OCT 17 1967

MASTER

GENERAL ATOMIC
DIVISION OF
GENERAL DYNAMICS

JOHN JAY HOPKINS LABORATORY FOR PURE AND APPLIED SCIENCE
P.O. BOX 608, SAN DIEGO, CALIFORNIA 92112

INFORMAL AEC RESEARCH
AND DEVELOPMENT REPORT

GAMD-8119

BLOOST-6-A KINETICS CODE CONTAINING A THERMODYNAMIC
MODEL OF COATED PARTICLES FOR HTGR APPLICATIONS

by

R. C. Dahlberg and M. H. Merrill

This document, which was prepared primarily for internal use at General Atomic, may contain preliminary or incomplete data. It is informal and is subject to revision or correction; it does not, therefore, represent a final report.

U.S. Atomic Energy Commission
Contract AT(04-3)-167 P.A. 17
Project 317.2330

July 19, 1967

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

The BLOOST-6 computer code is described herein as it existed on July 19, 1967. The code has been in continuous development for 2 years and in its presented form has been applied successfully by General Atomic to the kind of problems discussed later in this report. However, the development and improvement of the code are being continued, so that duplication of results (or even close agreement) between problems run with the code as published and the code as it existed either before or after this time is not necessarily to be expected.

General Atomic has exercised due care in preparation, but does not warrant the merchantability, accuracy, and completeness of the code or of its description contained herein. The complexity of this kind of program precludes any guarantee to that effect. Therefore, any user must make his own determination of the suitability of the code for any specific use, and of the validity of the information produced by use of the code.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights, or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

CONTENTS

I.	DISCUSSION OF BLOOST-6	1
II.	KINETICS INPUT	6
III.	DISCUSSION OF RESULTS	9
APPENDIXES		
A.	COMMENTS ON THE DOPPLER COEFFICIENT IN CORE USING SEGREGATED FUEL	17
B.	INPUT DATA FOR BLOOST-6	20
	REFERENCES	24

I. DISCUSSION OF BLOOST-6

BLOOST-6 consists of three parts: a space-independent kinetics code, a two-dimensional time-dependent heat transfer code called RAT, and a spherical geometry time-dependent heat transfer code for fuel particles called FUGRA. The kinetics code and the RAT code were previously combined in the BLOOST-5 program.⁽¹⁾ Many of the features of the two-dimensional version of RAT are described in a report on the newer three-dimensional version.⁽²⁾ The input data for the BLOOST-6 code are described in Appendix B.

BLOOST-6 operates under the control of the kinetics code, which does a fourth-order Runge-Kutta integration of the reactor kinetic equations using a variable time step based on the speed of the change in the reactor power level. At selected time intervals, the FUGRA code is called to compute the temperature distribution in the particles* based on the quantity of heat generated, stored, and lost during the interval. The average temperatures of the fuel-bearing portions of the particles are computed and supplied to the kinetics code for computing reactivity feedback using the fuel temperature coefficients.

The RAT portion of the code computes the temperature distribution in RZ geometry for an entire average fuel element. The RAT model used in the test represents a portion of a typical HTGR hexagonal block fuel element (see Fig. 1). The fuel region contains the homogenized fissile and fertile particles and some graphite binder material. The RAT code is used at the same time intervals as the FUGRA code.

The heat generation rate in the RAT fuel region is computed as the total heat lost from all particles divided by the time interval since the last use of RAT. This heat generation rate is evaluated at each axial point in the fuel region. The temperature distribution in the fuel element and coolant is computed, and the average temperature of all moderator regions (excluding reflectors) is given back to the kinetics code for computing feedback using the moderator coefficient.

The coupling between FUGRA and RAT is through a heat transfer coefficient that is specified by a FORTRAN function statement, which can be easily modified to accommodate different models. At the outer surface

*The code is currently programmed for two types of particles and dimensioned for six.

Fig. 1. Fluid flow and heat transfer model for an HTGR kinetics test

of each particle, the heat loss to the RAT fuel region (also called the bed) is given by

$$q = hA (T_{\text{surface}} - T_{\text{bed}}) .$$

This equation provides the outer boundary condition for the FUGRA calculation, with T_{bed} always coming from the previous RAT time step. The average heat generation rate in RAT at any axial position is then

$$\sum_i q_i \times \left(\frac{\text{particles}}{\text{ft}^3} \right)_i ,$$

where the sum is made over all particle types.

A fertile particle, which generates no heat, receives its first heat from the bed during the FUGRA step following the first RAT step. Care must be taken to use sufficiently small steps to avoid introducing a physically unreal time lag between particles.

In the FUGRA calculation of transient heat transfer within the particle, the thermal conductivities of the particle kernels and coatings are included accurately and explicitly in the calculation (see Table 1). The thermal conductivity of the ensemble of coated particles and binder material is also taken into account accurately in the determination of heat flow rates from the fuel region to the bulk moderator. The bed conductivity is taken to be that of the mixture of particles and binder.

The treatment of specific heat (or heat capacity) is arbitrary, however. The total heat capacity of the fuel region must be divided between the particles and the bed. To define the bed as all of the binder material (i. e., all of the nonparticle graphite) leads to numerical instabilities for problems that have reasonable computer running times. It is necessary to include some fraction of the specific heat of the particle coatings in the definition of the bed. The specific heat of the coatings in the FUGRA particle calculations must, of course, be consistent with the definition of the bed so that the heat capacity of the entire fuel region is correct.

This arbitrariness in the model was investigated, and the results show that for the slow transients typical of HTGR rod withdrawal accident conditions, for example, the arbitrariness does not appear to introduce large uncertainties in the transient temperatures. The definitions of the heat capacities for the various fuel region components used in this test are listed in Table 2. Definition 2 is the most appealing

Table 1

HEAT TRANSFER PROPERTIES

Quantity	Units	Material	Value (Best Estimate) (T in $^{\circ}\text{R}$)
Specific heat ↓	$\text{Btu/ft}^3\text{-}^{\circ}\text{F}$ ↓	ThC_2 kernels	$31 + 0.00325 T - (1.45 \times 10^{-6}) T^{-2}$
		$\text{ThC}_2\text{-UC}_2$ kernels	$33 + 0.00323 T - (1.53 \times 10^{-6}) T^{-2}$
		Buffer graphite	$0.15 + 0.0151 T - (2.7 \times 10^{-6}) T^2$
		Isotropic graphite	$0.40 + 0.040 T - (7.3 \times 10^{-6}) T^2$
		Binder material	$0.28 + 0.022 T - (3.9 \times 10^{-6}) T^2$
		Total fuel region	$3.34 + 0.0275 T - (4.88 \times 10^{-6}) T^2 - (0.141 \times 10^6/T^2)$
Density ↓	$\text{Btu/lb-}^{\circ}\text{F}$ ↓	Bulk graphite	$0.00352 + (3.48 \times 10^{-4}) T - (6.26 \times 10^{-8}) T^2$
		Bulk graphite	107 (1.71 g/cm^3)
Thermal conductivity ↓	lb/ft^3 ↓	Particle kernels	24
		Buffer graphite	~ 0.05 to 0.5
		Isotropic graphite	~ 5.0
		Fuel region ^a	$-0.58 + (2.67 \times 10^{-3}) T - (1.34 \times 10^{-6}) T^2 + (2.25 \times 10^{-10}) T^3$
		Bulk graphite	16 to 18

^a The bed conductivity is defined as the fuel region conductivity.

Table 2

DEFINITIONS OF FUEL REGION HEAT CAPACITIES

	Heat Capacity (Btu/ft ³ -°F)
<u>Definition 1</u>	
Kernel in FUGRA	
Fissile kernel	$33 + 0.00323 T - (1.53 \times 10^6 / T^2)$
Fertile kernel	$31 + 0.00325 T - (1.45 \times 10^6 / T^2)$
Buffer layer in FUGRA	0.1
Isotropic layer in FUGRA	0.1
Binder	$0.28 + 0.022 T - (3.9 \times 10^{-6}) T^2$
Total RAT bed	Binder plus essentially all of the coatings
Total for fuel region	$3.34 + 0.0275 T - (4.88 \times 10^{-6}) T^2 - (0.141 \times 10^{-6} / T^2)$
<u>Definition 2</u>	
Kernels in FUGRA	Same as definition 1
Buffer layer in FUGRA	$0.15 + 0.0151 T - (2.7 \times 10^{-6}) T^2$
Isotropic layer in FUGRA	$0.40 + 0.040 T - (7.3 \times 10^{-6}) T^2$
Binder	Same as definition 1
Total RAT bed	Same as binder
Total for fuel region	Same as definition 1
<u>Definition 3</u>	
Kernels in FUGRA	Same as definitions 1 and 2
Buffer layer in FUGRA	One-half of definition 2
Isotropic layer in FUGRA	One-half of definition 2
Binder layer in FUGRA	Same as definitions 1 and 2
Total RAT bed	Binder plus one-half of the coatings
Total for fuel region	Same as definitions 1 and 2

physically but, as mentioned above, gives rise to numerical instabilities. The heat capacity of the RAT bed in definition 1 includes the particle coatings as well as the binder; definition 3 includes only one-half of the coating heat capacity and thus is intermediate to the first two cases. The total fuel region heat capacity is correct for all definitions.

II. KINETICS INPUT

The kinetics input to BLOOST is described in Ref. 1 and Appendixes A and B. The numerical data are presented in the following tables. These data are typical of an equilibrium fuel cycle in an HTGR which contains a mixture of U^{233} and U^{235} as the fissile material.

Table 3

TEMPERATURE COEFFICIENTS USED

Temp (°K)	Reactivity Defect Due to Fuel Temp	Reactivity Defect Due to Moderator Temp
300	0	0
600	-0.0212	-0.0002
900	-0.0337	0.00424
1200	-0.0439	0.00883
1500	-0.0521	0.01190
1800	-0.0590	0.01349
2200	-0.0667	0.01344
2600	-0.0732	0.01175
3000	-0.0789	0.00951
3400	-0.0838	0.00762

Table 4

DELAYED NEUTRON DATA USED

Delay Group	Beta (β)	Decay Constant (sec^{-1})
1	0.000222	0.0125
2	0.00112	0.0316
3	0.000978	0.1194
4	0.001667	0.3063
5	0.000446	1.135
6	0.0001831	2.876
Total	0.004611	

(The prompt neutron lifetime used in this test was 2.63×10^{-4} sec.)

Table 5

 NORMALIZED AXIAL POWER DISTRIBUTION
 (Volume Average = 1.0)

Axial Position (Fraction of Distance From Coolant Inlet)	Normalized Power Density
0.04	0.71
0.13	0.90
0.21	1.10
0.29	1.23
0.37	1.31
0.46	1.34
0.54	1.12
0.63	1.06
0.71	0.97
0.79	0.86
0.87	0.73
0.96	0.64

The reactivity transient assumed for this test was a slow rod withdrawal. A total of $0.01 \Delta \rho$ was introduced into the core in 100 sec. This was done at a nearly linear rate, as shown in Table 6.

Table 6

REACTIVITY INSERTION RATE

<u>Time (sec)</u>	<u>$\Delta \rho$ Added to Core</u>
0	0
2.39	0.00012
7.30	0.00050
12.4	0.001
17.8	0.0016
23.3	0.0023
29.0	0.0030
34.9	0.0039
41.1	0.0047
47.4	0.0056
53.9	0.0064
60.7	0.0072
67.6	0.0080
74.7	0.0086
82.0	0.0094
89.6	0.0097
97.0	0.0099
100.0	0.010

No scram was assumed. Since the important parameters in the model are evident during the reactivity addition phase of the transient, a scram does not test any special features of the program. The core gas inlet temperature and gas flow rate were assumed to remain constant during the transient. These are also simplifying assumptions.

III. DISCUSSION OF RESULTS

The BLOOST-6 problems run in this test are listed and described in Table 7. The information obtained in the runs includes the core power level, the average particle temperatures, the temperature distribution in the bed of the average fuel element, the temperature distribution in the two types of particles, the average moderator temperature, and the average outlet gas temperature. The core power, outlet gas temperature, and average particle temperatures are compared in this analysis. The transient core power level is shown in Fig. 2; the fuel particle temperatures and gas outlet temperature are presented in Tables 8 and 9, respectively.

CASE 1

Case 1 is a base case. It was run not only to provide comparative data for the other BLOOST-6 runs, but also to a prior BLOOST-5 run. The thermal conductivities within the particle were chosen large enough so that the average particle temperatures were nearly equal to each other and to the average fuel temperature at any instant.

Some comparative data for BLOOST-5 and BLOOST-6, case 1, are shown in Tables 8 and 9. The average fuel temperatures after 100 sec differ by only about 8°C (after a temperature rise of about 500°C), and the average gas outlet temperature differs by less than 10°C . These differences are due to the numerical structure of the code and to slight differences in the initial steady-state conditions.

Due to the frequency with which the RAT and FUGRA calculations were done in these problems, the temperatures at any given time are probably uncertain by $\sim 5^{\circ}$ to 10°C . Differences of less than this amount at a given time are probably not significant.

CASE 2

Case 2 differs from case 1 in the thermal conductivity of the buffer coating (layer). A conductivity of $0.5 \text{ Btu/hr-ft-}^{\circ}\text{F}$ instead of 24 is used. There are no significant changes in the average particle temperatures or the outlet gas temperature from those of case 1. It is concluded, therefore, that for slow rod withdrawal-type reactivity transients, transient temperatures are insensitive to the buffer layer conductivity in the range 0.5 to $24 \text{ Btu/hr-ft-}^{\circ}\text{F}$.

Table 7
LISTING OF BLOOST-6 CASES FOR SLOW ROD WITHDRAWAL (0.01 $\Delta\rho$ IN 100 SEC)

BLOOST Case No.	Initial Power Level	Thermal Conductivity (Btu/hr-ft- ^o F)			Heat Capacity Definition ^a	Time Intervals Between RAT Calculations (Time t_1 to Time t_2)/ Δt^b	Bed Conductivity	Temperature Coefficients
		Kernel	Buffer Region	Isotropic Region				
1	Full	24	24	24	1	0 $\rightarrow$ 25/0.1, 25 $\rightarrow$ 50/0.3, 50 $\rightarrow$ 200/1.0, 200 $\rightarrow$ 300/5.0	Table 1 value	Table 3 value
2	Full	24	0.5	5.0	1		Table 1 value	Table 3 value
3	Full	24	0.5	5.0	1		Table 1 value	Table 3 value
4	Full	24	0.05	5.0	1		Table 1 value	Table 3 value
5	Full	24	0.01	5.0	1	0 $\rightarrow$ 25/0.3, 25 $\rightarrow$ 50/0.5, 50 $\rightarrow$ 200/5.0, 200 $\rightarrow$ 300/5.0	Table 1 value	Table 3 value
6	Full	24	0.01	5.0	1		Table 1 value	Modified value
7	Full	24	0.5	5.0	1		1/2 Table 1 value	Table 3 value
8	Full	24	0.5	5.0	2	0 $\rightarrow$ 25/0.1, 25 $\rightarrow$ 50/0.3, 50 $\rightarrow$ 100/1.0	Table 1 value	Table 3 value
9	Full	24	0.05	5.0	3	0 $\rightarrow$ 25/0.1, 25 $\rightarrow$ 50/0.03, 50 $\rightarrow$ 150/1.0	Table 1 value	Table 3 value
10	Source power	24	0.05	5.0	3	0 $\rightarrow$ 35/5.0, 35 $\rightarrow$ 45/0.1, 45 $\rightarrow$ 150/1.0, 150 $\rightarrow$ 350/5.0	Table 1 value	Table 3 value

^a See definitions in Table 2.

^b From time t_1 to time t_2 (in sec), the time interval between successive RAT calculations is Δt sec, etc.

Fig. 2 Transient core power level

Table 8
TRANSIENT AVERAGE PARTICLE TEMPERATURES ($^{\circ}\text{C}$)

Time (sec)	BLOOST-5 Base Case	BLOOST-6 Cases																	
		1		2		3		4		5		6		7		8 ^a		9	
		Type 1	Type 2	Type 1	Type 2	Type 1	Type 2	Type 1	Type 2	Type 1	Type 2	Type 1	Type 2	Type 1	Type 2	Type 1	Type 2	Type 1	Type 2
0	804	805	804	805	804	805	804	812	804	842	804	842	804	883	882			812	804
10	812	813	812	813	812	813	812	821	811	857	811	856	810	892	891			822	812
20	841	843	843	843	842	843	842	853	840	897	835	891	832	923	922			854	842
30	889	892	892	893	891	894	892	904	887	958	877	938	865	977	975			904	887
40	949	954	954	954	952	955	953	971	949	1031	933	1001	913	1054	1052			967	946
50	1027	1032	1031	1032	1029	1034	1032	1053	1027	1119	1001	1065	964	1128	1125			1048	1025
60	1105	1117	1117	1118	1114	1113	1109	1135	1106	1204	1072	1136	1023	1200	1197			1132	1105
70	1178	1188	1188	1189	1185	1188	1184	1209	1179	1286	1144	1200	1079	1272	1270			1205	1176
80	1238	1249	1249	1250	1246	1245	1242	1265	1235	1347	1202	1261	1133	1340	1337			1262	1232
90	1292	1306	1306	1308	1304	1305	1301	1323	1293	1397	1256	1298	1179	1396	1393			1319	1290
100	1334	1342	1342	1343	1340	1341	1338	1358	1329	1431	1295	1320	1206	1428	1425			1356	1327
110	1357	1368	1368	1368	1365	1368	1365	1383	1356	1448	1322								
120	1374	1383	1383	1383	1381	1383	1381	1397	1373	1459	1340								
130	1386	1394	1394	1394	1391	1394	1392	1407	1384	1466	1353								
140	1394	1402	1402	1401	1399	1401	1399	1414	1392	1471	1363								
150																			

NOTE: Type 1 refers to particle Type 1, the fissile particle; Type 2 refers to the fertile particle.

^aNo data was obtained for case 8.

Table 9
TRANSIENT OUTLET GAS TEMPERATURE ($^{\circ}\text{C}$)

Time (sec)	BLOOST-5 Base Case	BLOOST-6 Cases								
		1	2 ^a	3 ^a	4	5	6	7	8 ^b	9
0	785	785			785		785	785		785
10	785	785			785		785	785		785
20	788	787			787		787	787		789
30		796			796	795	793	793		796
40		812			812	810	805	805		810
50	834	836			835	829	824	824		833
60		868			867	856	846	847		863
70	899	906			903	890	873	876		902
80	938	948			945	927	902	909		943
90		991			986	970	935	945		987
100	1028	1035			1029	1010	970	982		1031
110	1065	1078			1071	1050	1001	1019		1072
120							1029			

^a Results were essentially the same as for case 1.

^b No data was obtained for case 8.

CASE 3

Case 3 differs from case 2 only in the time interval between RAT and FUGRA calculations. There is no significant difference between the results of cases 2 and 3.

CASE 4

In case 4, the buffer conductivity is $0.05 \text{ Btu/hr-ft-}^{\circ}\text{F}$; otherwise, it is identical to cases 1 and 2. As shown in Fig. 2 and Table 9, the core power and gas outlet temperature are very insensitive to the buffer conductivity. With such low buffer conductivities, however, the temperature difference between the average particle temperatures after about 100 sec increases from 1° to 2°C in cases 1 and 2 to about 30°C . The fissile particle runs about 15°C hotter with $K(\text{buffer}) \approx 0.05$ than with $K(\text{buffer}) \approx 0.5$ to 24 .

These results indicate that the transient temperatures during rod withdrawal-type transients are sensitive functions of the buffer layer conductivity only when this conductivity is as low as or lower than

0.05 Btu/hr-ft-°F. The best estimate of this conductivity for PSC-type fuel particles is larger than 0.05 Btu/hr-ft-°F.

CASE 5

The buffer layer conductivity is 0.01 Btu/hr-ft-°F; otherwise, cases 4 and 5 are identical. The results of this run confirm the conclusions reached from the results of case 4. After 100 sec, the average particle temperatures differ by about 150°C, and the fissile particle is running significantly hotter (~100°C) than is the case with a high conductivity buffer layer.

A 1-μ radiation gap has an equivalent conductivity much less than 0.01 Btu/hr-ft-°F at temperatures of the order of 1000°C. If a small radiation gap existed in the particles, due perhaps to the manufacturing process or to radiation damage, then transient heat transfer rates would be dominated by the gap, and transient temperatures would be markedly influenced by the gap even for slow rod withdrawal transients. This effect would be much less, of course, if the gap were filled with gas. Such cases have not been studied.

CASE 6

Case 6 is identical to case 5 except that the temperature coefficient is modified to account for axial importance weighting. Because of importance weighting, the actual effective temperature coefficient is about 10% more negative than the volume-weighted average coefficient. A comparison with case 5 shows that the 10% change in the temperature coefficient (making it more negative) reduces the average fuel temperatures after 100 sec by about 100°C a significant effect. The outlet gas temperature is also reduced after 100 sec, by about 40°C, and the transient power is markedly affected, as shown in Fig. 2.

The sensitivity of transient temperatures to uncertainties in the temperature coefficient is significant. It emphasizes the difficulty in making "best-estimate" kinetics analyses, and suggests that only conservative "limiting" situations should be studied.

CASE 7

In this case, the bed conductivity was one-half that of the reference case, case 3. (In prior cases, the bed conductivity was the value recorded in Table 1, which is the best-estimate experimental value.) As shown in Table 8, average particle temperatures increase about 100°C over the

reference (case 3) value at all times. For these slow transients, this difference does not appear to be strongly time dependent. The average gas temperature is reduced about 50°C after 100 sec because of the slower heat transfer to the coolant.

CASE 8

For case 8, the definition of the bed heat capacity was changed. In prior cases, the bed heat capacity consisted of the binder plus the fuel particle coatings. In this case, only the binder is assumed to contribute to the bed heat capacity, i. e., definition 2 in Table 2. This definition is intuitively appealing because the particle calculation is then entirely separate from the calculation dealing with heat transfer to the bulk graphite. In the original definition, the particle thermal conductivities were treated accurately in the particle calculation, but the heat capacity of the coatings in that calculation was arbitrarily set to a small value.

This calculation is numerically unstable for reasonably sized time steps. For very small time steps, stability could be achieved, but the problem running time would be long. The instability is due to the small heat capacity of the bed (i. e., the binder), which undergoes enormous variations in temperature between successive heat transfer calculations.

CASE 9

The definition of the bed heat capacity in this case is changed to definition 3 in Table 2. The bed heat capacity is assumed to consist of one-half of the heat capacity of the coatings. In case 9, the average particle temperatures after 100 sec are about the same as for case 4, which is the reference case. The results signify that to some extent the transient temperatures for slow transients are insensitive to reasonable variations in the definition of the bed heat capacity. The assumption that the coating heat capacity is part of the bed heat capacity appears valid.

CASE 10

Prior calculations assumed a full-power reactor as an initial condition. Case 10 is a source-power accident that assumes an initial power of about 1 watt. In this case, the power level remains very low for about 40 sec. The subsequent transient power level is tabulated in Table 10.

Heat transfer from the fissile to the fertile material is quite rapid; the particle temperatures are different at any given time by only a few degrees. A buffer conductivity of 0.05 Btu/hr-ft-°F is assumed in this calculation.

If heat transfer to the fertile particle were instantaneous, an additional negative feedback component of about -2×10^{-4} (or less) would occur. This may not be negligible with respect to peak power, but the effect on transient temperatures should be fairly small.

Table 10
TRANSIENT POWER LEVEL AND TEMPERATURES FOR
SOURCE-POWER ACCIDENT (CASE 10)

Time (sec)	Power Level (MW)	Average Particle Temp (°C)		Outlet Gas Temp (°C)
		Type 1	Type 2	
0	10^{-6}	200	200	200
40	4	200	200	200
41	41	200	200	200
42	400	206	203	200
42.85	1127	226	215	200
43	1106	229	219	200
44	780	244	236	200
45	670	252	245	
46	720	260	250	
47	830	265	258	
48	670	271	265	
49	600	277	271	
50	560	279	274	206
55	510			210
60	500			215
100		365	362	245

The results indicate that in slow rod withdrawal accidents from source-power levels, transient temperature will be affected to a small (probably negligible) extent by particle effects.

Appendix A

COMMENTS ON THE DOPPLER COEFFICIENT IN CORE
USING SEGREGATED FUEL

In a packed bed of coated thorium particles, which may or may not also contain fissile material, the Doppler coefficient that is effective during a reactivity transient is difficult to determine. The analysis presented below shows that the most straightforward approach to the problem is reasonably satisfactory; i. e., the assumption that the Doppler coefficient arising from an increase in temperature of N_o thorium atoms is directly proportional to N_o appears valid.

The flux in the fuel zone, which contains the Th^{232} , is given by the expression⁽³⁾

$$\phi_o \left(\sigma_{t_o} + \sigma_m \right) = (1 - P_o) \left[\frac{1}{\alpha_o} \int_E^{E/(1-\alpha_o)} \phi_o(E') \sigma_{s_o} \frac{dE'}{E'} \right. \\ \left. + \frac{1}{\alpha_m} \int_E^{E/(1-\alpha_m)} \phi_o \sigma_m \frac{dE'}{E'} \right] + P_1 \frac{A}{E} \sigma_{s_1} \quad (1)$$

The following definitions and assumptions have been made:

- $A/E = \phi_1$ = the flux in the moderator,
- P = escape probability,
- $(1 - \alpha)$ = maximum fractional decrease in energy due to an elastic scattering event, and
- σ = cross section (cm^{-1}) per absorber atom.

The subscripts are defined as follows:

- l = moderator outside the fuel region,
- m = moderator inside the fuel region,
- o = absorber inside the fuel region,
- t = total, and
- s = scattering.

If the reciprocity theorem is used and the narrow resonance approximation is made for moderator scattering, Eq. (1) becomes

$$\phi_o \left(\sigma_{t_o} + \sigma_m \right) = (1 - P_o) \frac{1}{\alpha_o} \int_E^{E/(1-\alpha_o)} \phi(E') \sigma_{s_o} \frac{dE'}{E'} + \frac{A}{E} \left(P_o \sigma_{t_o} + \sigma_m \right). \quad (2)$$

Now the infinite mass approximation can be made for scattering by the absorber nucleus. If the rational approximation is also made for the escape probability, then Eq. (2) becomes

$$\phi_o = \frac{A}{E} \left(\frac{\sigma_e + \sigma_m}{\sigma_{a_o} + \sigma_e + \sigma_m} \right), \quad (3)$$

where a refers to absorption and σ_e is the escape cross section.

Equation (3) is probably a good estimate of the actual flux. The resonance integral of interest in Doppler coefficient calculations is

$$I = \frac{1}{\xi \sigma_s} \int \phi_o \sigma_{a_o} dE, \quad (4)$$

and the derivative of I is proportional to the logarithmic derivative of the resonance escape probability (i. e. , proportional to the Doppler coefficient):

$$\frac{\delta p}{p} \sim \delta I.$$

We are interested in the dependence of the Doppler coefficient on N_o , the number of heavy resonance-absorbing nuclei.

If ϕ_o from Eq. (3) is substituted into Eq. (4) and the derivative is taken, and if the dependency of the cross sections on N_o is shown explicitly, we obtain

$$\frac{\delta p}{p} = \frac{1}{\xi \sigma_{s_1} (V_1/V_o)} \delta \left[\int \frac{A}{E} dE \frac{\sigma_{a_o} (\Sigma_e + \Sigma_m)}{\sigma_{a_o} + \frac{\Sigma_e}{N_o} + \frac{\Sigma_m}{N_o}} \right]. \quad (5)$$

To further simplify Eq. (5), we assume that in the resonance $\sigma_{a_o} \gg (\Sigma_e + \Sigma_m)/N_o$, while off the resonance, $\sigma_{a_o} \ll (\Sigma_o + \Sigma_m)/N_o$.

Then Eq. (5) becomes

$$\frac{\delta p}{p} = \frac{1}{\xi \sigma_{s_1} (V_1/V_o)} \delta \left(\int_{\text{Off}}^{\text{res}} \frac{A}{E} dE N_o \sigma_{a_o} \right) . \quad (6)$$

To the extent (mainly) that the above assumption is valid, and it is probably fairly accurate for thorium since the important resonances are very sharp, the Doppler coefficient is directly proportional to N_o . This has been found to be a good rule of thumb in some numerical work with GAM-II. Another important finding from this work is that the net Doppler coefficient from thorium atoms at different temperatures is just the sum of the partial Doppler coefficients:

$$\frac{\delta p}{p} = \frac{1}{\xi \sigma_{s_1} (V_1/V_o)} \left\{ \delta \left[\int_{\text{Off}}^{\text{res}} \frac{A}{E} dE N_o(T_1) \sigma_{a_o}(T_1) \right] + \left[\int \frac{A}{E} dE N_o(T_2) \sigma_{a_o}(T_2) \right] + \dots \right\} ,$$

where $N_o(T_1)$ is the number of thorium atoms at temperature T_1 , and $\sigma_{a_o}(T_1)$ is the thorium cross section at T_1 .

Appendix B

INPUT DATA FOR BLOOST-6

The BLOOST-6 program was obtained by combining BLOOST-5⁽¹⁾ and FUGRA. FUGRA is a program that treats transient heat transfer in coated particles. For BLOOST-6, the following input data must be added to that required for BLOOST-5. A familiarity with BLOOST-5 is assumed in the following discussion.

The cards are all in 6E12.4 format, the same as the RAT input, and are placed between the RAT cards and the kinetics cards (no extra blank cards are required).

<u>Card No.</u>	<u>Col. No.</u>	<u>Description</u>
1	1-12	Number of particle types (up to 2 in present version).
2	1-12	Particles/ft ³ of fuel region for particle type 1.
	13-24	Particles/ft ³ of fuel region for particle type 2.
3	1-12	Ratio of number of fueled particles to the total number of particles. This may be left blank unless needed for the definition of the heat transfer coefficient.

Cards 4 through 9 are repeated for each type of particle.

4	1-12	Initial power density at level 1* for this particle, Btu/hr-ft ³ (1×10^{-6} for nonfueled particle).
	12-24	Initial power density at level 2, etc.

Card 4 is repeated until all levels are specified. Maximum levels allowed = 20.

5		Blank card
6	1-12	Radius at center of particle; enter zero.
	13-24	First radial point of particle, μ .
	25-36	Second radial point of particle, μ .

* Levels in FUGRA correspond to temperature points inside the RAT fuel region and exclude the reflector and/or boundary points. Thus, level 1 is at axial temperature point 2 in RAT for a model with no axial reflector.

<u>Card No.</u>	<u>Col. No.</u>	<u>Description</u>
-----------------	-----------------	--------------------

Card 6 is repeated until all radial points are specified (up to 25 radii).

7		Blank card
8	1-12	Outer radius of shell 1 (fuel region), μ .
	13-24	Outer radius of shell 2 (nonfuel region), μ .
	25-36	Outer radius of shell 3 (nonfuel region), μ .
	37-48	Outer radius of shell 4 (nonfuel region), μ .
	49-60	Outer radius of shell 5 (nonfuel region), μ .
	61-72	Outer radius of shell 6 (nonfuel region), μ .

The maximum allowable number of shells is 6.

9	1-12	Initial temperature at radial point 1, level 1. If only this temperature is given, all other radial temperatures and bed temperature at this level are assigned the same value.
	13-24	Initial temperature at radial point 2, level 1.

Continue until all levels are specified. (This set of cards is punched at the end of each run.)

As in the case of RAT, an initial run is necessary to obtain the initial temperature distribution for other than isothermal cases. If the initial steady-state RAT temperatures are already known, the steady-state problem should be run with a very large heat capacity for the RAT fuel region to avoid perturbing the RAT distribution during the calculation of initial particle temperatures.

FUNCTION STATEMENTS

At present, the thermal conductivity and heat capacity of the particle shells, and the heat transfer coefficient from particle to bed, are specified by FORTRAN statements in separate subroutines, which are reassembled to change the data. The conductivity and heat capacity are defined in the subroutines FUG1 and FUG2 for particle types 1 and 2. Heat transfer coefficients are specified in HFN1 and HFN2. The function statements are in the form given below.

Thermal Conductivity

Thermal conductivity is specified as follows:

$$\text{RADK } 12 \text{ (DUM)} = A$$

where RADK = thermal conductivity, Btu/hr-ft- $^{\circ}$ F,

1 = particle type 1,

2 = shell 2,

A = some FORTRAN expression using DUM, and
DUM = a dummy argument to be replaced by the temperature at
some radial point and level in shell 2, particle type 1.

Thermal conductivity for particle type 1 (RADK 11, RADK 12.....
RADK 16) must be supplied in subroutine FUG1, and for particle type 2
(RADK 21, RADK 22..... RADK 26) must be supplied in subroutine
FUG2.

Specific Heat

In a manner similar to that for conductivity, specific heat is stated as
follows:

$$\text{XRCP } 12 (\text{DUM}) = \text{B}$$

where XRCP = specific heat, Btu/ft³-°F,

1 = particle type 1,

2 = shell 2,

B = some FORTRAN expression using DUM, and

DUM = a dummy argument to be replaced by the temperature at
some radial point and level in shell 2, particle type 1.

Specific heat for particle type 1 (XRCP 11, XRCP 12..... XRCP 16)
must be supplied in subroutine FUG1, and for particle type 2 (XRCP 21,
XRCP 22..... XRCP 26) must be supplied in subroutine FUG2.

Heat Transfer Coefficient (Btu/hr-ft²-°F)

The subroutines HFN1 and HFN2 are set up to allow the coefficients
to be functions of several variables. However, in the model in current
use for particles with very little external binder material, the following
very large constant heat transfer coefficients are used:

$$\begin{aligned}\text{HFN1} &= 10^5, \\ \text{HFN2} &= 10^5.\end{aligned}$$

ADDITIONAL MODIFICATIONS

In BLOOST-6, the following additional modifications to the BLOOST-5
kinetics input are required.

1. The fuel temperature coefficients tabulated in locations 25 through
84 are for particle type 1.

2. A map of the particle temperature is printed each time the number of RAT time steps exceeds the number given in location 158. A map of the RAT bed temperature is given each time the number of RAT time steps exceeds the number given in location 147 (AVAIL (3)).
3. The maximum time between RAT time steps is governed by the numbers in locations 152 through 155 and not by DELTMX (location 22).
4. AVAIL (16) applies to particle type 1; AVAIL (18) contains a similar multiplier for particle type 2.
5. AVAIL (156) and (157) apply to particle types 1 and 2, respectively.
6. In locations 607 through 636, the temperature coefficients for particle type 2 are tabulated.
7. The power table option used in BLOOST-5 is not available in BLOOST-6. The form of the UNIVAC-1108 starter deck for BLOOST-6 is as follows:

```

▽      ASG      A=2019
▽      XQT CUR
      IN A
      TRI A
▽P     HDG DATA
▽I     FØR, * DATA/A, DATA/A, DATA/A1
-53
      (Insert data cards for RAT here. )
▽P     HDG FUG1
▽I     FØR, * FUG1/A, FUG1/A, FUG1/A1
-21
      (Insert function statements for RADK-11(DUM).....RADK-
      16(DUM), and XRCP11(DUM).....XRCP16(DUM) here. )
▽P     HDG FUG2
▽I     FØR, * FUG2/A, FUG2/A, FUG2/A1
-21
      (Insert function statements for RADK-21(DUM).....RADK-
      26(DUM), and XRCP-21(DUM).....XRCP-26(DUM) here. )
▽P     HDG HFN1
▽I     FØR, * HFN1/A, HFN1/A, HFN1/A1
-5
      (Insert function statement for HFN1 here. )
▽N     HDG
▽A     XQT BLØØS6

```

REFERENCES

1. Merrill, M., "BLOOST-5: A Combined Reactor Kinetics-Heat Code for the IBM-7044," USAEC Report GAMD-6644, General Atomic Division, General Dynamics Corporation, August 17, 1965; also, GAMD-6644, Addendum, November 9, 1965.
2. Clark, S.S., and M. Troost, "RAT-3D, A General Three-Dimensional Heat Transfer Code," USAEC Report GAMD-7346, General Atomic Division, General Dynamics Corporation, October 10, 1966.
3. Nordheim, L. W., "The Doppler Coefficient," Chap. 4 in The Technology of Nuclear Reactor Safety, Volume 1, Reactor Physics and Control, T. J. Thompson and J. G. Beckerley (eds.), The M.I.T. Press, Cambridge, Massachusetts, 1964.