16	.3403+16	.2751+00	.5559+01	.1676+01	.5270-01	.4015+01	.6800+00	.7991-01	-.1470-01
.4166-16	.3401+16	.2751+00	.5559+01	.1676+01	.5270-01	.4015+01	.6800+00	.7991-01	-.1470-01
.4166-16	.3401+16	.2751+00	.5559+01	.1676+01	.5270-01	.4015+01	.6800+00	.7991-01	-.1470-01
.4166-16	.3397+16	.2751+00	.5559+01	.1676+01	.5270-01	.4015+01	.6800+00	.7991-01	-.1469-01
.4166-16	.3389+16	.2751+00	.5559+01	.1676+01	.5270-01	.4015+01	.6800+00	.7991-01	-.1467-01
.4166-16	.3389+16	.2751+00	.5559+01	.1676+01	.5270-01	.4015+01	.6800+00	.7991-01	-.1467-01
.4166-16	.3378+16	.2751+00	.5559+01	.1676+01	.5270-01	.4015+01	.6800+00	.7991-01	-.1464-01

WORKING CAPITAL BY CASH FLOW METHOD

.4166-16	.3364+16	.2751+00	.5559+01	.1676+01	.5270-01	.4015+01	.6800+00	.7991-01	-.1461-01
.4166-16	.3364+16	.2751+00	.5559+01	.1676+01	.5270-01	.4015+01	.6800+00	.7991-01	-.1461-01
.4166-16	.3347+16	.2751+00	.5559+01	.1676+01	.5270-01	.4015+01	.6800+00	.7991-01	-.1457-01
.4166-16	.3347+16	.2751+00	.5559+01	.1676+01	.5270-01	.4015+01	.6800+00	.7991-01	-.1457-01
.4166-16	.3325+16	.2751+00	.5559+01	.1676+01	.5270-01	.4015+01	.6800+00	.7991-01	-.1452-01
.4166-16	.3325+16	.2751+00	.5559+01	.1676+01	.5270-01	.4015+01	.6800+00	.7991-01	-.1452-01
.4166-16	.3278+16	.2731+00	.5291+01	.1672+01	.5270-01	.4015+01	.6800+00	.7991-01	-.2550-01
.4166-16	.3112+16	.2731+00	.5291+01	.1672+01	.5270-01	.4015+01	.6800+00	.7991-01	-.2454-01
.4166-16	.2831+16	.2731+00	.5291+01	.1672+01	.5270-01	.4015+01	.6800+00	.7991-01	-.2291-01
.4166-16	.2423+16	.2643+00	.4117+01	.1663+01	.5270-01	.4015+01	.6800+00	.7991-01	-.5571-01
.4166-16	.1764+16	.2643+00	.4117+01	.1663+01	.5270-01	.4015+01	.6800+00	.7991-01	-.4233-01

	VFRAC2 -	CAYDES	1.00851						
BURN	.7325+00	.6633+00	.4366+00	.0000	.0000	.0000	.0000	.0000	.0000

APPENDIX A
FAST REACTOR COOLING GENERAL TREATMENT

Consider the core associated with one fuel rod of diameter d_o and core length ℓ . The coolant volume fraction within the boxes = x . With a heat balance made over a short length $\ell \, dy$, the gas temperature rise, assuming a chopped cosine heat production rate, is as follows ($0 \leq y \leq 1$):

$$cG \frac{\pi d_o^2}{4} \frac{x}{1-x} dt_g = AF_c \cos \pi \phi y \left(-\frac{1}{2}\right) \ell \, dy \quad , \quad (A-1)$$

where c is the gas heat capacity, G is the gas mass flow velocity, and F_c is the hot channel factor. The constant A is determined from the total gas temperature rise ΔT by integrating Eq. A-1 over the core length. First define M as follows:

$$M = \frac{\pi \phi d_o x}{4(1-x) K_H \ell} \quad , \quad (A-1a)$$

where K_H is the Stanton number = h/cG . Then

$$t_g - T_o = \frac{AF_c}{\pi M h d_o} \left[\sin \pi \phi \left(y - \frac{1}{2}\right) + \sin \frac{\pi \phi}{2} \right] \quad . \quad (A-2)$$

Now the overall temperature rise, ΔT , is obtained by evaluating Eq. A-2 at $y = 1$,

$$\Delta T = \frac{AF_c}{\pi M h d_o} \left(2 \sin \frac{\pi \phi}{2} \right) \quad ,$$

and

$$A = \frac{\Delta T}{F_c} \frac{\pi M h d_o}{2 \sin \frac{\pi \phi}{2}} \quad (A-3)$$

Substituting this value of A into Eq. A-2 yields

$$t_g - T_o = \frac{\Delta T}{2 \sin \frac{\pi \phi}{2}} \left[\sin \pi \phi \left(y - \frac{1}{2} \right) + \sin \frac{\pi \phi}{2} \right] \quad (A-4)$$

The temperature difference between rod surface and gas is obtained from the heat flux as follows, referring to Eq. A-1 for source heat:

$$(t_s - t_g) \pi d_o h \ell dy = A F_f \cos \pi \phi \left(y - \frac{1}{2} \right) \ell dy \quad ,$$

where F_f is the hot film factor.

Substituting for A from Eq. A-3 yields

$$t_s - t_g = \frac{M \Delta T}{2 \sin \frac{\pi \phi}{2}} \frac{F_f}{F_c} \cos \pi \phi \left(y - \frac{1}{2} \right) \quad .$$

Then substituting for t_g from Eq. A-4 gives

$$t_s = T_o + \frac{\Delta T}{2} \left\{ 1 + \frac{1}{\sin \frac{\pi \phi}{2}} \left[\sin \pi \phi \left(y - \frac{1}{2} \right) + M \frac{F_f}{F_c} \cos \pi \phi \left(y - \frac{1}{2} \right) \right] \right\} \quad (A-5)$$

By differentiating Eq. A-5 with respect to y and setting it equal to zero, the following relations are obtained for the trigonometric terms:

$$\tan \pi \phi \left(y - \frac{1}{2} \right) = \frac{F_c}{F_f M} = \frac{1}{M_o} ,$$

$$\sin \pi \phi \left(y - \frac{1}{2} \right) = 1 / \sqrt{1 + M_o^2} ,$$

$$\cos \pi \phi \left(y - \frac{1}{2} \right) = M_o / \sqrt{1 + M_o^2} .$$

By inserting these values in Eq. A-5, the following relation is obtained for the maximum surface temperature:

$$\frac{T_{s \max} - T_o}{\Delta T} = \frac{1}{2} \left(1 + \frac{1 - M_o^2}{\sin \frac{\pi \phi}{2}} \right) . \quad (A-6)$$

This is the true maximum temperature if it corresponds to a value of $y \leq 1$, which can be obtained from

$$y_m = \frac{1}{2} + \frac{1}{\pi \phi} \cot^{-1} (M_o) .$$

If y_m is greater than 1, the maximum surface temperature will be at the core outlet. Physically, this situation would be approached only for a short core with a very thick axial reflector. In this case, Eq. A-6 should be replaced by the following relation, which is derived from Eq. A-5 by setting $y = 1$:

$$t_s = T_o + \Delta T \left(1 + \frac{M_o}{2} \cot \frac{\pi \phi}{2} \right) .$$

In the remainder of this section, the hot spot factors will be taken equal to unity, that is, $M_o = M$. Rearranging Eq. A-6 yields

$$\left(\frac{x}{1-x}\right) = \frac{4\ell K_H}{\pi \phi d_o} \left\{ \left[\frac{2(T_{s \max} - T_o)}{\Delta T} - 1 \right]^2 \sin^2 \frac{\pi \phi}{2} - 1 \right\}^{1/2}. \quad (A-7)$$

The total head pressure loss in a heated uniform channel is given by*

$$\Delta P = \frac{H_c^2}{2C_p^2 a^2 \bar{\rho} \Delta T^2} \left(\frac{4f\ell}{d_H} + \frac{\Delta T}{T_m} \right), \quad (A-8)$$

where f = Fanning friction factor,**
 H_c = channel power,
 C_p = specific heat,
 a = passage section (per element),
 $\bar{\rho}$ = mean density,
 T_m = mean absolute temperature.

However,

$$h_p = \frac{W \Delta P}{\rho_o} \text{ and } H_c = W C_p \Delta T,$$

where h_p = pumping power,
 W = mass flow per channel,
 ρ_o = entry density.

*"A 1000 MW(e) Gas-Cooled Fast Reactor Study for the Alternate Coolant Task Force," USAEC Report GA-A7804, General Atomic Company, July 21, 1967.

** Where the total channel length exceeds ℓ , the heated length, and/or where part of the length is roughened, an effective value for f must be taken, as discussed later.

Also,

$$\bar{\rho} = \frac{\rho_o}{1 + \frac{\Delta T}{2T_o}}$$

and

$$a = \frac{x}{1-x} \cdot \frac{\pi}{4} d_o^2 \quad \text{and} \quad d_H = \frac{x}{1-x} \frac{d_o}{B},$$

where x = coolant void fraction,

B = (total wetted perimeter)/(heated perimeter).

Putting these values into Eq. A-8 gives

$$\gamma = \frac{32 f \ell H_c^2 \left(\frac{1-x}{x} \right)^3 B x 10^{-7}}{\pi^2 C_p^3 \rho_o^2 \Delta T^3 d_o^5} \left\{ 1 + \frac{\Delta T}{2T_o} \left[1 + \frac{\left(\frac{x}{1-x} \right) d_o}{2 f \ell B} \right] \right\}, \quad (\text{A-9})$$

where γ_p is the pump power fraction. (Note that the factor 10^{-7} is to convert h_p from dyne-cm/sec to watts, to allow use of all CGS units, with heat expressed in watts. C_p here will be in joules/g°C = 4.19 x cal/g°C).

Consider the hottest channel, putting

$$F_1 = \left\{ \left[\frac{2(T_{smax} - T_o)}{\Delta T} - 1 \right]^2 \sin^2 \frac{\pi \phi}{2} - 1 \right\}^{1/2} \quad (\text{A-9a})$$

and

$$F_2 = \left\{ 1 + \frac{\Delta T}{2T_o} \left[1 + \frac{\left(\frac{x}{1-x} \right) d_o}{2f\ell} \right] \right\} .$$

Then, from Eq. A-7,

$$d_o = \frac{4\ell K_H}{\pi \phi} \left(\frac{1-x}{x} \right) F_1 . \quad (A-10)$$

Also, for the general case of hollow fuel elements,

$$H_c = (\text{fuel volume per rod}) \times \rho_F R \alpha ,$$

where ρ_F = fissile density in fuel,

R = rating (total power per unit fissile total inventory),

α = radial (max./mean) power,

so

$$H_c = \left(\frac{\pi d_o^2 \ell}{4K^2} \right) \rho_F R \alpha (1 - h^2) ,$$

where K = ratio of can outside to inside diameter,

h = ratio of fuel void hole diameter to can inside diameter.

Inserting this in Eq. A-9 gives

$$\gamma_P = \frac{\pi f \ell^2 \rho_F^2 R^2 \alpha^2 \phi \times 10^{-7} F_2 (1 - h^2)^2 B}{2 C_P^3 \rho_o^2 \Delta T^3 K_H \left(\frac{x}{1-x} \right)^2 K^4 F_1} , \quad (A-11)$$

where

$$\text{pump power fraction} = \gamma_p = \frac{h_p}{H_c} .$$

However,

$$x = \left[1 - \frac{K^2 x_F}{(1 - h^2)} - x_B \right] / (1 - x_B) = 1 - \frac{K^2 x_F}{(1 - x_B)(1 - h^2)} ,$$

where x = coolant void fraction (in boxes),

x_F = fuel volume fraction,

x_B = structure and control rod blockage ratio,

so

$$\left(\frac{x}{1 - x} \right)^2 K^4 = \left[\frac{(1 - x_B)(1 - h^2)}{x_F} K^2 \right]^2 .$$

Thus, Eq. A-11 may be rearranged to give the obtainable rating, R , in terms of the fuel volume fraction, x_F , required by nuclear considerations.

At the same time, substituting the perfect gas relation,

$$\rho_0 = 0.01215 M P_0 / T_0 ,$$

where M = molecular weight,

P_0 = absolute entry pressure (atm),

yields

$$R = \frac{30.8 P_O M}{\alpha \rho_F \ell (1 - h^2)} \frac{K_H^{1/2}}{f} \left[\frac{(1 - x_B) (1 - h^2)}{x_F} - K^2 \right] \frac{\gamma_P^{1/2} C_P^{3/2} F}{B^{1/2}}, \quad (A-12)$$

where

$$F = \frac{\Delta T^{3/2}}{\phi^{1/2} T_O} \sqrt{\frac{F_1}{F_2}}.$$

(Note: Rating is inversely proportional to l and independent of the core volume, if x_F is fixed.)

However,

$$F_2 = \left\{ 1 + \frac{\Delta T}{2T_O} \left[1 + \frac{\left(\frac{x}{1-x} \right) d_o}{2f\ell B} \right] \right\}.$$

But from Eq. A-10,

$$\left(\frac{x}{1-x} \right) \frac{d_o}{\ell} = \frac{4K_H F_1}{\phi \pi}.$$

Thus,

$$\left(\frac{F_2}{F_1} \right) = \frac{1 + \frac{\Delta T}{2T_O}}{F_1} + \frac{\Delta T K_H}{T_O f \pi \phi B}.$$

Therefore,

$$F = \frac{\Delta T^{3/2}}{\phi^{1/2} T_o} \sqrt{\frac{F_1}{F_2}} = \frac{\Delta T^{3/2}}{\phi^{1/2} T_o \sqrt{\frac{1 + \frac{\Delta T}{2T_o}}{F_1} + \frac{\Delta T K_H}{T_o f \pi \phi B}}}$$

So, finally

$$F = \frac{\Delta T^{3/2}}{T_o \sqrt{\left[\frac{1 + \frac{\Delta T}{2T_o}}{\phi} \right]^2 \sin^2 \frac{\pi \phi}{2} - 1}} + \frac{\Delta T K_H}{T_o f \pi} \quad (A-13)$$

The values of the corresponding dependent variables are obtained as follows.

From Eq. A-10,

$$d_o = \frac{4 \ell K_H}{\pi \phi} \left(\frac{1 - x}{x} \right) F_1, \quad (A-14)$$

where

$$F_1 = \left\{ \left[\frac{2(T_{smax} - T_o)}{\Delta T} - 1 \right]^2 \sin^2 \frac{\pi \phi}{2} - 1 \right\}^{1/2}. \quad (A-9a)$$

Also,

$$\text{max linear rating, } \lambda_{max} = \frac{\pi}{4} \left(\frac{d_o}{K} \right)^2 \rho_F R_{max} (1 - h^2).$$

However,

$$R_{\max} = \frac{R\alpha\phi}{2 \sin \frac{\pi\phi}{2}} .$$

Thus,

$$\lambda_{\max} = \frac{\pi^2 \left(\frac{d_o}{K}\right)^2}{4} \rho_F \cdot \frac{R\alpha\phi(1 - h^2)}{2 \sin \frac{\pi\phi}{2}} . \quad (A-15)$$

Also,

$$x = \left[1 - \frac{K^2 x_F}{(1 - h^2)(1 - x_B)} \right] . \quad (A-16)$$

The pressure drop is

$$\left(\frac{\Delta P}{P_o}\right) = 0.1215 MC_P \gamma_P \left(\frac{\Delta T}{T_o}\right) ,$$

where x_B = fraction of core blocked by structure and control rods, etc.,

K = ratio of can o.d. to i.d.

Also,

$$\text{Power density} = x_F \rho_F R , \quad (A-17)$$

$$\text{Core length, } \ell = \left(\frac{4VZ^2}{\pi} \right)^{1/3} , \quad (A-18)$$

where $z =$ core l/d ratio,

$$\text{Number of rods } n = \left[\frac{\ell^2 x_F K^2}{z^2 d_o^2 (1 - h^2)} \right] , \quad (\text{A-19})$$

$$\text{Reynolds number} = \frac{d_o \ell \rho_F R \alpha (1 - h^2)}{K^2 C_p \Delta T \mu B} , \quad (\text{A-20})$$

where $\mu =$ viscosity.

APPENDIX B
LENGTH NECESSARY TO BE ROUGHENED

Since the entry end of the rods is necessarily overcooled, it is not necessary to apply surface roughening all along the fuel rods. In fact, it is clearly necessary to start roughening only at a distance along which the limiting temperature is reached with smooth tubes. The following calculation gives a convenient relation for the location of the rough-smooth transition point required to equalize the maximum temperature reached in both sections.

The temperature distribution in the bare region is given by*

$$\frac{t_s - T_o}{T_1 - T_o} = \frac{1}{2} \left\{ 1 + \frac{\sin \pi \phi \left(S - \frac{1}{2} \right)}{\sin \frac{\pi \phi}{2}} + C_B \left[\frac{\cos \pi \sigma \left(S - \frac{1}{2} \right)}{\sin \frac{\pi \phi}{2}} \right] \right\}, \quad (B-1)$$

where

$$C_B = \frac{\pi d_o x \phi}{4 \ell K_{HB} (1 - x)},$$

with d_o = rod diameter (cm),

x = voidage fraction of coolant,

ℓ = rod length,

ϕ = length/extrapolated length,

s = fraction of channel length,

t_s = surface temperature °C,

T_1 = exit temperature, °C,

T_o = entry temperature, °C,

K_{HB} = Stanton number in the bare region.

*Compare with Eq. A-5 in Appendix A.

Now it is desired to start roughening at a fraction of length S_s , such that the maximum temperature is reached just at the rough point of start.

In the rough region, the maximum temperature is given by

$$\frac{T_{\text{smax}} - T_o}{T_1 - T_o} = \frac{1}{2} \left[1 + \frac{(1 + C_R^2)}{\sin \frac{\pi\phi}{2}} \right]^{1/2}, \quad (\text{B-2})$$

where

$$C_R = \left[\frac{\pi d_o x \phi}{4 \ell K_{HR} (1 - x)} \right] \quad (\text{B-3})$$

If the effect of roughening is to multiply K_H by η_1 , then

$$C_B = \eta_1 C_R$$

If it is desired to reach the same maximum temperature in rough and smooth sections, then it is necessary to have

$$\frac{\sin \pi\phi \left(S_s - \frac{1}{2} \right)}{\sin \frac{\pi\phi}{2}} + \eta_1 C_R \left[\frac{\cos \pi\phi \left(S_s - \frac{1}{2} \right)}{\sin \frac{\pi\phi}{2}} \right] = \frac{(1 + C_R^2)^{1/2}}{\sin \frac{\pi\phi}{2}}$$

or

$$\sin \left[\pi\phi \left(S_s - \frac{1}{2} \right) \right] + \eta_1 C_R \cos \left[\pi\phi \left(S_s - \frac{1}{2} \right) \right] = (1 + C_R^2)^{1/2}$$

Solution of this equation gives

$$S_s = \frac{1}{2} + \frac{1}{\pi\phi} \arcsin \left[\frac{\left(1 + C_R^2\right)^{1/2} - \eta_1^2 C_R^2 \left(1 - \frac{1}{\eta_1^2}\right)^{1/2}}{1 + \eta_1^2 C_R^2} \right], \quad (B-4)$$

where S_s = channel fraction at rough-smooth transition.

APPENDIX C
USE OF PARTIAL ROUGHENING AND ALLOWANCE
FOR REFLECTOR LOSS

Where surface roughening is used as a heat transfer aid, it is not generally necessary to apply it to all the heated length. Appendix B gives an expression for the fraction of the actual core length that can be left smooth in any particular circumstance so that the same limiting surface temperature is met in rough and smooth sections.

It is now necessary to consider the effect of this partial roughening on the overall pressure drop and at the same time to include the case where the channel length exceeds the heated channel length, l , to include the reflector section.

The equations developed in Appendix A may still be used, but an effective value of friction factor, f , must be used which will in general be higher than that for a smooth tube at the same Reynolds number.

The degree of surface roughening, which is of particular interest, is such that, locally, the normal smooth value of f is multiplied by a factor η_2 , and in return K_H , the heat transfer number, is multiplied by a factor η_1 .

Consider first only the active core section. An expression is desired for the effect of varied smooth fraction on the overall pressure drop. This is complicated by the fact that the local rate of pressure loss per unit length is proportional to local gas temperature. It is therefore necessary to know first the mean gas temperatures in the rough and smooth sections. Because of the unsymmetry of the gas temperature distribution in the separate parts of the fuel element length, these are not obtained from the arithmetic means of entry and exit, but must be obtained by proper integration. If all temperatures are normalized by subtracting entry temperature

and dividing by overall temperature rise, one obtains, with a chopped cosine heat production distribution,

$$t_s = \frac{\int_0^2 \cos \pi \phi \left(s - \frac{1}{2}\right) ds}{\int_0^1 \cos \pi \phi \left(s - \frac{1}{2}\right) ds} ,$$

where s is the fractional location of the point having gas temperature t_s .

Integrating gives

$$t_s = \frac{1}{2} + \frac{\sin \pi \phi \left(s - \frac{1}{2}\right)}{2 \sin \frac{\pi \phi}{2}} .$$

If $\bar{t}_s$ is the mean gas temperature in the bare part, then

$$\bar{t}_s = \frac{1}{S_s} \int_0^{S_s} t_s ds = \frac{1}{2S_s} \left[S_s - \frac{\cos \pi \phi \left(S_s - \frac{1}{2}\right) - \cos \frac{\pi \phi}{2}}{\pi \phi \sin \frac{\pi \phi}{2}} \right] . \quad (C-1)$$

Similarly, in the rough part,

$$\bar{t}_R = \frac{1}{2(1 - S_s)} \left[1 - S_s + \frac{\cos \pi \phi \left(S_s - \frac{1}{2}\right) - \cos \frac{\pi \phi}{2}}{\pi \phi \sin \frac{\pi \phi}{2}} \right] . \quad (C-2)$$

where S_s = total bare fraction of core length.

Now the friction in the rough part is η_2 times that in the smooth part.

If

$$F_c = \frac{\text{Pressure drop of rough part of tube}}{\text{Pressure drop of smooth tube}},$$

then

$$F_c = \frac{S_s \left(\frac{T_o}{\Delta T} + \bar{t}_s \right) + \eta_2 \left(1 - S_s \left(\frac{T_o}{\Delta T} + \bar{t}_R \right) \right)}{\left(T_o / \Delta T \right) + \bar{t}}, \quad (C-3)$$

where T_o = absolute inlet gas temperature,

ΔT = total gas temperature rise across core.

Inserting Eqs. C-1 and C-2, and noting from them also $\bar{t} = 1/2$, finally yields

$$F_c = \left[S_s + \eta_2 (1 - S_s) \right] + \left(\frac{\eta_2 - 1}{\frac{2T_o}{\Delta T} + 1} \right) \left[\frac{\cos \pi \phi \left(S_s - \frac{1}{2} \right) - \cos \frac{\pi \phi}{2}}{\pi \phi \sin \frac{\pi \phi}{2}} \right]. \quad (C-4)$$

Since the portion of the wetted surface area corresponds to the smooth inside area of the fuel smooth channels, the effective value of multiplier in the above equation is as follows:

$$\eta_2 \text{ effective} = \frac{\eta_2 + B - 1}{B},$$

where $B = (\text{total wetted area including channels})/(\text{rod area})$.

Return now to the complete case of active length, ℓ , with end reflectors each of length, L_F . The effective value of f used must be increased in the ratio

$$\frac{2F_c + 2L_F}{\ell} = \left(F_c + \frac{2L_F}{\ell} \right)$$

Returning to the relations of Appendix A, if only the active core section were considered, and if only smooth tubes were used, the value of K_H/f would be η_3 . However, K_H has been multiplied by η_1 by use of roughening, and f has been increased by the factor $(F_c + 2L_F/\ell)$. Therefore, it is necessary to use the value

$$\left(\frac{\eta_3 \eta_1}{F_c + \frac{2L_F}{\ell}} \right) \quad (C-5)$$

for the term KH/f where it appears in Eqs. A-12 and A-13. Then γ_p can be defined as the fractional pumping power expended across the complete core, consisting of partially roughened active section, plus smooth reflectors.

APPENDIX D INTERNAL TEMPERATURES

D.1. VALUES AT THE CORE MIDPLANE

It is convenient to calculate first the can and fuel radial temperature drops at the mid-channel, since the heat flux is at its maximum value there. The corresponding temperatures at any other point in the channel are then easily derived from these initial center of channel length figures.

Let T_F = temperature on fuel rod center line,
 T_{FM} = maximum value of T_F ,
 $\lambda_{\max}$ = maximum value of heat/unit rod length,
 K_F = fuel conductivity,
 K_C = can conductivity,
 d_o = can o.d.,
 K = ratio of can o.d. to can i.d.,
 $\Delta t_{C/2}$ = can temperature drop at mid-channel,
 $\Delta t_{F/2}$ = fuel temperature drop at mid-channel,
 $\Delta t_{T/2} = t_{C/2} + t_{F/2}$.

Consider the case of a fuel element with a center void hole fraction h of the fuel diameter.

D.2. FUEL TEMPERATURE DROP

Consider a length of annular element at the channel mid-plane. The heat per unit area crossing a radius r in the fuel equals

$$\frac{\lambda_{\max}}{2\pi r} \left(\frac{r^2 - R_1^2}{R_2^2 - R_1^2} \right),$$

where R_1 = fuel inner radius,
 R_2 = fuel outer radius.

Thus,

$$\left(\frac{dt}{dr}\right) = \frac{\lambda_{\max}}{2\pi r K_F} \left(\frac{r^2 - R_1^2}{R_2^2 - R_1^2} \right) .$$

Therefore,

$$\begin{aligned} \Delta t_{F/2} &= \frac{\lambda_{\max}}{2\pi(R_2^2 - R_1^2)K_F} \int_{R_1}^{R_2} \frac{r^2 - R_1^2}{r} dr , \\ &= \frac{\lambda_{\max}}{2\pi K_F} \left[\frac{1}{2} - \frac{R_1^2}{(R_2^2 - R_1^2)} \log R_2/R_1 \right] . \end{aligned}$$

Since $h = R_1/R_2$, then finally

$$t_{F/2} = \frac{\lambda_{\max}}{2\pi K_F} \left(\frac{1}{2} - \frac{\log 1/h}{1/h^2 - 1} \right) .$$

When $h = 0$ (solid rod), this reduces to

$$\Delta t_{F/2} = \frac{\lambda_{\max}}{4\pi K_F} .$$

In the can wall,

$$\left(\frac{dt}{dr}\right) = \frac{\lambda_{\max}}{2\pi K_C r} ,$$

$$\Delta t_{C/2} = \frac{\lambda_{\max}}{2\pi K_C} \int_{R_2}^{R_3} \frac{1}{r} dr = \frac{\lambda_{\max}}{2\pi K_C} \log K ,$$

where K = ratio of can o.d. to can i.d.

D.3. MAXIMUM FUEL TEMPERATURE

From knowledge of the mid-channel total internal temperature drop, the maximum fuel temperature with a chopped cosine flux distribution can be obtained as follows.

First, the surface temperature distribution along the channel is obtained from the well-known expression

$$\left(\frac{t_{sz} - T_o}{T_1 - T_o}\right) = \frac{1}{2} \left[1 + \frac{\sin \pi \phi z + \left(\frac{\pi d_H \phi}{4K_H \ell}\right) \cos \pi \phi z}{\sin \frac{\pi \phi}{2}} \right] ,$$

where t_{sz} = surface temperature at fraction z of the channel length beyond the mid-point,

T_o = gas entry temperature,

T_1 = gas outlet temperature,

ϕ = channel length/extrapolated length,

d = passage hydraulic diameter,

ℓ = channel length,

K_H = Stanton number.

However,

$$d_H = d_o \left(\frac{x}{1-x} \right) ,$$

where d_o = can o.d.,

x = coolant void fraction.

Also, the total internal temperature difference at any point is

$$\Delta t_{T/2} \cos \pi \phi z .$$

Adding these expressions yields

$$(T_F - T_o) = \frac{T_1 - T_o}{2} \left\{ 1 + \frac{\sin \pi \phi z + \left[C + \frac{2 \Delta t_{T/2}}{(T_1 - T_o)} \sin \frac{\pi \phi}{2} \right] \cos \pi \phi z}{\sin \pi \phi / 2} \right\} ,$$

where

$$C = \frac{\pi d_o \phi x}{4(1-x)K_H \ell} .$$

This is a maximum when

$$\tan \pi \phi z = \frac{1}{C + \frac{2 \Delta t_{T/2}}{(T_1 - T_o)} \sin \frac{\pi \phi}{2}} .$$

At this point, after substituting and simplifying, the result is

$$(T_{FM} - T_o) = \frac{T_1 - T_o}{2} \left[1 + \frac{\sqrt{1 + \left(C + \frac{2\Delta t_{T/2}}{T_1 - T_o} \sin \frac{\pi\phi}{2} \right)^2}}{\sin \pi\phi/2} \right]$$

The corresponding surface temperature maximum is, of course, obtained by inserting $\Delta t_{T/2} = 0$ in the above expression.

APPENDIX E
ALLOWANCE FOR SPACER PRESSURE DROP

Fuel rods must be supported at points along the length to reduce vibration and thermal bowing. The resulting pressure drop per spacer in terms of the local velocity head is given as follows:

$$\Delta P = \left(\frac{1}{2} \rho V^2 \right) \lambda \frac{S}{(1 - S)^2} ,$$

where S (solidity) is the ratio of spacer frontal area to unperturbed frontal area, and λ is an empirical loss coefficient. The number of spacers per unit length of core will be determined by bowing and vibration experiments, but a reasonable assumption is that the core length per spacer will be proportional to the rod diameter.

The program also makes a correction for the extra drag area of the supporting channel and for entrance and exit losses.

The following input quantities are required for the pressure drop corrections:

CINL - inlet loss coefficient,
COUT - outlet loss coefficient,
SPAN - number of rod diameters per spacer,
CSLD - solidity constant,
WRAT - ratio of spacer thickness to rod diameter,
DRGA - ratio of box inner area to rod area.

The loss coefficient per spacer (λ) is taken as 1.373, based on available spacer drop experiments.

APPENDIX F FUEL CYCLE COST EQUATIONS

The fuel cycle cost calculation used in the code is based on an equilibrium fuel cycle. This appendix describes the method used. In Appendix G, typical values and a sample calculation are shown.

The burnup term, E , in total thermal megawatt days of energy per metric tonne of fuel charged to the reactor core is

$$E = \frac{b E_m}{m} \left[\frac{\text{MWd}(t)}{\text{tonne}} \right] , \quad (\text{F-1})$$

where $E_m \equiv$ maximum core burnup, MWd(t)/tonne of metal,

$m \equiv$ max/avg burnup in core,

$b \equiv$ ratio of total fissions (core plus blanket) to core fissions.

Note that "fuel" refers to the mass of actinide metal in the fuel (and does not include O_2 or carbon).

It is useful to define an energy term G as the kilograms of fuel charged (to the core) per megawatt hour of electrical energy:

$$G = \frac{10^3}{24 E \gamma} \left[\frac{\text{kg fuel}}{\text{MW-hr}(e)} \right] , \quad (\text{F-2})$$

where $\gamma \equiv$ net thermal efficiency.

The total thermal energy yield per unit weight of fissile material destroyed (by neutron absorption) is

$$E_9 = \frac{E_f \zeta}{(1 + \alpha)} \left[\frac{\text{MW-hr}(t)}{\text{kg fissile destroyed}} \right] , \quad (\text{F-3})$$

where $E_f \equiv$ fission energy yield, MW-hr(t)/kg of fissile material fissioned,
 $\alpha \equiv$ average ratio of capture to fission rate in fissile material,
 $\zeta \equiv$ fast fission factor, total energy/energy from fission of fissile materials.

Note that the term "fissile" as used here refers to materials that are fissionable with thermalized neutrons. In the case of the depleted uranium-plutonium cycle, it is conventional to define fissile as Pu-239 and Pu-241. Energy from fission of U-238, U-235, Pu-240, and Pu-242 is then accounted for in the term ζ .

The ratio of total kilograms of fissile material destroyed to kilograms of fissile charged to the reactor core is

$$h = \frac{24 E}{10^3 E_9 \epsilon} , \quad (\text{F-4})$$

where $\epsilon \equiv$ weight ratio of fissile to fuel in fresh fuel.

The weight ratio of discharged fissile material to charged fissile is

$$\beta = 1 + h(r - 1) , \quad (\text{F-5})$$

where $r \equiv$ the total conversion ratio (average over lifetime) using the plutonium definition, i.e., grams of Pu-239 plus Pu-241 produced per gram of Pu-239 plus Pu-241 destroyed.

The fuel element lifetime, t_2 , is

$$t_2 = \frac{E}{365 \times 10^3 (S\epsilon)L} \quad (\text{years}) \quad , \quad (\text{F-6})$$

where $S\epsilon \equiv$ fuel specific power: total (rated) thermal megawatts
per kilogram of fuel in core,

$S \equiv$ initial specific power for fresh fuel, total MW(t)/kg
fissile charged to core,

$(S\epsilon/\epsilon)$ and $L \equiv$ load factor.

Using the above terms, the components of the fuel cycle cost can be written in terms (P_j) which have units of dollars per kilogram of fuel charged to the core. These values can be converted to the final fuel cycle costs (C_j), which have units of mills/kW-hr(e), by multiplying the P_j by the energy term G . The cost of purchasing fuel is

$$P_B = (1 + f)P_g \epsilon \left(\frac{\$}{\text{kg fuel}} \right) \quad , \quad (\text{F-7})$$

where $P_g \equiv$ value of fissile material, in \$/kg fissile, $f \equiv$ loss fraction, and the cost of purchased fuel in mills/kW-hr(e) is

$$C_B = GP_B \left[\frac{\text{mills}}{\text{kW-hr(e)}} \right] \quad . \quad (\text{F-8})$$

The receipt for selling fuel is

$$P_S = (1 - f)\beta P \epsilon \left(\frac{\$}{\text{kg fuel}} \right) \quad (\text{F-9})$$

and

$$C_S = GP_S \left[\frac{\text{mills}}{\text{kW-hr(e)}} \right] \quad (F-10)$$

The depletion cost is given by subtracting Eq. F-9 from Eq. F-7,

$$P_D = P_B - P_S \left(\frac{\$}{\text{kg fuel}} \right) \quad (F-11)$$

and, of course,

$$C_D = GP_D \left[\frac{\text{mills}}{\text{kW-hr(e)}} \right] \quad (F-12)$$

While Eq. F-12 is correct, it is somewhat misleading since the depletion charge is not a function of the burnup, E, or the energy yield, G. Algebraic substitution gives the more useful functional relationship

$$C_D = \frac{P_9(r-1)}{E_9\lambda} \left[1 - f \frac{(1+\beta)}{(1-\beta)} \right] \left[\frac{\text{mills}}{\text{kW-hr(e)}} \right] \quad (F-13)$$

The fabrication costs are

$$P_F = P_{Fc} + W_a P_{Fa} + W_r P_{Fr} \left(\frac{\$}{\text{kg fuel}} \right) \quad (F-14)$$

and

$$C_F = GP_F \left[\frac{\text{mills}}{\text{kW-hr(e)}} \right] \quad (F-15)$$

where P_{Fr} $\equiv$ fabrication of radial blanket, \$/kg,

P_{Fa} $\equiv$ fabrication cost of axial blanket, \$/kg,

P_{Fc} $\equiv$ fabrication cost of core, \$/kg,

W_a $\equiv$ weight ratio of fertile material charged to axial blanket to weight of fuel charged to core,

W_r $\equiv$ weight ratio of fertile material charged to radial plus corner blankets to fuel charged to core,

W $\equiv$ weight ratio of blanket to fuel ($W = W_a + W_r$).

The fabrication costs can be approximately fitted by the relationships

$$P_{Fi} = \frac{a_i}{R_i^{1-k} Q_i^n} \text{ (\$/kg)} ,$$

where i stands for c (core), a (axial blanket), or r (radial blanket),

a_i = a constant for region i ,

R_i = mass of fuel per pin in region i , kg/pin,

Q_i = fabrication plant throughput of material for region i (tonnes/day),

k = a scaling factor for R ,

n = a scaling factor for Q .

Note that

$$R_i = \frac{\pi d_i^2 \ell_i \rho_i}{4 \times 10^3} ,$$

where ρ_i = smear metal fuel density in region i , g/cm³,

ℓ_i = length of region i , cm,

d_i = fuel diameter (rod i.d.) in region i , cm.

The required throughput of core fuel to the fabrication plant is

$$Q_c = \frac{IL}{E\lambda L_r} \text{ (tonnes/day)}$$

where I = total installed electric capacity, MW(e),

L_r = reprocessing plant load factor (260/365 for Oak Ridge correlations).

Also, $Q_a = Q_c W_a$ and $Q_r = Q_c W_r$.

Note that the cost of converting plutonium nitrate and UF_6 to UO_2 or UC is to be included in the fabrication cost.

The reprocessing cost is given by

$$P_P = P_R \frac{1 + W}{Q_t^m} \left(\frac{\$}{\text{kg fuel}} \right) \quad (\text{F-16})$$

or

$$C_P = GP_P \left[\frac{\text{mills}}{\text{kE-hr}((e))} \right] , \quad (\text{F-17})$$

where P_R = average reprocessing charge, \$/kg,

Q_t = total throughput to the reprocessing plant,

= $Q_c (1 + W)$ (tonnes/day),

m = scaling factor for reprocessing throughput.

The shipping cost is given by

$$P_{Sh} = P_h (1 + W) \left(\frac{\$}{\text{kg fuel}} \right) ,$$

where P_h = shipping charge, \$/kg.

Likewise,

$$C_{Sh} = G P_{Sh} \left[\frac{\text{mills}}{\text{kW-hr}(e)} \right]$$

The working-capital charge can be rigorously calculated by the application of compound-interest factors. However, for the relatively short time periods involved, slightly more than half the fuel element lifetime, the difference between straight interest and compound interest is not significant. Therefore, the working capital charge, P_I , is taken to be

$$P_I = (i_f P_B + i_w P_F)(t_1 + 0.5 t_2) \quad (F-18)$$

$$+ (i_f P_S - i_w P_P)(t_3 + 0.5 t_2) \left(\frac{\$}{\text{kg fuel}} \right)$$

with

$$C_I = G P_I ,$$

where $i_f \equiv$ yearly carrying charge on fuel inventory,

$i_w \equiv$ yearly carrying charge for working capital, on items other than fuel material,

$t_1 \equiv$ hold-up time prior to insertion in reactor (i.e., average interval between pre-reactor payments and time fuel is charged to core), yr,

$t_3 \equiv$ hold-up time after discharge from reactor (i.e., average interval between discharge and post-reactor payments or receipts), yr.

Alternately, the working-capital charge can be written in the functional form

$$C_I = G i_w [P_F(t_1 + 0.5t_2) - P_P(t_3 + 0.5t_2)] \quad (F-19)$$

$$+ i_f P_9 \left[G \epsilon(t_1 + \beta t_3) + \frac{(1 + \beta)}{17520 \lambda SL} \right]$$

The sum of the components of the fuel cycle cost which are not capital cost items (C_N) is given by

$$C_N = C_D + C_F + C_P + C_{Sh} \left[\frac{\text{mills}}{\text{kW-hr}(e)} \right] \quad (F-20)$$

Finally, the net fuel-cycle cost, C , the sum of C_N and the working-capital cost, is

$$C = C_I + C_N \left[\frac{\text{mills}}{\text{kW-hr}(e)} \right] \quad (F-21)$$

APPENDIX G
SAMPLE CALCULATION OF FUEL CYCLE COST FOR OXIDE GCFR AT EQUILIBRIUM

Input Data

$$b = 1.1022$$

$$E_m = 10^5 \text{ MWd/tonne}$$

$$m = 1.40$$

$$\gamma = 0.395$$

$$E_f = 23,300 \text{ MW-hr/kg fissioned}$$

$$\alpha = 0.194$$

$$\zeta = 1.317$$

$$\epsilon = 0.127$$

$$r = 1.51$$

$$S = 0.92 \text{ MW(t)/kg fissile initially in core}$$

$$L = 0.8$$

$$L_R = 260/365 = 0.7123$$

$$a_c = 112$$

$$a_a = 6$$

$$a_r = 75$$

$$k = 0.35$$

$$n = 0.25$$

$$d_c = 0.7455 \text{ cm (rod o.d. = 0.8051, or 0.32 in.)}$$

$$l_c = 148.18 \text{ cm}$$

$$\rho_c = 8.7341 \text{ g metal/cm}^3$$

$$d_r = 1.20 \text{ cm}$$

$$l_r = l_c (1 + 0.8 W_a) = 244 \text{ cm}$$

$$I = 15,000 \text{ MW(e)}$$

$$W_a = 0.81$$

$$W_r = 1.32$$

$$P_R = 55 \text{ \$/kg (at } Q_t = 1 \text{ tonne/day)}$$

$$P_h = 11 \text{ \$/kg}$$

$$m = 0.53$$

$$P_g = 10,000$$

$$f = 0.005$$

$$i_f = 0.10$$

$$i_w = 0.06$$

$$t_1 = 0.5$$

$$t_3 = 0.5$$

$$E = \frac{1.1022 (10^5)}{1.40} = 78,700$$

$$G = \frac{10^3}{24(78,700)(0.395)} = 1.34 \times 10^{-3}$$

$$E_g = \frac{23,300 (1.317)}{1.194} = 25,700$$

$$h = \frac{24(78,700)}{10^3(25,700) (0.127)} = 0.579$$

$$\beta = 1 + 0.579 (0.51) = 1.295$$

$$t_2 = \frac{78,700}{365 (10^3)(0.92)(0.127)(0.08)} = 2.29$$

$$P_B = 10,000 (0.127)(1.005) = 1276$$

$$C_B = 1.71$$

$$P_S = 1.295 (1270) (0.995) = 1636$$

$$C_S = 2.19$$

$$P_D = 360$$

$$C_D = 0.48 \text{ or}$$

$$= \frac{-10,000 (0.51)}{25,700 (0.395)} \left[1 - 0.005 \frac{2.295}{0.295} \right] = 0.48$$

$$R_C = \frac{\pi(0.7455)^2 (148.18) (8.7341)}{4(10^3)} = 0.565$$

$$R_a = R_C W_a = 0.458$$

$$R_r = \frac{\pi(1.20)^2 (244) (8.7341)}{4(10^3)} = 2.41$$

$$Q_c = \frac{15,000 (0.8)}{78,700 (0.395) (0.7123)} = 0.5414 \text{ tonne/day}$$

$$Q_a = (0.3857) (0.81) = 0.4385$$

$$Q_r = (0.5091) (1.32) = 0.7146$$

$$Q_t = 1.6945$$

$$P_{FC} = \frac{112}{(0.565)^{0.65} (0.5414)^{0.25}}$$

$$P_{FC} = \frac{112}{(690) (0.858)} = 190$$

$$P_{Fa} = \frac{6}{(0.459)^{0.65} (0.4385)^{0.25}}$$

$$P_{Fa} = \frac{6}{(0.600)(0.814)} = 12$$

$$P_{Fr} = \frac{75}{(2.41)^{0.65} (0.7146)^{0.25}}$$

$$P_{Fr} = \frac{75}{1.77 (0.92)} = 46$$

$$P_F = 190 + 0.81 (12) + 1.32 (46)$$

$$PF = 190 + 10 + 61 = 261$$

$$C_F = 0.35$$

$$P_P = \frac{55 (3.13)}{(1.6945)^{0.53}} = \frac{55 (3.13)}{1.322} = 130$$

$$C_P = 0.17$$

$$P_{Sh} = 11 (3.13) = 35$$

$$C_{Sh} = 0.05$$

$$P_I = [(0.10)(1276) + (0.06)(261)] 1.64 + [(0.10)(1636) - (0.06)(130)] 1.64$$

$$P_I = 491$$

$$C_I = 0.66$$

$$C_N = -0.48 + 0.35 + 0.17 + 0.05$$

$$C_N = 0.09$$

So for 15,000-MW(e) installed nuclear capacity,

$$C = 0.66 + 0.09 = 0.75$$

For 75,000 MW(e) installed capacity;

$$C_F = \frac{0.35}{(5)^{0.25}} = \frac{0.35}{1.5} = 0.23$$

$$C_P = \frac{0.17}{(5)^{0.53}} = \frac{0.17}{2.35} = 0.07$$

$$C_N = -0.48 + 0.23 + 0.07 + 0.05 \text{ [mills/kW-hr(e)]}$$

$$C_N = 0.13$$

$$C = 0.66 - 0.13 = 0.53 \text{ [mills/kW-hr(e)]}$$

APPENDIX H
DISCO SUBROUTINE
by
M. Rothstein

A small computer program, called DISCO, has been written to compute fuel cycle costs (m/kwhe) and present value (\$) of actual cost transactions over any number of cycles from reactor startup. General inflation may be introduced as well as any anticipated additional escalation on fissile fuel prices resulting from U_3O_8 and/or SWU shortages (i.e., the so-called scarcity factor). Following several calculations to check against General Atomic's much more powerful and widely accepted GACOST fuel cycle cost code, DISCO was inserted into a CALIOP program as the subroutine DISCO. The stand-alone DISCO used for GACOST comparison has also been preserved.

On option, several different discount rates and related "working capital" rates may be used to accommodate some of the alternate persuasions of thought on these financial parameters, including inputting the user's own choice for each of these quantities as in GACOST.

Following are short descriptions of some features of the methods employed and possible implications:

1. Fuel Depletion: Running cost is calculated as simply the difference in total fuel value (mass times price) at beginning and end of cycle.
2. Output of Results: To keep the code small in computer memory, dimensioning of variables was avoided so that all results for a given level period must be printed together allowing the variables to be reinitialized and reused for the next level period. Thus, for each level period, four lines of results are printed sequentially: first, present value (to time of startup) of money

transactions (\$M) by component, the second, third, and fourth are running cost, working capital cost, and total FCC cost, respectively, by component in M/Kwhe).

Having achieved the desired smallness of the code (~10K stand-alone) as a final improvement and to facilitate comparison of DISCO results to others, a new set of variables were introduced, one for each FCC component running cost, and for each working capital cost and for total FCC. Each was dimensioned to be a 30 x 1 vector of values, 30 years being normally the longest horizon time for fuel cycle cost calculations. The code size increased about 10% to ~11K. With these variables, one additional page of results is printed after the editing of results for the longest level period requested (N2M of input instructions), namely, the undiscounted fuel cycle costs by cycle for all components in a GACOST type of distribution.

3. DISCO, besides introducing escalation possibilities and discounting for leveled FCC, also accounts for variable residence times and associated variable depletion (fuel) and depreciation (fab) factors. Thus, initial core and approach-to-equilibrium effects are reflected in the FCC costs.* CALIOP fuel cycle costs in contrast are calculated for a single equilibrium segment, and reflect no relative variation in depletion or depreciation factors. As a result, CALIOP FCC appear lower than DISCO FCC for all cycles.
4. Working Capital Cost (WCC): Although DISCO computes WCC for the fuel with almost the same formula as CALIOP, again it accounts for the variable residence times as described in 3 above. WCC for fab, of course, employs 100% depreciation of the initial value at

* Not done, however, in a symmetric manner at end-of-life (shutdown or decommissioning time).

insertion, including preirradiation WCC add-on, over actual irradiation times of each core segments.

Total cost for postirradiation components employs a sinking fund to accrue over each segment's actual in-core, energy-producing time, the (inflated) cost to ship and reprocess itself after discharge. The fund thus accrued earns additionally from discharge time to actual reprocessing, at the compounded WC rate. The WCC is this total cost minus the running cost.

5. Capital Gains (CG): DISCO calculates the fuel depletion running cost, as in 1. above, which is in the manner of conventional FCC codes (such as GACOST). It can be shown that such a calculation, which accounts for price change as well as change in fuel mass (i.e., fuel capital) incorporates the capital gain on the fuel due only to price change as a negative term (i.e., reduces depletion cost) but omits the reality that a tax must be paid on such a gain. The residual, or remaining term of the depletion cost, is the true depreciation (depletion) of the fuel capital (mass). DISCO, however, also calculates an after-tax capital gain (ATCG) for each segment discharged (i.e., one per cycle), in M/Kwhe. In deference to the conventional calculations, and especially during DISCO comparisons with GACOST (6(a) below and Table 1), this ATCG has not been included in DISCO FCC's, although it is printed out with the level FCC's.

It remains my contention, furthermore, that this ATCG should contribute to FCC. The remainder of this paragraph no. 5 explains how.

If such capital gains on fuel are long-term (i.e., time between buying and selling a segment's fissile mass is at least one year, which they will be for all segments for most pre- and post-irradiation times), then they would be eligible for long term

capital gains tax rates. According to IRS rules, these rates are generally one-half the rate on ordinary income (but not lower than 25%). Thus, the above definition of depletion may be overstating the capital gains tax liability, as brought out shortly.

It should be noted, however, that this writer has not investigated as yet the tax rules applicable to nuclear power reactor fuel material, leaving it at this point for some future investigator. Three features, in fact, require inquiry in such an investigation:

1. The tax rates on fissile capital gains actually allowed, as just discussed.
2. Whether, in fact, CG's are included in FCC's as realized, or whether they are to accrue over reactor lifetime.
3. Do capital gains include the growth in fissile material (i.e., for a breeder) in addition to the change in price of material originally charged to a reactor.

The assumptions made for DISCO about these issues are that CG's are included explicitly as realized (also implicitly included in GACOST as described earlier in this subsection), that long-term tax rates on a CG do apply (not so in GACOST; at $\gamma = 1/2$ or the ordinary tax rate in DISCO), and that material growth is taxable (in the CALIOP version of DISCO). This last assumption occurs rather naturally since the fissile sale price, PS, as defined in CYCOST (i.e., CALIOP) includes the growth factor.

With this re-examination of capital gains, the writer computed the following coefficient to the ATCG, which when applied to ATCG and added to the FCC accounts for adjustments suggested to

be necessary in the foregoing description. The coefficient, X, would be:

$$X = - \frac{T(1 - \gamma)}{(1 - \gamma^T)}$$

where again T = ordinary tax rate and γ = factor to apply to T such that $\gamma * T$ = capital gains tax rate. Note that if $\gamma = 1$ (i.e., CG taxed at ordinary tax rate), then $X = 0$ and no adjustment is necessary (in agreement with the opening statements of this subsection). The more probable and real world rates of $\gamma = T = 0.5$, however, give $X = -1/3$. Since these values are read into DISCO during this study, the corrected adjustments for U/Pu GCFR used in the GACOST comparison below (paragraph 6(a) and Table 1) decrease FCC as follows:

<u>Period</u>	<u>X*ATCG (m/KWHe)</u>
(0-5)	-0.78
(0-15)	-0.95
(0-20)	-1.09
(0-25)	-1.26

Briefly these adjustments reduce the total FCC by about 17%.

6. Fuel Masses in DISCO (i.e., Fuel "Capital"): While the fissile isotopes in the fuel give it value, the total mass of fuel (fissile and nonfissile, including fertile) must be accounted for in FCC calculations, since it is the total quantity that must be "handled" (i.e., fabricated, shipped, and reprocessed). In the development and checkout of the DISCO code, the required "mass flows" of fuel was obtained in two different ways, resulting actually in two different versions of DISCO. The following two subsections describe these different approaches.

(a) Mass Flow from GACOST Output

The necessity of determining accuracy of DISCO calculations by comparison with the much more powerful and widely accepted GACOST led to the initial version of DISCO being programmed to read and utilize representative mass flow data obtained from edited output of GACOST. About a dozen items of data are read, including masses of fissile material in for initial core and in and out for reload segments as well as nonfissile fuel masses for core, axial, and radial blankets, and breeding ratios. Besides reading in data, variables had to be defined in the calculations themselves that might not have been needed for the simpler version to be inserted into CALIOP [see (b) following]. This initial version is available as a stand-alone code. Table 1 displays the comparison of DISCO and GACOST results, from which DISCO results were deemed acceptable.

(b) Mass Flow from CALIOP DATA

Naturally the final DISCO version was to be inserted into CALIOP as a subroutine. To keep CALIOP as a self-contained stand-alone program, DISCO could not then read in GACOST data, but the required masses of fuel material had to come from data available within CALIOP. To this end, DISCO uses the G factor calculated in CALIOP (Eq. F-2 in Appendix F*) in a different manner than does CALIOP in its FCC calculations (SUBROUTINE CYCOST). The calculated value of G has units of (kg fuel charged to core per Mwhe). Then, upon calculating the component prices in units of (\$ per kg fuel charged to core), simple multiplication in CYCOST of those

* In the CALIOP code, this is the variable GG.

TABLE 1
GACOST AND DISCO COMPARISON
(1200 MWe U/Pu GCFR, HEDL Handling Prices)

FCC Component and Level Period	Zero Escalation			6% Inflation(b) + 4% Scarcity(b)		
	1. GACOST	2. DISCO	3. $\Delta = (2 - 1)(a)$ (%)	1. GACOST	2. DISCO	3. $\Delta(a)$ (%)
Fuel Depletion RC						
(0-5)	-1.28	-0.97	-24	- 5.57	- 4.17+2.34	-25
(0-15)	-1.15	-0.96	-17	- 7.81	- 7.05+2.85	-10
(0-20)	-1.13	-0.95	-16	- 9.21	- 8.50+3.29	-8
(0-25)	-1.12	-0.95	-15	-10.73	-10.00+3.78	-7
Depletion WC						
(0-5)	2.08	1.79	-14	5.79	4.59	-21
(0-15)	2.05	1.93	-6	8.53	7.40	-13
(0-20)	2.04	1.95	-4	10.12	8.87	-12
(0-25)	2.04	1.96	-4	11.83	10.40	-12
Fabrication RC						
(0-5)	1.96	2.17	+11	2.10	2.31	+10
(0-15)	1.71	1.75	+2	2.24	2.28	-2
(0-20)	1.68	1.70	+1	2.40	2.41	0
(0-25)	1.66	1.67	+1	2.56	2.55	0
Fabrication WC						
(0-5)	0.25	0.23	-8	0.51	0.46	-10
(0-15)	0.23	0.22	-4	0.58	0.54	-7
(0-20)	0.23	0.22	-4	0.62	0.59	-5
(0-25)	0.23	0.21	-9	0.67	0.63	-6
Reprocessing(c) RC						
(0-5)	2.73	2.66	-3	3.84	3.72	-3
(0-15)	2.32	2.25	-3	4.11	3.97	-3
(0-20)	2.27	2.20	-3	4.41	4.26	-3
(0-25)	2.24	2.17	-3	4.71	4.54	-4
Reprocessing(c) WC						
(0-5)	-0.56	-0.48	-14	-1.39	-1.19	-14
(0-15)	-0.54	-0.45	-17	-1.64	-1.39	-15
(0-20)	-0.54	-0.45	-17	-1.79	-1.50	-16
(0-25)	-0.53	-0.44	-17	-1.93	-1.62	-16
Total RC						
(0-5)	3.41	3.86	+13	0.37	1.85	+400
(0-15)	2.88	3.04	+6	4.11	-0.80	-119
(0-20)	2.81	2.94	+5	-2.41	-1.83	-24
(0-25)	2.78	2.88	+4	-3.45	-2.93	-15

TABLE 1 (Continued)

FCC Component and Level Period	Zero Escalation			6% Inflation ^(b) + 4% Scarcity ^(b)		
	1. GACOST	2. DISCO	3. $\Delta = (2 - 1)(a)$ (%)	1. GACOST	2. DISCO	3. $\Delta(a)$ (%)
Total WC						
(0-5)	1.77	1.53	-14	4.90	3.86	-21
(0-15)	1.74	1.70	-2	7.46	6.55	-12
(0-20)	1.74	1.72	-1	8.96	7.95	-11
(0-25)	1.73	1.73	0	10.57	9.44	-11
Total FCC						
(0-5)	5.17	5.39	+4	5.27	5.71	+8
(0-15)	4.62	4.74	+3	6.00	5.75	-4
(0-20)	4.55	4.66	+2	6.55	6.12	-7
(0-25)	4.51	4.62	+2	7.11	6.51	-8

(a) Δ 's show % deviation of DISCO from GACOST.

(b) Beginning at reactor startup time.

(c) Includes shipping in HEDL prices.

prices by G gives a value for component fuel cycle cost in units of (\$/Mwhe = m/kwhe), a very simple and clever use of units to get quickly a quantity in m/kwhe, i.e., an FCC. DISCO, however, wishing to retain as much of the initial version as possible, having been checked against GACOST, converts G into a new factor called GGG

$$GGG = (G \text{ or } GG) * E(Mwhe) / P(Gwe)$$

where E and P are constants with units indicated in parentheses and are calculable from data available in CALIOP. Combining with the units of G, the factor GGG has the units of (kg fuel charged to core per GWe), the same units as mass flow data obtained from GACOST for the initial version of DISCO. Thus, using the GGG factor, a "pseudo" mass flow is constructed by DISCO as follows:

$$\begin{aligned} \text{Reload Segment Fuel Charged} &= GGG \\ \text{Reload Segment Fuel Discharged} &= GGG \\ \text{Initial Core Fuel Charged} &= NS * GGG \end{aligned}$$

where NS = number of core segments, also calculable from CALIOP data. With such a definition, the variables and calculational procedures of the initial DISCO version could be utilized virtually intact, allowing the accuracy of DISCO reflected in Table 1 to be presumed, on the premise that the above definition of mass flow is valid. Table 2 compares FCC's as extracted from CALIOP with DISCO.

Table 2 shows total FCC per DISCO to be 0.57 m/kwhe greater than per CYCOST, with depletion cost (RC + WC) 0.646

* In the CALIOP code, this is the variable GG.

TABLE 2
 CALIOP (i.e., CYCOST) AND DISCO FCC COMPARISON
 U/Pu GCFR, HBA Case 121
 (WC Rate = 0.14)

FCC Component	1. CYCOST	2. DISCO (Cycles 4 to 30)(a)	3. Δ (m/kwhe) (2 - 1)
Fuel (Depletion) RC	-1.301	-0.383	+0.918
Fuel (Depletion) WC	3.809	3.537	-0.272
Fabrication RC	0.377	0.390(b)	+0.013
Fabrication WC ("old" prices)(c)	0.127	0.104(b)	-0.023
Shipping RC	0.167	0.167	0
Shipping WC	-0.056	-0.065	-0.009
Reprocessing RC	1.014	1.014	0
Reprocessing WC	-0.340	-0.395	-0.055
Subtotal RC	0.256	1.188	+0.932
Subtotal WC	3.540	3.180	-0.360
Total FCC	3.796	4.368	+0.572

(a) That is, undiscounted costs per cycle for 3 segment core. (Cycles 1, 2, 3, or course, have different FCC's.)

(b) DISCO includes the add-on of preirradiation working capital cost to the actual fabrication cost.

(c) By simple ratioing of "new" and "old" prices, fab costs would be:

Fab RC	2.354	2.435	+0.081
Fab WC	0.793	0.649	-0.144

m/kwhe higher. Depletion RC alone is almost a whole m/kwhe higher, while depletion WC is about one-quarter m/kwhe lower. Again, these changes in depletion costs are attributed to the recognition by DISCO of each segment undergoing full irradiation in equilibrium. CYCOST could, in fact, be better described as calculating fuel segment costs, rather than fuel cycle costs. Handling running costs agree very well (≤ 0.01 m/kwhe) as they should, while WC costs are lower, serving to offset somewhat the higher depletion cost. While good agreement with CYCOST was never an objective (as it was with GACOST), Table 2 gives, nevertheless, some reassurance in the past use of CALIOP FCC, if any, as well as more confidence in the future use of DISCO results.

7. Discount and Working Capital Rates: DISCO allows the use of up to three alternative discount rates (DFR) and associated working capital rates (RBT). The FCC's are calculated for as many options on DFR and RBT as are requested, which is specified by NDF in the input data (word 2 of card DISCO-2; see below). All are calculated by DISCO internally, although an additional parameter, IDF1 (word 3, same card) allows the user to input his own choice of both DFR and RBT, in the fashion of GACOST, which are input on card DISCO-4.

For all three alternative choices on DFR internally calculated, the same RBT is employed, which is calculated as follows:

$$RBT = (1-BF)*((1+RE)*1+FLAT)-1)/(1-AU)+BF*((1+RB)*(1+FLAT)-1)$$

where the variables on the right-hand side are financial parameters defined and read in per card DISCO-3 below. The three

choices on PFR are calculated as follows and used sequentially in obtaining level FCC (up to NDF):

1. $DFR = (1+RE)*(1+FLAT)-1$
2. $DFR = RAT = \text{After-tax rate of return}$
 $= (1- AU)*RBT$
 $= (1-BF*(1+RE)*(1+FLAT)-1)$
 $+ BF*(1-TAU)*((1+RB*(1+FLAT))-1)$

Note on 2: the use of read-in values for DFR and RBT is activated during this choice 2, according to value of IDF1 (IDF1 = 0, then DFR and RBT as just described; IDF1 = 1, then use read-in values, card DISCO-4).

Further, if NDF = 1, only calculate for one DFR, then choice A. is used or read-in values, again per IDF1.

3. $DFR (\text{for fuel only}) = RE-LAMB DFR (\text{for handling costs and energy per 1. above}).$

Additional input cards for CALIOP version of DISCO to perform level FCC with SUBROUTINE DISCO (follows format of description of CALIOP input):
DISCO data cards are inserted between CALIOP cards G(5) and EXTRA.

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
DISCO-1	1-72	12A6	Title(12)	Simply 72 character description of FCC being performed.
DISCO-2	1-4	I4	N2M	Longest level period to calculate (≤ 30); all periods (0-1) through (0-M2M) are calculated and printed.
	5-8	I4	NDF	Number of alternative discount rates (DFR) with which to calculate the level FCC and cumulative PV of cash transactions, $1 \leq \text{NDF} \leq 3$. See paragraph 7 in report. DISCO calculates RBT and uses it as WC rate for all DFR's. The three DFR's, used sequentially, are: (1) $\text{DFR} = \text{RE} + \text{FLAT}$ (2) $\text{DFR} = \text{RAT}$ $= (\text{L} - \tau) * \text{RBT}$ (3) $\text{DFR} = \text{RE} - \text{LAMB}$ (fuel depletion cost only. But if $\text{NDF} = 1$, DFR is according to (2) only.
	9-12	I4	IDF1	When alternative (2) above is being implemented (e.g., $\text{NDF} = 1$), $\text{IDF1} = 0$ means calculate DFR and RBT; but $\text{IDF} = 1$ means use read-in values for both DFR and RBT (see card No. DISCO-4).
DISCO-3				Financial data to calculate DFR and RBT.
	1-12	E12.6	BF*	Constant fraction of purchases of capital (fuel and handling) to be debt (bond) financed. Thus, $(1 - \text{BF})$ is equity (stock) financed.
	13-24	E12.6	RB*	Constant interest rate on bonds at zero inflation.

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
	25-36	E12.6	RE*	Constant required rate of return to equity investor (stock holder) at zero inflation to induce him to invest.
	37-48	E12.6	TAU*	Effective tax rate on ordinary income of the firm.
	49-60	E12-6	GAMMA*	Factor to apply to tax rate TAU for long term capital gains tax rate, i.e., $GAMMA * TAU$ = long term capital gain tax rate.
	61-72	E12.6	FLAT*	Long range estimate of general price inflation (% pa/100, e.g., 6%, $FLAT = 0.06$).
2nd card of DISCO	1-12	E12.6	LAMB*	Long range estimate of additional price inflation on fissile material (i.e., the "scarcity factor" on U-235 due to decreasing U ₃ O ₈ supplies and/or declining availability of enrichment) (% pa/100).
DISCO-4	(Must be included regardless of value on IDF1 on DISCO-2).			
	1-2	E12.6	DFRIN*1	Value of discount rate if $0.0 \leq DFRIN \leq 1.0$.
	13-24	E12.6	RBTIN*	Value of WC charge rate if $IDF1 = 1$, $0.0 \leq RBTIN \leq 1.0$.
DISCO-5	1-12	E12.6	TSU	Year of reactor startup.
	13-24	E12.6	TESC ($\leq$ TSU)	Year prescribed price escalation begins.

* Values are fractions, not percentages.

Input cards for GACOST version of DISCO (stand-alone program). Data cards follow VXQT statement in RUN deck.

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
DISCO-1	Same as for CALIOP-version above.			
DISCO-2	1-12	Same as for CALIOP-version above.		
DISCO-2	13-16	14	NRAB	Number of radial blanket segments in GCFR reactor.
DISCO-3	Same as above for CALIOP.			
DISCO-4	Same as above for CALIOP.			
*DISCO-5	1-12	E12.6	P	Reactor power level (MWe).
*	13-24	E12.6	CF	Capacity factor (decimal fraction of 1)
	25-36	E12.6	TSU	Same as CALIOP.
	37-48	E12.6	TECS ($\leq$ TSU)	Same as CALIOP.
**DISCO-6	1-12	E12.6	RI	Initial core breeding ratio.
	13-24	E12.6	RR	Reload breeding ratio.
	25-36	E12.6	FUIC	Initial core fissile Pu loading (kg/GWe).
	37-48	E12.6	FURECB	Reload segment fissile Pu charged (kg/GW3).
	49-60	E12.6	FURECS	Reload segment fissile Pu discharged (kg/GWe).
	61-72	E12.6	FUINV	Non-initial core fissile Pu inventory (kg/GWe).
**DISCO-7	(Additional core fuel quantities to handle)			
	1-12	E12.6	FABIC	Non-fissile (inc. fertile) fuel to fabricate for IC (kg/GWe).
	13-24	E12.6	FABREC	Same as FABIC, but for reload segments.

<u>Card No.</u>	<u>Position</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>
25-36	E12.6	REPREC		Non-fissile reload segment fuel to reprocess (kg/GWe)
**DISCO-8 1-12	E12.6	AXBSEG		Axial blanket fuel material to fab and repro (kg/GWe)
13-24	E12.6	RABSEG		Same for radial blanket segment.

* Data cards needed for CALIOP version also, but with additional quantities to be read.

** Additional cards for GACOST version (all data obtainable from corresponding GACOST).

APPENDIX I
NOMENCLATURE

Quantity	Units	Nomenclature	
		In Equations	In FORTRAN
Axial distance from core mid-plane/core length	Nil	x	x
Optimum smooth length fraction of core (to equalize max. surface temperatures in rough and smooth sections)	Nil	S _s	SS
Rating of reactor (core only)	MW per kg fillile	R	R
Coolant void fraction (in boxes, i.e., after deducting structure)	Nil	x	CV
Can outer diameter	cm	d _o	CD
Max. linear heat loading of rods	kW/ft	λ _{max}	XLMAX
Power density	kW/liter	D _p	PD
Number of rods	Nil	n	XN
Pressure drop/ambient pressure	Nil	(ΔP/P _o)	PDRK
Channel exit velocity head	atm	q	QU
Total power	MW	H	TP
Fuel element pitch (SQ)	cm	p	P
Fraction of fuel pellet diam. which is hollow	Nil	h	H
Max. value of fuel radial temperature difference	°C	Δt _F /2	DROP
Max. value of can radial temperature difference	°C	Δt _C /2	CROP
Sum of above	°C	Δt _T /2	CRAP
Local surface temperature	°C	t _s	TSURF
Local temperature at fuel axis	°C	t _F	TFAX
Ratio of outside/inside can diameter	Nil	K	Q
Stanton number	Nil	K _H	QH
Reflector saving length (i.e., cosine chop each end)	cm	m	XM

APPENDIX I (Continued)

Quantity	Units	Nomenclature	
		In Equations	In FORTRAN
Structure blockage, fraction of total core	Nil	x_B	XB
Absolute entry pressure	atm	P_O	PO
Specific heat of coolant (constant pressure)	joules/ g°C	C_P	CP
Molecular weight	g/mol	M	XMW
Fissile density in fuel pellets	g/cm ³	ρ_F	PF
Radial max./mean heat rate	Nil	α	AL
Length of one axial blanket	cm	L_F	XLF
Thermal conductivity of fuel	W/cm °C	K_F	AKF
Thermal conductivity of can	W/cm °C	K_C	AKC
Core volume	liters	V	V
L/D ratio of active core	Nil	z	Z
Entry gas temperature	°C	T_O	TO
Gas temperature rise (total)	°C	ΔT	DT
Ratio of ideal pump power to heat output	Nil	γ_P	GP
Volume fraction of core occupied by fuel (region between fuel center hole and cladding inner diameter)	Nil	x_F	SF
Max. surface temperature	°C	T_{smax}	TMAX
Active core length	cm	l	EL
Core length/extrapolated length	Nil	ϕ	FL
Max. fuel temperature	°C	T_{FM}	OTMAX
Roughening heat transfer increase factor	Nil	η_1	ETA 1
Roughening friction increase factor	Nil	η_2	ETA 2
Ratio of smooth heat transfer/friction factors	Nil	η_3	ETA 3
Viscosity of coolant	poise	μ	AMU

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