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UC-81, Power Reactors

COOLBALL

A Machine Code for Thermal Analysis of Pebble Bed Reactor Cores

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COOLBALL

A Machine Code for Thermal Analysis of Pebble Bed Reactor Cores.

Abstract

COOLBALL is an IBM 650 machine program designed to calculate local gas and ball temperatures, gas flow, and pressure loss as induced by non-uniform power generation and voidage within an axial flow Pebble Bed Reactor core. This code has been used extensively to study the thermal characteristics of Pebble Bed Reactor cores in support of a broad program for the development of the PBR concept.

Section 1.0 Introduction

This report presents the details in the development and application of a machine program named COOLBALL, which has been instrumental in demonstrating that there are no flow instabilities in a Pebble Bed Nuclear Reactor core. This work was prompted by reports that flow instabilities had been observed in a number of packed bed chemical reactors which possessed operating characteristics similar in certain respects to those of a nuclear reactor. Some support for the persistent rumors of flow instability can be found in the fundamental correlation for pressure drop in compressible fluids. These relationships indicate that the specific pressure drop will be higher in regions of high temperature than in regions of low temperature. This would cause flow divergence from the high temperature zone which would cause the temperature to rise to higher levels which would accentuate the flow divergence and so on.

Analysis of this problem is complicated by the fact that specific flow paths through a packed bed defy description and, whereas locally conditions may differ from the average, one must average these differences before calculations can be made. Adding to the complications is the cyclicly varying voidage which has been found to exist in packed beds of uniformly sized particles in regions adjacent to container walls. These complications and the feedback effect referred to above indicated that a numerical-iterative approach would be required.

This approach of dividing the core into a number of regions, each of which was assumed to be homogeneous, with step changes between adjacent

regions was tried and found to be satisfactory. To achieve significance in the results, relatively many subdivisions are required.

Unfortunately the practical limitations of hand calculations ruled out anything but coarse grid structures with few subdivisions. Obviously by programming the calculations for machine solution much finer meshes could be studied and results could be obtained in reasonable times, thereby eliminating the dilemma entirely.

In addition to the analysis of the fluid dynamics of pebble beds and the details of the machine program, this report contains a fully developed example problem in Section 4.0.

Section 2.0 Pebble Bed Fluid Dynamics

The Pebble Bed Reactor core consists of a randomly packed, static bed, of spherical uranium-graphite fuel elements of a type as illustrated in Figure 2.1. These elements contain fissile and/or fertile material as a ceramic and provide the moderator and heat transfer surface in the reactor.

2.1 Packing of Spheres

The packing of spheres in a pebble bed is of prime interest in the use of this configuration as a reactor core. In 1935, Graton & Fraser (1) made a thorough study of the stacking of spheres and concluded that there are four formal stacking arrangements having voidages which vary from 26% in the case of the rhombohedral packing to 48% in the case of cubic packing as shown in Figure 2.2, and its associated table. It should be noted that there are two orthorhombic and two rhombohedral cases listed in the table. These cases are identical as far as the arragementsof spheres is concerned but differ in their orientation with respect to the major axis of flow. Martin et al (2) have shown that this anisotropy is unimportant in the case of the rhombohedral packing but is important in the case of the orthorhombic packing.

Another method of recognizing the regular packing configuration is by the arrangement and number of tangent neighbors associated with each sphere. Twelve points of contact are typical of rhombohedral packing while cubic packing has only six.

Actually a packed bed prepared in a random fashion could not be as ordered as implied in Figure 2.2. Smith et al (3) based on a study of ball contact points concluded that a randomly packed bed could be considered as a mixture of simple cubic and rhombohedral packing configurations. More recently Wadsworth (4) in a carefully executed study of contact

(1) Graton, L.C. & Fraser, H.J. J. Geol. 43 785 & 910 (1935)
(2) Martin, J.J., McCabe, W.L. & Monrad, C.C., Chem. Eng. Prog. 47 91 (1951)
(3) Smith, W.O., Foote, P.D., Busang, P.F., Phys. Rev. 34 1271 (1929)
(4) Wadsworth, J. Nat. Res. Council of Canada, Report MT-41 (1960)

TYPICAL FUEL ELEMENTS FOR THE PEBBLE BED REACTOR

FIG. 2.1

CUBIC ORTHORHOMBIC TETRAGONAL RHOMBOHEDRAL

FORMAL PACKING ARRANGEMENTS OF SPHERES

Layer Type	Square			Rhombic		
Case	I	II	III	IV	V	VI
Geometrical Relationship						
Name	Cubic	Orthorhombic	Rhombohedral	Orthorhombic	Tetragonal	Rhombohedral
Spacing of Layers	$R\sqrt{4}$	$R\sqrt{3}$	$R\sqrt{2}$	$R\sqrt{4}$	$R\sqrt{3}$	$2R\sqrt{2/3}$
Tangent Neighbors	6	8	12	8	10	12
Properties						
Volume of Unit Cell	$8.00R^3$	$6.93R^3$	$5.66R^3$	$6.93R^3$	$6.00R^3$	$5.66R^3$
Volume of Unit Void	$3.81R^3$	$2.74R^3$	$1.47R^3$	$2.74R^3$	$1.81R^3$	$1.47R^3$
Voidage - %	47.64	39.54	25.95	39.54	30.19	25.95

FIG. 2.2

points, using a technique similar to that of Smith, has shown that all randomly produced packing configurations tend toward rhombohedral. Thus a sphere having fewer than 12 contact points is experiencing rhombohedral packing with one, two or more contacts missing, i.e. an incomplete rhombohedral array. Wadsworth concludes that in a randomly packed bed of hard, smooth homogeneous spheres, the local packing configuration is incomplete rhombohedral with the degree of incompleteness randomly distributed throughout the bed.

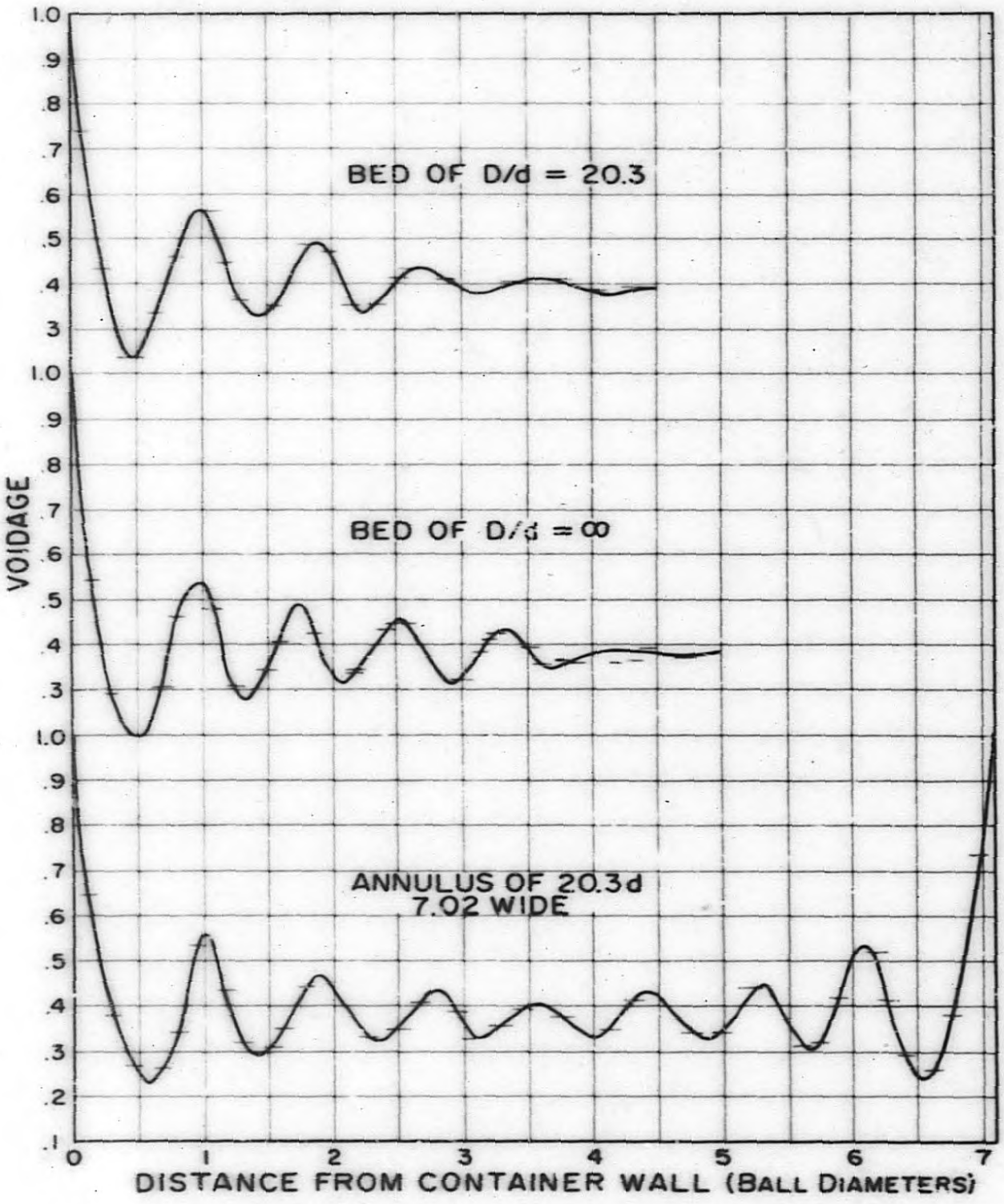
2.2 Void Distribution

The most highly oriented region of a ball bed exists adjacent to container walls and any other smooth surfaces which may exist within the bed. These surfaces result in a radial variation of voidage within a bed of randomly packed spheres which varies from 100% at the surface to about 37% at a distance determined to be about five ball diameters in from the surface. This variation was determined (5) by an experimental technique which consisted of pouring lead shot into a cylindrical mold and filling the void with epoxy resin which upon curing resulted in a packed bed, fixed within a cylinder. This cylinder was then machined to successively smaller diameters and the density of each annular ring which was machined off was determined. Knowledge of the densities of the plastic and lead permit one to determine the relative volume of plastic and lead and hence the voidage in each annular ring.

Three sets of detailed results for a bed having a d/Dp ratio of ∞, 20.3 and an annular ring of 7.025 Dp in width, are shown in Figure 2.3.

These data show the maximum voidage at the interface between the outermost row of spheres and the wall. Proceeding in from the wall, the voidage decreases to a minimum at half a ball diameter, after which it starts to increase. It cannot increase to unity, however, since the second row of spheres rests in cusps between the spheres in the first row. Proceeding in from the first row the pattern is repeated and since each row is more random than the row which precedes it, the voidage oscillates with a decreasing amplitude around a mean value. These oscillations are not completely damped out until a point is reached about five ball diameters in from the wall.

(5) Benenati, R.F. & Brosilov, C. A.I.Ch.E. Journal, 7 (1961)



VOID FRACTION DISTRIBUTION IN BEDS & AN ANNULUS

FIG. 2.3

The presence of a convex wall in a bed, such as would result from a graphite column containing control rods, has the same effect as concave surfaces on the orientation of balls adjacent to it. This is shown in the lowest curve of Figure 2.3 which shows the void distribution in an annulus about 7 ball diameters wide. It should be noted thzt unless such solid surfaces within a bed are spaced quite far apart, say 15 ball diameters, the average voidage in such a bed will be greater than the voidage in a bed not so perturbed.

Figure 2.4 shows the integrated voidage as a function of the ratio of bed diameter to ball diamater and the distance from the wall, based on the above-mentioned void distribution studies. It can be seen that for small beds or beds of large particles ($d/Dp < 20$) the average void fraction is generally higher than the often-quoted 39%. This is also shown in Figure 2.5 (6). which shows that the voidage in a packed bed of uniform spheres is independent of the sphere diameter but is a function of the ratio of bed to sphere diameter. Wadsworth (4) who has experimentally confirmed this plot of Carman's has concluded that the wall voidage accounts for nearly all the voidage change with increasing container size since the packing configuration (incomplete rhombohedral) is not effected by container size.

2.3 Fluid Friction Characteristics

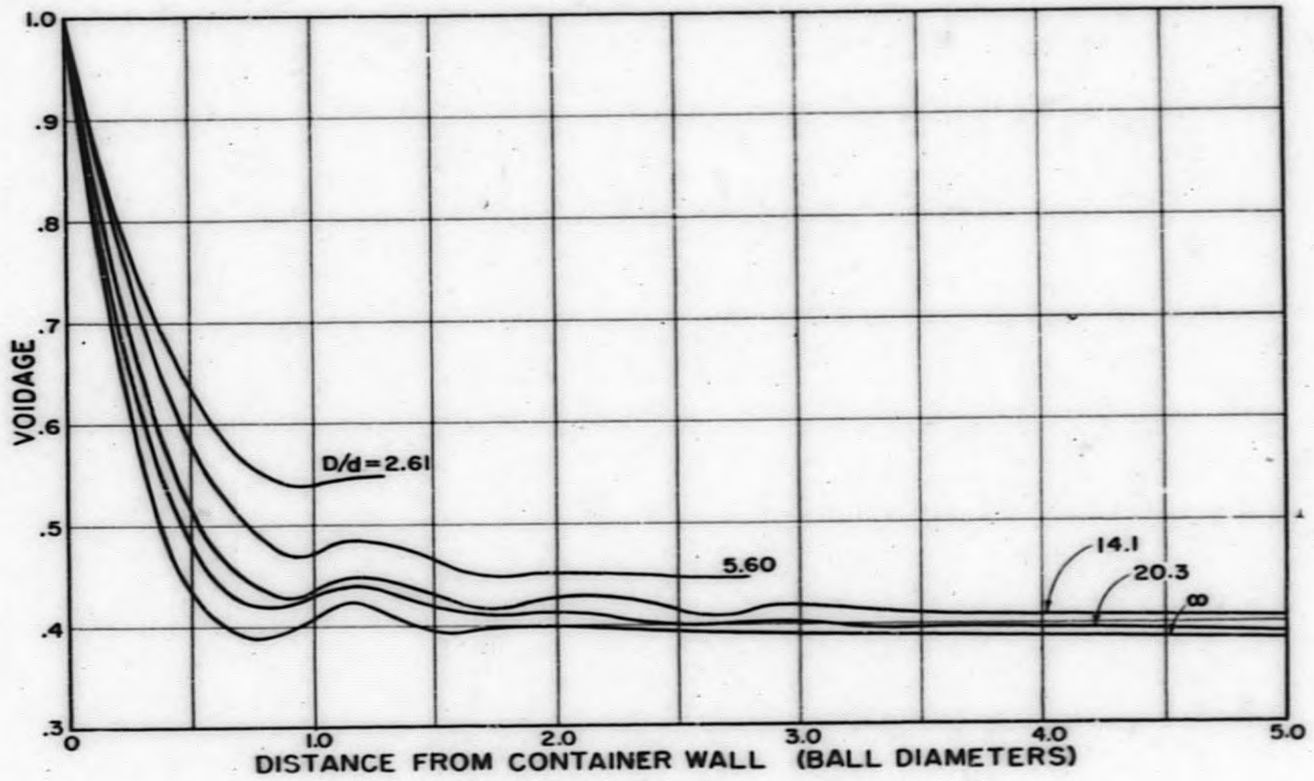
Dimensional analysis of the problem of determining the total pressure drop through randomly packed beds of spherical particles where the bed has an appreciable depth leads to the expression:

$$\frac{\Delta p}{\rho L}\frac{g\,Dp}{vs^2} = F\left[\frac{Dp\,vs\,\varphi}{\mu}, \varepsilon, \frac{e}{Dp}, \frac{d}{Dp}, \beta\right] \qquad (1)$$

where:

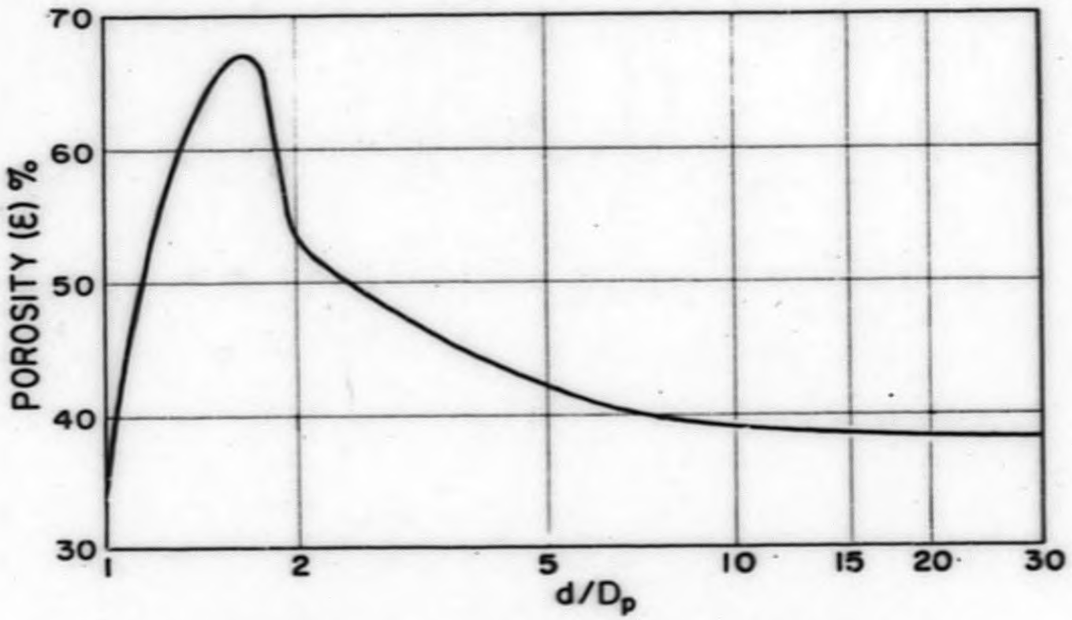
- Δp is the total pressure drop through the bed
- vs the superficial fluid velocity, referred to the total face area of the bed
- Dp is the particle diameter
- L is the bed length
- ε is the voidage
- e is a representative dimension of surface finish
- d is the bed or container diameter
- β is the loss associated with entrance and exit effects

(6) Carman, P. C. Trans. A.I.Ch.E. 15 (1937)



INTEGRATED VOID FRACTIONS

FIG. 2.4



CARMAN'S RELATION BETWEEN POROSITY OF BED & SIZE OF CONTAINER

FIG. 2.5

Pressure drop through beds of randomly packed spheres is usually correlated by plotting a modified friction factor f' vs. a modified Reynolds number Re', defined as follows:

$$f' = \frac{\Delta P}{L} \frac{\rho g D_p}{2 G_s^2} \frac{\varepsilon^3}{(1-\varepsilon)} \qquad (2)$$

$$Re' = \frac{D_p G_s}{\mu (1-\varepsilon)} \qquad (3)$$

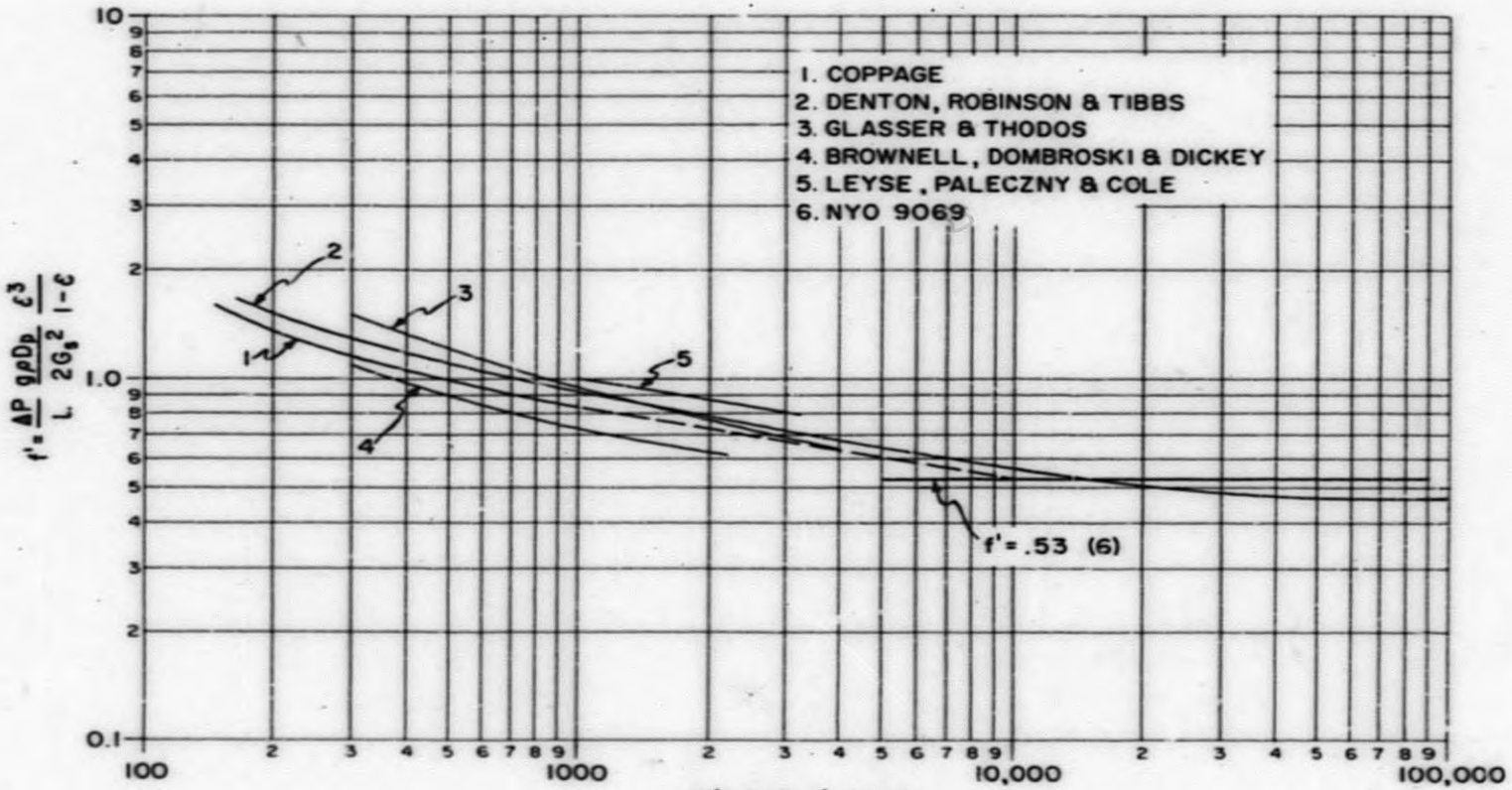
where G_s is the superficial mass flow through the bed, i.e. $G_s = v_s \rho$.

Figure 2.6 presents a plot of friction factor f' vs Reynolds number Re' for beds of randomly packed spheres as determined by a number of investigators. In general these data were obtained in beds where Dp was quite small and the ratio of d/Dp quite large. The data of curve #6 were obtained (7) using 3/4" and 1-1/2" diameter balls in beds approximately 7-1/2" and 15" diameter for a d/Dp of 10 and 20. The data of curve #2 were also obtained (8) using relatively large spheres.

These two sets of results are in excellent agreement in that both show friction factor to be independent of Reynolds number in the high range. The principal difference is that the work reported on in NYO-9069 shows the friction factor to be independent of Reynolds number, to values about one order of magnitude lower than shown in (8)

It has been recommended (9) that a value of f' of 0.53 be used for design of Pebble Bed Reactor cores where the bed has a d/Dp $\geq$ 20 and modified Reynolds number is $\geq$ 5000. This value of f' has therefore been used in developing the program described in this report.

(7) NYO-9069 Pebble Bed Friction Factor & Thermal Expansion Tests
(8) HPC-35 Heat Tarnsfer & Pressure Loss in Fluid Flow through Randomly Packed Spheres
(9) NYO-9071 Progress Report-Pebble Bed Reactor Program



FRICTION FACTOR CORRELATION FOR PEBBLE BEDS

FIG. 2.6

2.4 Heat Transfer Characteristics

Figure 2.7 presents a heat transfer correlation for pebble bed from the data obtained by three investigators. These data are presented in terms of a heat transfer grouping j_s, defined as:

$$j_s = h\,Pr^{.66}/G_s C_p \qquad (4)$$

and a modified Reynolds number Re' defined as:

$$Re' = D_p G_s/\mu(1-\varepsilon) \qquad (5)$$

The data of principal interest is that of Coppage (10) and Denton (8). The results of Coppage were found to be represented by the following expression:

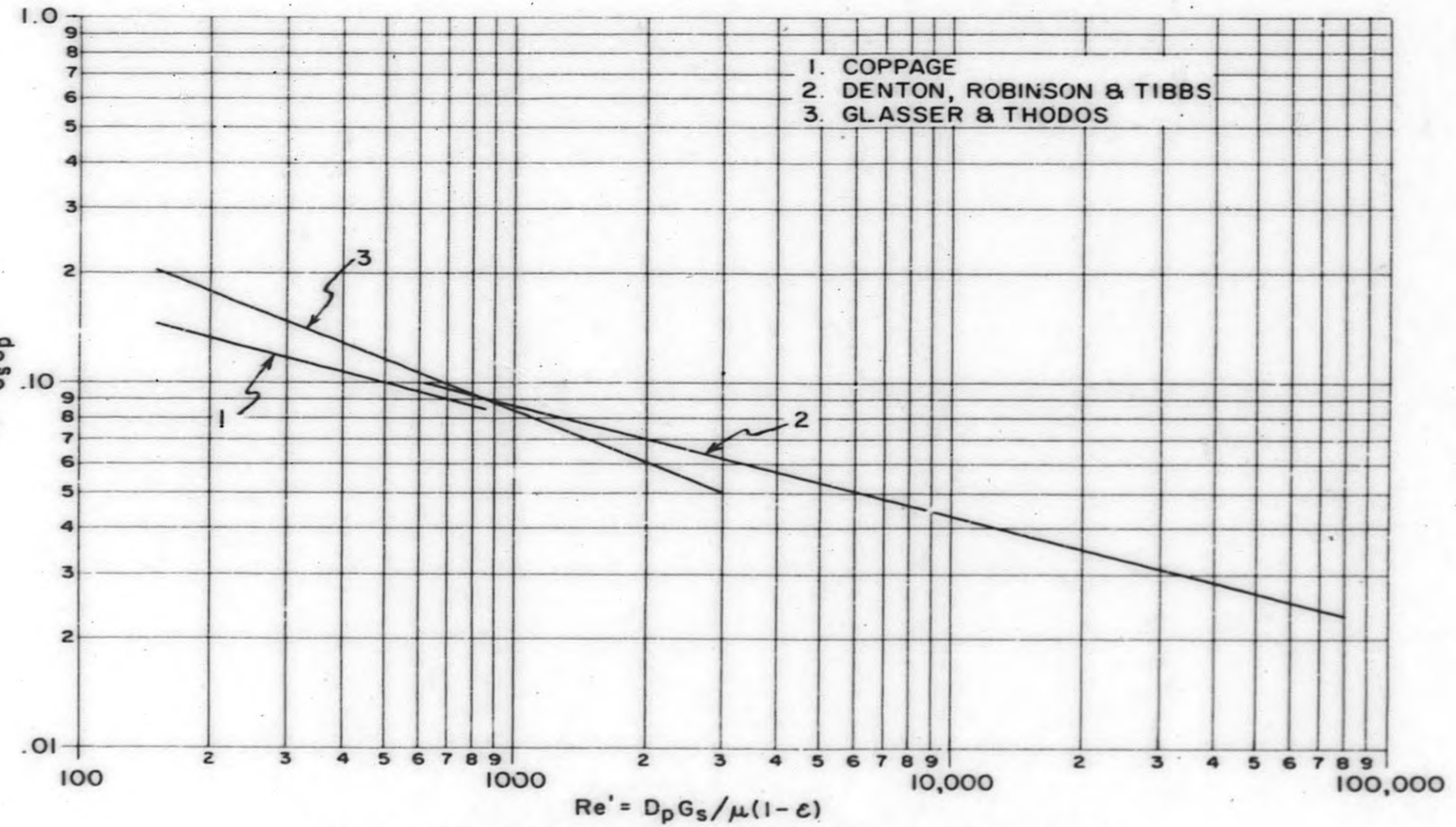
$$\frac{h\,Pr}{G\,C_p} = \frac{0.21}{\left(\frac{D_p G}{\mu}\right)^{.31}} \qquad \text{for } 25 < Re < 550 \qquad (6)$$

for a bed of voidage of 39%.

It will be noted that the data are reduced in terms of the mass flow through the interstices of the bed itself and the hydraulic diameter of the flow passage. The data can also be expressed in terms of mass flow at the face of the bed (G_s), particle diameter (Dp), and modified Reynolds number (Re'), and made applicable for any gas, as follows:

$$j_s = \frac{h\,Pr^{.66}}{G_s C_p} = \frac{0.68}{\left[\frac{D_p G_s}{\mu(1-\varepsilon)}\right]^{.31}} \qquad (7)$$

(10) TR-No.-16 Heat Transfer & Flow Friction Characteristics of Porous Media - Stanford University



HEAT TRANSFER CORRELATION FOR PEBBLE BEDS

FIG. 2.7

The results of Denton were found to be represented by the following expression:

$$\frac{h}{G_s C_p} = \frac{0.72}{\left(\frac{D_p G_s}{\mu}\right)^{.3}} \qquad (8)$$

at a value of Pr of 0.73 and voidage of 37%. Expressing in terms of $\frac{h\ Pr^{.66}}{Gs\ Cp}$ and in terms of the modified Reynolds number Re':

$$j_s = \frac{h\ Pr^{.66}}{G_s C_p} = \frac{0.677}{\left[\frac{D_p G_s}{\mu(1-\epsilon)}\right]^{.3}} \qquad (9)$$

The correlation of these data is remarkable, considering that the tests were run by different laboratories at different times and over different Reynolds number ranges. One piece of data is simply an extension of the other and in view of the fact that the bulk of the data is that of Denton, we choose to represent the mean by the expression:

$$j_s = \frac{0.68}{Re'^{0.3}} \qquad 100 < Re' < 80,000 \qquad (10)$$

The data of Glasser & Thodos (11) is included in Figure 2.7 because their results were obtained simultaneously with their friction factor results in Figure 2.6. Their values of j_g at the extreme of the range tested bracket the Coppage-Denton data.

To allow for spread in experimental data and to insure that maximum specified temperatures will not be exceeded, it has been recommended (9) that j_g be reduced by 15% for design purposes, or

$$j_g = .58/Re'^{0.3}$$

which is the value that has been used in developing the program described in this report.

(11) Glasser & Thodos Heat & Momentum Transfer in the Flow of Gases through Packed Beds - Ph. D. Thesis Nprthwestern Technical Institute

Section 3.0 Machine Program

A characteristic of a Pebble Bed Reactor core is that its coolant flow passages are interconnected radially as well as axially. This gives rise to radial coolant flow components which are effected by radial variation in temperature and voidage. Radial temperature variations stem from the radial power distribution while radial voidage distributions stem from the effect of the bed boundaries. Roughly parallel situations arise in chemical reactors in which catalized exothermic reactions take place in packed beds.

3.1 Problem Analysis

The technique employed for thermal and flow analysis consists of dividing the bed into annular rings and axial slices with the assumption that the system is homogeneous within each matrix cell resulting from this subdivision. Radial flow between adjacent matrix cells is only permitted at the boundaries of axial slices and it is assumed that there is no resistance to radial flow at these points, i.e. the pressure is constant across any axial slice. The flow in each matrix cell is determined in an interative process for each layer. The analysis proceeds layer by layer in the gas flow direction.

The problem was further subdivided into one program which developed the local heat generation rates and a second program which analyzes the flow and temperatures resulting therefrom.

3.2 Code Details

COOLBALL (parts I and II) is an IBM 650 machine code designed to solve for local gas and ball temperatures, gas flow and pressure loss as induced by non-uniform power generation and voidage within an axial flow Pebble Bed Reactor core. Input data required for COOLBALL I are normalized radial and axial power distribution and gross power. COOLBALL II requires the system pressure, flow rate, fuel element size, matrix cell dimensions, certain thermodynamic properties of the gas as detailed later, and the complete output of COOLBALL I.

3.2.1 COOLBALL I

Before using the code, unit cells are established by dividing the core into a convenient number of annular rings (not to exceed 20) and axial layers (not to exceed 20). Voidage distribution is established, based on d/Dp ratio of the bed or any perturbations in voidage that are to be introduced. Weight flow through the core is determined from the specified power output and temperature rise through the core. COOLBALL I generates an average power output for each matrix cell from the radial and axial power distribution. The input power distribution may be in the form of ratios of local to average power or ratios of local to peak power. The core specific power (BTU/sec/ft^3 bulk bed) may be the average or peak value but must be compatible with the power distribution.

The program was written for the basic 650 using FORTRANSIT I. All data must therefore be floating point numbers in the form .XXXXXXXXYY where XXXXXXXX represents the eight most significant figures and YY is 50 plus the power of ten needed to relocate the decimal point.

Table 3.1 lists the card format for input and output to COOLBALL I.

Figure 3.1 shows the calculation flow sheet for this program.

Table 3.2 lists the last 15 cards of the program deck in the standard 5 word per card format. This deck must, or course, be preceded by the 85 card SOAP-PACKAGE deck which contains the FORTRANSIT interpretive routines which are common to all FORTRANSIT programs.

Figure 3.2 indicates the operating instructions for COOLBALL I.

3.2.2 COOLBALL II

In COOLBALL II, analysis proceeds layer by layer in the gas flow direction. As a start, the local mass velocity for each matrix cell of the first layer is assumed to equal the average mass velocity which is read in as input. The local temperature rise in each matrix cell of the first layer is determined from a heat balance over the cell, and the arithmetic mean temperature in the cell is computed. Gas Properties in the cell

TABLE 3.1

CARD FORMAT COOLBALL PART I

INPUT

Card								CC73
1	RP_1	RP_2	RP_3	RP_4	RP_5	RP_6	RP_7	+
2	RP_8	RP_9	RP_{10}	RP_{11}	RP_{12}	RP_{13}	RP_{14}	+
3	RP_{15}	RP_{16}	RP_{17}	RP_{18}	RP_{19}	RP_{20}	$\bar{Q}$ or Q^*_{max}	+
4	AP_1	blank	blank	blank	blank	blank	blank	+
5	AP_2	blank	blank	blank	blank	blank	blank	+
23**	AP_{20}	blank	blank	blank	blank	blank	blank	+

OUTPUT

1	$Q_{1,1}$	$Q_{2,1}$	$Q_{3,1}$	$Q_{4,1}$	$Q_{5,1}$	$Q_{6,1}$	$Q_{7,1}$	blank
2	$Q_{8,1}$	$Q_{9,1}$	$Q_{10,1}$	$Q_{11,1}$	$Q_{12,1}$	$Q_{13,1}$	$Q_{14,1}$	blank
3	$Q_{15,1}$	$Q_{16,1}$	$Q_{17,1}$	$Q_{18,1}$	$Q_{19,1}$	$Q_{20,1}$	blank	blank
4	$Q_{1,2}$	$Q_{2,2}$	$Q_{3,2}$	$Q_{4,2}$	$Q_{5,2}$	$Q_{6,2}$	$Q_{7,2}$	blank
60	$Q_{15,20}$	$Q_{16,20}$	$Q_{17,20}$	$Q_{18,20}$	$Q_{19,20}$	$Q_{20,20}$	blank	blank

* If power profiles are normalized to max. power = 1.0, Q_{max} must be used; if however power profiles are normalized to avg. power = 1.0, $\bar{Q}$ must be used.

** If fewer than 20 axial layers are used, unnecessary axial power input cards may be eliminated and correspondingly fewer output cards will be produced.

TABLE 3.2

COOLBALL I LISTING IN FIVE-PER-CARD FORM

7842210086	201	6500520057	2019680071	6500740079	2019690072	199900	5700710079
7842210087	6500750129	6900821913	203	6500850089	2019680121	72012900	820089
7842210088	6501240179	6901321913	202	6501350139	2000440047	121017900	1320139
7842210089	1000106	6500500055	2000000053	6500440049	3500040059	4700	5500530049
7842210090	1500620067	6900008002	2400210125	204	6500420097	59006700	6200000125
7842210091	6500430147	2000000054	6901001902	2019660069	6500440099	54009701	4701000069
7842210092	3500040109	1501128002	6500010105	2000000103	6519660171	99010901	1201050103
7842210093	6901741902	6500440149	3500040159	1501620117	6900008002	171017401	4901590117
7842210094	2400210155	1	6500020107	2000020155		162000001	401070000
7842210095	6501350189	1500440199	2000440197		6680020205	155018901	9900000197
7842210096	1500580063	4600660047	2	6501190073	2019680221	205006300	560073
7842210097	6502740229	6901821907	206	2320082	205	221022900	1820000
7842210098	80008000		20	10002	200021	232005000	5802740119
7842210099	1	10023	42	20021	200001	135012400	8500750074
7842210100	41	10023	42	20021	1999	52000000	1980

NOTE: The above listing does not include the FORTRANSIT interpretive routines which are common to all FORTRANSIT programs.

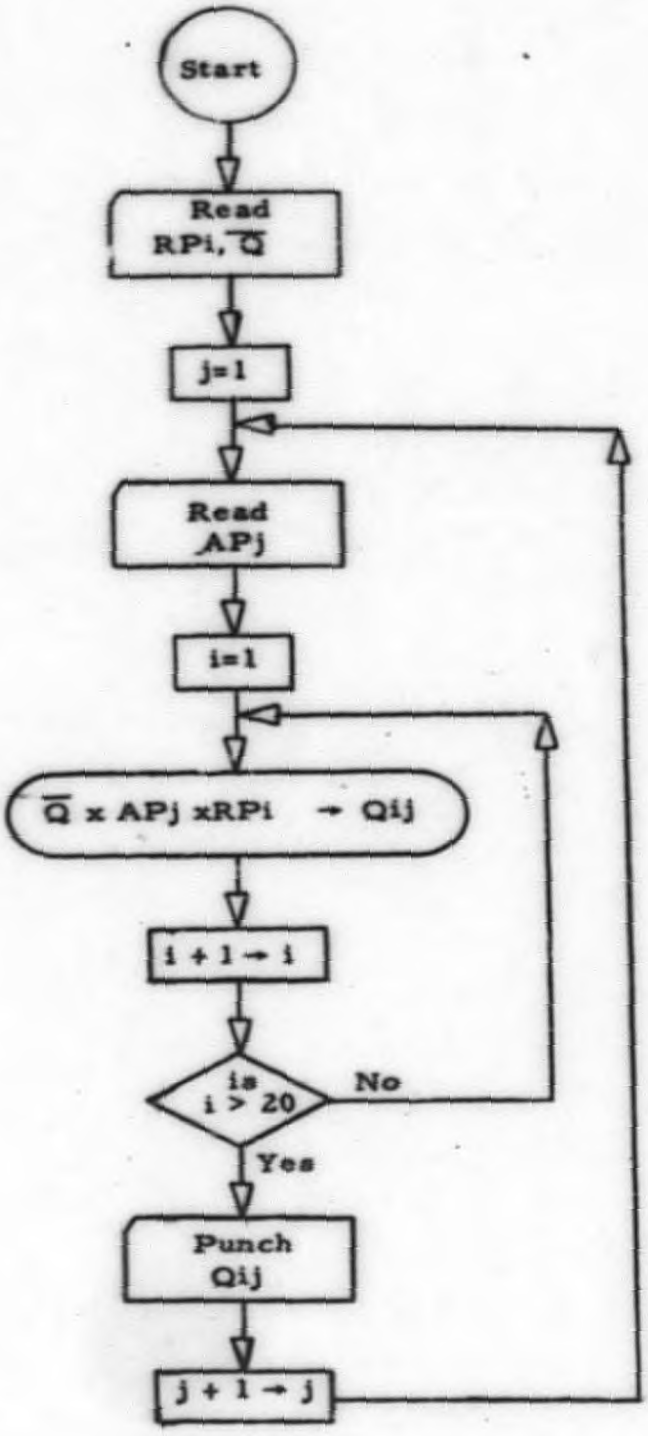


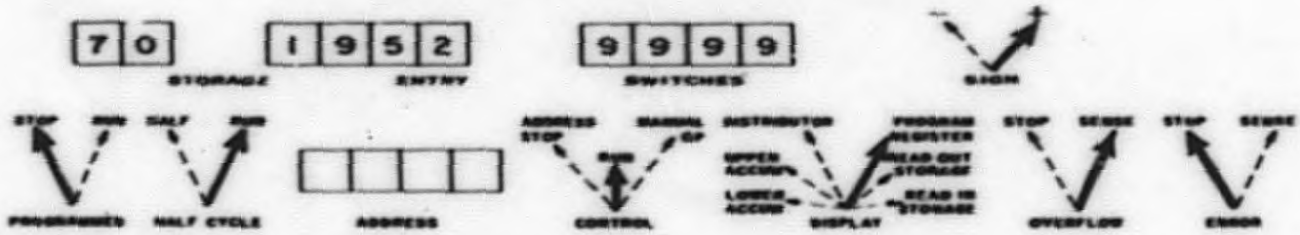
Figure 3.1

Calculation Flow Sheet

COOLBALL Part I

COOLBALL I

IBM 650 PROGRAM OPERATING INSTRUCTIONS



I. Initial Console Setting as shown above.

A. Normal Starting Procedure: Computer Reset; Program Start.

B. Special Instructions: None

II. Card Input – Output (533 or 537)

READ FEED

NO. OF CARDS	FILE DESCRIPTION
100	PROGRAM DECK
	DATA DECK (see below)

PUNCH FEED

CARD FORM
80 – 80

CONTROL PANELS

FORTRANSIT II

III. Other Instructions and Remarks:

NOTE: Only one set of data may be loaded at a time

IV. Program Stops and Required Action:

STOP ADDRESS	MESSAGE – EXPLANATION – ACTION
	None

FIG. 3.2

are determined from the following equations:

$$\rho = \frac{PMW}{RT} \tag{11}$$

$$C_p = \overline{C_p}\,(T/\bar{T})^{CpX} \tag{12}$$

$$\mu = \bar{\mu}\,(T/\bar{T})^{\mu X} \tag{13}$$

$$Pr = \overline{Pr}\,(T/\bar{T})^{PrX} \tag{14}$$

The appropriate exponents have to be determined in advance for the gas in question. The local mass velocity through each matrix cell is then determined from:

$$G = \left[\frac{g\rho D_p \Delta p\, \varepsilon^3}{2f'L(1-\varepsilon)}\right]^{.5} \tag{15}$$

As was indicated earlier, a constant value of f' = 0.53 was used. Substituting the ideal gas low density gives:

$$G = \left[\frac{g}{2}\frac{PMW\, D_p \Delta p\, \varepsilon^3}{RTf'L(1-\varepsilon)}\right]^{.5} \tag{16}$$

which upon removal of all terms which are constant in any axial layer becomes:

$$G = CONST\left[\frac{\varepsilon^3}{T(1-\varepsilon)}\right]^{.5} \tag{17}$$

where T is the local average temperature in each matrix cell in the given axial layer. Using just the argument of the square root in equation (17), the relative mass velocity in each matrix cell of a given layer is determined. For each axial layer, a mass balance prescribes that:

$$W = \Sigma G_i A_i \tag{18}$$

from which actual mass velocities in each cell are determined. The new mass velocities are used to compute new local average temperatures and the operation repeated until a predetermined agreement is reached between the assumed and calculated mass velocities.

The corrected local gas outlet temperatures and pressure of the preceding layer furnish the inlet conditions for the next layer, the corrected mass velocities of the preceding layer serve as first assumptions for mass velocities in the next layer and so on until the entire core is traversed.

For each layer, mixed mean outlet temperature is calculated from:

$$\overline{T_2} = \frac{\Sigma T_i W_i}{\Sigma W_i} \tag{19}$$

The film temperature drop is determined from the expression:

$$\Delta T_f = \frac{272\, D_p^{1.3} G^{.3}}{L[\mu(1-\varepsilon)]^{.3}} \tag{20}$$

The ball surface temperature is simply:

$$\overline{T_S} = \overline{T} + \Delta \overline{T_f} \tag{21}$$

Finally the temperature in the center of the fuel ball in each matrix cell is obtained from

$$T_C = T_S + \frac{75\, Q\, D_p^2}{(1-\varepsilon)\, k} \tag{22}$$

where k, the thermal conductivity of irradiated graphite is given by

$$k = 19.5\left(\frac{2660-t}{390.6}\right)^{2.} \qquad (23)$$

where t is the average graphite temperature in the ball and is determined by iteration between equations 22 and 23.

COOLBALL II is also a FORTRANSIT program and therefore all data and results are in the floating point form mentioned earlier.

Table 3.3 lists the card format for input and output to COOLBALL II.

Figure 3.3 shows the calculation flowsheet for this program.

Table 3.4 lists the running deck in standard seven-per-card format. The word -01(LOC)8000 is listed in all unused drum positions.

Figure 3.4 indicates the operating instructions for COOLBALL II.

TABLE 3.3

CARD FORMAT COOLBALL PART II

INPUT

Card	Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	CC73
1	Identification	MW*	T_{in}	P	W	A	ΔL_1	*
2	ΔL_2	ΔL_3	ΔL_4	ΔL_5	ΔL_6	ΔL_7	ΔL_8	*
3	ΔL_9	ΔL_{10}	ΔL_{11}	ΔL_{12}	ΔL_{13}	ΔL_{14}	ΔL_{15}	*
4	ΔL_{16}	ΔL_{17}	ΔL_{18}	ΔL_{19}	ΔL_{20}	ρ	XMU	*
5	$\overline{T}$	blank	blank	blank	blank	blank	blank	*
6	$\overline{C}_p$	CpX	δ	ε 1	ε 2	ε 3	ε 4	*
7	ε 5	ε 6	ε 7	ε 8	ε 9	ε 10	ε 11	*
8	ε 12	ε 13	ε 14	ε 15	ε 16	ε 17	ε 18	*
9	ε 19	ε 20	D_p	J*	$\overline{Pr}$	PrX	I*	*
10	A_1	A_2	A_3	A_4	A_5	A_6	A_7	*
11	A_8	A_9	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	*
12	A_{15}	A_{16}	A_{17}	A_{18}	A_{19}	A_{20}	blank	*
13-72	COOLBALL Part I							

* Fixed point number

OUTPUT

Card								
1	Identification	MW	T_{in}	P	W	$\overline{G}$	blank	blank
2	P_j	j	blank	blank	blank	blank	blank	blank
3	$\overline{T}_2$	$T_{*1,1}$	$T_{*2,1}$	$T_{*3,1}$	$T_{*4,1}$	$T_{*5,1}$	$T_{*6,1}$	blank
4	$T_{*7,1}$	$T_{*8,1}$	$T_{*9,1}$	$T_{*10,1}$	$T_{*11,1}$	$T_{*12,1}$	$T_{*13,1}$	blank
5	$T_{*14,1}$	$T_{*15,1}$	$T_{*16,1}$	$T_{*17,1}$	$T_{*18,1}$	$T_{*19,1}$	$T_{*20,1}$	blank
6	$T_{1,1}$	$T_{2,1}$	$T_{3,1}$	$T_{4,1}$	$T_{5,1}$	$T_{6,1}$	$T_{7,1}$	blank
7	$T_{8,1}$	$T_{9,1}$	$T_{10,1}$	$T_{11,1}$	$T_{12,1}$	$T_{13,1}$	$T_{14,1}$	blank
8	$T_{15,1}$	$T_{16,1}$	$T_{17,1}$	$T_{18,1}$	$T_{19,1}$	$T_{20,1}$	$T_{b1,1}$	blank
9	$T_{b2,1}$	$T_{b3,1}$	$T_{b4,1}$	$T_{b5,1}$	$T_{b6,1}$	$T_{b7,1}$	$T_{b8,1}$	blank
10	$T_{b9,1}$	$T_{b10,1}$	$T_{b11,1}$	$T_{b12,1}$	$T_{b13,1}$	$T_{b14,1}$	$T_{b15,1}$	blank
11	$T_{b16,1}$	$T_{b17,1}$	$T_{b18,1}$	$T_{b19,1}$	$T_{b20,1}$	$G_{1,1}$	$G_{2,1}$	blank
12	$G_{3,1}$	$G_{4,1}$	$G_{5,1}$	$G_{6,1}$	$G_{7,1}$	$G_{8,1}$	$G_{9,1}$	blank
13	$G_{10,1}$	$G_{11,1}$	$G_{12,1}$	$G_{13,1}$	$G_{14,1}$	$G_{15,1}$	$G_{16,1}$	blank
14	$G_{17,1}$	$G_{18,1}$	$G_{19,1}$	$G_{20,1}$	blank	blank	blank	blank

Cards 2 through 14 repeated for each axial layer

TABLE 3.4

COOLBALL II PROGRAM LISTING IN SEVEN-PER-CARD FORM

80001953	1094646854	7019040000	8000	6919521955	6919531956	1058251354	1051059554
80001904	1094646854	7019040000	8000	6919521955	6919531956	1058251354	1051059554
80001905	1119871991	1019948003	1080011985	2419841906	2419901958	2419958000	6919541957
80001905	1019881993	4419958000	6719511986	2419851906	2419911958	2419968000	6919541957
80001905	1519921990	2399999988	6919521955	2419861906	2419921958	2419978000	6919541957
80001905	6919588002	1580018003	6919521955	2419871906	2419931958	2419988000	6919541957
80001905	10000	6919528002	6919531956	2419881906	2419941958	2419998000	6919541957
1996	5000000050	2019680471	1072692654	1093364954	1095497454	1094892054	1096737554
71996	1094646854	1090380754	1083001254	1076491154	1072356654	1058251354	1051059554
141996	1058089054	1053494854	1045936954	1038755554	1029387854		
211996		9920247553	1060000854	1062125054	1045131054	1033447654	1009016854
281996	9590988853	8847501353	8220847553	7859725053	7126858853	6075355053	6054112553
351996	5431707353	4495975153	3754611953	3101405053			
421996	4067873452	4622507452	4742210052	4708503452	4812383052	4695363352	4456725252
491996	4044244052	3680847252	3450240852	2664814252	2266004052	2656851552	2401887052
561996	1982901452	1585312052	1067545052	100598000-	100608000-	100618000-	7998875251
631996	6409325051	6260061451	6203997051	60022217[illegible]1	6006393451	6014939551	6114585451
701996	6242413651	6367026351	7475064951	7493672651	6368937051	6320734251	6337332951
771996	6619635151	8119999851				7998923251	6408909951
841996	6259596151	6203543951	6001725551	6005942051	6014575451	6114361651	6242302251
911996	6366981751	7475245951	7493907751	6369056651	6320888551	6337531551	6619867251
981996	8120286951				1000000051	8012215850	7825548550
1051996	7755473750	7503166850	7508438150	7519231450	7643981150	7803928150	7959798550
1121996	9345315250	9368645650	7962392550	7902174350	7922980850	8275948050	1015172551
1191996	101198000-	101208000-	101218000	-5884272051	9038620851	9461408551	9637087351
1261996	1028338352	1028338352	1028338352	1000025452	9637087351	9289529651	6804866851
1331996	6804866851	9375000051	9548766451	9548766451	8795721551	5884272051	
1401996			5470000050	5960000050	6010000050	6030000050	6100000050
1471996	6100000050	6100000050	6070000050	6030000050	5990000050	5640000050	5640000050
1541996	6000000050	6020000050	6020000050	5930000050	5470000050	101598000-	101608000-
1611996	101618000-	2253568850	1986091550	1959103050	1948576050	1911104150	1911459450
1681996	1912186350	1929385850	1951803850	1973856650	2164438150	2165895350	1971116450
1751996	1961284050	1962677650	2012187950	2262770350			
1821996	6240000050	7510000050	1092000051	1275000051	1427000051	1616000051	3720000051
1891996	4395000051	2434000051	1994000051	2100000051	2630000051	3010000051	5970000051
1961996	8120000051	2790000051	3362000051				1093032054
2031996	1070252354	1071786454	1071349554	1072675654	1071170054	1068097054	1062780054
2101996	1058086854	1055105254	1044927354	1029729554	1044804854	1041485354	1036022454
2171996	1030829054	1024050054				1198228054	1229227554
2241996	1231931154	1229257754	1230053254	1224798954	1214069854	1196896354	1182089754
2311996	1173119254	1148570954	1128022054	1135682154	1123156354	1103575854	1086690254
2381996	1068533554				4100000050	4100000050	4100000050
2451996	4100000050	4100000050	4100000050	4100000050	4100000050	4100000050	4100000050

TABLE 3.4 (cont.)

2521996	4100000050	4100000050	4100000050	4100000050	4100000050	4100000050	4100000050
2591996	4100000050	4100000050	2920000050	6240000050	6017174150	6545499050	9888229050
2661996	1070701951	1213363651	2797154151	3359589751	1899476151	1587183851	1962516251
2731996	2463953851	2396680151	4717394151	6433460451	2308989551	3413009951	102798000-
2801996	102808000-	102816000-	6000000000	4	1010000054	9854077053	3095000053
2871996	4731000052	2400000046	5800000050	1360000054	1250000051		3280000049
2941996	1250000050	20	7650000050	6000000049-	17	6541957351	1
3011996	4890000048	1419992849	2140200050	2083333349	1156600051	3	3869270852
3081996	9707077053	103098000-	8077414050	4071989068	103128000-	2000001254	6503560511
3151996	1503180473	4513700712	2019680971	2400010504	4604720353	103208000-	6503240389
3221996	6503250379	6503260331	288	287	200241	286	285
3291996	2019690322	283	2019710374	281	2019730376	6503560561	2019750378
3361996	6503390393	2019770380	6604910845	1	6503430347	2000000454	2008650338
3431996	200181	2002990358	6906241802	103468000-	2019680371	6506011009	103498000-
3501996	2003030606	6909541950	6503550359	6503560411	2403570360	296	
3571996	2000000658	2003021205	2019680421	6780020357	2019680321	200021	6503661422
3641996	6503560611	1503680523	309	1506708008	2400610314	6506071111	103708000-
3711996	6504240529	6504250579	6504260481	6503270381	6503280333	6504290383	6503300335
3781996	6504310385	2019700323	6504330387	2019720375	290	2019740377	2003010854
3851996	2019760479	6905891908	6903401913	6505911045	2000000803	6502870341	6903441602
3921996	2003080912	2003000353	6503970001	2400000576	6919670520	3000000051	6519670821
3991996	2000001104	104008000-	2000001054	104028000-	6503000405	6511560563	3500040315
4061996	6506370721	289	6503390943	6000000051	6507241080	2000000403	200201
4131996	6519661027	20	1504180573	2000000859	1507200775	2400610334	6502890843
4201996	6602920447	6503280633	6504290683	6503300535	297	296	295
4271996	294	293	284	292	282	6500020707	100021
4341996	6503391243	2019750478	104368000-	2019770480	6506911095	2000001408	6906431902
4411996	6904941302	104428000-	1503000705	6505970551	6903981950	104468000-	2019690522
4481996	6504511155	6904521802	104508000-	5800000050	2003040657	6503000455	6502860391
4551996	3500040365	1509598002	1000000051	4604621207	6503620317	6503391093	2000000453
4621996	6514650669	6680020828	6503000855	1504680623	1522	1508208002	2401610364
4691996	6503001455	6502940399	6503000905	6503390473	6900008002	6504270531	6504280483
4761996	6506290533	6504300435	6505810485	6503320337	6505830487	2019710474	6503561461
4831996	2019730476	6503391493	2019760679	104868000-	6903901913	104988000-	6903421852
4901996	104908000-	1470000052	104928000-	2003000753	2019660619	6904481902	104968000-
4971996	6903501852	2019681021	4605130459	105008000-	2000001154	105028000-	6503000505
5041996	6503560461	3500040415	6902940395	2700000050	3500040769	2406120916	6503391143
5111996	2000000503	4607120316	80008000	6503390543	1505180673	4515700466	1505708002
5181996	2402210574	6503000706	2400001203	2400000853	6502890743	6900008002	6504310505
5251996	6503320537	6507290733	3000051539	6919690672	2019690372	6519681323	2019720475
5321996	6602930647	2019740477	105348000-	2019710524	105368000-	2019730526	105388000
5391996	6903921852	105408000-	6905441800	105428000-	1503001105	2003110966	2019710974
5461996	105468000-	2019690622	2400610564	2400001263	105508000-	2019670620	105528000-
5531996	6503000555	6503390443	3500040465	6519660871	6670000050	3500040819	6503001106

TABLE 3.4 (cont.)

5601996	6503391193	2000000553	6500021058	6910661852	1110671423	1505680723	6919671026
5671996	1509700875	2402010554	6503001256	6503061361	6503000955	6502970401	6900008002
5741996	6503560661	2000000654	6502830587	1502981412	2019661319	2019700373	2019661019
5811996	291	6603100416	1000222	-1058848000	-2019720525	-1058868000	-6904401801
5881996	-1058880000	-6680020697	-1059080000	1	-1059280000	-1059380000	-1059480000
5951996	6904981902	-1059680000	-2000000051	-1059880000	-1059980000	-1060080000	
6021996	-1060280000	-6503000605	6503000805	3500040515	6504090313	3000000050	6519671571
6091996	6504120767	3500041126	2000000603		6501410745	6680020173	1506180773
6161996	2000000860	1510208002	2400010604	6503001307	6503001555	1180011528	6502900545
6231996	6900008002	6503001005	6919680521	2019690572	2445000048	6507310885	2001221
6301996	6503001060	6903841802	-1063280000	-2019690482	-1063480000	-2019660569	-1063680000
6371996	-1063780000	-1063880000	-1063980000	-1064080000	-2000000659	-1064280000	-6506270631
6441996	-1064480000	-2000001503	-1064680000	-2019660719	-1064880000	-1064980000	-1065080000
6511996	-1065180000	-1065280000	-6503000655	6504570761	3500040565	6502910595	6502890893
6581996	6519660922	6507631218	3500041176	2000000653	6900210286	2006380671	6519691173
6651996	1506688002	2003111164	1510708002	6601210575	2019681521	6500010756	6907240928
6721996	2400001353	6900008002	6502990953	6905281800	6502900445	6905301802	6507810935
6791996	6503820437	2402211127	6904841907	-1068280000	-2019700423	-1068480000	-2000000608
6861996	-1068680000	-1068780000	-1068880000	-1068980000	-1069080000	-6900081803	-1069280000
6931996	-1069380000	-1069480000	-2000001354	-1069680000	-2000000911	-1069880000	-1069980000
7001996	-1070080000	-1070180000	-1070280000	-6680020711	6503000456	2003000703	3500040367
7071996	2000021255	6503000758	6911251902	2019661419	1504140319	6502850439	6911161902
7141996	2019660419	1507180823	6903110766	1511200925	2401410394	6502980508	2402011454
7211996	6908761852	6506381028	6900008002	3500000053	2000000553	2019670570	2000000658
7281996	6508310985	60001	6500410995	200001	-1073280000	-6903361907	-1073480000
7351996	2000000808	-1073680000	-1073780000	-1073880000	-1073980000	-1074080000	-1074180000
7421996	-1074280000	-2000001004	-1074480000	-6903481800	-1074680000	-6503000863	-1074880000
7491996	-1074980000	-1075080000	-1075180000	-1075280000	-6502840389	6503001258	3500040615
7561996	2000001404	5000000050	3500040869	6519661372	3500041226	6904641852	5
7631996	2000000052	6519660921	1507680002	2400001462	2019681421	6501210625	1508228002
7701996	6503000856	4609781130	6680020981	6900008002	2019660369	6900008002	6919670920
7771996	6900008002	6508811035	6904321913	6500011210	2002221	-1078280000	-2019691524
7841996	-1078480000	-6900008002	-1078680000	-1078780000	-1078880000	-1078980000	-1079080000
7911996	-1079180000	-1079280000	-6903961802	-1079480000	-2000000759	-1079680000	-1079780000
7981996	-1079880000	-1079980000	-1080080000	-1080180000	-1080280000	-6503000755	6915781587
8051996	3500040665	3500040417	6908571802	6503000858	6908621902	3500041326	1502981103
8121996	3500041523	6907471852	6504571311	1508188002	6514651519	1511708002	6501410345
8191996	1508728002	6502010906	6907741800	6600611515	6900008002	6502910495	2000001006
8261996	2400000754	6905801802	1502950499	6904821907	6503001310	310	-1083280000
8331996	6900008002	-1083480000	-6900008002	-1083680000	-1083780000	-1083880000	-1083980000
8401996	-1084080000	-1084180000	-1084280000	-2000001204	-1084480000	-2000000909	-1084680000
8471996	-1084780000	-1084880000	-1084980000	-1085080000	-1085180000	-1085280000	-6905711950
8541996	6505570961	3500040715	3500040467	2019681321	3500040919	6502850489	6519691376
8611996	-1086180000	-2003100363	1509668002	2003050408	1508680923	6913240878	1512208002

TABLE 3.4 (cont.)

8681996	2401210674	1509728002	6501210825	6908241902	6500810685	1270000051	6502920497
8751996	6900008002	6514290883	2000001508	2403001213	6905321907	2400011114	40003
8821996	108828000-	6903861800	108848000-	2019690678	108868000-	108878000-	108888000-
8891996	108898000-	108908000-	108918000-	108928000-	2000001304	108948000-	6919671425
8961996	108968000-	108978000-	108988000-	108998000-	109008000-	109018000-	109028000-
9031996	6915361590	6502960351	3500040765	2000001504	6503000957	2003000958	6502850539
9101996	3500041476	6512141069	4604660516	1511661172	6503391043	1509180973	1715781535
9171996	1512700975	2400610514	1510220777	2400001056	6908741852	6910251852	6900008002
9241996	10033	6900008002	6502410795	2019681572	2400001554	6905821907	6900011460
9311996	2006390772	109328000-	6680020641	109348000-	2019700728	109368000-	109378000-
9381996	109388000-	109398000-	109408000-	109418000-	109428000-	2003060459	109448000-
9451996	2019691276	109468000-	109478000-	109488000-	109498000-	109508000-	109518000-
9521996	109528000-	2000001003	2019670420	3500040815	3500040517	3500040817	6680020967
9591996	6602211075	6519681576	2000000904	2019661219	2003001113	2003070510	1509688002
9661996	6502211078	1502981008	6500011355	109698000-	2401011156	6509240779	6500810735
9731996	6900008002	6503001305	6900008002	6500610566	20012	6906391072	2019671575
9801996	6502611560	2000000410	109828000-	109838000-	109848000-	2019710778	109868000-
9871996	109878000-	109888000-	109898000-	109908000-	109918000-	109928000-	2003001253
9941996	109948000-	2019661469	109968000-	109978000-	109988000-	109998000-	110008000-
10011996	110018000-	110028000-	6503001055	6506071011	3500040865	6501220677	6503071511
10081996	4605620708	6906631902	6904131902	6906141902	2019671325	6680021322	6503391343
10151996	1510188002	110168000-	6915201950	6500611065	6512220877	6501810635	6503001405
10221996	2400611014	2000000406	6502410645	2003080512	2400001509	6906301852	6909311802
10291996	6503021559	110308000-	110318000-	110328000-	110338000-	110348000-	6904381907
10361996	110368000-	110378000-	110388000-	110398000-	110408000-	110418000-	110428000-
10431996	1503001456	110448000-	1503061562	110468000-	110478000-	110488000-	110498000-
10501996	110508000-	110518000-	110528000-	6680020811	6505571061	3500040915	6905591950
10571996	2003001107	2000021108	6503031109	3500041077	6906641902	6519661475	4608160704
10641996	6503000660	2000001403	2006371420	2400810564	6500210725	6907221852	6501011306
10711996	1510248002	2407240671	2000001153	2019660469	2000000404	6910291902	1506800785
10781996	6910811852	2401611064	6909331852	6503000913	110828000-	110838000-	110848000-
10851996	110858000-	110868000-	110878000-	110888000-	110898000-	110908000-	110918000-
10921996	110928000-	2003000907	110948000-	1005481163	110968000-	110978000-	110988000-
10991996	110998000-	111008000-	111018000-	111028000-	4605060753	6502880793	2003001053
11061996	3500040567	6680021365	7120432	2019671574	3500041177	2019670470	6519661076
11131996	3000041013	6503001410	1510688002	6680021023	111178000-	2400410444	6503060812
11201996	2402610914	6910741800	2400000813	6906261852	6503001505	2019661119	1510790833
11271996	6503001110	1010671163	6502010710	6506391122	2006010704	111328000-	111338000-
11341996	111348000-	111358000-	111368000-	111378000-	111388000-	111398000-	111408000-
11411996	111418000-	111428000-	1503001057	111448000-	111458000-	111468000-	111478000-
11481996	111488000-	111498000-	111508000-	111518000-	111528000-	6519691123	6605571161
11551996	6903581902	6503001206	4605600907	2660000054	3500041169	3500041227	6907141902
11621996	6503000610	1013241230	6503391543	1511181273	2400611264	111678000-	6500410695
11691996	1512258002	6502611315	6911241902	6900008002	6906761852	2019660519	6503010809

TABLE 3.4 (cont.)

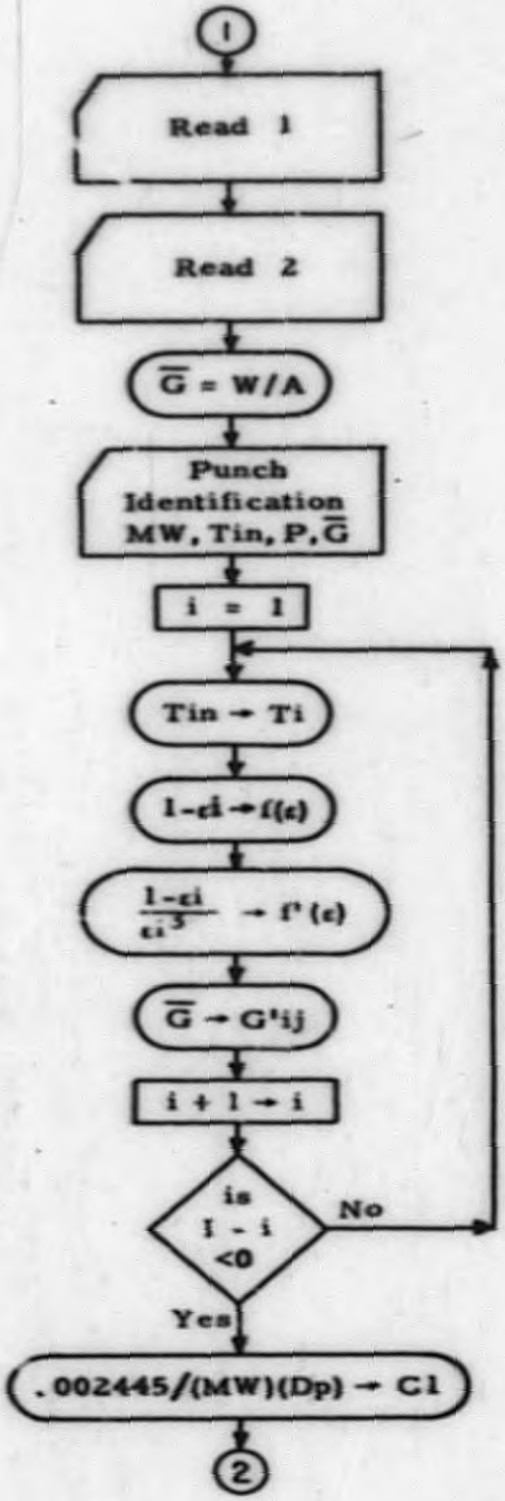
11761996	15111298002	15073080O2	69113119O2	65014109 45	15030009 63	111818000-	111828000-	
11831996	1111838000-	1118480O0-	111858000	-1111868000-	1118780O0-	111888000-	111898000-	
11901996	1119080O0-	111918000-	1119280O0	-2003001207	111948000-	111958000-	111968000-	
11971996	1119780O0-	111988000-	111998000	-1120080O0-	1120180O0-	1120280O0-	6905561950	
12041996	6506071211	6502970501	35000406 17	65030715 61	15066280O2	6919671275	2000001260	
12111996	6907641902	2403111059	6502940549	19150000 52	15116880O2	6515691178	1121780O0-	
12181996	6907711852	6506071012	6501011357	69117418 00	2000000051	6907261902	6503000806	
12251996	6502011209	1511798002	1507808002	1122880O0-	6501610616	1513248002	1123180O0-	
12321996	1123280O0-	112338000-	112348000	-1123580O0-	1123680O0-	1123780O0-	1123880O0-	
12391996	1123980O0-	112408000-	112418000	-1124280O0-	1503001507	1124480O0-	1124580O0-	
12461996	1124680O0-	112478000-	112488000	-1124980O0-	1125080O0-	1125180O0-	1125280O0-	
12531996	6502920547	6502940449	6503390993	35000406 67	65028604 41	15061380O2	6909621950	
12601996	6519661277	6908141902	6503111527	69121619 02	65132411 80	1502981556	1126680O0-	
12671996	1126780O0-	112688000-	1513758002	24008104 34	69122418 52	6915581902	6900008002	
12741996	6503001406	2400001259	6503000810	69083018 52	1127880O0-	2019681426	1128080O0-	
12811996	1128180O0-	112828000-	112838000	-1128480O0-	1128580O0-	1128680O0-	1128780O0-	
12881996	1128880O0-	112898000-	112908000	-1129180O0-	1129280O0-	2003000708	1129480O0-	
12951996	1129530O0-	112968000-	112978000	-1129880O0-	1129980O0-	1130080O0-	1130180O0-	
13021996	1130280O0-	6519710675	6505071261	35000409 65	20000013 56	3500040867	5200000050	
13091996	3500041269	3500041327	6908641852	20030013 62	1131380O0-	1131480O0-	2000001007	
13161996	1131680O0-	113178000-	113188000	-6515250979	6502980558	6503000956	1502981063	
13231996	6907761902	10000	6503001309	15122980 02	15088008 35	1132880O0-	6500211526	
13301996	1133080O0-	113318000-	113328000	-1133380O0-	1133480O0-	1133580O0-	1133680O0-	
13371996	1133780O0-	113388000-	113398000	-1134080O0-	1134180O0-	1134280O0-	1503000908	
13441996	1134480O0-	113458000-	113468000	-1134780O0-	1134880O0-	1134980O0-	1135080O0-	
13511996	1135180O0-	113528000-	6906561950	65196711 21	20000013 03	6519661371	2000001407	
13581996	1107621517	6910621950	6903561212	35000410 71	66800205 77	1136380O0-	1136480O0-	
13651996	1502981157	1136680O0-	113678000	-1136880O0-	1509768002	1474	6912741902	
13721996	6911751902	1137380O0-	6503001457	65014109 95	69127919 02	1509308002	1137880O0-	
13791996	6503041010	1138080O0-	113818000	-1138280O0-	1138380O0-	1138480O0-	1138580O0-	
13861996	1138680O0-	113878000-	113888000	-1138980O0-	1139080O0-	1139180O0-	1139280O0-	
13931996	1139380O0-	113948000-	113958000	-1139680O0-	1139780O0-	1139880O0-	1139980O0-	
14001996	1140080O0-	114018000-	114028000	-6519681223	6519661271	3500041015	3500040717	
14071996	6519661471	6501220827	3500041369	35000413 77	20196707 70	4607161059	1141380O0-	
14141996	1141480O0-	1502980458	1141680O0	-1141780O0-	1141880O0-	6503000760	6503001208	
14211996	6513240829	2019681472	4411280388	69072703 54	24000013 59	6503000910	6503001510	
14281996	1142880O0-	3906405053	1143080O0	-1143180O0-	1143280O0-	1143380O0-	1143480O0-	
14351996	1143580O0-	1143680O0-	1143780O0	-1143880O0-	1143980O0-	1144080O0-	1144180O0-	
14421996	1144280O0-	1144380O0-	1144480O0	-1144580O0-	1144680O0-	1144780O0-	1144880O0-	
14491996	1144980O0-	2416091681	1145180O0	-1145280O0-	2416061759	6507571411	3500041115	
14561996	2003001506	3500040917	6916111453	35000814 86	24000014 27	2003070460	6503070541	
14631996	1146380O0-	1146480O0-	4000061	1146680O0-	3000071681	1146880O0-	6503001160	
14701996	1147080O0-	6513741902	6513240929	31000314 83	65033912 93	6905781902	1513298002	
14771996	15098080O2	2019331486	1147980O0	-1148080O0-	1148180O0-	1148280O0-	6080021491	

TABLE 3.4 (cont.)

14841996	11148480000-	11148580000-	20199111494	11148780000	-68199116645	11148980000-	11149080000-		
14911996	19194414467	11149280000-	20030011360	16800116856	11149580000-	11149680000-	11149780000-		
14981996	11149880000-	11149980000-	24157915532	16800220509	30000661567	65519671121	65502020807		
15051996	35000411165	66800221265	20030011557	65000621017	69111121950	35000411477	69009641852		
15121996	2001161	11151380000-	11151480000	-20196711320	11151680000-	44062211372	11151880000-		
15191996	20196806288	65196661272	65132408779	11147114714	1,09868008	65097770681	70000000050		
15261996	20000000960	69066661852	44158813772	11152980000-	22153561589	20115811534	69800011538		
15331996	71157770527	21158011533	69157771530		16800221545	24157811531	30000511501		
15401996	69157791541		11154280000	-15030011312	22154811551	17154800804	11546600000-		
15471996	11154780000-	90311550	22157711537	24157911577	30000311358	24154111588	65196611171		
15541996	65113080713	35000411215	46060911253	66800211415	65002020709	69116211902	69118621902		
15611996	20000011257	20030600463	11156380000	-11156480000-	11156580000-	11156680000-	10061211568		
15681996	15115811540	75000000052	65157311527	69142411852	65042907833	305	65030011159		
15751996	65030011409	69137911800	59800011538	11157880000-	11157980000-	11158080000-	11158180000-		
15821996	11158280000-	11158380000-	11158480000	-11158580000-	11158680000-	23154111544	30000511502		
15891996	35000411549	24157711591	69157911577	11159280000-	11159380000-	11159480000-	11159580000-		
15961996	11159680000-	11159780000-	11159880000	-11159980000-	24160511458	1	24160511459		
16031996	65029110595	20000011605	69196711920	24160911681	31000011478	10000000051	70000000000-		
16101996	69145011453	24160911473	11161280000	-44162211842	24119211675	45167711940	20119811788		
16171996	24000111922	65119251631	20119251733	10800311840	22119251833	30000111932	44172711928		
16241996	35000711743	10020811001	65119111669	20119311699	11183111703	20119841638	15193311887		
16311996	45163611916	44168611694	45116911696	10119391644	20160811811	16119391619	65000011605		
16381996	60199111695	35000211998	16199311749	20000011704	1647	24119161668	21199811618		
16451996	15194811756	15160911813	70119521997	69195283002	69195380002	69119548002	69119558002		
16521996	69119568002	11119651934	65116121963	20119911848	67800211915	69119221985	35000811716		
16591996	30000211683	20119311841	16181711821	69119171824	10001180011	69000118003	44178511692		
16661996	10501180011	64119221842	69172211851	46165411928	65173011988	30000511731	18198511630		
16731996	60193111888	60183111748	69167911682	65800311992	67193116933	65193116639	15193911793		
16801996	44188831737	69193711643	23198511618	64199111879	65000011755	15161178003	11193911694		
16871996	20199111894	65199111895	69164211945	45119191996	69174611901	60000011705	16191711873		
16941996	10199811911	15195311909	66000011814	24160911757	60199811912	60160811665	69190311606		
17011996	60800131859	24160511658	64119251847	67191111633	44117171735	20191111684	10800111863		
17081996	35000811768	21119161920	21119161789	44167311699	69193111740	69800311621	15181171771		
17151996	69192411880	21119331738	46173511928	19182811857	69800311947	24198511838	35000411632		
17221996	20193111605	16198511889	30000411834	60199111845	65119291722	66193111992	20193311786		
17291996	30000411835	15156511802	22198511739	68800211742	15179611002	69199011844	65199111615		
17361996	68800211645	69174111671	68800211798	45170911797	24000011858	35000011807	15199511899		
17431996	20199811809	35000811772	31000111751	69196411902	69160511663	21160411764	20160911812		
17501996	24160311994	64116411875	24160511791	30000811867	65193311787	24161211938	46194911661		
17571996	45186011604	46172311773	46174711763	10191411748	46171411923	10800111731	35000811620		
17641996	60192511930	60193111785	14182611770	23192511878	21119311936	24119221935	21119251830		
17711996	46194311825	20160911674	15198511889	24119771922	24119781922	24119791922	24119801922		
17781996	24198111922	24198211922	24198311836	46163411985	15198511790	20160911862	60199111898		
17851996	30000111667	15199111655	35000411998	60199111822	69199311697	15800111700	69189511801		

TABLE 3.4 (cont.)

17921996	601998 1758	711977 1629	1005080001	1980011829	601968 1729	211609 1869	151906 1761
17991996	201953 1921	241605 1660	241604 1710	241605 1858	111906 1718	241608 1662	191608 1946
18061996	101914 1681	158001 1613	691816 1872	651917 1672	691866 1872	601914 1822	601922 1828
18131996	171916 1871	461676 1940	101917 1935	678002 1783	100000 0000	161827 1782	211925 1628
18201996	141927 1853	461724 1726	101831 1866	350001 1680	241931 1837	300004 1734	230258 5093
18271996	693147 1806	191931 1842	310010 1635	241933 1936	200000 0000	151985 1616	168001 1690
18341996	151989 1843	118003 1849	211991 1799	201991 1896	608001 1795	360000 1767	441893 1949
18411996	650000 1712	691895 1851	201998 1754	221998 1678	198001 1837	601601 1805	201401 1720
18481996	601604 1760	300006 1762	241603 1706	241604 1757	241605 1808	201608 1711	201916 1870
18551996	241608 1861	191826 1607	300007 1818	691864 1872	101914 1819	441715 1865	300002 1868
18621996	181916 1823	698002 8003	441732 1949	608002 1874	678002 1640	451624 1672	211922 1925
18691996	651922 1877	211931 1890	461949 1876	241928 1687	451676 1928	691927 1880	451728 1784
18761996	441949 1881	691931 1985	658003 1885	451832 1884	241933 1839	201985 1792	651685 1689
18831996	461688 1637	601998 1803	310002 1892	211991 1846	350008 1646	191991 1627	300008 1604
18901996	600000 1855	111926 1781	201998 1753	201998 1701	350008 1854	200000 1605	671608 1820
18971996	451707 1960	300001 1806	201609 1765	241605 1708	241605 1610	241605 1810	802000 0000
19041996	201911 1918	461919 1960	500000 0000	241960 1713	231984 1941	111965 1922	241916 1670
19111996	788744 5650	691815 1769	241916 1719	100000 0000	201911 1633	510000 0000	1
19181996	691891 1614	691984 1908	651934 1657	651984 1679	100000 0000	658003 1895	12
19251996	5	9999	2	651931 1992	100000 0051	191933 1745	100000 0000
19321996	350001 1842	12	691957 8002	111942 1897	241991 1744	400000 0000	691641 1801
19391996	100000	691603 1625	691698 1910	1774	691605 1666	434294 4819	241998 1904
19461996	211601 1659	221925 1882	520000 0000	691605 1794	241603 1656	20013	650018 1994
19611996	1196 18000-	1196 28000-	141927 1623	691626 1900	7	203393 6752	500000 0050
19681996	100000 0051	200221		136000 0054	282	281	200121
19751996	292	291	812028 6951				
80001997			280003	241982 1999	241983 1958	241984 8000	691954 1957
80001997	510000 0000	8008	100000000	241985 1999	241986 1958	241987 8000	691954 1957
80001997	691942 1945	310011 1766	309999 1895	241988 1999	241989 1958	241990 8000	691954 1957
80001997	100000 0051	200000 1603	580000 0000	241991 1999	241992 1958	241993 8000	691954 1957
80001997	690000 1804	490000 0000	108000 1905	241994 1999	241995 1958	241996 8000	691954 1957
80001998	691951 8002	100000000	650407 0361	241997 1999	241998 1958	241999 8000	691954 1957
1999							



Read 1
Identification
MW, Tin, P, W
A, ΔLj, $\bar{\mu}$, XMU, $\bar{T}$

Read 2
$\bar{C}p$, CpX, & ci, Dp
J, $\bar{P}r$, PrX, I, Ai

Calculation Flowsheet
COOLBALL II

FIG. 3.3
page 1 of 5

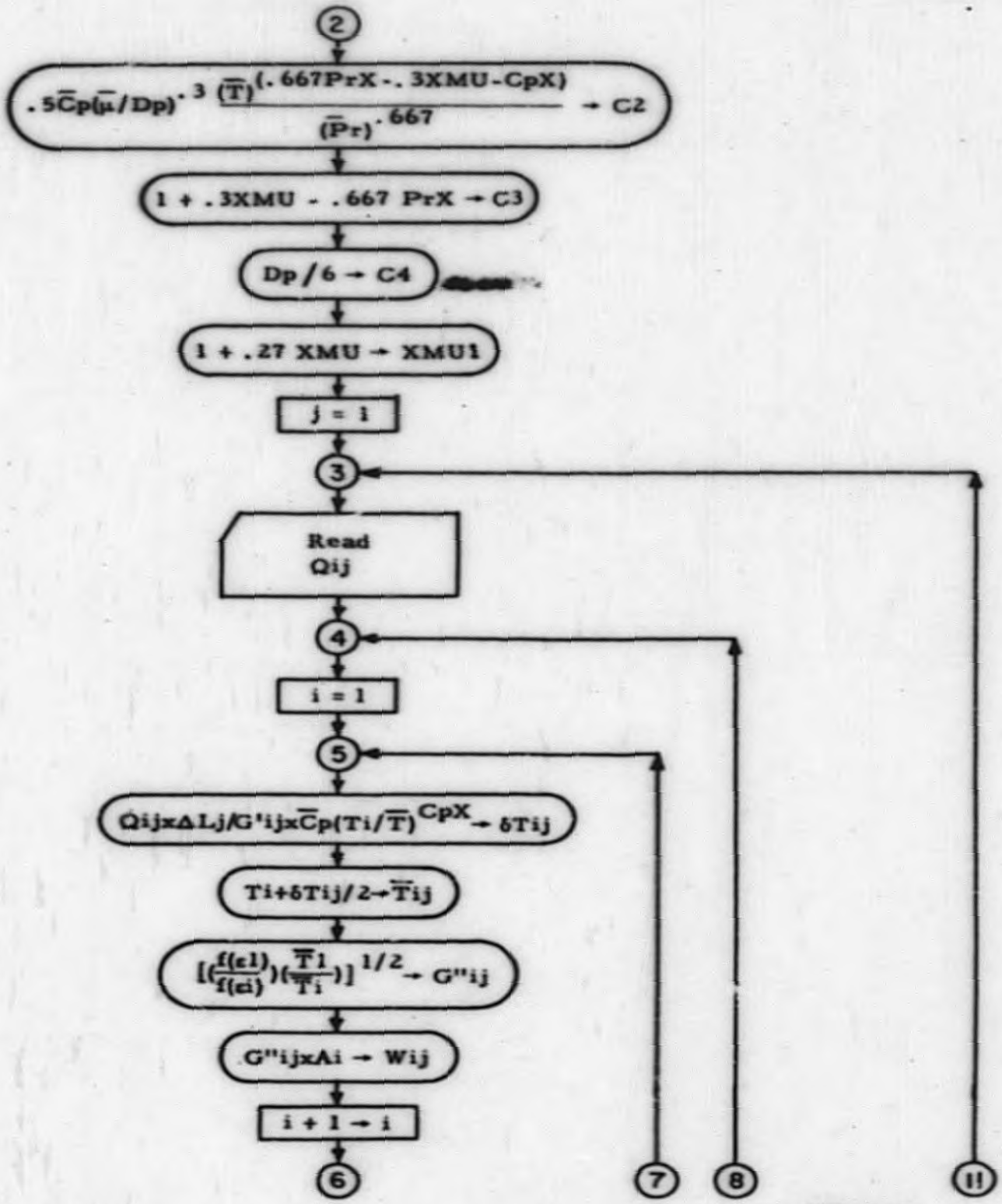


FIG. 3.3
page 2 of 5

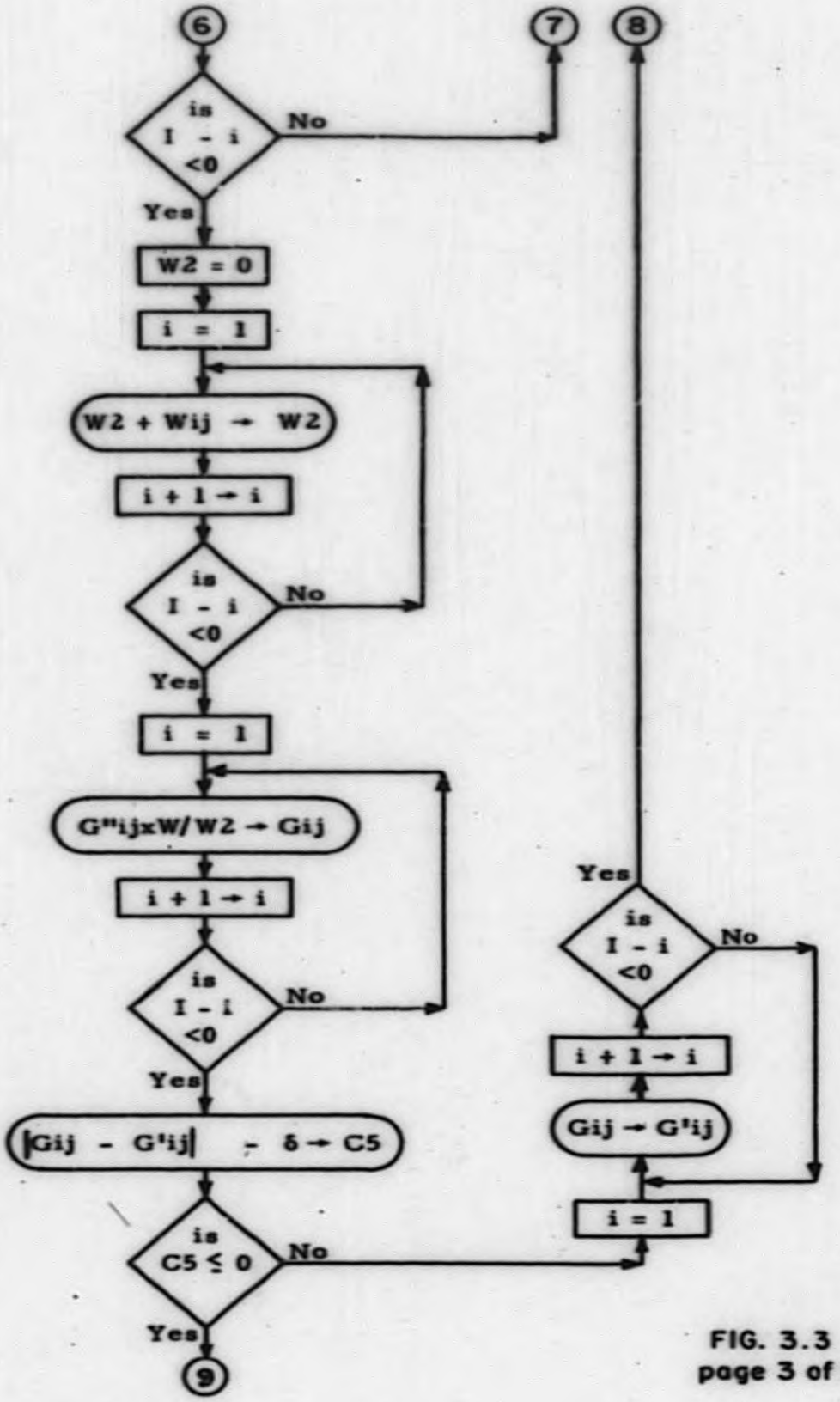


FIG. 3.3
page 3 of 5

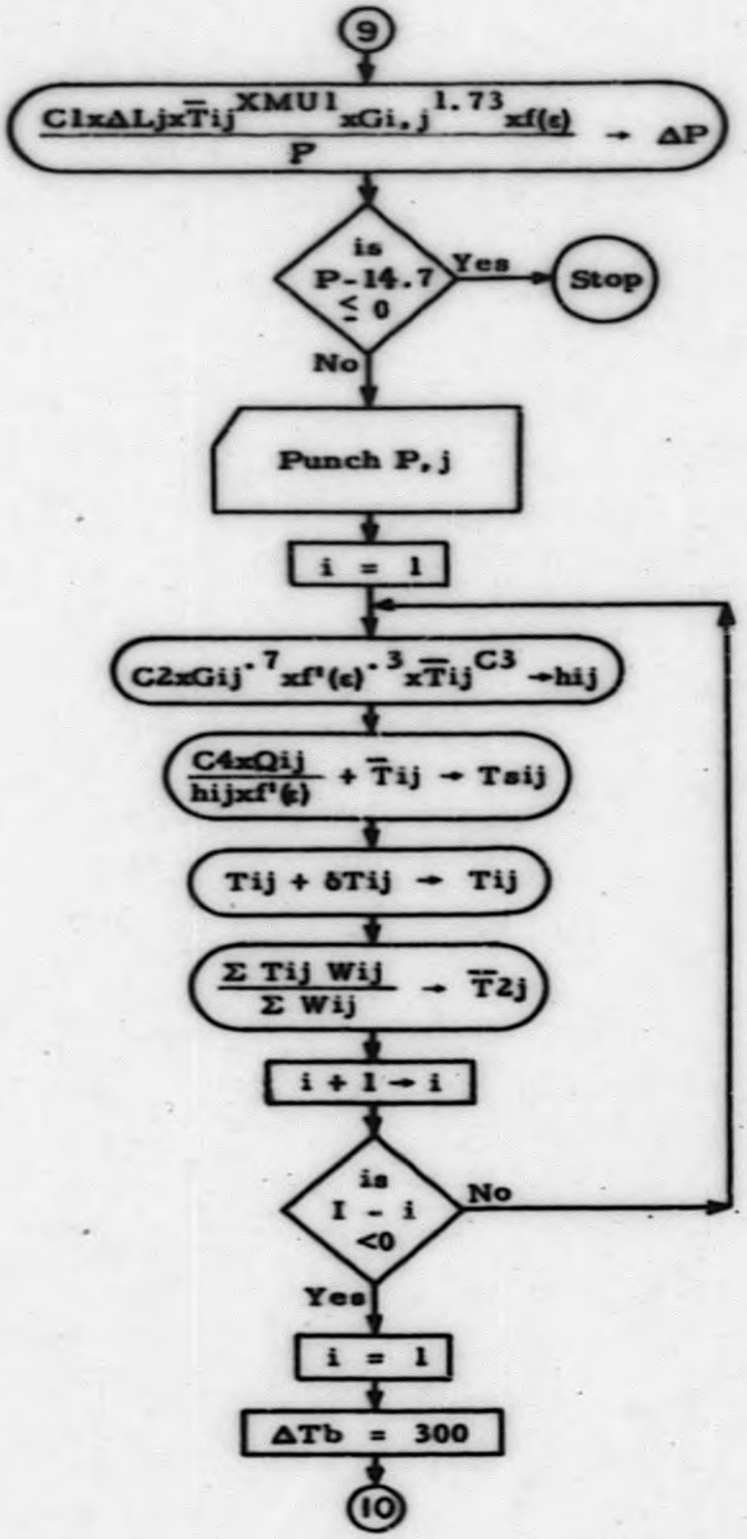


FIG. 3.3
page 4 of 5

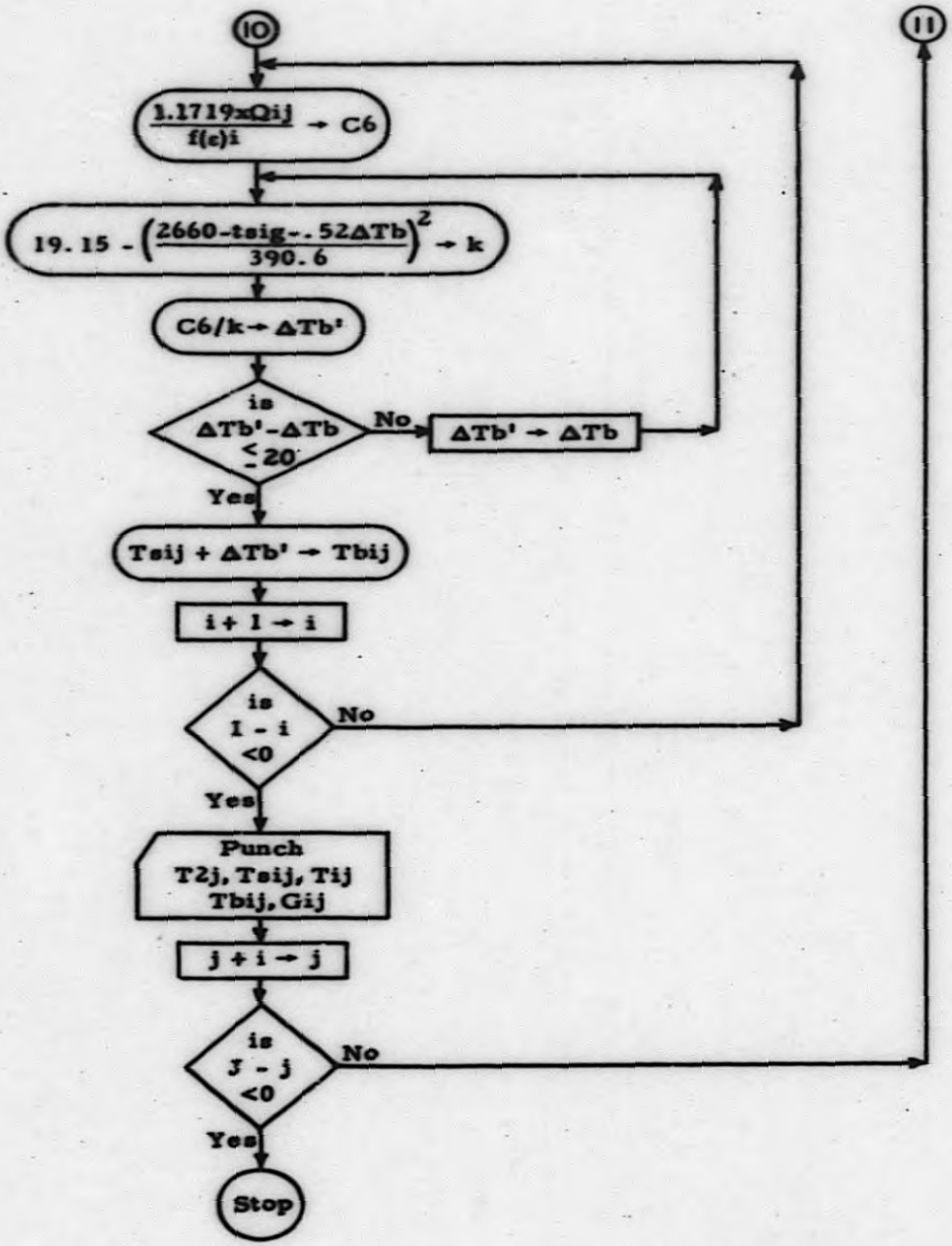
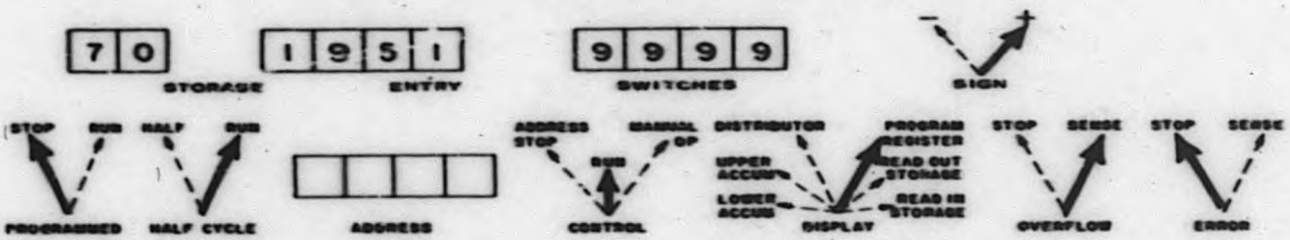


FIG. 3.3
page 5 of 5

COOLBALL II

IBM 650 PROGRAM OPERATING INSTRUCTIONS



I. Initial Console Setting as shown above.

A. Normal Starting Procedure: Computer Reset; Program Start.

B. Special Instructions: None

II. Card Input - Output (533 or 537)

READ FEED

NO. OF CARDS	FILE DESCRIPTION
296	PROGRAM DECK
12	DATA DECK
	COOLBALL I OUTPUT
	Repeat A for any other cases
	to be run at same time

} A

PUNCH FEED

CARD FORM
8 WORD

CONTROL PANELS

80-80

III. Other Instructions and Remarks:

IV. Program Stops and Required Action:

STOP ADDRESS	MESSAGE - EXPLANATION - ACTION
1522	Pressure is less than atmospheric - No action required

FIG. 3.4

Section 4.0 Illustrative Problem

As an illustration of the use of the COOLBALL codes, there is presented the following analysis of a power reactor core of 750 tMW output such as might be used for a large central station power plant. Preliminary analysis of such a Pebble Bed Reactor results in the characteristics indicated in Table 4.1.

TABLE 4.1

Characteristics of 750 tMW Core

Type	Axial Upflow
Core Diameter, ft	17.5
Core Length, ft	14.0
Gas	Helium
Gas Temperature (inlet/outlet), °F	550/1260
Gas Flow, Lbs/sec	755
System pressure, psia	1000
Core Gross Output, tMW	712.5
Core Power Density, MW/Ft^3	.212
Fuel Ball Diameter, inches	3.0

Figure 4.1 shows the assumed radial and axial power profiles (see Ref. 9). A constant voidage of 39% was selected (since the core was surrounded by a reflector of smaller balls and the orienting effect of the wall was negligible). The core region was arbitrarily divided into eleven axial slices and fourteen annular rings, and the average power in each slice and in each ring determined.

Table 4.2 lists the actual input to and output from COOLBALL I. It should be noted that the blank spaces indicated on the third card of the input are actually zeros and are required to fill out the unused radial positions (20 total). In addition, the third output card for each axial slice contains zeros in the first six word positions.

Table 4.3 lists the complete input to and output from COOLBALL II.

TABLE 4.2

COOLBALL I INPUT & OUTPUT FOR 17.5 Ft. Dia. × 14.0 Ft. 750 tMW PEBBLE BED REACTOR

INPUT

13544000051	13466400051	13279000051	13001000051	12634000051	12182000051	11644000051	1965210001
11057000051	10425000051	9736300050	8987400050	8247100050	7775000050	8459200050	
						20070000053	
6400000050							
8600000050							
10700000051							
13000000051							
13300000051							
12400000051							
12300000051							
10300000051							
8200000050							
6000000050							
4000000050							

OUTPUT

17396997553	17294239553	17056610553	16699524553	16228120553	15647535553	14956485553	10002
14402495553	13390704553	12506083553	11546705553	10593235553	9986832052	10865673553	20002
							30002
23377215553	23229133553	22919820553	22439986553	21806537553	21026376553	20097777553	40002
19084603553	17993758553	16805049553	15515588553	14234660553	13419806553	14600748553	50002
							60002
29085605553	28913805553	28516520553	27919517553	27131389553	26160723553	25005374553	70002
23744797553	22387585553	20908607553	19304647553	17710565553	16696735553	18166047553	80002
							90002
35337650553	35128922553	34646239553	33920909553	32963369553	31784056553	30380360553	100002
28848819553	27199868553	25402980553	23454244553	21517509553	20285753553	22070899553	110002
							120002
36153135553	35939590553	35445767553	34703699553	33724063553	32517534553	31081446553	130002
29514561553	27827557553	25989203553	23995495553	22014067553	20753885553	22580227553	140002
							150002
33706682553	33507588553	33047182553	32355329553	31441983553	30317100553	28978190553	160002
27517335553	25944489553	24230535553	22371740553	20524395353	19549487553	21052244253	170002
							180002
33434854553	33237365553	32780672553	32094379553	31188419553	30072607553	28744495553	190002
27495421553	25735259553	24035128553	22191323553	20358867453	19193443553	20882466553	200002
							210002
27998292553	27853291553	27450482553	26875797553	26117131553	25182752553	24070593553	220002
22857141553	21550664553	20126977553	18582975553	17048488553	16072558553	17486944553	230002
							240002
22289903553	22158243553	21853781553	21396266553	20792279553	20048405553	19162997553	250002
18196947553	17156840553	16023418553	14794215553	13572582553	12795629553	13921644553	260002
							270002
16309685553	16213344953	15990572553	15655480453	15213863553	14669564553	14021705553	280002
13314839553	12553785553	11724452553	10825035553	9931157852	9362655052	10186569553	290002
							300002
10887312353	10808899953	10660381553	10437203553	10142575553	9779709652	9347803252	310002
8876559652	8369190052	7816301652	7216690352	6620771952	6241770052	6791045852	320002
							330002

TABLE 4.3

COOLBALL II INPUT & OUTPUT FOR 17.5 Ft. Dia. x 14 Ft. 750 tMW PEBBLE BED REACTOR

INPUT

1965210001	4	1010000054	1000000054	7550000053	2405300053	7000000050	
1400000051	1400000051	1400000051	1400000051	1400000051	1400000051	1400000051	
1400000051	1400000051	7000000050			2400000046	5800000050	
1368000054							
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OUTPUT

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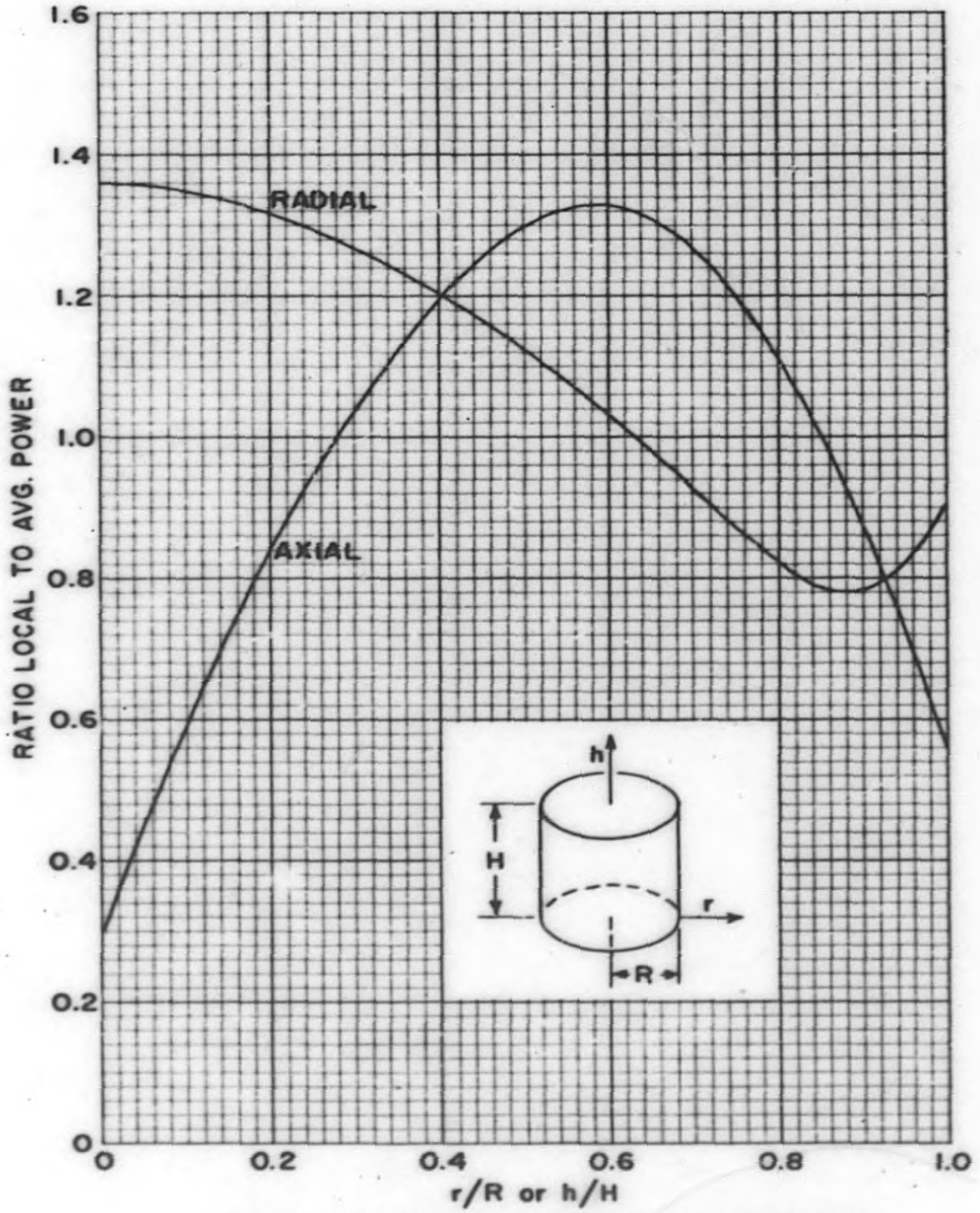
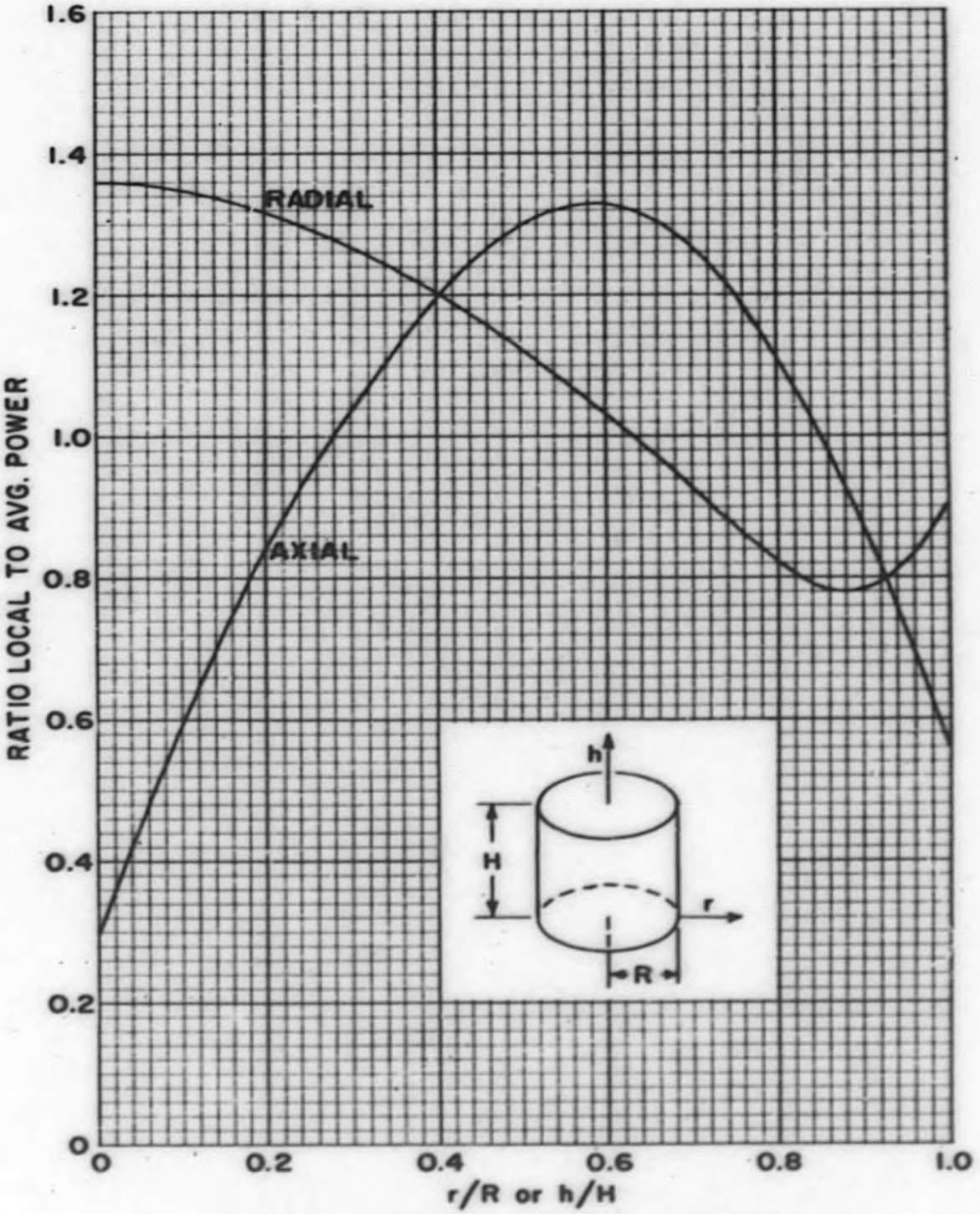


AXIAL & RADIAL POWER DISTRIBUTION
IN A 750 tMW PBR CORE

FIG. 4.1



AXIAL & RADIAL POWER DISTRIBUTION
IN A 750 tMW PBR CORE

FIG. 4.1

Figures 4.2 through 4.7 show the results of this analysis. Figure 4.2 is an axial slice along a diameter and shows lines of constant gas mass velocity through the core. The flow divergence from the high temperature regions is clearly indicated and amounts to slightly less than 10% in this case. The flow concentration in the low temperature region near the wall is also indicated. The remaining figures show the consequence of this flow divergence on the pertinent temperatures and temperature drops throughout the core.

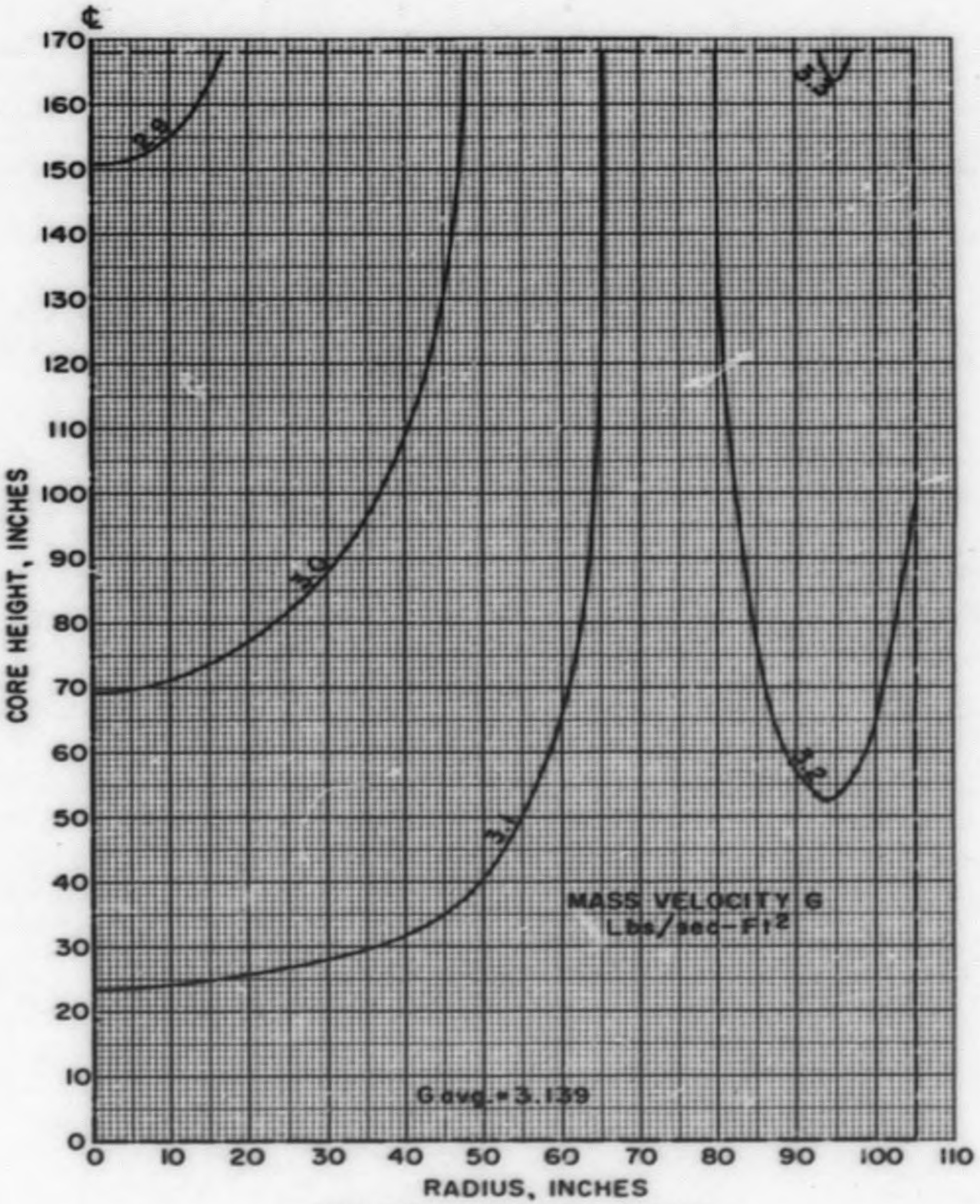
Figure 4.3 shows the change of bulk gas temperature with axial position in the core. This is obtained from the mixed mean gas output temperature leaving each axial slice.

Figure 4.4 shows the radial variation of gas temperature at the outlet end of the core and clearly indicates the high gas temperature in the region of low flow and lower gas temperature in the region of higher flow near the walls.

Figure 4.5 shows an axial slice through the core on the diameter. The region to the left of the centerline shows lines of constant graphite temperature while the region to the right of the centerline shows lines of constant gas temperature (solid) and lines of constant gas film temperature drop (broken). The relatively uniform temperature near the inlet end of the bed can be seen along with the effect of flow divergence as the gas passes through the bed.

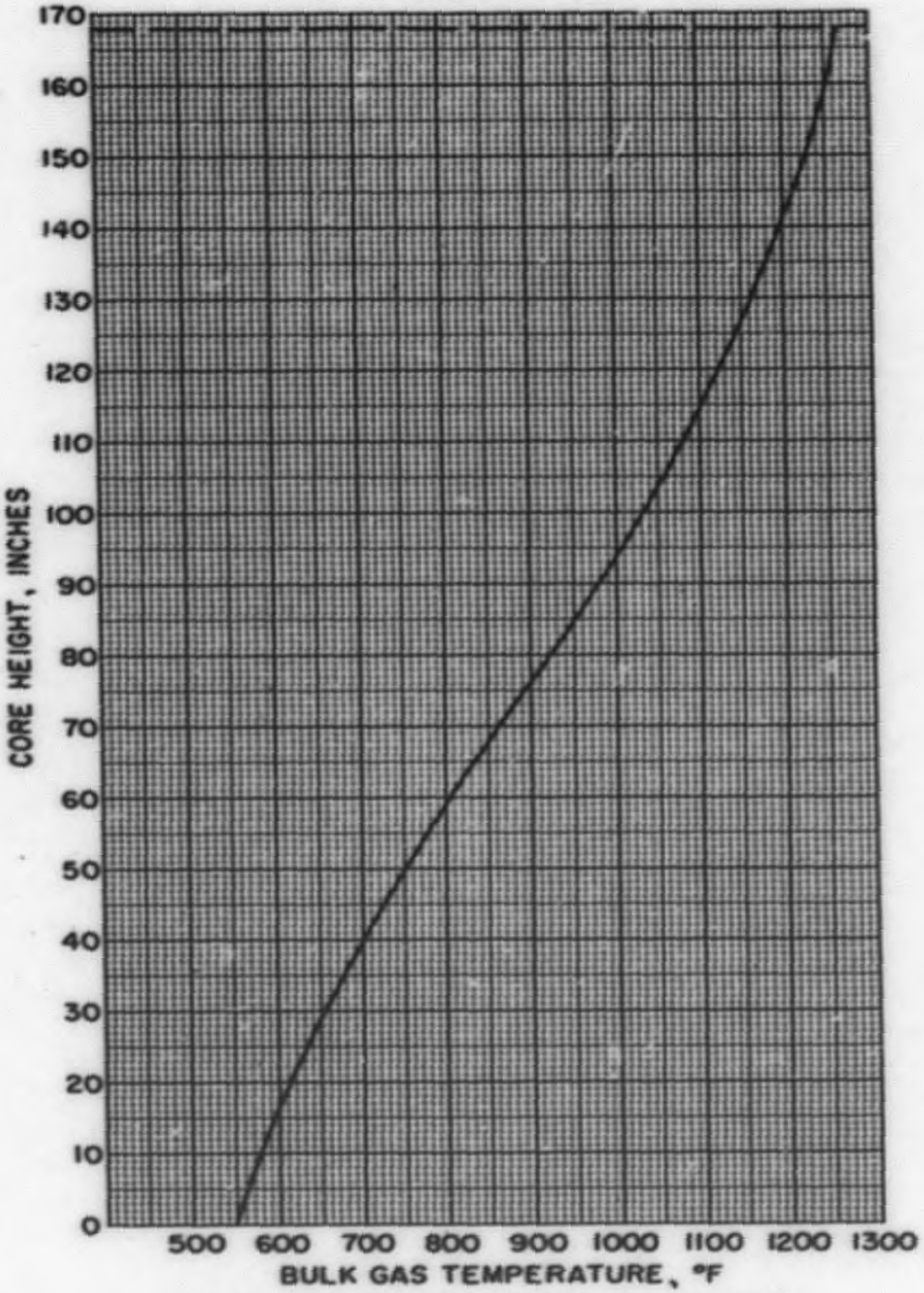
Figure 4.6 indicates the percentage of the bed which is at any indicated temperature and compares this temperature distribution with the average graphite temperature.

Figure 4.7, another axial slice through the core along the centerline, shows lines of constant ball surface temperature (solid) and lines of constant ball center temperature (dot-dash). Also shown are lines of constant ΔT_b, the temperature difference between the ball center and ball surface.



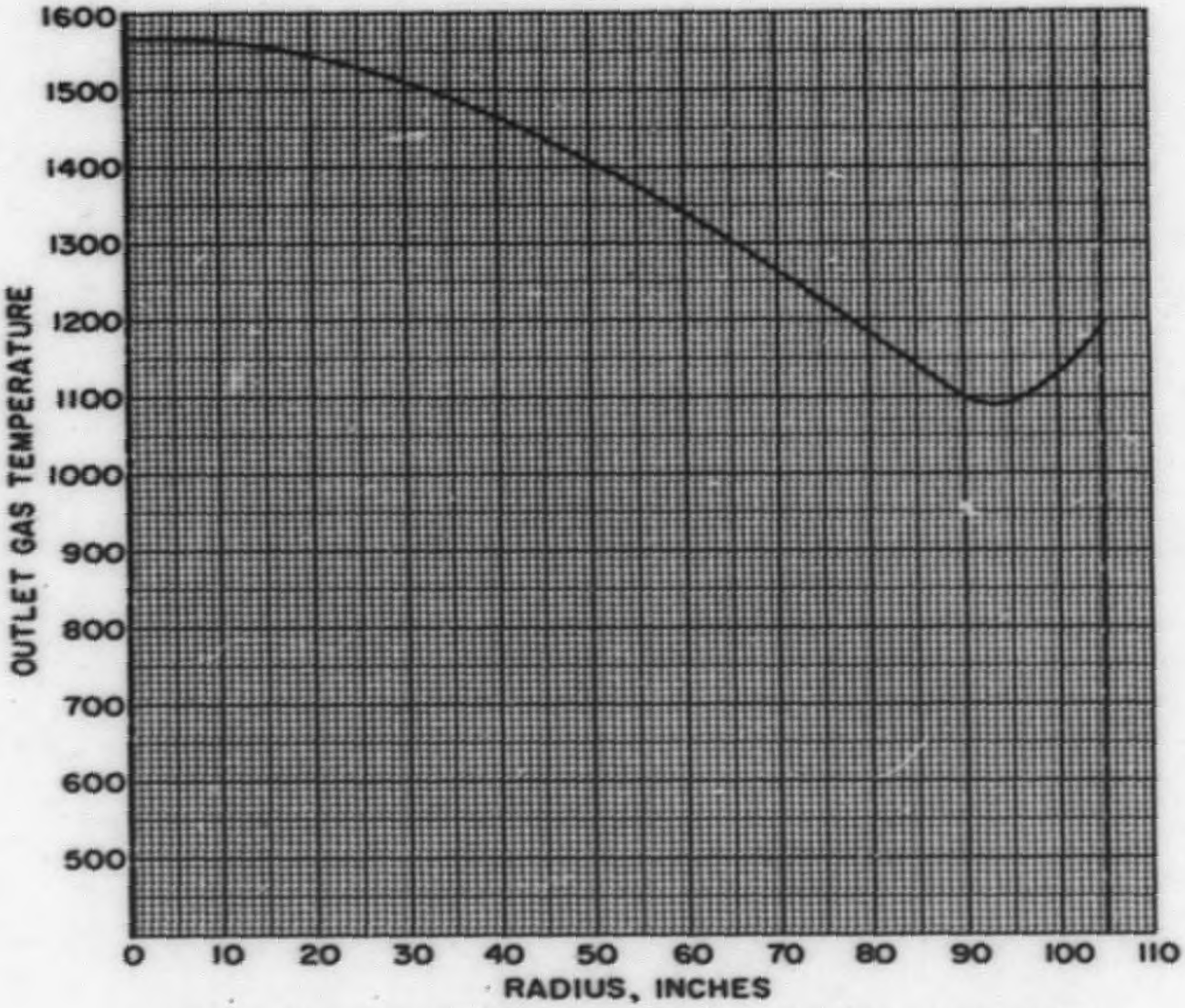
VELOCITY DISTRIBUTION
IN A 750 tMW PBR CORE

FIG. 4.2



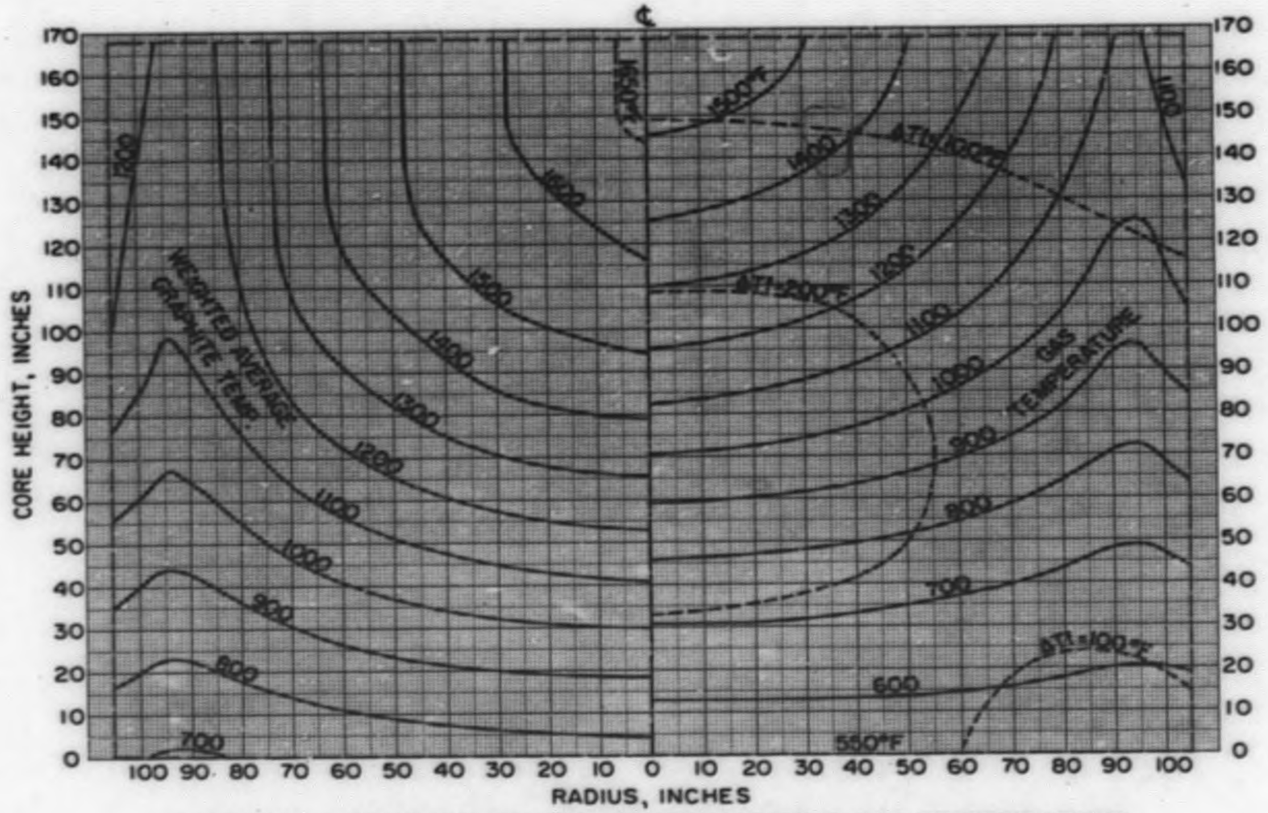
BULK GAS TEMPERATURE vs. HEIGHT
IN A 750 tMW PBR CORE

FIG. 4.3



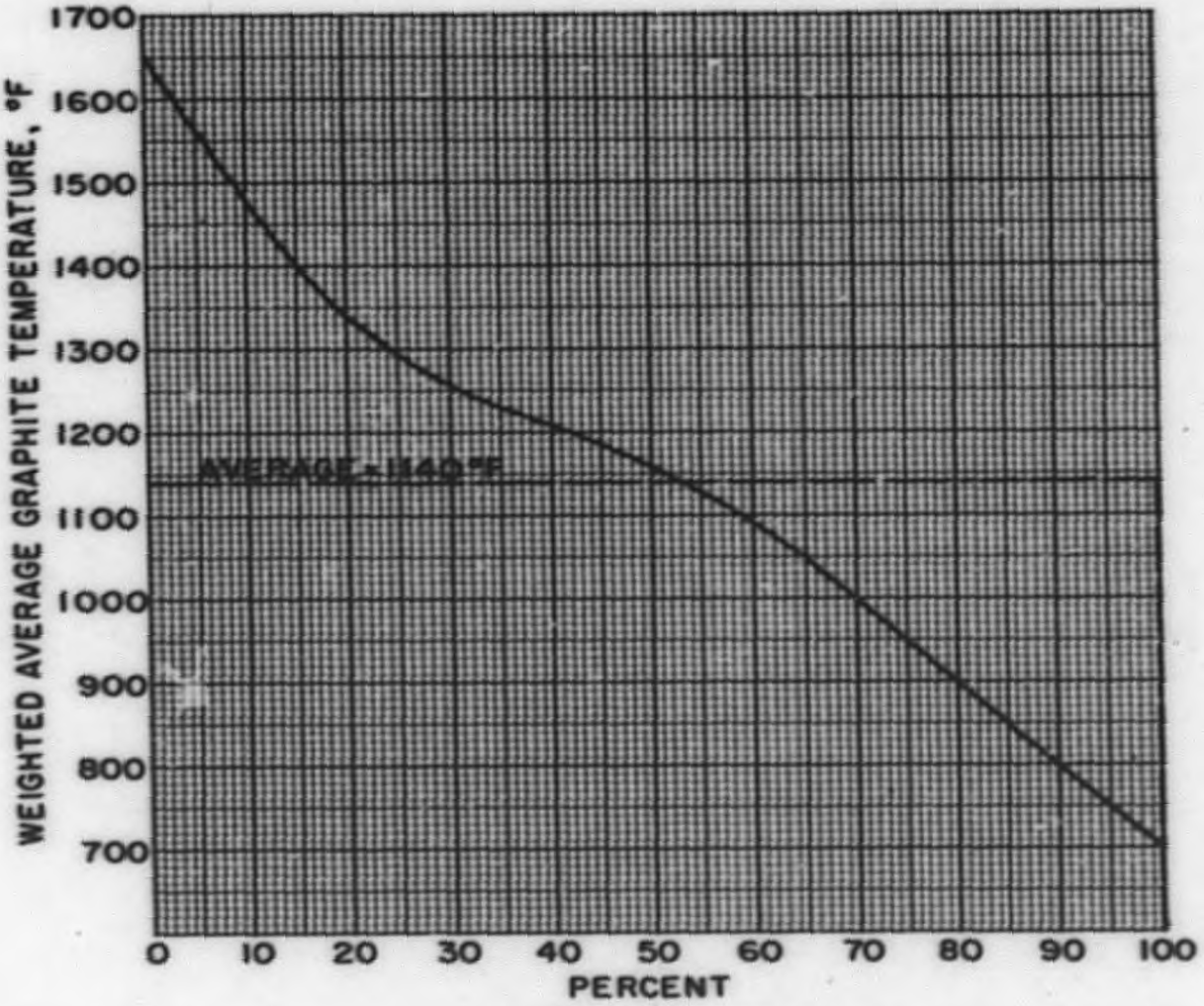
OUTLET GAS TEMPERATURE vs. RADIAL POSITION
IN A 750 tMW PBR CORE

FIG. 4.4



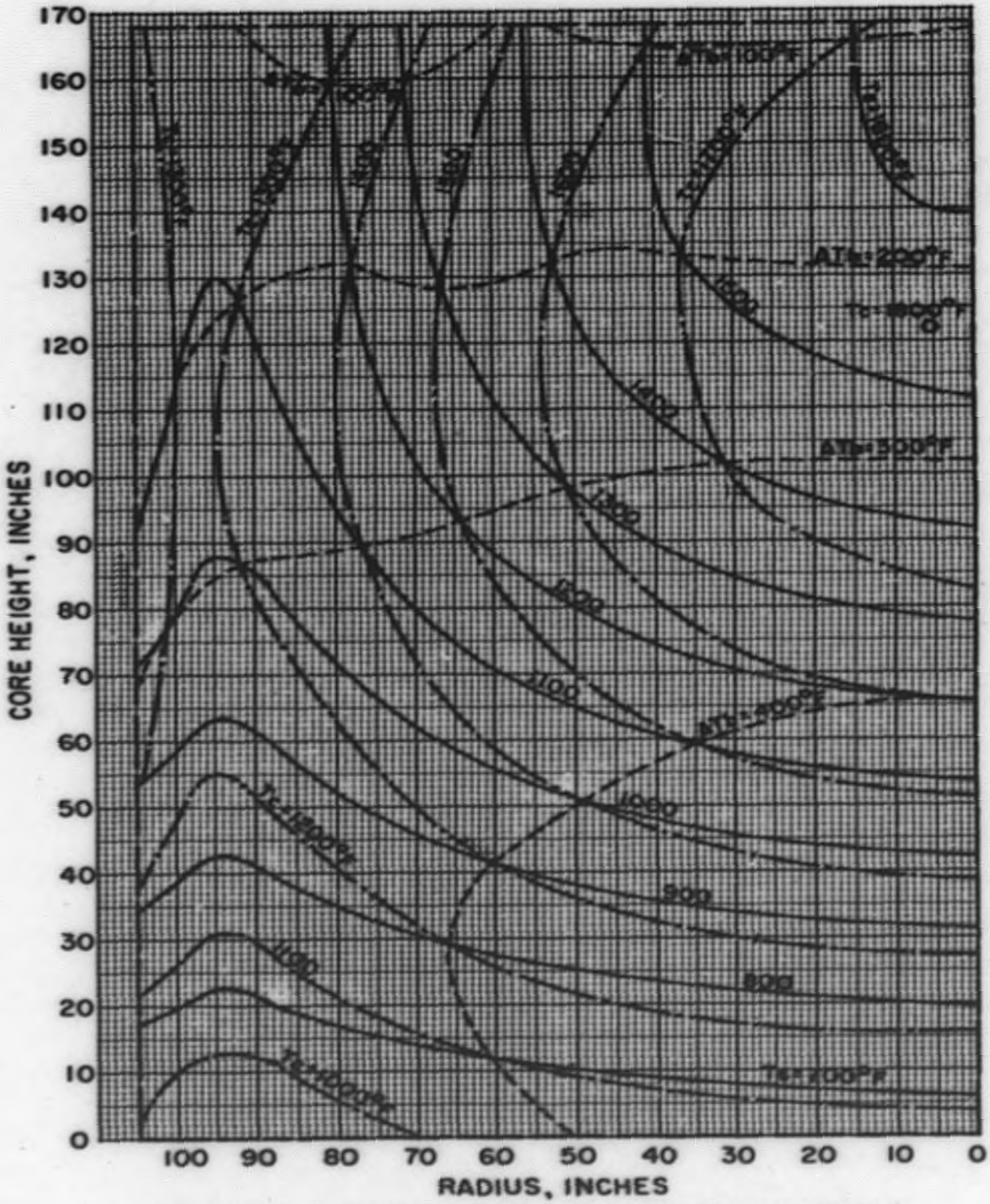
WEIGHTED AVERAGE GRAPHITE TEMPERATURE & GAS TEMPERATURE
IN A 750 tMW PBR CORE

FIG. 4.5



PERCENT OF CORE
AT OR ABOVE ANY TEMPERATURE
IN A 750 MW PBR CORE

FIG. 4.6



GRAPHITE CENTER & SURFACE TEMPERATURES
IN A 750 MW PBR CORE

FIG. 4.7

COOLBALL NOMENCLATURE

Symbol	Identification
A	Frontal are, ft^2
Ai	Local frontal area region i
$\overline{APj}$	Normalized axial power layer j
$\overline{Cp}$	Avg. gas heat capacity, BTU/Lb °R
CpX	Heat capacity temperature exponent
Dp	Ball diameter, ft
G	Avg. mass velocity, lbs/sec/ft^2
Gij	Local mass velocity, lbs/sec/ft^2
G'ij	Local mass velocity previous iteration, lbs/sec/ft^2
I	No. of axial layers
J	No. of radial regions
MW	Gas molecular weight
P	Gas pressure, psia
$\overline{Pj}$	Outlet pressure each layer, psia
$\overline{Pr}$	Avg. gas Prandtl number
PrX	Prandtl number temperature exponent
$\overline{Q}$	Avg. power density, BTU/sec/ft^3 bulk volume
Qmax	Maximum power density, BTU/sec/ft^3 bulk volume
Qij	Local power generation, BTU/sec/ft^3 bulk volume
RPi	Normalized radial power region i
t	Local avg. graphite temperature, °R
Tin	Reactor gas inlet temperature, °R
$\overline{Ti}$	Local gas inlet temperature in any matrix cell, °R
$\overline{Tij}$	Local avg. gas temperature
$\overline{\Delta Tij}$	Local gas temperature rise
$\overline{T}$	Core avg. gas temperature. °R
T2	Mixed mean outlet temperature, °R
Tbij	Local ball center temperature
Tsij	Local surface temperature, °R
W	Total gas flow rate, lbs/sec
Wi	Local gas flow rate, lbs/sec
XMU	Viscosity temperature exponent
δ	Convergence criterion on gas flow
ΔLj	Length increment axial direction, ft.
$\Delta Tfij$	Local film temperature drop
$\overline{\varepsilon i}$	Local voidage
μ	Avg. gas viscosity, lbs/ft/sec

Subscripts:

i index defining radial region
j index defining axial layer

END