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A COMPUTER CODE, NATCON, FOR THE ANALYSES OF STEADY-STATE THERMAL-HYDRAULICS AND SAFETY MARGINS IN PLATE-TYPE RESEARCH REACTORS COOLED BY NATURAL CONVECTION

by

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RERTR Program

December 1988

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A Computer Code, NATCON, for the
Analyses of Steady-state Thermal-hydraulics and
Safety Margins in Plate-type
Research Reactors Cooled by Natural Convection

R. S. Smith and W. L. Woodruff

ABSTRACT

The NATCON code provides a capability for the analysis of the thermal-hydraulics of plate-type research reactors cooled by natural convection. The code includes steady-state estimates of what are often considered safety margins. These estimates may include power peaking factors, hot channel factor components, and laminar flow entrance effects. A listing of the code and a description of the input are included along with some sample results. The current version of the code has only properties data for light water.

1. INTRODUCTION

A computer code, NATCON, has been written to analyze the steady-state thermal-hydraulics of plate-type fuel in a research reactor cooled by natural convection. The reactor core is immersed within a pool of water that is assumed to be at a constant average temperature.

The code computes coolant flowrate, axial temperature distributions in the coolant and the fuel plate surface and centerline, and the approach to onset of nucleate boiling (ONB). An automatic search for the power at ONB may be selected.

Flow is driven by density differences in the coolant that are the results of coolant heating by the fuel. Resulting buoyant forces are counter-balanced by viscous forces that result from the flow.

Hot channel factors may also be introduced for determining safety margins. The Worcester Polytechnic Institute (WPI) reactor is used as an example for these analyses.

2. THERMAL-HYDRAULIC METHOD

Because a heated column of water weighs less than a column at ambient temperatures a buoyant force is exerted on the former. The buoyant force on the heated column is:

$$F_B = \left(\bar{\rho}_C - \rho_{AMB}\right) A_C L_C$$

where $\bar{\rho}_C$ = average density of column = $\frac{1}{L_C} \int_0^{L_C} \rho_C(x)\,dx$

ρ_{AMB} - density of coolant in tank

A_C = coolant channel cross sectional area

L_C = heated length of coolant channel.

The buoyant force causes a flow that is resisted by frictional forces that produce a pressure drop. The velocity of the flow will reach a value where the buoyant forces are just balanced by the frictional forces. The latter can be expressed as:

$$F_F = \frac{(\rho\ V)_{in}^2}{2g} A_C \left[\frac{1}{2\ \rho_{in}} + \sum_{i=1}^{n} \frac{f\ \Delta Z_i}{\rho_i D_H} + \frac{1}{\rho_{out}}\right],$$

where ρ - density of coolant at indicated locations

V - velocity of coolant at inlet

g - acceleration due to gravity

f - friction factor

ΔZ_i - incremental height of nodes in coolant channel

D_H - hydraulic diameter of coolant channel.

The first and third terms in the brackets account for entrance and exit losses, while the middle term is the pressure loss over the channel due to flow. The friction factor is computed from

$$f = C_f/Re,$$

where C_f is a friction factor constant per Ref. 1 and Re is the Reynolds No. Inlet coolant velocity is iterated until a balance between buoyant and viscous forces is obtained. Once velocity is known, the heat transfer coefficient and steady state temperatures of the coolant, clad and fuel can be determined.

The Nussult No. for fully developed laminar flow in rectangular ducts of various dimensions is given in Fig. 1. It is taken from Ref. 2 and uses the average value between constant heat flux and constant temperature boundary conditions. A second option is available for computation of Nusselt No. in NATCON. Over the length of the core, velocity and thermal profiles are developing. The effect of this is to increase the heat transfer coefficient compared to the fully developed profiles (Ref. 3). For steady conditions at a given power, coolant outlet temperature and flowrate are not affected but peak clad temperature is decreased. Because of this, the power level at which ONB occurs is 30-60% higher when entrance effects are considered. The code has an option that allows either the fully developed assumption or entrance effects to be included. The results presented in this memo include entrance effects.

A linear interpolation scheme is used to get the Nussult No. for a particular ratio of side lengths. Such a scheme is also used to get a friction factor constant for a given channel shape and water properties versus temperature. The heat transfer coefficient is computed from the definition of Nussult No. as:

$$h = \frac{k}{D_H} Nu$$

where k - thermal conductivity of water. The wall temperature for the i'th axial node is computed from:

$$T_{w_i} = T_{c_i} + Q_i/h_i A_i$$

where T_c is coolant temperature, Q_i is the total heat generated in the i'th node of area A_i, and h_i, the heat transfer coefficient is obtained from Fig. 1.

Fuel centerline temperatures are obtained from:

$$T_{CL_i} = T_{w_i} + \frac{q_i}{t_f/k_f + t_c/k_c}$$

where q_i is the heat flux per unit area in the i'th node, t_f and t_c are fuel and clad thicknesses, and k_f and k_c are fuel and clad thermal conductiv-ities. Also computed at each axial location is heat flux, pressure, and saturation temperature. The wall temperature at which ONB occurs is determined from the Bergles-Rohsenow correlation listed in the "Handbook of Heat Transfer," section 13, equation 9 (also Ref. 4):

$$q/A)_{ONB} = 15.60p^{1.156}(T_w-T_s)^{(2.30/p^{0.0234})}$$

where the heat flux q/A is in Btu/hr ft^2, the pressure p is in lb_f/in^2 abs. and T's are in °F.

3. HOT CHANNEL FACTORS

Thermal-hydraulic safety margins may be evaluated using this code. The input parameters required for analysis of the limiting (hottest) channel in the core include (1) nuclear power peaking factors for the limiting fuel element, and (2) engineering hot channel factors that account for fuel fabrication tolerances, uncertainties in calculated parameters, and uncertainties in the ability to measure certain variables such as the reactor power.

The nuclear power peaking factors may be introduced as an axial power distribution and a radial peaking factor.

The engineering hot channel factors are applied as three separate components corresponding to:

(1) Uncertainties that affect the heat flux, F_q

(2) Uncertainties in the flow or enthalpy change in the channel, F_H

(3) Uncertainties in the heat transfer to the coolant, F_h

These factors are introduced as:

$$q''_{hc} = F_q \cdot q''_{nc}$$

$$h_{hc} = h_{nc}/F_h$$

$$MFR_{hc} = MFR_{nc}/F_H$$

where the notation hc refers to the hot channel and nc refers to the nominal channel values for the heat flux (q"), the heat transfer coefficient (h), and the mass flow rate (MFR).

The hot channel factor for flow cannot be applied directly because the flowrate is determined iteratively from the balance between buoyancy and friction. Therefore, the square of this factor is applied to increase the frictional component of the balance. In this manner, the flowrate is reduced approximately by this factor. The closer the factor is to to unity, the more accurate the reduction in flowrate.

4. CODE INPUT AND OUTPUT

Table I shows input variables as read by the IBM NAMELIST read statement in the fortran code. Table II gives definitions and units for these variables. Additional cases may be run by inserting a "&END" and a "&INPUT" as shown in Table I. Table III provides an input description for the fixed (non-IBM) format option, and sample input is shown in Table IV. Detailed information on each iteration for equilibrium flowrate is suppressed unless IPRT is not equal to zero. Two modes of running the code are possible: If CPWR is positive, the cooling performance is computed for that power only; If it is zero, computations are made for 10 kW and then increments up to the point of ONB.

The code listing is attached (Table V). A short description and definitions of input and output variables are included.

The main program reads in data, performs iterations on forces to establish steady flow and on total core power to reach ONB, and prints output. Three subroutines are used to compute water properties, water saturation pressure, and channel geometry dependent values of friction factor and Nussult No.

Output is in SI units with some British equivalents given in the summary data. Sample output data is listed in Table VI. Input data is echoed in a readable manner and the average of the axial power distribution is computed.

5. SAMPLE OUTPUT

For a sample case, core geometry and power level were taken from the 10 kW WPI research reactor. The fuel specified for the LEU conversion is similar to that for the Ford Nuclear Reactor (FNR). Some characteristics of the HEU and LEU Fuel are listed in the following table:

Characteristics of HEU and LEU Core

		HEU	LEU
Number of Elements		24	24
Number of Plate per Element		10	18
Fuel:	Height (m)	0.5969	0.5969
	Width (m)	0.0635	0.05842
	Thickness (m)	0.000991	0.000762
Clad:	Thickness (m)	0.000762	0.000381
Channel:	Height (m)	0.6223	0.6255
	Width (m)	0.0646	0.0646
	Thickness (m)	0.005085	0.002498

HEU cases were run for power levels to ONB at 482 kW. Figure 2 shows coolant temperature rise for the core at power levels of 10 kW, 200 kW, and 482 kW. In going from 10 to 482 kW the coolant temperature rise goes up by a factor of only 6.6 because the inlet coolant velocity increases by a factor of 7.3. Figure 3 gives fuel plate surface temperature versus axial position. A small skewing toward the top of the core is due to the coolant temperature rise. The ONB wall temperature of 109°C is reached near the centerline in the 482 kW core.

6. THERMAL-HYDRAULIC SAFETY MARGINS

Thermal-hydraulic safety margins were evaluated for the WPI reactor using this code with both the original HEU fuel and LEU fuel of the FNR design.

6.1 Nuclear Power Peaking Factors

The nuclear power peaking factors used in evaluating the thermal-hydraulic safety margins were obtained directly from the neutronics calculations for the limiting fuel element in both the HEU and LEU cores.

In the three-dimensional neutronics calculations, the total power peaking factor is defined as the product of two components: (1) a radial factor defined as the average power density in each fuel element divided by the average power density in the core, and (2) an element factor defined as the peak power density in each fuel element when the control blades are fully-withdrawn divided by the average power density in that fuel element. The values that were obtained for the HEU and LEU cores are tabulated below:

	Nuclear Power Peaking Factors		
Core	Radial	Element	Total
HEU Core	1.24	1.59	1.99
LEU Core	1.23	1.76	2.17

6.2 Engineering Hot Channel Factors

The hot channel factors selected for analysis of the thermal-hydraulic safety margins are based in part on the LEU fuel plate specifications for the FNR at the University of Michigan and in part on steady-state computations with natural convection flow. The original specifications for the current WPI HEU fuel elements are not available.

The hot channel factors are applied as three separate components corresponding to the heat flux, F_q, the flow or enthalpy change in the channel, F_H, and the heat transfer to the coolant, F_h. These hot channel factors are typically broken down into subfactors based on uncertainties in the manufacturing process, measurements, and tolerances in the specifications. The subfactors may be combined by simply multiplying them together, by treating them statistically, or a combination of the two. The first method is conservative, but somewhat unrealistic. The second two methods recognize that all of these conditions do not occur at the same time and location. The subfactors are combined statistically as

$$F = 1 + \sqrt{\sum_i (1 - f_i)^2}$$

where the f_i are the subfactors of F.

The specifications for the FNR fuel plates give the following fabrication tolerances:

Fuel Plate Thickness	0.062/0.058 in.
^{235}U Loading Variation	± 2% per plate
Homogeneity of ^{235}U in Fuel Meat	± 20% per 0.08 in. diameter over the fuel core; ± 30% per 0.08 in. diameter area near the ends (dogbone region)
Coolant Channel Thickness	0.103 - 0.123 in. (10% reduction used) 0.109 nominall

The fuel plate tolerance, ± 0.002, is assumed to result in a direct variation in the meat thickness. The spot variances in density are used as the local variation in homogeneity with an additional end-to-end component.

These variances translate into the following fabrication subfactors:

Uncertainty In	Hot Channel Subfactor
Fuel Meat Thickness	1.07
235U Loading per Plate	1.02
235U Homogeneity (Local)	1.20
235U Homogeneity (End-to-End)	1.10
Reduction in Coolant Flow	1.16 (increase in outlet temp.)
Channel Thickness (10%) (1)	1.14 (increase in clad surface temperature)

(1) Calculated using the NATCON natural-convection heat-transfer code. Additional uncertainties that were included are:

Uncertainty In	Hot Channel Subfactor
Power Measurement (5%)	1.05
Calculated Power Density (10%)	1.10
Heat Transfer Coefficient (20%)	1.20
[Treated here as a multiplicative factor in F(h)]	
Coolant Flow Rate (10%) (2)	1.10

(2) Since the flow in a natural convection reactor is somewhat self-adjusting (the buoyant forces increase with heating and are offset by the friction forces), uncertainties in the coolant flow rate due to friction, orificing, and plenums are difficult to assess. An uncertainty of 10% in the coolant flow rate has been assigned here.

The hot channel factors and the hot channel components used in the calculations for the WPI reactor are summarized in the following table:

Uncertainty	F_q	F_H	F_h
Fuel Meat Thickness	1.07	-	-
^{235}U Loading	1.02	1.02	-
^{235}U Homogeneity	1.20	1.10	-
Coolant Channel Thickness	-	1.16	1.14
Power Measurement	1.05	1.05	-
Calculated Power Density	1.10	1.10	-
Coolant Flow Rate	-	1.10	1.10
Heat Transfer Coefficient	-	-	1.20
	-----	-----	-----
Multiplicative Combination	1.51	1.65	1.51
Statistical Combination	1.24	1.24	1.41*

*Factors for coolant channel thickness and coolant flow rate are treated statistically. Factor for heat transfer coefficient is multiplicative.

6.3 Computed Results

The margin to ONB for the hot channel is based on the Bergles-Rohsenow correlation[4] and is a function of the above nuclear power peaking factors and hot channel factors for both the 10 plate HEU elements and the 18 plate LEU elements. The margin to ONB is sometimes refered to as the overpower factor. That is, the ratio of the reactor power at ONB to the nominal reactor power (10 kW).

In these calculations, the reactor power was simply increased until an indication of ONB was obtained in the hottest channel, according to the Bergles-Rohsenow correlation for three combinations of the engineering hot channel factors. The coolant inlet temperature in all cases was 26.7°C. The results for a 10 kW reactor are shown in the table on the following page.

With the use of statistically combined subfactors, the margin to ONB (or the overpower factor) for the HEU core with 10 plates per element is 24.8 and the margin for the LEU core with 18 plates per element is 44.2. With the larger multiplicatively combined factors, the margins to ONB were calculated to be 16.9 and 30.1 for the 10 plate HEU elements and 18 plate LEU elements, respectively. The basic reason for the increased thermal-hydraulic safety margins in the LEU core is the lower heat load per channel with 18 fuel plates per element rather than 10 fuel plates per element in the HEU core.

Hot Channel Factors			10 kW Power			At ONB			
F_q	F_H	F_h	Coolant Outlet Temp., C	Coolant Flow Rate per Channel, kg/s	Maximum Clad/Fuel Temp., C	Reactor Power for ONB, kW	Coolant Outlet Temp., C	Coolant Flow Rate per Channel, kg/s	Maximum Clad/Fuel Temp., C
					HEU Core				
1.00	1.00	1.00	29.9	0.00487	31.1/31.1	482 (1)	47.7	0.03536	108.9/109.3
1.24	1.24	1.41	31.0	0.00443	33.4/33.4	248 (2)	46.7	0.02365	108.4/108.6
1.51	1.65	1.51	32.9	0.00374	36.0/36.0	169 (3)	49.7 (4)	0.01709	108.2/108.4
					LEU Core				
1.00	1.00	1.00	32.9	0.00151	33.1/33.1	818 (1)	69.1	0.01790	109.0/109.3
1.24	1.24	1.41	35.0	0.00139	35.5/35.5	442 (2)	68.9	0.01203	108.5/108.7
1.51	1.65	1.51	38.5	0.00119	39.1/39.1	301 (3)	75.2 (4)	0.00868	108.2/108.4

(1) Nominal Case, no hot channel factors.
(2) Hot channel factors combined statistically, except for heat transfer coefficient factor, which is multiplicative.
(3) Multiplicative hot channel factors.
(4) Coolant temperature rise is greater in spite of lower power because the flow is reduced by high F_H.

REFERENCES

1. E. R. G. Eckert and T. F. Irvine, Jr., "Incompressible Friction Factor, Transition and Hydrodynamic Entrance Length Studies of Ducts with Triangular and Rectangular Cross Sections," WADC Tech. Report 58-85, 1957.

2. W. M. Kays, Convection Heat and Mass Transfer, McGraw-Hill Book Co., Inc. 1966.

3. R. K. Shah and A. L. London, "Laminar Flow Forced Convection in Ducts," Advances in Heat Transfer, 1978, Supplement 1.

4. A. E. Bergles and W. M. Rohsenow, "The Determination of Forced Convection Surface Boiling Heat Transfers", Transactions of the ASME 86 (Series C - Journal of Heat Transfer), pp. 365-371 (August 1964).

Table I. Sample Input with IBM Namelist

```
WORCESTER POLYTECHNIC INSTITUTE RESEARCH REACTOR,(HEU) FW=FQ=FH=1.0
 &INPUT
       NN=20
     , NTRANC=1
     , IPRT=0
     , CPWR=  0.
     , TPOOL=26.67
     , FUELWT=.5969
     , FUELHT=.06350
     , FUELTK=.000991
     , FUELK=156.
     , CLADTK=.000762
     , CLADK=180.
     , CHANHT=.62230
     , CHANWT=.0646
     , CHANTK=0.005085
     , CHIMNY=.1905
     , NSTDEL=24
     , NPLTSE=10
     , NCONEL=1
     , NPLTCE=0
     , DELTA=.0001
     , VGUESS=.03
     , DEPTH=2.4334
     , RPEAK=1.0
     , FW=1.0
     , FQ=1.0
     , FH=1.0
 ,ZR=0.0,      0.0714,   0.119,   0.167,   0.214,   0.262,   0.310,
     0.357,    0.405,    0.452,   0.500.   0.548,   0.595,   0.643,
     0.690,    0.738,    0.786,   0.833,   0.881,   0.9286,  1.0,
 QVZ=0.7312,   1.0331,   1.2209,  1.3927,  1.5433,  1.6769,  1.7885,
     1.8750,   1.9390,   1.9769,  1.9900,  1.9769,  1.9390,  1.8750,
     1.7885,   1.6769,   1.5433,  1.3927,  1.2209,  1.0331,  0.7312
     , &END
WORCESTER POLYTECHNIC INST. RES. REACTOR,(HEU) FW=1.24,FQ=1.24,FH=1.41
 &INPUT
       FW=1.24,FQ=1.24,FH=1.41
     , &END
WORCESTER POLYTECHNIC INST. RES. REA.,(HEU) FW=1.65,FQ=1.51,FH=1.51
 &INPUT
       FW=1.65,FQ=1.51,FH=1.51
     , &END
```

Table II. Definitions and Units for Input Variables to NATCON

NN - No. of axial nodes in reactor coolant channel.

NTRANC - Include entrance effects (=1) or assume fully developed (=0).

IPRT - If non-zero debugging output will be printed.

TPOOL - Average temperature of water pool - •C.

FUELHT - Length of fuel meat - m.

FUELWT - Width of fuel meat - m.

FUELTK - Thickness of fuel meat - m.

FUELK - Thermal conductivity of fuel meat - w/mK.

CLADTK - Thickness of clad - m.

CLADK - Thermal conductivity of clad - w/mk.

CHANHT - Coolant channel height - m.

CHANWT - Coolant channel width - m.

CHANTK - Coolant channel thickness - m.

CHIMNY - Unheated section of element above fuel plates - m.

NSTDEL - No. of standard elements.

NPLTSE - No. of plates in a standard element.

NCONEL - No. of control elements.

NPLTCE - No. of plates in a control element.

DELTA - Criterion for convergence of frictional and buoyant forces to same value.

VGUESS - Initial guess for inlet velocity of coolant - m/s.

DEPTH - Distance from pool surface to bottom of reactor - m.

RPEAK - Factor by which this channel differs from average channel.

FW - Hot channel factor for flow or enthalpy (F_H).

FQ - Hot channel factor for heat flux (F_q).

FH - Hot channel factor for heat transfer coefficient (F_h).

CPWR - Fixed input power level, if desired (default-omit) - kW.

ZR - Increments into which fuel height is divided (based on normalized unity height).

QVZ - Axial power shape based on ZR.

Table III. Input Description (Fixed Format)

<u>Card 1</u> Format (6I6)

NN, NTRANC, NSTDEL, NPLSE, NCONEL, NPLTCE, IPRT

<u>Card 2</u> Format (6E12.5)

FUELHT, FUELWT, FUELTK, FUELK, CLADTK, CLADK

<u>Card 3</u> Format (5E12.5)

CHANHT, CHANWT, CHANTK, DEPTH, CHIMNY, TPOOL

<u>Card 4</u> Format (4E12.5)

DELTA, VGUESS, RPEAK, CPWR

<u>Card 5</u> Format (3E12.5)

FW, FQ, FH

<u>Card 6</u> Format (6E12.5) NN + 1 pairs

(ZR(I), QVZ(I), I = 1, NN + 1)

<u>Card 7</u> Card 1 for another case or blank - end of job (omit)

Table IV. Sample Input with Fixed Format

```
WORCESTER POLYTECHNIC INSTITUTE RESEARCH REACTOR,(HEU) FW=FQ=FH=1.0
    20      1    24    10      1      0      0
0.5969      0.06350     0.000991    156.          0.000762    180.
0.6223      0.06460     0.005085    2.4384        0.1905      26.67
0.0001      0.03        1.0         0.0
1.0         1.0         1.0
0.0         0.7312
.0714       1.0331
.119        1.2209
.167        1.3927
.214        1.5433
.262        1.6769
.310        1.7885
.357        1.8750
.405        1.9390
.452        1.9769
.500        1.9900
.548        1.9769
.595        1.9390
.643        1.8750
.690        1.7885
.738        1.6769
.786        1.5433
.833        1.3927
.881        1.2209
.9286       1.0331
1.00        0.7312
0
```

Table V. NATCON Code

```
C    -MAIN PROGRAM (NATCON)
C
C                           DESCRIPTION
C
C   THIS CODE COMPUTES THE NATURAL CONVECTION CONDITIONS FOR A SINGLE
C CHANNEL IN A RESEARCH REACTOR THAT OPERATES AT STEADY CONDITIONS.
C FLAT PLATE (MTR TYPE) FUEL COOLED BY WATER IN RECTANGULAR CHANNELS
C IS IMPLICIT IN THE FORMULATION.  GEOMETRICAL DIMENSIONS, HOT CHANNEL
C FACTORS, AXIAL HEAT DISTRIBUTION, AND AMBIENT POOL TEMP ARE REQUIRED
C AS INPUT.  LIGHT WATER PROPERTIES ARE INCLUDED IN A SUBROUTINE.
C   BUOYANT FORCES ARE COMPUTED BASED UPON DENSITY DIFFERENCES BETWEEN
C THE CHANNEL AND THE POOL WHICH ARE COMPUTED FROM THE WATER TEMPERATURE
C THE STEADY VELOCITY IS OBTAINED FROM AN ITERATION IN WHICH BUOYANT
C AND FRICTION FORCES ARE BALANCED.  RESULTS LIST HEAT FLUX, TEMPERATURE
C AND PRESSURES AS A FUNCTION OF AXIAL POSITION.  THESE DATA ARE GIVEN
C IN SI UNITS WHILE ADDITIONAL DATA (INCIPIENT BOILING MARGIN, CHANNEL
C DIMENSIONS, BUOYANT & FRICTIONAL FORCES, FLOWRATE, AND COOLANT TEMP-
C ERATURES) ARE GIVEN IN BOTH SI AND ENGLISH UNITS.
C   NATCON MAY BE RUN AT A SPECIFIC POWER OR THE PROGRAM CAN INCREASE
C THE POWER TO THE VALUE AT WHICH INCIPIENT BOILING IS JUST REACHED.
C (SEE CPWR BELOW).
C
C       ****   INPUT VARIABLES****
C NN          - NO. OF AXIAL NODES IN MODEL
C NTRANC      - ENTRANCE EFFECTS ON HT COEF. (=1:YES,=0:NO)
C IPRT        - IF NON-ZERO, ITERATION OUTPUT WILL BE PRINTED
C NSTDEL      - NO. OF STANDARD ELEMENTS
C NPLTSE      - NO. OF PLATES IN A STANDARD ELEMENT
C NCONEL      - NO. OF CONTROL ELEMENTS
C NPLTCE      - NO. OF PLATES IN A CONTROL ELEMENT
C FUELHT      - HEIGHT OF FUEL IN ELEMENT
C FUELWT      - WIDTH  "   "   "      "
C FUELTK      - THICKNESS  "   "      "
C FUELK       - FUEL THERMAL CONDUCTIVITY
C CLADTK      - THICKNESS  "   "      "
C CLADK       - CLAD THERMAL CONDUCTIVITY
C CHANHT      - HEIGHT OF CHANNEL
C CHANWT      - WIDTH  "      "
C CHANTK      - THICKNESS     "
C DEPTH       - DISTANCE FROM POOL SURFACE TO BOTTOM OF REACTOR
C CHIMNY      - DISTANCE ELEMENT EXTENDS ABOVE FUEL PLATES
C TPOOL       - AMBIENT POOL TEMPERATURE
C DELTA       - CONVERGENCE FOR BUOYANT VS FRICTION FORCES
C VGUESS      - INITIAL ESTIMATE FOR COOLANT VELOCITY
C RPEAK       - MULTIPLICATIVE FACTOR FOR POWER
C CPWR        - IF ZERO: COMPUTE FOR EACH 100KW INCREMENT UP TO INCIPENT
C                     BOILING
C               IF POSITIVE: COMPUTE ONLY FOR THIS POWER(KW)
C FW          - HOT CHANNEL FACTOR FOR FLOW; FRICTION IS INCREASED BY
C               SQUARE OF THIS VALUE. THEREFORE FLOW IS REDUCED ONLY
C               APPROXIMATELY BY THIS VALUE.
C FQ          - HOT CHANNEL FACTOR FOR HEAT FLUX
C FH          -  "     "        "    "  HEAT TRANSFER COEFFICIENT
C ZR          - AXIAL POSITION NORMALIZED TO ONE
C QVZ         - AXIAL POWER DISTRIBUTION
C
C      ****   OUTPUT VARIABLES****
C BUOYF       - BUOYANT FORCE ON FLUID COLUMN OF COOLANT
C FRICF       - FRICTIONAL FORCE DUE TO COOLANT MOVEMENT
```

```
C TOUT       - OUTLET COOLANT TEMPERATURE
C MDOT       - COOLANT FLOWRATE
C Z          - AXIAL HEIGHT
C QFLUX      - SURFACE HEAT FLUX(Z)
C QIN        - HEAT GENERATION(Z)
C HCI        - HEAT TRANSFER COEFFICIENT(Z)
C TFCL       - FUEL CENTERLINE TEMPERATURE(Z)
C TWALL      - FUEL PLATE SURFACE TEMPERATURE(Z)
C TAVE       - COOLANT TEMPERATURE(Z)
C P1         - TOTAL PRESSURE
C TSAT       - SATURATION TEMPERATURE(P)
C TINCIP     - BERGLES-ROHSENOW PREDICTED TEMPERATURE FOR INCIPIENT BOIL
C QTOTAL     - CORE POWER
C NTOTAL     - TOTAL NUMBER OF FUEL PLATES IN CORE
C QPLATE     - HEAT GENERATION PER PLATE
C DTINCP     - MARGIN TO INCIPIENT BOILING
C CAREA      - CROSS SECTIONAL CHANNEL AREA
C HYDIAM     - CHANNEL HYDRAULIC DIAMETER
C VGS,VO     - INLET, OUTLET COOLANT VELOCITY
C
CIBM
C     IMPLICIT REAL*8(A-H,O-Z)
C     REAL*8 NUSSUL,NUSSX,KI,KIN,MSF,MDOT,MASSV,MASSVF
CIBM
CEXP
      REAL NUSSUL,NUSSX,KI,KIN,MSF,MDOT,MASSV,MASSVF
CEXP
      DIMENSION QVZ(21),Z(21),DZ(21),ZR(21),QIN(21),TAVE(21),VG(30)
     X ,DELTF(30),HCI(30),TWALL(30),P(30),TSAT(30),TINCIP(30),RHO(30)
     X ,QFLUX(30),TITLE(20),CNOT(2)
      DATA CNOT/4HNOT ,4H    /
CIBM
C     NAMELIST /INPUT/NN,NTRANC,IPRT,TPOOL,FUELHT,FUELWT,FUELTK,
C    X FUELK,CLADTK,CLADK,CHANHT,CHANWT,CHANTK,CHIMNY,NSTDEL,NPLTSE,
C    X  NCONEL,NPLTCE,DELTA,VGUESS,DEPTH,RPEAK,CPWR,FW,FQ,FH,ZR,QVZ
CIBM
CEXP
      OPEN(UNIT=5,STATUS='OLD')
      OPEN(UNIT=6,STATUS='NEW')
CEXP
      TGC=2.
      RPEAK=1.0
      CPWR=0.0
      IPRT=0
      ICASE=0
      IOP=1
      NTRANC=0
      INOT=1
      FW=1.0
      FQ=1.0
      FH=1.0
C
C    -ENTER PARAMETERS
C
  500 READ(5,11,END=9999) TITLE
   11 FORMAT(20A4)
CIBM
C     READ(5,INPUT)
CIBM
CEXP
```

```
      READ(5,1000) NN,NTRANC,NSTDEL,NPLTSE,NCONEL,NPLTCE,IPRT
 1000 FORMAT(7I6)
CEXP
      IF (NN.EQ.0) GOTO 9999
      NN1=NN+1
CEXP
      READ(5,2000) FUELHT,FUELWT,FUELTK,FUELK,CLADTK,CLADK
      READ(5,2000) CHANHT,CHANWT,CHANTK,DEPTH,CHIMNY,TPOOL
      READ(5,2000) DELTA,VGUESS,RPEAK,CPWR
      READ(5,2000) FW,FQ,FH
 2000 FORMAT(6E12.5)
      READ(5,2500) (ZR(I),QVZ(I),I=1,NN+1)
 2500 FORMAT(2E12.5)
CEXP
CIBM
C     IF (DABS(ZR(NN1)-1.).LT. .001) GO TO 13
CIBM
CEXP
      IF (ABS(ZR(NN1)-1.).LT. .001) GO TO 13
CEXP
      WRITE(6,14)ZR(NN1)
   14 FORMAT('      THE AXIAL INCREMENTS FOR POWER DISTRIBUTION SHOULD ',
     1 'BE SCALED SO THAT THE LAST VALUE IS 1.0,     ZR(NN1)=',E15.8)
      STOP
   13 ICASE=ICASE+1
    1 FORMAT('1   * * * * * * * * * * *' /'     *                      *'/
     1 '     *  CASE NO:',I3,'    *',10X,20A4/'     *                      *'/
     2        '     * * * * * * * * * * *')
      WRITE(6,1)ICASE,TITLE
      DTINCP=1000.
      NEWCAS=0
      QTOTAL=10.0
      QINC= 100.
      SIGN=1.0
      IF(CPWR.GT.0.0) QTOTAL=CPWR
C     -UNHEATED LENGTH
      UNHTZ=(CHANHT-FUELHT)
C
C     -ECHO INPUT DATA
C
      WRITE(6,3000) NN,NSTDEL,NPLTSE,NCONEL,NPLTCE
 3000 FORMAT('0NO. OF AXIAL NODES =',I4,/,' NO. OF STANDARD ELEMENTS =',
     X I4,/,' NO. OF PLATES/STD =',I4,/,' NO. OF CONTROL ELEMENTS =',I4,
     X /,' NO. OF PLATES/CNTL =',I4)
      WRITE(6,4000) FUELHT,FUELWT,FUELTK,FUELK
 4000 FORMAT(/'         ( ALL LENGTHS IN METERS )'/
     X ' FUEL:  HEIGHT    =',F10.7,/,8X,'WIDTH     =',F10.7,
     X /,8X,'THICKNESS =',F10.7,/,8X,'THERM. K(W/M*K)=',F10.2)
      IF (NTRANC.NE.0) INOT=2
      WRITE(6,5000) CLADTK,CLADK,CNOT(INOT)
 5000 FORMAT('0CLAD:  THICKNESS =',F10.7,13X,'THERMAL ENTRANCE EFFECTS'
     1 ,/,8X,'THERM. K(W/M*K)=',F10.2,8X,A4,'INCLUDED')
      WRITE(6,6000) CHANHT,CHANWT,FW,CHANTK,FQ,FH
 6000 FORMAT('0CHANNEL:  HEIGHT    =',F10.7,10X,'HOT CHANNEL FACTORS:',
     X/,11X,'WIDTH     =',F10.7,10X,'FLOW(APPROX.) =',F7.4/
     X 11X,'THICKNESS =',F10.7,10X,'HEAT FLUX     =',F7.4/42X,
     X 'H.T. COEF.    =',F7.4)
      WRITE(6,7000) DEPTH,CHIMNY,TPOOL,DELTA,VGUESS,RPEAK,CPWR
 7000 FORMAT(' WATER DEPTH AT INLET =',F10.7,/,' DISTANCE ELEMENT ',
     X 'EXTENDS ABOVE FUEL =',F10.7/' TEMPERATURE (C) =',F10.2/
```

```
     X ' CONVERGENCE =',E12.4,/,' COOLANT VELOCITY(M/S), INITIAL GUESS='
     X ,F10.6,/,' RADIAL PEAKING FACTOR =',F10.6,/   ' FIXED POWER -',
     X ' OPTION (KW) =',F10.4)
      WRITE(6,8000)
 8000 FORMAT('ORELATIVE AXIAL POSITION AND POWER DATA:',/,
     X '       INDEX     POSITION     POWER')
      DO 10 I=1,NN1
      WRITE(6,9000) I,ZR(I),QVZ(I)
   10 CONTINUE
 9000 FORMAT(3X,I6,4X,2F10.5)
      QAV=0.0
      DO 15 I=2,NN1
      I1=I-1
   15 QAV=QAV+(ZR(I)-ZR(I1))*(QVZ(I)+QVZ(I1))/2.
      WRITE(6,16)QAV
   16 FORMAT('      AXIAL DISTRIBUTION AVERAGE:',F8.4)
      IF (QAV.LT. 1.001) GO TO 81
      WRITE(6,80)
   80 FORMAT('  BECAUSE THIS VALUE IS GREATER THAN 1, THIS IS A HOT ',
     X  'CHANNEL AND THEREFORE WILL NOT REFLECT TOTAL CORE POWER.')
      GO TO 84
   81 IF (QAV.GT. 0.999) GO TO 83
      WRITE(6,82)
   82 FORMAT('  BECAUSE THIS VALUE IS LESS THAN 1, THIS IS A COOL ',
     X  'CHANNEL AND THEREFORE WILL NOT REFLECT TOTAL CORE POWER.')
      GO TO 84
   83 WRITE(6,85)
   85 FORMAT('  BECAUSE THIS VALUE IS ABOUT 1, THIS CHANNEL REFLECTS',
     X  ' TOTAL CORE POWER.')
C
C
C
   84 CAREA=CHANWT*CHANTK
      HYDIAM=4.*CAREA/(2.*(CHANWT+CHANTK))
      CALL WATER(TPOOL,RHOIN,DVISIN,CPIN,KIN)
      PBOTT=101326.+9.8*RHOIN*DEPTH
      QOLD=-100.
C
C    -SYSTEM CALCULATIONS
C
 501  ITR=0
      IF (IOP .EQ. 1) WRITE(6,9)QTOTAL
    9 FORMAT(//'1CORE POWER =',F7.1,' KW'/'+',22('_'))
      IDONE=0
      NPLATE=NSTDEL*NPLTSE+NCONEL*NPLTCE
      QPLATE=FQ*QTOTAL*RPEAK/FLOAT(NPLATE)
      CALL FFCON(FFC,NUSSUL,CHANWT,CHANTK)
      DO 20 I=2,NN1
      I1=I-1
      Z(I1)=(ZR(I1)+ZR(I))*FUELHT/2.
      DZ(I1)=(ZR(I)-ZR(I1))*FUELHT
C
C    -HEAT PER AXIAL NODE:  KW
C
      QIN(I1)=QPLATE*DZ(I1)*(QVZ(I1)+QVZ(I))/(2.*FUELHT)
C
C    -LOCAL HEAT FLUX:  W/M**2
C
      QFLUX(I1)=1000.*QIN(I1)/(2.*FUELWT*DZ(I1))
   20 CONTINUE
```

```
C                                         * * * * * * * * * * * * * * * * * * * * *
C    - ITERATE ON VELOCITY TO BALANCE BUOYANT WITH FRICTION FORCES
C            AND ENTRANCE/EXIT LOSSES
C
   25 ITR=ITR+1
      IF (ITR.LT.30)GO TO 26
      WRITE(6,700)
  700 FORMAT(//' DID NOT CONVERGE - TRY LOOSENING TOLERANCE OR USE',
     X ' DOUBLE PRECISION')
        STOP
   26 VG(ITR)=VGUESS
C         ADJUST ESTIMATE OF VELOCITY IF NEW POWER
      IF (QOLD .LT. 0.0)GO TO 27
      VG(1)=VG(1)*(0.7+0.3*QTOTAL/QOLD)
      VGUESS=VG(1)
      QOLD=-100.
   27 RHOV=RHOIN*VGUESS
      RV2G=RHOV**2/TGC
      REYNUM=RHOV*HYDIAM
      MDOT=RHOIN*CAREA*VGUESS
C    -ENTRANCE LOSS(SHARP EDGED)
      FRICF=0.5/RHOIN
C    -UNHEATED LENGTH PRESSURE DROP
      REYNO=REYNUM/DVISIN
      FF=FFC/REYNO
      FRICF=FRICF+FF*UNHTZ/(HYDIAM*RHOIN)
      BUOYF=0.0
      CPOLD=CPIN
      TIN=TPOOL
C
C    -SUM BUOYANT AND FRICTIONAL FORCES NODE BY NODE                 * * * *
C
      DO 30 I=1,NN
      TOUT=TIN+QIN(I)/(MDOT*CPOLD)
      TAVE(I)=(TIN+TOUT)/2.
      CALL WATER(TAVE(I),RHO(I),DVISI,CPI,KI)
      BUOYF=BUOYF+9.8*(RHOIN-RHO(I))*DZ(I)
      REYNO=REYNUM/DVISI
      FF=FFC/REYNO
      FRICF=FRICF+FF*DZ(I)/(HYDIAM*RHO(I))
C    -ACTUAL AND INCIPIENT WALL TEMPS
      AZ=2.*FUELWT*DZ(I)
      IF (NTRANC .NE. 0) GO TO 28
      HCI(I)=KI*NUSSUL/(HYDIAM*FH)
      GO TO 29
   28 GRTZNO=1000.*REYNO*DVISI*CPI/(KI*Z(I)/HYDIAM)
      HCI(I)=KI*NUSSX(GRTZNO,NUSSUL)/(HYDIAM*FH)
   29 TWALL(I)=TAVE(I)+1000.*QIN(I)/(HCI(I)*AZ)
      P(I)=PBOTT-FRICF*RV2G
      VI=VGUESS*RHOIN/RHO(I)
      PSTAT=P(I)-RHO(I)*VI**2/TGC
      CALL WTSAT(PSTAT,TSAT(I))
      TINCIP(I)=TSAT(I)+(556.61*QFLUX(I)/
     X     (P(I)**1.156))**(P(I)**.0234/2.82845)/1.8
      TIN=TOUT
   30 CPOLD=CPI
C                                                                    * * * *
C    -EXIT LOSS ADDED IN & CORRECTED TO N/M 2 FROM M 3/KG
      FRICF=(FW**2)*(FRICF+1./RHO(NN))*RV2G
C    -BUOYANY CONTRIBUTION FROM ELEMENT ABOVE END OF PLATES PLUS
```

```
C          ONE HALF UNHEATED LENGTH IN PLATES
      BUOYF=BUOYF+9.8*(RHOIN-RHO(NN))*(UNHTZ/2.+CHIMNY)
      DELTF(ITR)=BUOYF-FRICF
CIBM
C     IF (DABS(DELTF(ITR)).LT.DELTA) IDONE=1
CIBM
CEXP
      IF (ABS(DELTF(ITR)).LT.DELTA) IDONE=1
CEXP
      IF (IPRT.EQ. 0) GO TO 36
C
C    -PRINT ITERATIONS ON BUOYANT VS FRICTION FORCES
      IF(ITR.EQ.1) WRITE(6,4)
      WRITE(6,5)ITR,BUOYF,FRICF,DELTF(ITR),TOUT,VGUESS,MDOT
    5 FORMAT(I5,8(1X,E13.6))
    4 FORMAT(//3X,'ITR',4X,'BUOYF',9X,'FRICF',9X,'DELTF',10X,'TOUT',9X,
     X       'VGUESS',9X,'MDOT')
C
   36 IF(IDONE.EQ.1) GO TO 50
C
C    -SET VGUESS
C
      IF (ITR.EQ.1) GO TO 40
      ITR1=ITR-1
      VGUESS=VG(ITR)-(VG(ITR1)-VG(ITR))*DELTF(ITR)/
     X (DELTF(ITR1)-DELTF(ITR))
      GO TO 25
   40 IF (DELTF(ITR).LT. 0.0) VGUESS=VGUESS*0.9
      IF (DELTF(ITR).GE. 0.0) VGUESS=VGUESS*1.1
      GO TO 25
C                                  * * * * * * * * * * * * * * * * * * * *
C
C    -PRINT RESULTS
C
  50  VOUT=RHOIN*VGUESS/RHO(NN)
      IF(NEWCAS.EQ.0)DTOLD=DTINCP
      DO 52 I=1,NN
   52 IF(TINCIP(I)-TWALL(I).LT.DTINCP)DTINCP=TINCIP(I)-TWALL(I)
      IF(IOP .EQ. 0) GO TO 74
      WRITE(6,6)
    6 FORMAT('0  I  HEIGHT HT FLUX  Q/NODE  H T COEF TFUEL C/L T WALL   '
     X ,'T WATER   DENSITY  PRESSURE T SAT    T INCIP')
      WRITE(6,8)
    8 FORMAT('            M     W/M 2     KW     W/(M2 K)      C         C  '
     X,'   C         KG/M3       KPA      C         C')
      WRITE(6,12)TPOOL
   12 FORMAT(' INLET  0.0',46X,F6.2)
      DO 35 I=1,NN
      P1=P(I)/1000.
      TFCL=TWALL(I)+QFLUX(I)*(FUELTK/(2.*FUELK)+CLADTK/CLADK)
   35 WRITE(6,7)I,Z(I),QFLUX(I),QIN(I),HCI(I),TFCL,TWALL(I),TAVE(I)
     X ,RHO(I),P1,TSAT(I),TINCIP(I)
    7 FORMAT(I4,3X,F6.3,2X,F6.0,2X,F6.4,2X,F6.1,2X,3(2X,F6.2),4X,
     X        F6.2,2X,3(2X,F6.2))
      WRITE(6,17)FUELHT,TOUT
   17 FORMAT(' EXIT   ',F6.3,44X,F6.2)
C
C    - CONVERSION TO BRITISH UNITS
        DF= DTINCP*1.8
        CWF=CHANWT/.3048
```

```
      CTF=CHANTK/.3048
      FLF=FUELHT/.3048
      CAREAF=CAREA/.0929
      HYDM=HYDIAM/.3048
      BF=BUOYF/47.88
      FRF=FRICF/47.88
      VGS=VGUESS*100.
      VO=VOUT*100.
      VGF=VGS/30.48
      VOF=VO/30.48
      MSF=MDOT/.4536
      TWF=(TPOOL+273.15)*1.8-459.67
      TOF=(TOUT+273.15)*1.8-459.67
    MASSV=VGUESS*RHO(1)
      MASSVF=MASSV*0.204806
    WRITE(6,60)QTOTAL,NPLATE,QPLATE,DTINCP,DF
    WRITE(6,61)CHANWT,CHANTK,FUELHT,CAREA,HYDIAM,CWF,CTF,FLF,CAREAF,
   X HYDM
    WRITE(6,62)ITR,BUOYF,FRICF,BF,FRF
    WRITE(6,63)VGS,VO,MDOT,TPOOL,TOUT,VGF,VOF,MSF,TWF,TOF
    WRITE(6,64)MASSV,MASSVF
 60 FORMAT(/////1X,F10.2,'KW REACTOR COOLED BY NATURAL CONVECTION(',
   X I5,' PLATES AT AN AVERAGE OF ',F8.4,'KW PER PLATE)'/9X,
   X 'APPROXIMATE MARGIN TO INCIPIENT BOILING:',F8.2,' C',F8.2,' F')
 61 FORMAT(///' CHANNEL DIMENSIONS:        WIDTH     THICKNESS ',
   X '    HEIGHT      AREA     HYDRAULIC DIAMETER'/20X,'(M) ',
   X 5(1X,F10.7)/20X,'(FT)',5(1X,F10.7))
 62 FORMAT(///' AFTER',I4,' ITERATIONS, PRESSURES: BUOYANT='
   X   ,F8.5,' FRICTION=',F8.5,'  PA'/41X,'=',F8.5,9X,'=',F8.5,
   X ' LB/FT 2')
 63 FORMAT(///' VELOCITY(IN,OUT)CM/S=',2F7.3,' FLOWRATE  KG/S=',F8.5,
   X ', WATER TEMPERATURE(IN,OUT)DEG C=',2F7.1/17X,'FT/S=',2F7.4,
   X 9X,'LB/SEC=',F8.5,27X,'DEG F=',2F7.1)
 64 FORMAT(///' MASS VELOCITY  KG/(M2 S)=',F8.2/15X,'LB/(FT2 S)=',F8.2)
C
C    -RECYCLE TO NEW CASE(500) OR NEW POWER FOR CURRENT CASE(501)
C
    IF(NEWCAS.EQ.2) GO TO 500
CIBM
C 74 D2INCP=DABS(DTOLD-DTINCP)
CIBM
CEXP
 74 D2INCP=ABS(DTOLD-DTINCP)
CEXP
    IF (DTINCP.GT.0.0.AND.NEWCAS.EQ.0)GO TO 75
CIBM
C   IF (DABS(QTOTAL-100.) .LT. .1) QINC=90.
CIBM
CEXP
    IF (ABS(QTOTAL-100.) .LT. .1) QINC=90.
CEXP
    QINC=SIGN*QINC*DTINCP/D2INCP
    NEWCAS=NEWCAS+1
    DTOLD=DTINCP
    SIGN=-SIGN
    IF(NEWCAS.EQ.2)IOP=1
    DTINCP=1000.
 75 QOLD=QTOTAL
    QTOTAL=QTOTAL+QINC
    IF(CPWR.GT.0.0) GO TO 500
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```
      IF (QTOTAL.GT.109.9.AND. QTOTAL.LT.110.1)QTOTAL= 100.
      IF(QTOTAL.LT.199. .OR. NEWCAS.NE.0)GO TO 501
C    -PROJECT MARGIN TO INCIPIENT TEMP & IF NEGATIVE DON'T PRINT
C  TILL NEWCASE=2 (WHEN POWER HAS BEEN ADJ SO MARGIN=0.0)
      DTPROJ=2.*DTINCP-DTOLD
      IF(DTPROJ.LT.0.0)IOP=0
      GO TO 501
 9999 CONTINUE
      WRITE(6,9998)
9998  FORMAT(/////'    ALL PROBLEMS PROCESSED')
      STOP
      END
      SUBROUTINE WATER(TEMP,RHO,DVIS,SPHT,K)
CCBM
C     IMPLICIT REAL*8(A-H,O-Z)
C     REAL*8 K
CIBM
CEXP
      REAL K
CEXP
      DIMENSION T(23),DEN(23),DYNVIS(23),CP(23),TCON(23)
C
C    - RETURNS DENSITY(KG/M 3), DYNAMIC VISCOSITY(N*S/M**2)
C           SPECIFIC HEAT( KJ/KG X DEG C), AND THERMAL CONDUCTIVITY
C           (W/(M X DEG K)) AS A FUNCTION OF TEMPERATURE
C
C           DATA FROM "HEAT TRANSFER", J.R. HOLMAN, 1966
C           DENSITY REVISED PER KEENAN & KEYES 1936 & ASME 1967
C
C                 USE NMAX=29  (& SET DIMENSIONS TO 29)
C     DATA T/        0.,       4.44,     10.,      15.56,    21.11,
C    X               26.67,    32.22,    37.78,    43.33,    48.89,
C    X               54.44,    60.,      65.55,    71.11,    76.67,
C    X               82.22,    87.78,    93.33,    104.4,    115.6,
C    X               126.7,    137.8,    148.9,    176.7,    204.4,
C    X               232.2,    260.,     287.7,    315.6/
C     DATA DEN/      999.8,    999.8,    999.2,    998.6,    997.5,
C    X               996.1,    994.5,    992.7,    990.6,    988.5,
C    X               985.8,    983.3,    980.3,    977.3,    973.7,
C    X               970.2,    966.7,    963.2,    955.1,    946.7,
C    X               937.2,    928.1,    918.0,    890.4,    859.4,
C    X               825.7,    785.2,    735.5,    678.7/
C     DATA DYNVIS/   179.E-5,  155.E-5,  131.E-5,  112.E-5,  98.E-5,
C    X               86.E-5,   76.5E-5,  68.2E-5,  61.6E-5,  56.2E-5,
C    X               51.3E-5,  47.1E-5,  43.0E-5,  40.1E-5,  37.2E-5,
C    X               34.7E-5,  32.7E-5,  30.6E-5,  26.7E-5,  24.4E-5,
C    X               21.9E-5,  19.8E-5,  18.6E-5,  15.7E-5,  13.6E-5,
C    X               12.0E-5,  10.7E-5,  9.51E-5,  8.68E-5/
C     DATA CP/       4.225,    4.208,    4.195,    4.186,    4.179,
C    X               4.179,    4.174,    4.174,    4.174,    4.174,
C    X               4.179,    4.179,    4.183,    4.186,    4.191,
C    X               4.195,    4.199,    4.204,    4.216,    4.229,
C    X               4.250,    4.271,    4.296,    4.371,    4.467,
C    X               4.585,    4.731,    5.024,    5.703/
C     DATA TCON/     .566,     .575,     .585,     .595,     .604,
C    X               .614,     .623,     .630,     .637,     .644,
C    X               .649,     .654,     .659,     .665,     .668,
C    X               .673,     .675,     .678,     .684,     .685,
C    X               .685,     .685,     .684,     .677,     .665,
C    X               .646,     .616,     .574,     .517/
```

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C                                                                       NAT04800
C     THE DATA BELOW TAKEN FROM PARET PROPERTY LIBRARY, USE NMAX=23     NAT04810
C                               (& SET DIMENSIONS TO 23)                NAT04820
      DATA T/        0.,      4.944,   10.534,   16.131,   21.718,      NAT04830
     X               27.301,  32.879,  38.450,   44.022,   49.583,      NAT04840
     X               55.144,  60.694,  66.239,   71.778,   77.311,      NAT04850
     X               82.839,  88.356,  93.867,   99.37,    104.867,     NAT04860
     X               110.356, 115.828, 121.294/                         NAT04870
      DATA DEN/      999.65,  999.53,  999.15,   998.47,   997.54,      NAT04880
     X               996.30,  994.81,  993.08,   991.06,   988.79,      NAT04890
     X               986.30,  983.57,  980.62,   977.39,   974.00,      NAT04900
     X               970.46,  966.66,  962.76,   958.67,   954.44,      NAT04910
     X               950.09,  945.66,  941.16/                          NAT04920
      DATA DYNVIS/   168.E-5, 148.E-5, 128.E-5,  112.E-5,  97.4E-5,     NAT04930
     X               85.5E-5, 75.5E-5, 67.3E-5,  60.4E-5,  54.7E-5,     NAT04940
     X               49.9E-5, 45.8E-5, 42.2E-5,  39.2E-5,  36.7E-5,     NAT04950
     X               34.5E-5, 32.6E-5, 30.9E-5,  29.2E-5,  27.7E-5,     NAT04960
     X               26.3E-5, 25.0E-5, 23.8E-5/                         NAT04970
      DATA CP/       4.153,   4.155,   4.158,    4.161,    4.165,       NAT04980
     X               4.168,   4.171,   4.175,    4.179,    4.183,       NAT04990
     X               4.187,   4.192,   4.196,    4.201,    4.206,       NAT05000
     X               4.212,   4.217,   4.223,    4.230,    4.236,       NAT05010
     X               4.244,   4.251,   4.259/                           NAT05020
      DATA TCON/     .574,    .583,    .592,     .601,     .610,        NAT05030
     X               .618,    .626,    .633,     .640,     .646,        NAT05040
     X               .652,    .658,    .663,     .668,     .672,        NAT05050
     X               .676,    .680,    .683,     .686,     .688,        NAT05060
     X               .690,    .692,    .694/                            NAT05070
      NMAX=23                                                           NAT05080
      IF (TEMP.LT.T(1).OR.TEMP.GT.T(NMAX)) GO TO 200                    NAT05090
      DO 10 I=2,NMAX                                                    NAT05100
   10 IF (TEMP.LT.T(I)) GO TO 15                                        NAT05110
   15 I1=I-1                                                            NAT05120
      RHO=DEN(I1)+(DEN(I)-DEN(I1))*(TEMP-T(I1))/(T(I)-T(I1))            NAT05130
      DVIS=DYNVIS(I1)+(DYNVIS(I)-DYNVIS(I1))*(TEMP-T(I1))/(T(I)-T(I1))  NAT05140
      SPHT=CP(I1)+(CP(I)-CP(I1))*(TEMP-T(I1))/(T(I)-T(I1))              NAT05150
      K=TCON(I1)+(TCON(I)-TCON(I1))*(TEMP-T(I1))/(T(I)-T(I1))           NAT05160
      RETURN                                                            NAT05170
  200 WRITE(6,1)TEMP,T(1),T(NMAX)                                       NAT05180
    1 FORMAT(' TEMPERATURE ',F10.2,' DEG C IS OUT OF RANGE(',2F8.2,')') NAT05190
      STOP                                                              NAT05200
      END                                                               NAT05210
      SUBROUTINE FFCON(C,NU,W,THK)                                      NAT05220
CIBM                                                                    NAT05230
C     IMPLICIT REAL*8(A-H,O-Z)                                          NAT05240
C     REAL*8 NU,NUSSUL(8)                                               NAT05250
CIBM                                                                    NAT05260
CEXP                                                                    NAT05270
      REAL NU,NUSSUL(8)                                                 NAT05280
CEXP                                                                    NAT05290
      DIMENSION RATIO(11),CON(11),RATION(8)                             NAT05300
C                                                                       NAT05310
C     -FRICTION FACTOR CONST FOR RECTANGULAR DUCT IN F=CON/REYNOLDS NO. NAT05320
C               FROM ECKERT & IRVINE, HT LAB U. MINN, 1957              NAT05330
C                                                                       NAT05340
C     -NUSSULT NO. FOR RECTANGULAR DUCT (AVG. BETWEEN CONST Q & CONST T) NAT05350
C               FROM "CONV. HEAT & MASS TRANSFER", W. M. KAYS, 1966     NAT05360
C                                                                       NAT05370
      DATA CON/ 58., 63., 69., 72.5, 77., 80., 83., 85., 88., 89., 96./ NAT05380
      DATA RATIO/1., 2.,  3.,  4.,   5.,  6.3, 8.,  11., 15., 18.,100./ NAT05390
```

```
      DATA NUSSUL/3.3, 3.8, 4.9, 5.7,  6.28, 6.9, 7.2, 7.89/           NAT05400
      DATA RATION/1.,  2.2, 4.,  5.8,  8.,  13.8, 19., 200./           NAT05410
      IF (THK.GT.W) GO TO 200                                          NAT05420
      WOT=W/THK                                                        NAT05430
      IF (WOT.LT.RATIO(11))GO TO 9                                     NAT05440
      C=CON(11)                                                        NAT05450
      GO TO 100                                                        NAT05460
    9 DO 10 I=2,11                                                     NAT05470
   10 IF (WOT.LT.RATIO(I))GO TO 15                                     NAT05480
   15 I1=I-1                                                           NAT05490
      C=CON(I1)+(CON(I)-CON(I1))*(WOT-RATIO(I1))/(RATIO(I)-RATIO(I1))  NAT05500
  100 IF (WOT.LT.RATION(8))GO TO 19                                    NAT05510
      NU=NUSSUL(8)                                                     NAT05520
      RETURN                                                           NAT05530
   19 DO 20 I=2,8                                                      NAT05540
   20 IF (WOT.LT.RATION(I))GO TO 25                                    NAT05550
   25 I1=I-1                                                           NAT05560
      NU=NUSSUL(I1)+(NUSSUL(I)-NUSSUL(I1))*(WOT-RATION(I1))/           NAT05570
     X                      (RATION(I)-RATION(I1))                     NAT05580
      RETURN                                                           NAT05590
  200 WRITE(6,1)W,THK                                                  NAT05600
    1 FORMAT(' WIDTH(',F8.2,') CAN NOT BE LESS THAN THE THICKNESS(',   NAT05610
     X F8.2,')')                                                       NAT05620
      STOP                                                             NAT05630
      END                                                              NAT05640
      FUNCTION NUSSX(GRTZNO,NUSSUL)                                    NAT05650
CIBM                                                                   NAT05660
C     IMPLICIT REAL*8(A-H,O-Z)                                         NAT05670
CIBM                                                                   NAT05680
C                                                                      NAT05690
C     THIS FUNCTION COMPUTES NUSSULT NO. ACCOUNTING FOR ENTRANCE EFFECTSNAT05700
C     DATA WAS TAKEN FROM PAPER BY S.R. MONTGOMERY AND P. WIBULSWAS    NAT05710
C     PUB. IN APPL. SCIENCE RESEARCH #18, PG. 247-259, DEC. 1967       NAT05720
C     FIG. 5 WITH EXTRAPOLATION.  THIS CURVE WAS USED TO ESTIMATE THE  NAT05730
C     DIFFERENCE BETWEEN THE FULLY DEVELOPED VALUE AND THAT FOR THE    NAT05740
C     LOCAL POINT IN THE ENTRANCE REGION.  BECAUSE THE ENTRANCE LENGTH NAT05750
C     IS 1-2 METERS THE ENTIRE CORE WILL USUALLY BE AFFECTED.  AN      NAT05760
C     OPTION ON INPUT ALLOWS USE OF EITHER THESE ENTRANCE VALUES OR    NAT05770
C     THE FULLY DEVELOPED VALUE(NTRANC = 1 OR 0 RESPECTIVELY.          NAT05780
C                                                                      NAT05790
C     GRAETZ NO.: RE*PR/(Z/DH)                                         NAT05800
C                                                                      NAT05810
      DIMENSION  GRAETZ(9),NUINC(9)                                    NAT05820
CIBM                                                                   NAT05830
C     REAL*8 NUINC,NUSSX,NUSSUL                                        NAT05840
CIBM                                                                   NAT05850
CEXP                                                                   NAT05860
      REAL NUINC,NUSSX,NUSSUL                                          NAT05870
CEXP                                                                   NAT05880
      DATA  GRAETZ/ 0.,  120.,  240.,  360.,  480.,                    NAT05890
     X              600., 720., 1000., 10000./                         NAT05900
      DATA  NUINC / 0.,   3.2,   5.5,   7.0,   7.9,                    NAT05910
     X               8.4,  8.7,   8.9,   8.9/                          NAT05920
      NMAX=9                                                           NAT05930
      IF (GRTZNO.LT.GRAETZ(1).OR.GRTZNO.GT.GRAETZ(NMAX)) GO TO 200     NAT05940
      DO 10 I=2,NMAX                                                   NAT05950
   10 IF (GRTZNO.LT.GRAETZ(I)) GO TO 15                                NAT05960
   15 I1=I-1                                                           NAT05970
      ANU=(NUINC(I)-NUINC(I1))*(GRTZNO-GRAETZ(I1))                     NAT05980
     1                           /(GRAETZ(I)-GRAETZ(I1))               NAT05990
```

```
      NUSSX=NUSSUL+NUINC(I1)+ANU
      RETURN
  200 WRITE(6,1)GRTZNO,GRAETZ(1),GRAETZ(NMAX)
    1 FORMAT(' GRAETZ NO. ',F12.2,' IS OUT OF RANGE(',2F12.2,')')
      STOP
      END
       SUBROUTINE WTSAT (PX,TSATX)
CIBM
C     IMPLICIT REAL*8(A-H,O-Z)
CIBM
       DIMENSION T(30),P(30)
       DATA T/
     1 5.,        10.,        15.,        20.,        25.,
     2 30.,       35.,        40.,        45.,        50.,
     3 55.,       60.,        65.,        70.,        75.,
     4 80.,       85.,        90.,        95.,        100.,
     5 105.,      110.,       115.,       120.,       125.,
     6 130.,      135.,       140.,       145.,       150./
       DATA P/
     1 .008719E5, .012277E5, .017041E5, .02337E5, .03166E5,
     2 .04241E5,  .05622E5,  .07375E5,  .09584E5, .12335E5,
     3 .15740E5,  .19917E5,  .2501E5,   .3117E5,  .3855E5,
     4 .4736E5,   .5781E5,   .7011E5,   .8451E5,  1.0131E5,
     5 1.2079E5,  1.4326E5,  1.6905E5,  1.9854E5, 2.3208E5,
     6 2.7011E5,  3.130E5,   3.614E5,   4.155E5,  4.760E5/
       DO 100 N=1,29
       NN=N
       NP1=N+1
       IF (PX .LT. P(NP1)) GO TO 110
 100   CONTINUE
 110   CONTINUE
       TSATX=T(NN)+(PX-P(NN))/(P(NP1)-P(NN))*(T(NP1)-T(NN))
       RETURN
       END
```

Table VI. Sample NATCON Output

```
WORCESTER POLYTECHNIC INSTITUTE RESEARCH REACTOR,(HEU) FW=FQ=FH=1.0

* * * * * * * * * *
*                 *
*  CASE NO:   1   *
*                 *
* * * * * * * * * *

NO. OF AXIAL NODES =  20
NO. OF STANDARD ELEMENTS =  24
NO. OF PLATES/STD =  10
NO. OF CONTROL ELEMENTS =   1
NO. OF PLATES/CNTL =   0

       ( ALL LENGTHS IN METERS )
FUEL:  HEIGHT     = 0.5969000
       WIDTH      = 0.0635000
       THICKNESS = 0.0009910
       THERM. K(W/M*K)=     156.00

CLAD:  THICKNESS = 0.0007620
       THERM. K(W/M*K)=     180.00

CHANNEL:  HEIGHT     = 0.6223000          HOT CHANNEL FACTORS:
          WIDTH      = 0.0646000          FLOW(APPROX.) = 1.0000
          THICKNESS = 0.0050850           HEAT FLUX     = 1.0000
                                          H.T. COEF.    = 1.0000
WATER DEPTH AT INLET = 2.4384000
DISTANCE ELEMENT EXTENDS ABOVE FUEL = 0.1905000
TEMPERATURE (C) =      26.67
CONVERGENCE =  0.1000D-03
COOLANT VELOCITY(M/S), INITIAL GUESS=  0.030000
RADIAL PEAKING FACTOR =  1.000000
FIXED POWER - OPTION (KW) =      0.0

RELATIVE AXIAL POSITION AND POWER DATA:
     INDEX    POSITION      POWER
       1       0.0         0.73120
       2       0.07140     1.03310
       3       0.11900     1.22090
       4       0.16700     1.39270
       5       0.21400     1.54330
       6       0.26200     1.67690
       7       0.31000     1.78850
       8       0.35700     1.87500
       9       0.40500     1.93900
      10       0.45200     1.97690
      11       0.50000     1.99000
      12       0.54800     1.97690
      13       0.59500     1.93900
      14       0.64300     1.87500
      15       0.69000     1.78850
      16       0.73800     1.67690
      17       0.78600     1.54330
      18       0.83300     1.39270
      19       0.88100     1.22090
      20       0.92860     1.03310
      21       1.00000     0.73120
    AXIAL DISTRIBUTION AVERAGE:  1.5473
 BECAUSE THIS VALUE IS GREATER THAN 1, THIS IS A HOT CHANNEL AND THEREFORE WILL NOT REFLECT
 TOTAL CORE POWER.
```

CORE POWER = 10.0 KW

I	HEIGHT M	HT FLUX W/M 2	Q/NODE KW	H T COEF W/(M2 K)	TFUEL C/L C	T WALL C	T WATER C	DENSITY KG/M3	PRESSURE KPA	T SAT C	T INCIP C
INLET	0.0						26.67				
1	0.021	485.	0.0026	930.5	27.26	27.26	26.73	996.43	125.14	105.97	106.31
2	0.057	619.	0.0022	699.5	27.74	27.74	26.85	996.40	125.14	105.97	106.35
3	0.085	718.	0.0026	626.2	28.13	28.12	26.97	996.37	125.14	105.97	106.37
4	0.114	807.	0.0029	581.0	28.50	28.50	27.11	996.34	125.14	105.97	106.40
5	0.142	885.	0.0032	553.9	28.86	28.86	27.26	996.31	125.14	105.97	106.42
6	0.171	952.	0.0035	535.7	29.21	29.20	27.42	996.27	125.14	105.97	106.43
7	0.199	1007.	0.0036	522.9	29.53	29.52	27.60	996.22	125.14	105.97	106.44
8	0.227	1048.	0.0038	513.4	29.83	29.82	27.78	996.17	125.14	105.97	106.45
9	0.256	1076.	0.0038	506.0	30.10	30.10	27.97	996.12	125.14	105.97	106.46
10	0.284	1090.	0.0040	500.2	30.35	30.34	28.16	996.07	125.14	105.97	106.46
11	0.313	1090.	0.0040	495.4	30.57	30.56	28.36	996.02	125.14	105.97	106.46
12	0.341	1076.	0.0038	491.4	30.75	30.74	28.55	995.97	125.13	105.97	106.46
13	0.369	1048.	0.0038	488.1	30.89	30.88	28.74	995.92	125.13	105.97	106.45
14	0.398	1007.	0.0036	485.3	31.00	30.99	28.92	995.87	125.13	105.97	106.44
15	0.426	952.	0.0035	482.9	31.07	31.06	29.09	995.82	125.13	105.97	106.43
16	0.455	885.	0.0032	480.8	31.10	31.10	29.26	995.78	125.13	105.97	106.42
17	0.483	807.	0.0029	478.9	31.10	31.09	29.41	995.74	125.13	105.97	106.40
18	0.512	718.	0.0026	477.3	31.05	31.05	29.54	995.70	125.13	105.97	106.37
19	0.540	619.	0.0022	475.8	30.97	30.96	29.66	995.67	125.13	105.97	106.35
20	0.576	485.	0.0026	474.2	30.81	30.80	29.78	995.64	125.13	105.97	106.31
EXIT	0.597						29.85				

10.00KW REACTOR COOLED BY NATURAL CONVECTION(240 PLATES AT AN AVERAGE OF 0.0417KW PER PLATE)
APPROXIMATE MARGIN TO INCIPIENT BOILING: 75.30 C 135.55 F

CHANNEL DIMENSIONS:

	WIDTH	THICKNESS	HEIGHT	AREA	HYDRAULIC DIAMETER
(M)	0.0646000	0.0050850	0.5969000	0.0003285	0.0094279
(FT)	0.2119423	0.0166831	1.9583335	0.0035360	0.0309314

AFTER 7 ITERATIONS, PRESSURES: BUOYANT= 3.93787 FRICTION= 3.93787 PA
= 0.08224 = 0.08224 LB/FT 2

VELOCITY(IN,OUT)CM/S= 1.488 1.489 FLOWRATE KG/S= 0.00487, WATER TEMPERATURE(IN,OUT)DEG C= 26.7 29.8
FT/S= 0.0488 0.0488 LB/SEC= 0.01073 DEG F= 80.0 85.7

MASS VELOCITY KG/(M2 S)= 14.82
LB/(FT2 S)= 3.04

CORE POWER = 100.0 KW

I	HEIGHT M	HT FLUX W/M 2	Q/NODE KW	H T COEF W/(M2 K)	TFUEL C/L C	T WALL C	T WATER C	DENSITY KG/M3	PRESSURE KPA	T SAT C	T INCIP C
INLET	0.0						26.67				
1	0.021	4849.	0.0262	1027.0	31.63	31.59	26.87	996.40	125.14	105.97	106.96
2	0.057	6195.	0.0224	969.0	33.68	33.63	27.24	996.31	125.13	105.97	107.08
3	0.085	7183.	0.0261	884.2	35.79	35.74	27.61	996.22	125.13	105.97	107.15
4	0.114	8069.	0.0287	816.1	37.98	37.92	28.03	996.11	125.13	105.97	107.22
5	0.142	8850.	0.0322	758.6	40.23	40.16	28.50	995.98	125.13	105.97	107.28
6	0.171	9524.	0.0347	716.7	42.37	42.30	29.01	995.84	125.13	105.97	107.32
7	0.199	10068.	0.0359	687.2	44.27	44.20	29.55	995.70	125.13	105.97	107.36
8	0.227	10482.	0.0381	665.3	45.94	45.86	30.11	995.55	125.13	105.97	107.38
9	0.256	10762.	0.0383	644.1	47.48	47.40	30.69	995.39	125.13	105.97	107.40
10	0.284	10902.	0.0397	625.2	48.81	48.73	31.29	995.23	125.13	105.97	107.41
11	0.313	10902.	0.0397	609.7	49.86	49.78	31.89	995.07	125.13	105.97	107.41
12	0.341	10762.	0.0383	597.0	50.60	50.52	32.49	994.91	125.13	105.97	107.40
13	0.369	10482.	0.0381	586.3	51.03	50.95	33.07	994.75	125.13	105.97	107.38
14	0.398	10068.	0.0359	577.1	51.16	51.08	33.64	994.57	125.13	105.97	107.36
15	0.426	9524.	0.0347	569.2	50.98	50.91	34.18	994.41	125.13	105.97	107.32
16	0.455	8850.	0.0322	562.3	50.49	50.43	34.69	994.25	125.13	105.96	107.27
17	0.483	8069.	0.0287	556.3	49.72	49.66	35.15	994.10	125.13	105.96	107.22
18	0.512	7183.	0.0261	550.9	48.66	48.61	35.57	993.97	125.13	105.96	107.15
19	0.540	6195.	0.0224	546.0	47.33	47.28	35.94	993.86	125.13	105.96	107.07
20	0.576	4849.	0.0262	540.7	45.31	45.28	36.31	993.74	125.13	105.96	106.95
EXIT	0.597						36.51				

100.00KW REACTOR COOLED BY NATURAL CONVECTION(240 PLATES AT AN AVERAGE OF 0.4167KW PER PLATE)
APPROXIMATE MARGIN TO INCIPIENT BOILING: 56.27 C 101.29 F

CHANNEL DIMENSIONS:	WIDTH	THICKNESS	HEIGHT	AREA	HYDRAULIC DIAMETER
(M)	0.0646000	0.0050850	0.5969000	0.0003285	0.0094279
(FT)	0.2119423	0.0166831	1.9583335	0.0035360	0.0309314

AFTER 5 ITERATIONS, PRESSURES: BUOYANT=13.10943 FRICTION=13.10943 PA
= 0.27380 = 0.27380 LB/FT 2

VELOCITY(IN,OUT)CM/S= 4.800 4.813 FLOWRATE KG/S= 0.01571, WATER TEMPERATURE(IN,OUT)DEG C= 26.7 36.5
FT/S= 0.1575 0.1579 LB/SEC= 0.03463 DEG F= 80.0 97.7

MASS VELOCITY KG/(M2 S)= 47.82
LB/(FT2 S)= 9.79

CORE POWER = 300.0 KW

I	HEIGHT	HT FLUX	Q/NODE	H T COEF	TFUEL C/L	T WALL	T WATER	DENSITY	PRESSURE	T SAT	T INCIP
	M	W/M 2	KW	W/(M2 K)	C	C	C	KG/M3	KPA	C	C
INLET	0.0						26.67				
1	0.021	14546.	0.0787	1027.3	41.28	41.17	27.01	996.36	125.13	105.97	107.62
2	0.057	18584.	0.0671	1023.6	45.94	45.80	27.64	996.21	125.13	105.97	107.81
3	0.085	21548.	0.0784	994.8	50.09	49.94	28.27	996.04	125.13	105.97	107.95
4	0.114	24206.	0.0862	947.7	54.71	54.53	28.99	995.85	125.13	105.96	108.06
5	0.142	26550.	0.0966	903.3	59.37	59.17	29.78	995.64	125.13	105.96	108.15
6	0.171	28571.	0.1040	855.7	64.25	64.04	30.65	995.41	125.13	105.96	108.22
7	0.199	30204.	0.1076	822.4	68.52	68.29	31.57	995.16	125.13	105.96	108.28
8	0.227	31445.	0.1144	788.8	72.63	72.39	32.53	994.90	125.13	105.96	108.33
9	0.256	32285.	0.1150	759.0	76.30	76.06	33.52	994.61	125.13	105.96	108.35
10	0.284	32706.	0.1190	735.3	79.26	79.02	34.54	994.29	125.12	105.96	108.37
11	0.313	32706.	0.1190	715.9	81.49	81.25	35.57	993.97	125.12	105.96	108.37
12	0.341	32285.	0.1150	700.1	82.94	82.70	36.58	993.66	125.12	105.96	108.35
13	0.369	31445.	0.1144	686.9	83.59	83.36	37.58	993.35	125.12	105.96	108.32
14	0.398	30204.	0.1076	675.6	83.47	83.24	38.54	993.05	125.12	105.96	108.28
15	0.426	28571.	0.1040	663.8	82.71	82.50	39.45	992.72	125.12	105.96	108.22
16	0.455	26550.	0.0966	651.5	81.27	81.07	40.32	992.40	125.12	105.96	108.15
17	0.483	24206.	0.0862	640.9	79.07	78.89	41.11	992.11	125.12	105.96	108.05
18	0.512	21548.	0.0784	631.4	76.12	75.96	41.83	991.86	125.12	105.96	107.94
19	0.540	18584.	0.0671	622.8	72.43	72.29	42.46	991.63	125.12	105.96	107.81
20	0.576	14546.	0.0787	613.3	66.91	66.80	43.09	991.40	125.12	105.96	107.61
EXIT	0.597						43.43				

300.00KW REACTOR COOLED BY NATURAL CONVECTION(240 PLATES AT AN AVERAGE OF 1.2500KW PER PLATE)
APPROXIMATE MARGIN TO INCIPIENT BOILING: 24.97 C 44.94 F

CHANNEL DIMENSIONS:	WIDTH	THICKNESS	HEIGHT	AREA	HYDRAULIC DIAMETER
(M)	0.0646000	0.0050850	0.5969000	0.0003285	0.0094279
(FT)	0.2119423	0.0166831	1.9583335	0.0035360	0.0309314

AFTER 5 ITERATIONS, PRESSURES: BUOYANT=24.17199 FRICTION=24.17199 PA
= 0.50485 = 0.50485 LB/FT 2

VELOCITY(IN,OUT)CM/S= 8.452 8.495 FLOWRATE KG/S= 0.02767, WATER TEMPERATURE(IN,OUT)DEG C= 26.7 43.4
FT/S= 0.2773 0.2787 LB/SEC= 0.06099 DEG F= 80.0 110.2

MASS VELOCITY KG/(M2 S)= 84.21
LB/(FT2 S)= 17.25

CORE POWER = 482.3 KW

I	HEIGHT M	HT FLUX W/M 2	Q/NODE KW	H T COEF W/(M2 K)	TFUEL C/L C	T WALL C	T WATER C	DENSITY KG/M3	PRESSURE KPA	T SAT C	T INCIP C
INLET	0.0						26.67				
1	0.021	23383.	0.1266	1027.5	50.03	49.86	27.10	996.34	125.13	105.96	108.02
2	0.057	29874.	0.1078	1029.4	57.14	56.91	27.89	996.14	125.13	105.96	108.27
3	0.085	34640.	0.1260	1019.8	62.91	62.66	28.69	995.93	125.13	105.96	108.43
4	0.114	38913.	0.1386	990.8	69.15	68.86	29.59	995.69	125.13	105.96	108.57
5	0.142	42679.	0.1553	955.4	75.57	75.25	30.58	995.42	125.13	105.96	108.69
6	0.171	45929.	0.1671	919.8	81.95	81.61	31.68	995.13	125.13	105.96	108.78
7	0.199	48555.	0.1730	882.1	88.23	87.87	32.83	994.82	125.12	105.96	108.85
8	0.227	50549.	0.1839	850.5	93.85	93.47	34.04	994.45	125.12	105.96	108.91
9	0.256	51900.	0.1849	826.3	98.48	98.10	35.29	994.06	125.12	105.96	108.94
10	0.284	52576.	0.1913	799.7	102.70	102.31	36.56	993.67	125.12	105.96	108.96
11	0.313	52576.	0.1913	774.9	106.10	105.71	37.86	993.26	125.12	105.96	108.96
12	0.341	51900.	0.1849	754.6	108.29	107.91	39.13	992.83	125.12	105.96	108.94
13	0.369	50549.	0.1839	737.7	109.28	108.91	40.38	992.38	125.12	105.96	108.91
14	0.398	48555.	0.1730	723.3	109.08	108.72	41.59	991.94	125.12	105.96	108.85
15	0.426	45929.	0.1671	710.9	107.69	107.35	42.74	991.52	125.12	105.96	108.78
16	0.455	42679.	0.1553	700.1	105.11	104.80	43.83	991.13	125.12	105.96	108.68
17	0.483	38913.	0.1386	690.5	101.47	101.18	44.83	990.73	125.11	105.96	108.57
18	0.512	34640.	0.1260	682.0	96.77	96.52	45.72	990.36	125.11	105.96	108.43
19	0.540	29874.	0.1078	671.9	91.20	90.98	46.52	990.04	125.11	105.96	108.27
20	0.576	23383.	0.1266	659.6	82.93	82.76	47.31	989.72	125.11	105.96	108.02
EXIT	0.597						47.74				

482.26KW REACTOR COOLED BY NATURAL CONVECTION(240 PLATES AT AN AVERAGE OF 2.0094KW PER PLATE)
APPROXIMATE MARGIN TO INCIPIENT BOILING: 0.00 C 0.00 F

CHANNEL DIMENSIONS:

	WIDTH	THICKNESS	HEIGHT	AREA	HYDRAULIC DIAMETER
(M)	0.0646000	0.0050850	0.5969000	0.0003285	0.0094279
(FT)	0.2119423	0.0166831	1.9583335	0.0035360	0.0309314

AFTER 4 ITERATIONS, PRESSURES: BUOYANT=31.94530 FRICTION=31.94533 PA
= 0.66720 = 0.66720 LB/FT 2

VELOCITY(IN,OUT)CM/S= 10.804 10.877 FLOWRATE KG/S= 0.03536, WATER TEMPERATURE(IN,OUT)DEG C= 26.7 47.7
FT/S= 0.3545 0.3569 LB/SEC= 0.07796 DEG F= 80.0 117.9

MASS VELOCITY KG/(M2 S)= 107.64
LB/(FT2 S)= 22.05

FIGURE 1. Nusselt Number for Fully Developed Profiles

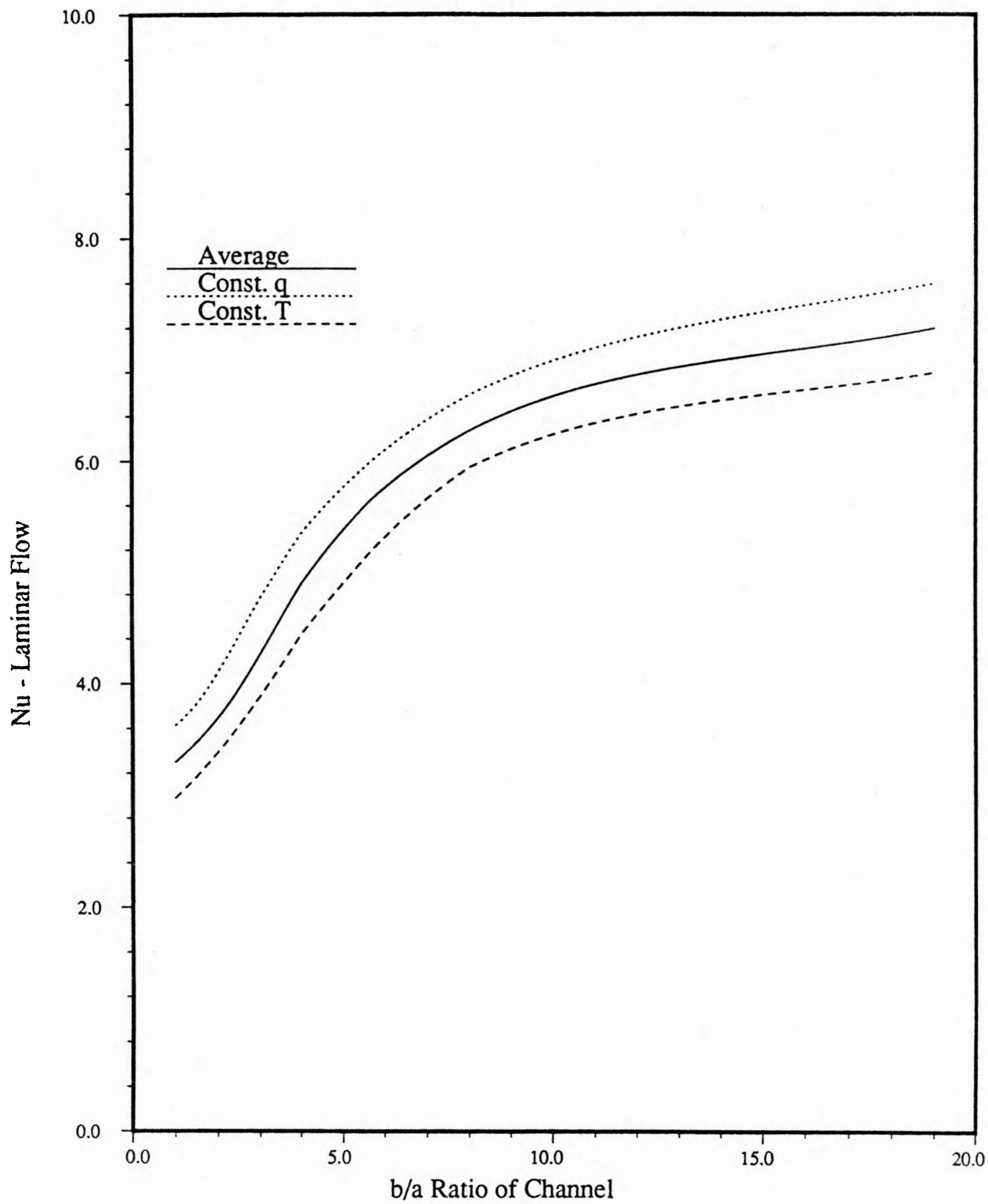


FIGURE 2. Coolant Temperature Rise Through Core

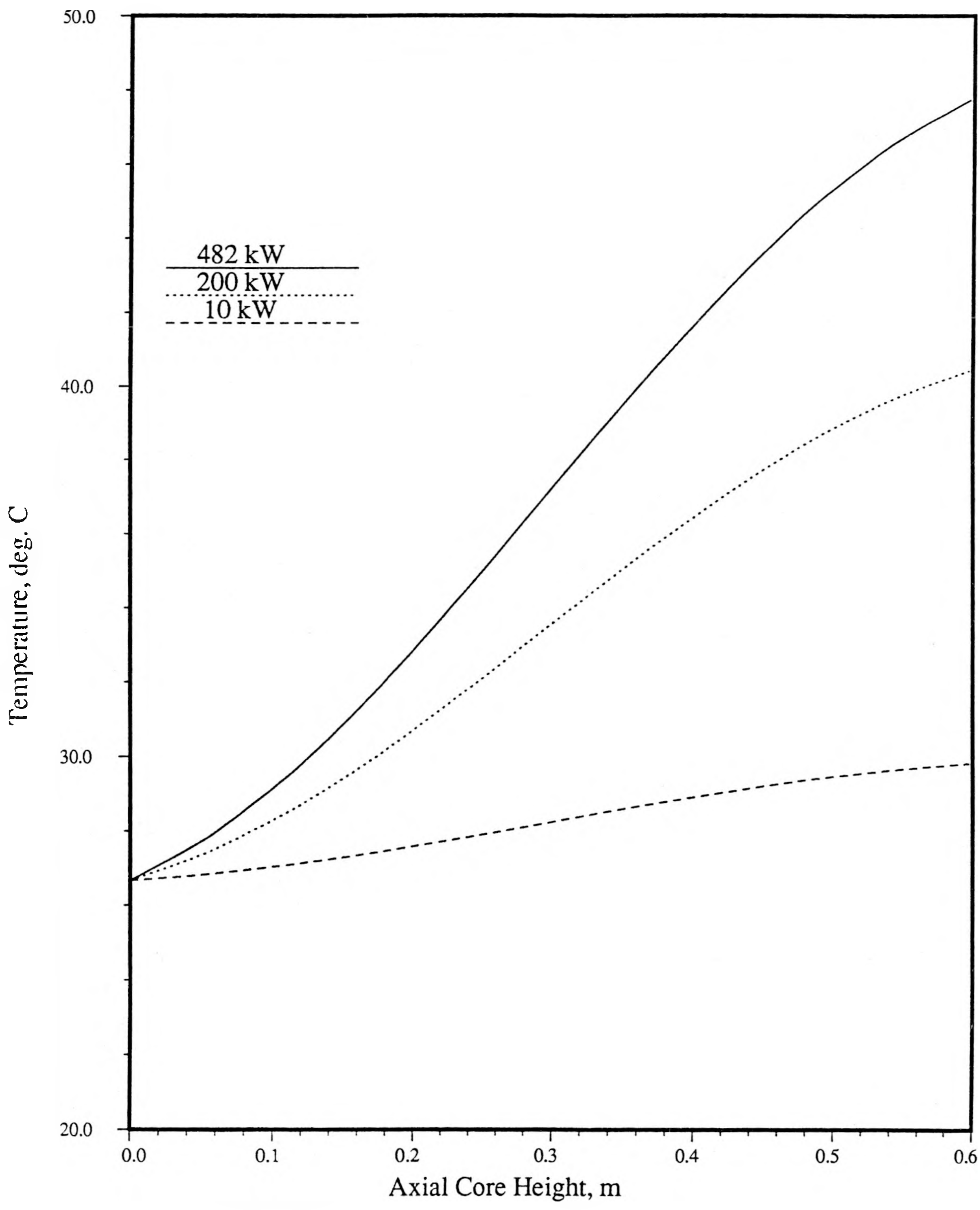
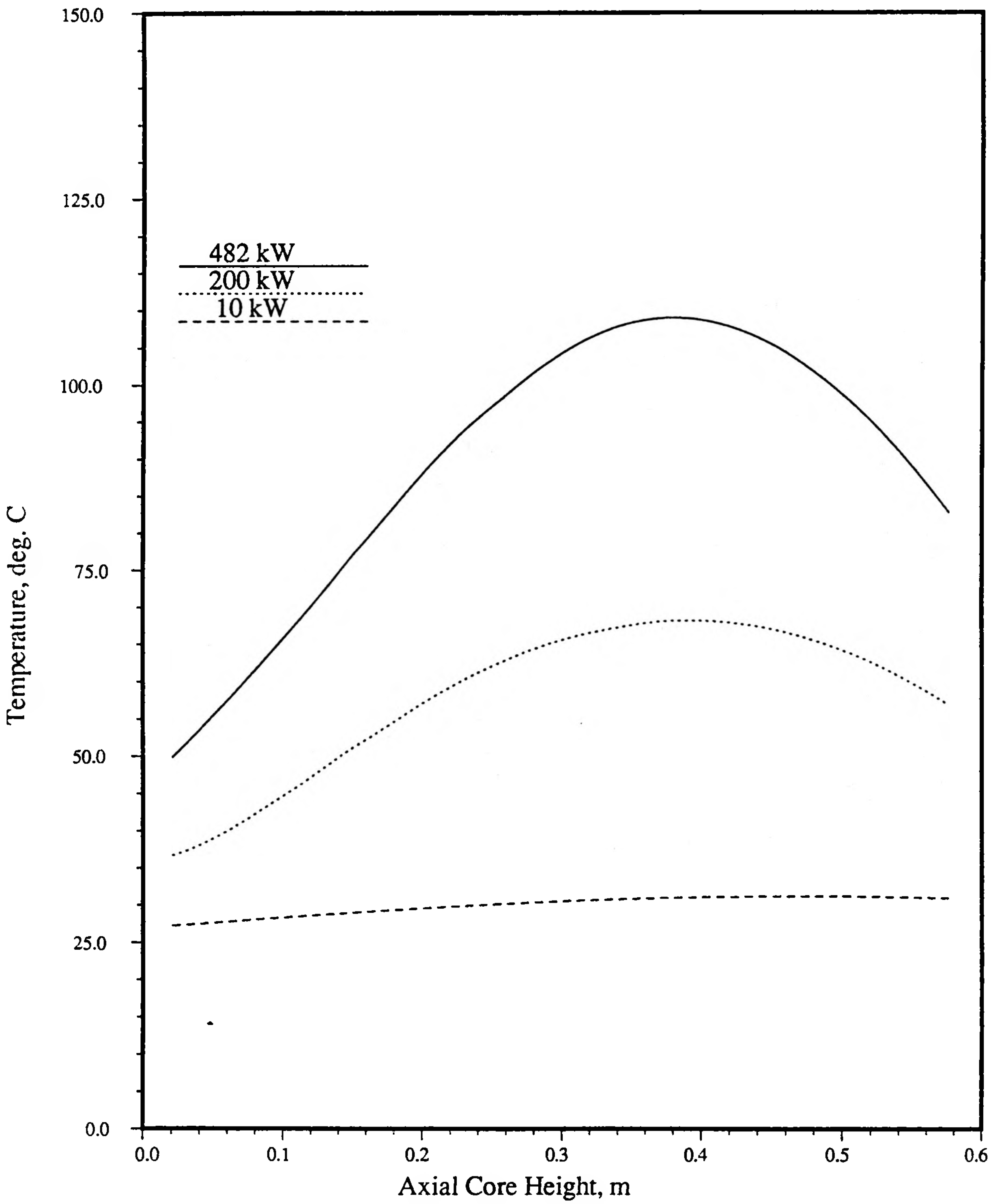


FIGURE 3. Clad Surface Temperature Through Core



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