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POSTIRRADIATION THERMAL ANALYSIS OF CAPSULE P13T

by
J. W. KETTERER

Prepared under
Contract EY-76-C-03-0167
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GENERAL ATOMIC COMPANY

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ABSTRACT

In determining fuel rod temperature histories for the P13T capsule, a technique which combined measured temperature and dimensional data, TAC2D* computer modeling, and a calculational procedure was employed. TAC-2D models were constructed for each of the capsule's four fuel bodies and temperature matching runs were made at five time points of the irradiation history. The agreement between TAC-calculated and measured temperatures was good; at all times the TAC-calculated temperatures were within 20°C of the Chromel-Alumel (C/A) measurements and 40°C of the corrected tungsten-rhenium (W/Re) temperatures. Thermocouple decalibration was treated in detail and corrected temperatures for all W/Re thermocouples were calculated over the irradiation period.

The calculational procedure involved curve fitting the TAC-calculated values and then, using the daily measured data as input, calculating peak fuel, surface fuel, and average graphite temperatures, which were plotted as a function of exposure time.

The end-of-life gaps between the fuel rod and crucible were much smaller than the predicted values used to estimate and control fuel temperatures during irradiation. The effect of this was that temperatures in the graphite crucible were held too low; the analysis discussed here showed that the fuel temperatures were as much as 100°C below the desired level in three crucibles during the latter part of the irradiation.

*Thermal Analysis Code - Two Dimensional.

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1. INTRODUCTION

1.1. PURPOSE OF THERMAL ANALYSIS

Capsule irradiation experiments provide a great deal of useful information. Some of the important contributions from past test capsules have been qualification of fuel particle types, evaluation of particle coating process parameters, determination of the effect of severe exposure conditions on fuel integrity, and determination of the behavior of graphite and matrix materials under irradiation. Many of the variables tested in these capsules are strongly temperature dependent, and any information gained would be incomplete without a knowledge of the temperatures experienced during the course of the experiment. To this end, a postirradiation thermal analysis of capsule P13T was performed.

1.2. SCOPE

This report primarily describes the work performed in obtaining the time-temperature history of the fuel rods in P13T. For this reason, descriptions of the capsule, its design basis, and operational details are brief. Reports which provide more detailed information on these and other aspects of the experiment are referenced throughout this report.

2. EXPERIMENT DESCRIPTION

2.1. PURPOSE OF TEST

The goal of the P13T experiment was the irradiation of fresh and recycle LHTGR-type fuels at peak LHTGR fuel temperature conditions (Ref. 1). It was also the first test with fuel rods that were cured in place within the graphite crucibles prior to the irradiation. A number of other concepts concerning the fuel particle type and design were also evaluated for the first time in capsule P13T. These are described in detail in the Preirradiation Report (Ref. 2), which characterizes the fuel irradiated in this capsule.

2.2. CAPSULE OPERATION

Capsule P13T was irradiated in the E-3 position of the Oak Ridge Reactor (ORR) from May 1975 to July 1976; nominal reactor power was 30 MW. The reactor was operated through cycles 125 to 132 inclusive during this time. Throughout the irradiation thermocouple readings and gas flow data were recorded several times daily and reported to GA via magnetic tape. A more detailed description of the capsule operation can be found in the Test Operations Report (Ref. 3).

2.3. CAPSULE DESCRIPTION

The P13T experiment consisted of a long stainless steel tube sealed at both ends comprising the secondary containment and an inner steel tube also sealed at the ends making the primary containment. An Inconel bulkhead brazed into the primary tube divided it into two separate cells. As shown in Fig. 1, cell 1 was located at the bottom of the capsule. It contained one graphite body, crucible 1, which was 200 mm long and was constructed of H-451 graphite. Cell 2, occupying the upper portion of the capsule, contained crucibles 2, 3, and 4 which were made of TS-1240, H-451, and TS-1240

Fig. 1. Pictorial drawing of capsule P13T

graphites, respectively. Crucibles 2 and 3 were both 115 mm in length, while crucible 4 was 137.5 mm long. Since cell 1 was completely isolated at the bottom of the capsule, a tube on the exterior of the capsule was used to route the thermocouples and gas lines of this cell to the top of the capsule. Helium at 70 psig was used to purge the secondary containment while separate helium-neon mixtures swept each primary cell as a means of temperature control and fission gas release monitoring.

The arrangement of fuel rods within the capsule is shown in Fig. 2. Some rods were shorter (30.5 mm) than the reference length (61 mm) to facilitate fuel loadings and to eliminate large axial temperature differences within single rods.

Gaps between the primary and secondary containments and between the fuel rods and fuel holes in the crucibles were designed, along with the sweep gases, to achieve the desired fuel temperatures. Fuel rods in cell 1 were to operate at 1300°C and those in cell 2 at 1100°C (peak fuel temperatures).

ENLARGED VIEW
OF PIGGYBACK HOLES
FOR BODIES 3 AND 4

CELL 2				CELL 1			
BODY 4				BODY 3			
4A4*	4A3	4A2	4A1	3A2	3A1	2A2*	2A1
4B4*	4B3	4B2	4B1	3B2	3B1	2B2*	2B1
4C4*	4C3	4C2	4C1	3C2	3C1	2C2*	2C1
BODY 2**				BODY 1			
1A4	1-1A3	1-1A2	1-1A1*	1B4	1B3	1-1B2	1-1B1*
1C4	1C3	1C2	1-1C1*				

PEAK TEMPERATURE 1100°C
PEAK FLUENCE 3.0 TO 8.0 X 10²⁵ N/M²
(E>29 fJ)_{HTGR}

1300°C
3.5 TO 7.7 X 10²⁵ N/M²

FUEL ROD HOLES

PIGGYBACK HOLES

HOLE CONTAINING
THERMOCOUPLES AND DOSIMETERS

*THERMOCOUPLE RODS

**BODY 2 IS ROTATED 60° WITH RESPECT TO BODIES 3 AND 4 SO THERMOCOUPLES CAN BE
INSERTED THROUGH COOLANT HOLES INTO FUEL RODS

Fig. 2. Schematic layout of capsule P13T

3. METHOD OF THERMAL ANALYSIS

3.1. DESCRIPTION OF METHOD

The technique employed in this thermal analysis combined measured data and analytical calculations in determining the capsule temperature history over the entire irradiation period. The measured data (Section 4) consisted of temperature readings and control gas flow rates that were recorded on a daily basis during irradiation and capsule dosimetry and postirradiation examination (PIE) measurements obtained after irradiation. The analytical portion (Section 5) included TAC-2D (Ref. 4) computer modeling and a calculational technique for determining peak fuel rod temperatures.

A 60° section of symmetry from an axial cross section of P13T is shown in Fig. 3. The temperatures at points A and B (T_A and T_B , respectively) were measured with thermocouples in each of the capsule's four crucibles. Figure 4 shows a typical temperature profile radially outward from the capsule centerline through one of the fuel rods. Note that if the temperature at the outer edge of the fuel rod hole, T_{OF} , is known, then the peak fuel rod temperature is simply

$$T_{PEAK} = T_{OF} + \Delta T_{GAP} + \Delta T_{FUEL} \quad . \quad (1)$$

It will be shown that ΔT_{GAP} and ΔT_{FUEL} can be determined for each day of capsule operation; however, without T_{OF} as a starting point, this information is useless. Fortunately, an observation that has been made in previous TAC analyses (Ref. 1) of this type capsule is that outboard of the fuel rod holes the temperature distribution in the graphite is one of concentric isotherms (refer again to Fig. 3). This being the case, the temperature measured at point B in the graphite is nearly identical to the temperature

Fig. 3. Radial 60° section of symmetry of P13T capsule

Fig. 4. P13T radial temperature profile

at the edge of the fuel rod hole and the two can be interchanged in Eq. 1 to give

$$T_{PEAK} = T_B + \Delta T_{GAP} + \Delta T_{FUEL} \quad . \quad (2)$$

Similarly, the fuel rod surface temperature will be

$$T_{SURFACE} = T_B + \Delta T_{GAP} \quad . \quad (3)$$

Referring again to Fig. 3, consider the temperature drop between points A and B, ΔT_{AB} . Since there are no gas gaps between these two points, over short periods of time ΔT_{AB} will change only as the local reactor power changes (rod bank movement). Thus, a "power factor" (PF) can be defined as follows:

$$PF = \Delta T_{AB} / \Delta T_{AB \text{ REF.}} \quad , \quad (4)$$

where $\Delta T_{AB \text{ REF.}}$ = reference value,

ΔT_{AB} = measurement made at any other time (within a relatively short period).

Computer models of a 60° sector of each of the four graphite crucibles were constructed as detailed in Section 5.3. Temperature matching runs were then made for several irradiation time points for each of the crucibles. From these "reference" TAC runs, the reference ΔT_{AB} , ΔT_{GAP} , and ΔT_{FUEL} values were obtained. In order to use this scheme to obtain fuel temperatures for each day of the irradiation, these reference values were then curve fitted and expressed as functions of megawatt days. Since the ΔT across the fuel is a function of reactor power only and the ΔT across the gap is a function of both reactor power and gas conductivity, the calculation for peak fuel rod temperature becomes:

$$T_{\text{FUEL PEAK}} = T_B + \left(\frac{\Delta T_{\text{FUEL}}}{\Delta T_{\text{FUEL REF.}}} \right) (PF) + \left(\frac{\Delta T_{\text{GAP}}}{\Delta T_{\text{GAP REF.}}} \right) (PF) \left(\frac{K_{\text{GAS REF.}}}{K_{\text{GAS MEAS.}}} \right) , \quad (5)$$

Power factor (PF)
which corrects for
local power varia-
tions, i.e., rod
bank movement
Corrects for sweep
gas mixture changes

where T_B = daily measured temperature at point B,
 $\Delta T_{\text{FUEL REF.}}$ = temperature drop across fuel rod from reference curve fit,
 $\Delta T_{\text{GAP REF.}}$ = temperature drop across fuel-crucible gap from reference curve fit,
 PF = power factor as detailed in Eq. 4,
 $K_{\text{GAS REF.}}$ = gas mix conductivity from reference runs,
 $K_{\text{GAS MEAS.}}$ = daily measured gas mix conductivity,

and the rod surface temperature is

$$T_{\text{SURFACE}} = T_B + \left(\frac{\Delta T_{\text{GAP}}}{\Delta T_{\text{GAP REF.}}} \right) (PF) \left(\frac{K_{\text{GAS REF.}}}{K_{\text{GAS MEAS.}}} \right) . \quad (6)$$

3.2. METHOD JUSTIFICATION

While this method is admittedly not as detailed or exhaustive as some, it filled the need for a quick and accurate technique for determining capsule operating temperatures on a daily basis. Given the uncertainties associated with previous thermal analysis results (Ref. 5), it was felt that the reduction in complexity and time spent more than justified any slight losses in accuracy. Normally the temperature matching phase is followed by a complex SHAPE and CAPTEM (Refs. 6, 7) analysis, which this

method replaces. Overall computer usage is therefore greatly reduced. This method was employed in the analysis of capsule P13Q (Ref. 8) with satisfactory results.

4. MEASURED DATA

The experiment was closely monitored during operation; thermocouple readings and gas flow data were recorded four to five times each day that the reactor was operating. These data were then sent via magnetic tape to GA, where they were recorded and punched on computer cards. Since, for thermal analysis purposes, the four or five daily readings resulted in an unnecessarily large amount of data, a program was written to average the values into one data set for each day of operation. Previous to this, however, the data cards were inspected for erroneous values, which were either eliminated or corrected. The 100% helium data were not included in these averaged values since the capsule was only operated in this mode long enough for normalization of temperatures and for the data to be recorded. Table 1 shows the complete data set for cell 1 for the second reactor cycle of the test and Table 2 contains the corresponding averaged values for that cycle along with the values for the first cycle that were used for the thermal analysis. The averaged values for both cells 1 and 2 for all reactor cycles have been filed.

Dosimetry wires included in the experiment were recovered during the PIE. The information obtained from these wires was used in the determination of the flux and fluence levels at the reactor location occupied by the capsule during the test (Ref. 9). The fluxes and fluences were then used to determine heating rates and fluence-dependent property changes.

Measurements made on the capsule components during the PIE gave an indication of the extent of the dimensional changes of graphite and fuel rods. These measurements were especially important in the case of fuel rods since the early Design Data Manual (Ref. 10) values did not agree with the observed values (see Table 9, Section 7). The measured dimensional change rates were used to calculate gap widths for use in the TAC thermal models.

TABLE 1
COMPLETE DATA SET FOR CELL 1, SECOND REACTOR CYCLE OF THE IRRADIATION

ROW	DATE	TIME	THERMOCOUPLE NUMBER (K = CHROMEL/ALUMEL, W = TUNGSTEN/RHENIUM)												GAS FLOWS	
			W1	W2	W3	K4	W5	W10	K6	W7	W11	K8	W9	W12	HELIUM	NEON
33	5/29/75	16 0	1270	1329	1271	945	978	1167	1002	1039	1176	1019	990	1172	9.62	13.45
34	5/29/75	2150	1263	1322	1263	941	974	1163	1001	1037	1176	1019	991	1173	9.65	13.83
35	5/30/75	340	1262	1320	1262	940	973	1162	1001	1036	1174	1021	993	1175	8.97	13.39
36	5/30/75	810	1260	1318	1260	939	971	1160	999	1037	1174	1021	993	1175	9.93	14.33
37	5/30/75	14 2	1253	1311	1253	934	968	1155	996	1033	1168	1017	990	1170	10.04	14.06
38	5/30/75	2151	1271	1328	1270	949	983	1172	1012	1051	1188	1034	1006	1187	8.91	15.22
39	5/31/75	341	1270	1328	1270	949	982	1172	1013	1051	1185	1034	1006	1187	9.13	15.66
40	5/31/75	933	1269	1327	1268	947	981	1171	1012	1051	1184	1034	1006	1188	9.11	15.83
41	5/31/75	1523	1268	1323	1265	946	979	1168	1010	1049	1180	1032	1005	1185	8.94	15.72
42	5/31/75	2114	1262	1319	1260	943	976	1163	1008	1046	1178	1029	1002	1181	9.02	15.83
43	6/ 1/75	3 6	1267	1323	1264	945	979	1168	1011	1052	1180	1033	1006	1186	9.05	15.97
44	6/ 1/75	857	1264	1320	1262	943	977	1166	1009	1048	1179	1032	1005	1185	9.08	16.14
45	6/ 1/75	1448	1263	1317	1259	941	975	1162	1007	1046	1176	1029	1003	1182	9.00	16.00
46	6/ 1/75	2039	1257	1313	1255	938	972	1159	1004	1044	1173	1027	1001	1179	9.08	16.00
47	6/ 2/75	230	1254	1309	1250	936	969	1148	1001	1041	1169	1026	1000	1176	9.08	16.30
48	6/ 2/75	820	1252	1306	1248	934	968	1155	1000	1040	1168	1025	997	1175	8.91	16.36
49	6/ 2/75	1412	1250	1291	1246	932	966	1150	997	1037	1164	1023	995	1172	9.16	15.94
50	6/ 2/75	22 9	1247	1301	1243	931	964	1150	997	1037	1165	1024	995	1174	8.94	16.27
51	6/ 3/75	4 0	1244	1298	1240	928	963	1147	996	1036	1160	1022	994	1169	9.10	16.77
52	6/ 3/75	9 6	1259	1313	1255	941	975	1160	1009	1050	1175	1035	1009	1183	7.63	17.16
53	6/ 3/75	16 0	1260	1314	1256	942	976	1163	1010	1052	1174	1036	1013	1187	6.79	15.61
54	6/ 3/75	2151	1257	1311	1257	940	973	1159	1009	1049	1175	1034	1007	1187	7.52	16.27
55	6/ 4/75	343	1254	1308	1250	938	971	1156	1007	1047	1172	1033	1006	1181	7.77	16.80
56	6/ 4/75	818	1252	1305	1249	935	969	1153	1005	1045	1169	1031	1003	1179	7.85	17.02
57	6/ 4/75	1413	1244	1298	1240	931	964	1149	999	1040	1163	1028	999	1174	7.47	15.83
58	6/ 4/75	20 3	1240	1292	1236	928	961	1144	996	1037	1158	1025	996	1169	7.69	15.72
59	6/ 5/75	154	1242	1295	1238	929	963	1146	998	1039	1161	1027	999	1173	7.85	16.25
60	6/ 5/75	745	1249	1292	1235	927	960	1147	996	1037	1159	1025	996	1170	7.99	16.72
61	6/ 5/75	1422	1244	1295	1237	931	965	1146	1001	1043	1162	1023	1003	1174	6.60	16.05
62	6/ 5/75	21 3	1256	1306	1250	939	975	1152	1011	1056	1173	1037	1011	1181	5.84	16.33
63	6/ 6/75	258	1228	1303	1245	936	971	1144	1008	1051	1169	1034	1004	1178	6.06	16.83
64	6/ 6/75	1053	1265	1297	1239	931	966	1144	1004	1046	1161	1031	1004	1172	5.73	16.56
65	6/ 6/75	1820	1251	1301	1244	936	972	1146	1009	1054	1167	1035	1007	1177	5.65	17.27
66	6/ 6/75	22 8	1252	1302	1244	936	971	1146	1009	1054	1165	1035	1007	1178	5.54	17.49
67	6/ 7/75	358	1253	1302	1245	936	971	1148	1009	1054	1167	1037	1007	1177	5.63	17.72
68	6/ 7/75	950	1247	1297	1240	932	968	1145	1007	1050	1164	1035	1004	1175	4.79	16.94
69	6/ 7/75	1541	1247	1297	1240	933	968	1145	1006	1051	1163	1035	1004	1175	5.25	16.99
70	6/ 7/75	2132	1243	1292	1234	929	965	1140	1004	1047	1158	1032	1003	1173	5.71	17.49
71	6/ 8/75	322	1243	1293	1235	929	966	1140	1004	1048	1161	1033	1006	1172	5.65	17.83
72	6/ 8/75	914	1238	1286	1229	925	960	1133	994	1043	1157	1028	1002	1166	5.68	17.99
73	6/ 8/75	15 5	1241	1292	1233	928	963	1139	1002	1047	1157	1031	1003	1171	5.68	17.74
74	6/ 8/75	2056	1238	1289	1230	925	961	1135	1000	1044	1155	1031	1003	1168	5.73	18.10
75	6/ 9/75	247	1235	1285	1228	924	959	1135	999	1043	1154	1024	1003	1168	5.79	18.49
76	6/ 9/75	828	1232	1283	1225	922	958	1131	997	1042	1152	1024	1001	1165	5.73	18.49
77	6/ 9/75	1416	1237	1286	1228	926	961	1137	1001	1047	1155	1026	1006	1170	5.06	18.10
78	6/ 9/75	2011	1235	1285	1227	924	960	1135	999	1045	1152	1026	1006	1167	4.52	17.30
79	6/10/75	2 2	1233	1283	1225	923	958	1133	997	1042	1149	1029	1002	1164	4.92	17.84
80	6/10/75	753	1230	1279	1222	921	957	1130	997	1042	1148	1028	1001	1162	4.68	17.77
81	6/10/75	1411	1227	1295	1238	935	971	1148	1014	1058	1165	1043	1017	1178	3.36	18.94
82	6/10/75	2057	1243	1291	1236	932	968	1142	1010	1055	117	1043	1014	1175	3.36	18.94
83	6/11/75	247	1240	1288	1231	931	966	1142	1009	1053	1159	1034	1014	1174	3.36	18.88
84	6/11/75	854	1241	1289	1231	930	967	1140	1009	1053	1158	1034	1014	1173	3.36	18.88
85	6/11/75	1447	1236	1284	1226	927	962	1134	1005	1051	1155	1033	1013	1172	2.82	17.66
86	6/11/75	2244	1231	1278	1221	923	959	1133	1002	1047	1154	1034	1007	1166	3.49	18.63
87	6/12/75	435	1176	1275	1219	922	957	1125	999	1045	1147	1033	1005	1163	3.09	18.21
88	6/12/75	814	1227	1274	1217	920	956	1126	998	1045	1145	1032	1004	1161	3.20	18.05
89	6/12/75	1411	1233	1280	1223	927	962	1134	1005	1052	1153	1038	1013	1169	3.20	21.21
90	6/12/75	2115	1232	1279	1223	925	961	1132	1005	1051	1152	1037	1012	1167	3.25	21.51
91	6/13/75	3 5	1234	1281	1224	926	962	1134	1006	1053	1154	1039	1013	117	2.63	21.60
92	6/13/75	835	1231	1277	1221	923	971	1129	1004	1050	115	1036	1011	1166	3.47	22.60
93	6/13/75	1429	1226	1272	1216	920	956	1126	999	1046	1145	1034	1007	1162	3.47	23.70
94	6/13/75	2218	1241	1279	1221	925	960	1131	1006	1053	1152	1034	1013	1169	3.47	24.79
95	6/14/75	4 9	1228	1274	1218	923	958	1129	1004	1051	1151	1036	1012	1164	2.42	24.04
96	6/14/75	10 0	1228	1273	1218	922	958	1127	1003	1051	1148	1037	1013	1167	2.87	24.65
97	6/14/75	1550	1221	1267	1212	918	953	1120	998	1045	1142	1034	1007	1160	3.17	24.15
98	6/14/75	2142	1218	1263	1208	916	951	1119	996	1044	1141	1033	1007	1160	3.33	24.15
99	6/15/75	333	1220	1265	1209	917	951	1119	994	1046	1142	1034	1008	1162	3.49	24.70
100	6/15/75	924	1215	1261	1205	913	944	1085	943	1043	1137	1032	1005	1158	3.38	24.70

TABLE 2
AVERAGED GAS FLOWS AND THERMOCOUPLE READINGS FOR CELL 1 DURING THE FIRST TWO REACTOR CYCLES

DATE	MEGA-WATT DAYS	GAS FLOWS		THERMOCOUPLE NUMBER											
		HELIUM	NE-1	W1	W2	W3	K4	W5	K6	W7	K8	W9	W10	W11	W12

CYCLE 1

750513	92	13.25	13.83	1249	1304	1257	951	976	998	1018	1006	981	1159	1171	1154
750514	122	12.98	14.85	1248	1302	1254	952	977	999	1022	1008	984	1159	1172	1156
750515	152	12.63	15.64	1243	1297	1248	950	976	999	1024	1010	986	1156	1170	1131
750516	182	12.09	16.31	1241	1294	1245	949	976	999	1026	1011	990	1154	1169	1158
750517	212	10.87	16.30	1241	1293	1244	949	977	1001	1030	1015	994	1154	1171	1160
750518	242	10.88	16.25	1231	1281	1233	940	969	993	1021	1009	987	1144	1160	1151
750519	272	10.05	16.11	1233	1283	1234	941	971	996	1025	1015	992	1146	1164	1156
750520	302	9.38	16.18	1241	1289	1240	947	976	1003	1033	1024	1001	1152	1170	1165
750522	362	8.24	16.70	1233	1280	1232	940	973	1000	1032	1023	1002	1175	1164	1161
750523	392	7.60	18.52	1234	1279	1231	942	974	1002	1036	1027	1005	1144	1165	1164
750524	422	6.95	20.23	1236	1280	1228	944	986	1006	1040	1031	1010	1146	1168	1168
750525	452	7.05	19.77	1228	1270	1223	937	971	1000	1033	1026	1004	1136	1158	1160
750526	482	6.86	19.89	1224	1265	1218	934	967	996	1030	1024	990	1131	1154	1156
750527	512	6.94	20.90	1220	1261	1213	930	964	994	1028	1022	999	1122	1151	1155
750528	520	6.90	21.99	1224	1265	1222	932	967	998	1033	1026	1004	907	1155	1160

CYCLE 2

750529	537	13.67	9.09	1178	1235	1181	871	898	920	952	938	931	1069	981	1083
750530	567	9.46	14.25	1261	1319	1261	940	973	1002	1039	1023	995	1162	1175	1176
750531	597	9.05	15.76	1267	1324	1265	946	979	1010	1049	1032	1005	1168	786	1165
750601	627	9.05	16.03	1262	1318	1260	941	975	1007	1047	1030	1003	1171	1177	1183
750602	657	9.02	16.22	1250	1301	1246	933	966	998	1038	1024	996	1150	1166	1174
750603	687	7.77	16.45	1255	1309	1252	937	971	1006	1046	1031	1018	1157	1172	1111
750604	717	7.69	16.34	1247	1300	1243	933	966	1001	1042	1029	1001	1150	1165	1175
750605	746	7.07	16.34	1237	1297	1240	931	965	1001	1043	1029	1002	1130	1163	1174
750606	776	5.74	17.04	1243	1300	1243	934	970	1007	1051	1034	1008	1147	1166	1176
750607	806	5.34	17.28	1247	1297	1239	932	968	1006	1050	1034	1007	1144	1162	1175
750608	836	5.68	17.91	1240	1290	1231	926	962	1001	1045	1030	1004	1136	1145	1169
750609	866	5.27	18.19	1234	1284	1227	924	959	999	1044	1029	1004	1134	1153	1167
750610	896	4.08	18.38	1238	1287	1230	927	963	1004	1049	1035	1008	1133	1142	1169
750611	926	3.26	18.51	1237	1284	1227	927	963	1006	1051	1037	1011	1137	1155	1171
750612	956	3.18	19.74	1217	1277	1220	923	959	1001	1048	1035	1008	1130	1149	1165
750613	986	3.26	23.05	1230	1277	1220	923	962	1003	1050	1037	1011	1130	1150	1166
750614	1016	2.93	24.25	1223	1269	1214	919	955	1000	1047	1035	1009	1123	1145	1164
750615	1036	3.38	24.54	1215	1260	1205	913	948	995	1043	1032	1005	1105	1137	1158

5. TAC-2D COMPUTER MODELS

5.1. ASSUMPTIONS EMPLOYED

Simplifying assumptions are a necessary part of any thermal analysis in order that the complexity of the problem be kept within practical limits. Several assumptions were made in the construction and use of the TAC thermal models used in this analysis.

The first problem encountered in modeling a capsule is that it is a three-dimensional object and a rigorous analysis requires a three-dimensional mathematical model. Such models tend to be very cumbersome and time consuming, especially when many computer runs are required. For this reason an approximation is needed that will reduce the problem to two dimensions. In capsules such as P13R and P13S (Ref. 11), the azimuthal symmetry allows the assumption that heat will only flow in the axial and radial directions and that different axial slices of the capsule will all exhibit the same temperature distribution (Fig. 5). Thus, an r,z two-dimensional model was used to simulate these capsules. However, the P13T capsule did not have this type of symmetry, and it was necessary to account for azimuthal heat flow. A recent study had shown that at certain locations within test capsules the axial flow of heat could be ignored without introducing significant error (see Appendix A). In particular, the midplane of uniformly loaded fuel rods and the middle area of fuel rod stacks are such locations. Therefore, by appropriate choice of model location, as detailed in Section 5.2, the assumption of zero axial heat flow was made, and four r,θ TAC-2D computer models were constructed, one for each of the four crucibles in P13T.

The second assumption employed was that the corresponding temperatures on opposite sides of the capsule were the same. Estimates of typical cross-capsule ΔT s vary from 10° to 40°C , which are small compared to the total radial ΔT of $\sim 900^\circ\text{C}$. Also, radial flux profiles for the test reactors

Fig. 5. An r, z two-dimensional model (top) as used in P13R and P13S as compared with an r, θ model similar to that used to model P13T

are seldom available, so that an accurate determination of this effect would not be easy. This assumption allows the use of 60° sectors for the computer models since the same pattern is repeated six times around the axis of the capsule.

The assumption of concentric isotherms outboard of the fuel rod holes was discussed in Section 3.1.

5.2. THERMAL MODEL LOCATIONS

A schematic diagram of the capsule with thermocouple positions and fuel rod placements is shown in Fig. 6. The portions of each of the four crucibles represented by the four TAC models are identified in the figure. The models were located at the midplane of the fuel stacks in all except crucible 4. In all the crucibles except crucible 3 there were also inner and outer graphite thermocouples at these locations. In crucible 3 the readings of TC28 and TC29 were averaged for the inner graphite temperature in model 3.

5.3. DETAILED DESCRIPTION OF MODELS

The TAC-2D code allows the user to choose one of three coordinate systems, as shown in Fig. 7. Because it was decided to model 60° sectors of the capsule, the circular geometry was the obvious choice. In this system radial grid lines are specified in inches and theta grid lines in degrees. The circular thermocouples and fuel rod and piggyback samples could not be modeled exactly with this coordinate system; their shapes had to be approximated with angled blocks. The only problem in doing this is that the volumes are not always correct and, in the case of the fuel rod, this is an important consideration. Care was taken, therefore, in modeling the fuel rod so that the sum of the volumes of the blocks comprising the fuel rod very nearly equaled the actual rod volume. Figure 8 shows a preliminary block by block layout of the computer model used to specify grid lines and dimensions. Each component was assigned a number for the purpose of specifying material properties. The models were constructed to scale

Fig. 6. Axial position of thermocouples and thermal models in P13T

Fig. 7. Choice of coordinate systems with TAC-2D code

Fig. 8. Block by block layout of the TAC-2D thermal analysis computer model

using as-built capsule dimensions from the P13T Irradiation Test Design Data Manual (Ref. 1).

The specification of gaps between material blocks is a useful feature of the TAC codes. Gaps existed between the primary and secondary containments, between the crucibles and primary cans, and between the fuel rods and the crucible holes in which they were inserted. The gap between the fuel rod and crucible presented some problems. Since the fuel rod had to be modeled with stepped blocks, the gap had to be modeled in the same manner. This meant that in the model the surface area exchanging heat by radiation was much greater than in the actual capsule. To account for this the emissivity of the fuel rod was lowered. Since it was calculated that there was 1.3 times more surface area with the stepped gap arrangement, the emissivity was decreased by one-third.

The thermal resistance of the gaps was varied by specifying the conductivity of the gas mixture present in the gap. The gap between the primary and secondary containments was swept with 100% He and the interior of each cell was swept with a He-Ne mixture.

Adiabatic boundaries could be specified on two sides of the model because of the capsule symmetry mentioned earlier. The third boundary modeled the reactor pool to which all the heat generated within the capsule was eventually transferred.

The primary output of the TAC code is a temperature map showing the temperature distribution across the modeled section. Usually the map is the same shape as the model and a transparent overlay is used to show material boundaries, gaps, etc. The maps printed with the circular geometry, however, are rectangular rather than pie-shaped like the model. The reason for the rectangular layout is that there are just as many temperature nodes at the narrow end of the wedge as there are at the wide end and provision has to be made to print all of the temperatures.

5.4. MATERIAL PROPERTIES AND INPUT DATA

All material properties used in the TAC computer models are given in Appendix B. For those properties that are a function of temperature, T is in degrees Rankine and $T_{REF.}$ is 70°F or 530°R.

Postirradiation measurements of the P13T fuel rods revealed that the amount of irradiation-induced dimensional change differed considerably from that predicted by the thermal design. Normally the beginning-of-life fuel gap is specified as input into the models and the gap-expansion option of the TAC code automatically adjusts the size of the gap according to the dimensional change equation that is also input. For this analysis, however, a "best guess" curve fit was drawn through the PIE data and the curve was used to obtain the dimensional change values for the fuel rods. These values were then input directly into the models each time a computer run was made so that the fuel-crucible gap was correct. The gap-expansion feature was thus bypassed for this analysis.

The gamma heat, flux, and fluence curves are included in Appendix B (Figs. B-4 through B-6). The flux and fluence values are also given in Table B-2. These values were obtained using the dosimetry included in the capsule. Values of thermal flux originally reported were later corrected giving slightly higher values (this is discussed in greater detail in Section 7).

5.5. TEMPERATURE-MATCHING RUNS

A temperature-matching run is a set of calculations done on the computer using a mathematical model that simulates a definite set of conditions that existed at some point in time during the irradiation of the capsule. The TAC-2D models employ an iterative calculational technique that converges to a steady-state solution.

The sequence in making a run is as follows. First, a time point is chosen. In this analysis five time points [beginning of life (BOL),

1/4 life, mid-life (MOL), 3/4 life, and end of life (EOL)] were run for each of the four graphite crucibles. Figure 9 shows the measured crucible ΔT history for crucible 3 of cell 2. The ΔT s for the other crucibles would exhibit similar behavior. As discussed in Section 3.1, the change in this ΔT reflects changes in local power as the control rods move during reactor cycles. Each of the five time points was chosen at the approximate midpoint of a subcycle. (Each reactor cycle contains several subcycles as a result of the frequent refueling of the ORR.) It was reasoned that choosing temperature match points in this way would facilitate the computer runs since roughly the same power level would exist at those times. At the selected time point, the fluence levels, fission heat values, control gas mixture, and other pertinent data are identified so that they can be input into the model. (These can also be calculated within the code if the user wishes to program functions identifying their behavior throughout the irradiation period.) A list of the input parameters used in the P13T models is given in Table 3. In addition to these, the gap between the fuel rod and crucible was specified, as mentioned in Section 5.4. The computations were then performed until all temperatures had stabilized and a steady-state thermal condition was achieved. (This analysis was not concerned with transient periods of the irradiation; these occupied only a small portion of the total exposure time.) The steady-state condition is checked with an energy balance that is printed with each run. The heat generated in the section of capsule modeled is compared to the heat gained by the coolants in that vicinity; it is sufficient if the two agree within 1% of each other. If they do not, the last temperature distribution calculated is punched on cards and these temperatures are used as input in another run that is continued from that point until the steady state is reached.

In evaluating a run the temperature distribution is compared to measured temperatures for the corresponding day of operation. It is futile, given the uncertainties involved, to expect all temperatures to match exactly. Usually agreement within 2% to 3% is satisfactory. Thus in cell 1, fuel rod temperatures within 40°C of those measured and graphite temperatures within 30°C constituted a good match. When temperatures do not agree, there are two variables that can be adjusted to obtain better results.

Fig. 9. Measured crucible ΔT_{AB} history for crucible 3 of cell 2

TABLE 3
P13T TAC MODEL INPUT PARAMETERS

A1 is for graphite dimensional change; if $A1 = 1$ the dimensions are calculated automatically within the code and if $A1 = 0$ they are not calculated. This is a useful option when checking gap size changes.

A2 + A3 were used to specify the type of crucible graphite for each model: $A2 = 0$ for TS-1240 and 1 for H-451; $A3 = 1$ for TS-1240 and 0 for H-451.

A4 is a multiplier affixed to the gamma heat function. It provides a way of varying the gamma heating which is not always known precisely.

A5 accounts for fuel burnup. The BOL fission heat value is used in the fission heat equation and this factor modifies it to account for the reduction in fission power as the irradiation progresses.

A6 is fast fluence $\times 10^{-25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$)_{HTGR}. This is used in all materials that undergo irradiation-induced dimensional changes.

A7 is a fraction which gives the conductivity of the sweep gas mixture in relation to the conductivity of pure helium.

A8 is the average graphite crucible temperature ($^{\circ}\text{C}$).

A9 is the axial location of the model within the core of the reactor. This is used in "lookup" routines to determine flux and gamma heat levels at that location.

A10 + A11 are not used.

A12 enables one to vary the power in the model to account for the variation in power at each position in time. The local power will vary because of the way the reactor is loaded and subsequent rod bank movement.

These are the gamma heating and fission power which change with rod bank movement, as mentioned earlier. Since rod bank positions were not reported in the P13T experiment, the input parameter A12 was used to account for power variations. If a good temperature match cannot be obtained after reasonable "tweaking" of the model in this manner, the underlying assumptions, modeling techniques, and input data should be examined for errors or discrepancies.

6. THERMOCOUPLE DECALIBRATION

6.1. GENERAL

It is a well established fact that the W3%Re/W25%Re thermocouples used in capsule experiments decalibrate or progressively indicate lower than actual temperatures as the irradiation proceeds (Ref. 12). Although not completely understood, it is known that the alloys of which the thermocouple wires are constructed transmute to different forms as a result of neutron capture. Also, in almost every instance, the W/Re thermocouple reads slightly higher initially than the true temperature. This is due to gamma heating, the thermocouple being constructed of fairly dense materials. A typical emf response curve of a W/Re thermocouple exposed to a neutron flux and held at a constant temperature is shown in Fig. 10.

In earlier capsule analysis work, it was desired to find a decalibration relationship which could be used for any experiment to predict the amount of irradiation-induced emf loss of the W/Re thermocouples. As data accumulated, however, it became apparent that factors other than just thermal fluence had an effect on decalibration. The routing of the thermocouple within the capsule, the length of lead wire used, and the thermal and flux gradients seen by the thermoelements all affect the emf response of the thermocouple. This explains why decalibration factors from different irradiation tests seldom correlate with each other; subtle differences in geometry and exposure will affect thermocouple behavior and, thus, decalibration rates. Due to the complexity of this phenomenon, it is doubtful that a generalized decalibration equation will ever exist. This being the case, decalibration factors need to be determined for each test, as was done with the P13T capsule.

Fig. 10. Thermocouple calibration cell contained in irradiation capsule P13M (GA19-2) measured the effect of neutron bombardment on emf output of W3%Re/W25%Re thermocouples by measuring melting point of copper

6.2. CONTROL WITH THERMOCOUPLES

It was determined in the preirradiation thermal analysis that certain locations in the graphite crucibles of each cell would need to be at specific temperature levels for the fuel to operate at the design temperatures. Control was then achieved by placing C/A thermocouples in these graphite locations and adjusting the sweep gas mixtures to always maintain the set point temperature. In P13T an alternate method of control was attempted in cell 2. Since crucible 2 of that cell contained W/Re thermocouples in the fuel rods, control was initially placed with a fuel thermocouple so that fuel temperatures could be controlled with less uncertainty. As for decalibration of this thermocouple, it was planned that the relationship between it and the nearest C/A thermocouple would be identified and corrections made as needed. This method of control was not successful, however, as discussed in Section 7.2, and control was eventually shifted to graphite thermocouple K19, also in crucible 2.

6.3. P13T DECALIBRATION METHOD

Determining decalibration factors with a thermocouple pair can be done in two ways; the temperature readings of the C/A thermocouple (T_K) and the W/Re thermocouple (T_W) can be ratioed or the differences can be determined. In this analysis, differences were used. In either case the temperatures are always normalized so that the BOL ΔT is zero. This step negates the gamma heating effect in the W/Re thermocouple mentioned in Section 6.1 and any geometry effects that exist.

A plot of the ΔT s for each thermocouple pair in P13T for the entire irradiation is shown in Fig. 11. The best fit linear relationship was applied to each curve. Then the total ΔT ($T_W - T_K$) at EOL was divided by the thermal fluence seen at the location of each pair to obtain the decalibration factor. Table 4 shows decalibration rates calculated for the six thermocouple pairs in P13T. The corrected readings for any W/Re thermocouple in the capsule are determined by applying the decalibration factor of the nearest thermocouple pair.

Fig. 11. Decalibration in P13T (all ΔT s normalized to 0°C at BOL)

TABLE 4
W/Re THERMOCOUPLE DECALIBRATION RATES IN P13T

Thermocouple Pair	Cell Number	Distance from Bottom of Core [cm (in.)]	$\Delta T^{(a)}/\psi_{th}^{(b)} = \text{Decal. Factor } (^{\circ}\text{C/unit } \psi_{th})$
K4/W5	1	3.51 (1.38)	-112/3.80 = -29.5
K6/W7	1	9.65 (3.80)	-30.9 ^(c)
K8/W9	1	15.75 (6.20)	-181/5.60 = -32.3
K19/W20	2	27.89 (10.98)	-29.3 ^(d)
K21/W22	2	39.57 (15.58)	-162/4.80 = -33.8
K23/W24	2	55.40 (21.81)	-52/2.10 = -24.8

(a) ΔT is $(T_{W/Re} - T_K)$ after normalization at BOL.

(b) ψ_{th} is thermal fluence $\times 10^{-25} \text{ n/m}^2$.

(c) This pair failed early in life (W7 failed on July 17, 1975) so this decalibration factor is the average of K4/W5 and K8/W9 pairs.

(d) The calculated decalibration factor for this pair was $-8.2^{\circ}\text{C}/\psi_{th}$. This value does not correlate with the analytical results obtained for crucible 2 nor with any of the other thermocouple pairs. Therefore, the average of the other two pairs in crucible 2 was used for the K19/W20 pair.

7. PRESENTATION AND ANALYSIS OF RESULTS

7.1. RESULTS

The reference values obtained from the TAC models are given in Appendix C, Table C-1. As discussed in Section 5.5, five time points were run for each crucible. In curve-fitting these reference values, polynomials of third degree were used in all cases. The curve-fits are given in Table C-2.

With the reference curves and the daily data, Eq. 5 of Section 3.1 was then used to calculate the temperature histories. Figures 12 through 15 show the peak fuel, average fuel, and average graphite temperatures for each crucible. In each case, the following apply:

1. Peak fuel temperature is the highest temperature in a fuel rod; it is not usually the centerline rod temperature because of the asymmetric configuration of this capsule.
2. Average fuel temperature is half the sum of the peak fuel rod and rod surface temperatures. Volume-average rod temperatures are 10° to 20°C higher than these average values. This was determined using the CUSTOM subroutine of the TAC code, which allows the user to make extra calculations. The volumes of the temperature nodes were called out and used to "weight" the fuel rod node temperatures to obtain the volume average values (Ref. 13).
3. Average graphite temperature is half the sum of the inner and outer graphite crucible temperatures.

Because cell 2 contained three crucibles swept by the same gas mixture, it was impossible to control temperatures in each crucible. Since the control

*MEGAWATT DAYS = DAYS AT POWER X REACTOR POWER (30 MEGAWATTS)

Fig. 12. P13T temperature history for crucible 1

Fig. 13. P13T temperature history for crucible 2

Fig. 14. P13T temperature history for crucible 3

Fig. 15. P13T temperature history for crucible 4

thermocouples were located in crucible 2 of that cell, temperatures in crucibles 3 and 4 varied considerably during reactor cycles, thus the "see-saw" appearance of the temperature histories of these crucibles.

Figures 16 and 17 show only the peak fuel rod temperatures in crucibles 1 and 2. Rods within body 1 ran within $\pm 50^\circ\text{C}$ of the 1300°C design temperature during the first half of the irradiation and from 100° to 150°C below design during the remainder of the experiment. Cell 1 was plagued with thermocouple failures. All the fuel thermocouples had failed after 6500 MWD and by the end of the irradiation only thermocouples K6 and K8 were still operating. Fortunately, K6 was the control thermocouple for this cell, so temperature control was not sacrificed. The high failure rate of thermocouples in this cell was attributed to failure of the junctions where the thermocouple wires were joined to the compensated lead wires (Ref. 3).

In crucible 2 the fuel rod temperatures rose steadily from a BOL value of 950° to 1230°C until control was switched from fuel thermocouple W14 to graphite thermocouple K19. This is as expected since the set point for W14 remained at the 1100°C design temperature and, as this thermocouple decalibrated, the actual fuel temperature continued to rise. Although it was hoped that useful information about the decalibration rate could be obtained by this procedure, the unknowns in the decalibration phenomenon prevented an accurate determination of this effect (Ref. 14). Therefore, control was switched to thermocouple K19 on December 12, 1975 at the start of reactor cycle 129. Just prior to the change, K19 had been reading $\sim 775^\circ\text{C}$. The predetermined set point for K19 was 750°C and after the switch, K19 averaged 740°C . This 35°C drop in graphite temperature caused an even larger drop in fuel temperatures and thus the discontinuity in the crucible 2 fuel temperature history at ~ 5500 MWD (December 12, 1975). Of course, for reasons already discussed, this same abrupt drop in temperature was seen in crucibles 3 and 4 (refer to Figs. 14 and 15). This actually brought the fuel temperature in crucible 2 down to within 50°C of the design value, where it remained to the end of the irradiation.

Fig. 16. Crucible 1 peak fuel rod temperatures: rods 1-3A, 1-3B, and 1-3C

Fig. 17. Crucible 2 peak fuel rod temperatures: rods 2-1A, 2-1B, and 2-1C

Three of the crucibles contained W/Re thermocouples embedded in the fuel rods. A direct comparison between the temperatures measured and those calculated analytically is not meaningful because of the decalibration effect. However, the decalibrated or corrected temperature measurements can be compared to the calculated values; these are shown in Figs. 18, 19, and 20. Generally, it can be seen that the differences ranged between $\pm 100^{\circ}\text{C}$, averaging $\pm 50^{\circ}\text{C}$. Known errors and uncertainties in the calculational technique and decalibration estimates prevent good agreement.

The temperature distributions by percentages are presented in Tables 5 through 8. In each case, the values printed for one rod represent three rods. For example the peak temperatures given for rod 1-1 represent those for rods 1-1A, 1-1B, and 1-1C (refer to Fig. 2) since these were all at the same axial position within the capsule. The same applies for the fuel rod surface and volume-average temperatures.

Because the TAC-2D models represented only one axial slice of each crucible, the fuel temperatures calculated by the models were strictly correct only for the fuel rods at those locations. The variation of temperatures in the fuel rod stacks had to be determined if temperatures for all rods were to be reported. This was accomplished in the following manner. The total temperature difference in each rod stack reported in the preirradiation thermal analysis was obtained. This analysis used the TAC-3D code (Ref. 15) so axial effects were accounted for. Then the thermal flux, fuel loading, and crucible-to-can gap for each fuel rod location were lumped together to obtain a "weight" factor in order to determine the distribution of the variation within each stack. The calculated values are shown in Fig. 21, where the model locations are taken as the reference point. For instance, in body 2 the temperature at the midplane of rods 2-1A, 2-1B, and 2-1C would be expected to be 3°C higher than the corresponding temperature predicted by the crucible 2 TAC model. Similarly, temperatures in rods 2-2A, 2-2B, and 2-2C would be 3°C lower than the TAC-predicted values. Again, these are midplane temperatures. Actually, a continuous gradient will exist over the length of the fuel rod stacks.

Fig. 18. T (calculated) minus T (measured) for crucible 1 fuel thermocouple.
Note: All fuel thermocouples in this crucible had failed by ~6000 megawatt days.

Fig. 19. T (calculated) minus T (measured) for crucible 2 fuel thermocouple

Fig. 20. T (calculated) minus T (measured) for crucible 4 fuel thermocouple

TABLE 5
TEMPERATURE DISTRIBUTION BY PERCENTAGES, CRUCIBLE 1 OF CELL 1

	Peak Fuel Rod Temperature				Fuel Rod Surface Temperature				Volume Average Fuel Temperature			
	ROD 1-1	ROD 1-2	ROD 1-3	ROD 1-4	ROD 1-1	ROD 1-2	ROD 1-3	ROD 1-4	ROD 1-1	ROD 1-2	ROD 1-3	ROD 1-4
Minimum value	967	967	987	1005	970	970	990	1008	989	989	1009	1027
1% are less or equal	1105	1105	1125	1143	1003	1003	1023	1041	1074	1074	1094	1112
5% are less or equal	1128	1128	1148	1166	1034	1034	1054	1072	1102	1102	1122	1140
10% are less or equal	1144	1144	1164	1182	1046	1046	1066	1084	1115	1115	1135	1153
20% are less or equal	1153	1153	1173	1191	1058	1058	1078	1096	1126	1126	1146	1164
30% are less or equal	1164	1164	1184	1202	1067	1067	1087	1105	1135	1135	1155	1173
40% are less or equal	1182	1182	1202	1220	1076	1076	1096	1114	1150	1150	1170	1188
50% are less or equal	1213	1213	1233	1251	1097	1097	1117	1135	1174	1174	1194	1212
60% are less or equal	1245	1245	1265	1283	1119	1119	1139	1157	1205	1205	1225	1243
70% are less or equal	1264	1264	1284	1302	1137	1137	1157	1175	1218	1218	1238	1256
80% are less or equal	1277	1277	1297	1315	1146	1146	1166	1184	1232	1232	1252	1270
90% are less or equal	1290	1290	1310	1328	1157	1157	1177	1195	1241	1241	1261	1279
95% are less or equal	1297	1297	1317	1335	1166	1166	1186	1204	1248	1248	1268	1286
99% are less or equal	1332	1332	1352	1370	1193	1193	1213	1231	1280	1280	1300	1318
Maximum value	1409	1409	1429	1447	1216	1216	1236	1254	1332	1332	1352	1370
Average value	1215	1215	1235	1253	1100	1100	1120	1138	1177	1177	1197	1215

TABLE 6
TEMPERATURE DISTRIBUTION BY PERCENTAGES, CRUCIBLE 2 OF CELL 2

	Peak Fuel Rod Temperature		Fuel Rod Surface Temperature		Volume Average Fuel Temperature	
	ROD 2-1	ROD 2-2	ROD 2-1	ROD 2-2	ROD 2-1	ROD 2-2
Minimum value	881	875	731	725	826	820
1% are less or equal	949	943	793	787	891	885
5% are less or equal	978	972	823	817	920	914
10% are less or equal	997	991	840	834	938	932
20% are less or equal	1047	1041	893	887	989	983
30% are less or equal	1090	1084	939	933	1034	1028
40% are less or equal	1103	1097	949	943	1047	1041
50% are less or equal	1110	1104	961	955	1056	1050
60% are less or equal	1118	1112	971	965	1064	1058
70% are less or equal	1126	1120	976	970	1069	1063
80% are less or equal	1144	1138	991	985	1085	1079
90% are less or equal	1199	1193	1066	1060	1152	1146
95% are less or equal	1216	1210	1081	1075	1168	1162
99% are less or equal	1224	1218	1086	1080	1174	1168
Maximum value	1229	1223	1091	1085	1179	1173
Average value	1101	1095	952	946	1047	1041

TABLE 7
TEMPERATURE DISTRIBUTION BY PERCENTAGES, CRUCIBLE 3 OF CELL 2

	Peak Fuel Rod Temperature		Fuel Rod Surface Temperature		Volume Average Fuel Temperature	
	ROD 3-1	ROD 3-2	ROD 3-1	ROD 3-2	ROD 3-1	ROD 3-2
Minimum value	870	866	713	709	811	807
1% are less or equal	948	944	803	799	907	903
5% are less or equal	965	961	837	833	919	915
10% are less or equal	979	975	847	843	936	932
20% are less or equal	996	992	865	861	952	948
30% are less or equal	1013	1009	878	874	965	961
40% are less or equal	1030	1026	889	885	980	976
50% are less or equal	1051	1047	901	897	996	992
60% are less or equal	1069	1065	916	912	1014	1010
70% are less or equal	1090	1086	934	930	1030	1026
80% are less or equal	1110	1106	949	945	1051	1047
90% are less or equal	1141	1137	999	995	1088	1084
95% are less or equal	1163	1159	1027	1023	1113	1109
99% are less or equal	1186	1182	1044	1040	1135	1131
Maximum value	1195	1191	1054	1050	1143	1139
Average value	1054	1050	910	906	1002	998

TABLE 8
TEMPERATURE DISTRIBUTION BY PERCENTAGES, CRUCIBLE 4 OF CELL 2

	Peak Fuel Rod Temperature				Fuel Rod Surface Temperature				Volume Average Fuel Temperature			
	ROD 4-1	ROD 4-2	ROD 4-3	ROD 4-4	ROD 4-1	ROD 4-2	ROD 4-3	ROD 4-4	ROD 4-1	ROD 4-2	ROD 4-3	ROD 4-4
Minimum value	859	854	837	840	733	728	711	714	816	811	794	797
1% are less or equal	945	940	923	926	805	800	783	786	894	889	872	875
5% are less or equal	963	958	941	944	815	810	793	796	911	906	889	892
10% are less or equal	980	975	958	961	830	825	808	811	926	921	904	907
20% are less or equal	1000	995	978	981	848	843	826	829	945	940	923	926
30% are less or equal	1016	1011	994	997	862	857	840	843	959	954	937	940
40% are less or equal	1030	1025	1008	1011	875	870	853	856	970	965	948	951
50% are less or equal	1048	1043	1026	1029	888	883	866	869	988	983	966	969
60% are less or equal	1062	1057	1040	1043	903	898	881	884	1003	998	981	984
70% are less or equal	1081	1076	1059	1062	921	916	899	902	1019	1014	997	1000
80% are less or equal	1102	1097	1080	1083	941	936	919	922	1042	1037	1020	1023
90% are less or equal	1151	1146	1129	1132	974	969	952	955	1080	1075	1058	1061
95% are less or equal	1186	1181	1164	1167	1005	1000	983	986	1114	1109	1092	1095
99% are less or equal	1239	1234	1217	1220	1048	1043	1026	1029	1172	1167	1150	1153
Maximum value	1277	1272	1255	1258	1089	1084	1067	1070	1196	1191	1174	1177
Average value	1055	1050	1033	1036	896	891	874	877	995	990	973	976

BODY 4	4-4	-2°	← MODEL 4
	4-3	-5°	
	4-2	+12°	
	4-1	+17°	
BODY 3	3-2	-2°	← MODEL 3
	3-1	+2°	
BODY 2	2-2	-3°	← MODEL 2
	2-1	+3°	
BODY 1	1-4	+18°	← MODEL 1
	1-3	0°	
	1-2	-20°	
	1-1	-20°	

Fig. 21. Axial variation of fuel rod temperature relative to model reference temperatures based on TAC-3D results

7.2. DISCREPANCIES

In studying the temperature history of crucible 1, it is readily apparent that the design temperature was not met during the last half of the irradiation. This may at first seem strange since the control thermocouple K6 operated at its 1000°C set point during the entire experiment. The reason for the drop in temperature appears to be the fuel-crucible gap size. Table 9 shows the preirradiation thermal analysis gap sizes versus the actual values determined from the capsule PIE. While they agreed well at BOL, the EOL values differed considerably. The fuel rods did not shrink as much as expected and, as a result, the EOL gaps were small. Thus, in cell 1 the 1000°C graphite control temperature that would have meant design value fuel temperatures with the predicted gap size produced lower fuel temperatures with the 50% smaller gap.

TABLE 9
PREDICTED VERSUS ACTUAL FUEL ROD - CRUCIBLE GAP SIZES
(Gap size in inches)

Crucible No.	BOL		EOL		% Difference at EOL
	Predicted	Actual	Predicted	Actual	
1	0.0025	0.0023	0.009	0.0042	53
2	0.0025	0.0023	0.0065	0.0048	26
3	0.0025	0.0021	0.0088	0.0043	51
4	0.0025	0.0020	0.013	0.0079	40

If this was the case in crucible 1, then one might wonder how it was possible for crucible 2 fuel rods to operate at design temperature. Actually, however, the gap size difference for crucible 2 was only half that for crucible 1. More importantly, the control set point temperature in crucible 2 was adjusted twice during the latter part of the irradiation. Between December 12, 1974 when the control thermocouple switch was made and EOL, the set point of K19 was changed from 750° to 765° to 790°C to compen-

sate for the decreasing temperatures evident at that time. This allowed the fuel temperatures to stay within the design range despite the smaller fuel-crucible gaps.

Fuel temperatures for crucibles 3 and 4 were also below design (1100°C) since the gap size effect was quite large, 51% and 40% differences, respectively. Evidently, the change in control set point in cell 2 could not make up for the larger gap size differences in these two crucibles.

Another noteworthy occurrence is a large "depression" in the thermal flux and fluence curves. As shown in Appendix B, Figs. B-4 and B-5, there is a noticeable depression in the curves between crucibles 1 and 2. It was determined that the Inconel bulkhead separating the two cells acted as a neutron absorber. This did not seem to have any adverse effects on capsule performance, however. In fact, the heating rates of the fuel rods as calculated in the FISSIN code were a little higher than the design value of 200 W/cm. The values for rods 1-4 and 2-1, which would have been the most affected, were 205 and 202 W/cm, respectively.

There was also a discrepancy concerning the power factor used in the TAC models. This was input parameter A12 (see Table 3), which was used to account for local power variations due to rod bank movement. As mentioned in Section 5.5, the temperature match time points were chosen in such a way that approximately the same power level would apply at each of the five points. Only small variations, i.e., $\leq 10\%$, were expected during the temperature matching runs. Actually, however, this power fraction had to be varied as much as 25% to 30% in a few cases in order to obtain good temperature matches with the data. Reactor personnel confirmed that the analytical procedure mentioned above should have been accurate to within $\pm 10\%$. No explanation could be found to justify the variation other than inconsistencies in the models or a transient condition within the capsule causing considerable axial heat flow. The thermocouple data were examined and seemed consistent in each case preceding and following the match-point date.

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APPENDIX A VERIFICATION OF ASSUMPTION OF MINIMAL AXIAL HEAT FLOW

During thermal analysis work on capsule P13V, it was suspected that axial heat flow was minimal near the midplane of the cells within that capsule. To verify this, the output of a normal TAC-2D run modeling cell 5 was compared with (1) a TAC run with all axial conductivities set equal to zero and (2) a hand calculation assuming only radial heat flow. A comparison of the ΔT s calculated in each case across the different materials from the fuel rod to the reactor pool are shown in Table A-1. The following drawing shows the materials and gas gaps in the thin section of cell 5 considered in this study.

The agreement between the two TAC runs was within 3% and the hand calculations agreed very well with the computed values. It was necessary to use a trial and error technique when hand calculating the ΔT across the gaps since part of the heat flow across the gaps is by radiation, and thus agreement was not as close as for the ΔT across materials.

TABLE A-1
COMPARISON OF ΔT ($^{\circ}\text{C}$) VALUES

ΔT	Normal TAC-2D	Radial TAC	Hand Calculation
1	84	84	82
2	28	27	27
3	15	16	16
4	517	528	541
5	5	4	4
6	227	234	223
7	9	9	9
8	166	171	171
9	13	14	12

This study shows quite well that at certain locations within test capsules axial heat flow can be neglected without serious error. In particular, where axial flux gradients are minimal, fuel loadings are uniform, and near the center of fuel rods this will be the case.

APPENDIX B
MATERIAL PROPERTIES USED IN TAC COMPUTER MODELS

H-451 GRAPHITE

Thermal conductivity: see Fig. B-1
Density: 107 lb/ft^3
CTE: $2.5 \times 10^{-6} (T - T_{\text{REF}}) \text{ in./in.}$
Irradiation-induced dimensional change: see Fig. B-2
Emissivity: 0.84

TS-1240 GRAPHITE

All property values for TS-1240 except the irradiation-induced dimensional change were identical to the H-451 values. For that one exception, the TS-1240 value was 0.89 times that of H-451.

FUEL ROD

Thermal conductivity: see Table B-1 (Note: only rods of 15, 30, and 35 vol % shim content were irradiated in P13T)
Density: 106 lb/ft^3
CTE: $2.22 \times 10^{-6} (T - T_{\text{REF}}) - 0.000621 \text{ in./in.}$
Irradiation-induced dimensional change: see text, Section 5.4
Emissivity: 0.56

STAINLESS STEEL

Thermal conductivity: $6.73 + 3.74 \times 10^{-3} (T - T_{\text{REF}}) \text{ Btu/hr-ft-}^\circ\text{F}$
Density: 500 lb/ft^3
CTE: $[6.59 \times 10^{-6} + 1.2 \times 10^{-9} (T - 460)](T - T_{\text{REF}})$
Emissivity: 0.40

PIGGYBACK SAMPLES

Piggyback samples were modeled to have properties identical to H-451 graphite.

Fig. B-1. Thermal conductivity of irradiated graphite (Ref. B-1)

Fig. B-2. Irradiation strain vs. fast neutron fluence and irradiation temperature in near-isotropic graphite; radial orientation (Ref. B-1)

TABLE B-1
MEAN THERMAL CONDUCTIVITY OF LARGE HTGR FUEL RODS AT VARIOUS MEASUREMENT AND IRRADIATION TEMPERATURES FOR
FLUENCE OF 0 TO 8×10^{25} N/M² (E > 29 fJ)_{HTGR}

Shim Loading (Vol %)	Mean Thermal Conductivity ^(a) (Btu/ft-hr-°F)										
	800°F	1000°F	1200°F	1400°F	1600°F	1800°F	2000°F	2200°F	2400°F	2600°F	2800°F
0	2.756 (0.0114) ^(b)	2.998 (0.0121)	3.216 (0.0133)	3.433 (0.0142)	3.627 (0.0150)	3.869 (0.0160)	4.159 (0.0172)	4.473 (0.0185)	4.739 (0.0196)	5.029 (0.0208)	5.295 (0.0219)
5	2.756 (0.0114)	2.998 (0.0124)	3.216 (0.0133)	3.433 (0.0142)	3.627 (0.0150)	3.869 (0.0160)	4.159 (0.0172)	4.473 (0.0185)	4.788 (0.0198)	5.102 (0.0211)	5.416 (0.0224)
10	2.756 (0.0114)	2.998 (0.0124)	3.240 (0.0134)	3.482 (0.0144)	3.699 (0.0153)	3.917 (0.0162)	4.207 (0.0174)	4.546 (0.0188)	4.908 (0.0203)	5.295 (0.0219)	5.682 (0.0235)
15	2.756 (0.0114)	3.071 (0.0127)	3.361 (0.0139)	3.651 (0.0151)	3.893 (0.0161)	4.086 (0.0169)	4.352 (0.0180)	4.715 (0.0195)	5.126 (0.0212)	5.585 (0.0231)	6.045 (0.0250)
20	2.877 (0.0119)	3.240 (0.0134)	3.579 (0.0148)	3.917 (0.0162)	4.183 (0.0173)	4.376 (0.0181)	4.667 (0.0193)	5.005 (0.0207)	5.416 (0.0224)	5.948 (0.0246)	6.456 (0.0267)
25	3.095 (0.0128)	3.482 (0.0144)	3.893 (0.0161)	4.256 (0.0176)	4.522 (0.0187)	4.739 (0.0196)	5.005 (0.0207)	5.368 (0.0272)	5.827 (0.0241)	6.456 (0.0267)	7.061 (0.0298)
30	3.530 (0.0146)	3.917 (0.0162)	4.304 (0.0178)	4.667 (0.0193)	4.981 (0.0206)	5.223 (0.0216)	5.513 (0.0228)	5.900 (0.0244)	6.432 (0.0266)	7.133 (0.0295)	7.834 (0.0374)
35	4.038 (0.0167)	4.425 (0.0183)	4.812 (0.0199)	5.199 (0.0215)	5.585 (0.0231)	5.972 (0.0247)	6.287 (0.0260)	6.649 (0.0275)	7.230 (0.0299)	8.100 (0.0335)	8.995 (0.0372)

(a) Calculated values (Ref. B-1).

(b) Values in the parentheses are in units of cal/cm-sec-°C.

W-Re THERMOCOUPLE

Thermal conductivity: 1.61 Btu/hr-ft-°F

Density: 701 lb/ft³

CTE: 3.8×10^{-6} (T - T_{REF})

Emissivity: 0.19

CONTROL CASES

Helium conductivity: 1.29×10^{-3} (T - 674) Btu/hr-ft-°F

Neon conductivity: 3.91×10^{-4} (T - 674) BTU/hr-ft-°F

Mixture conductivity: see Fig. B-3

FLUX, FLUENCE, AND GAMMA HEAT DATA

See Figs. B-4 through B-6 and Table B-2.

REFERENCE

B-1. "Fuel Design Data Manual, Issue B," General Atomic unpublished data, December 1975.

Fig. B-3. Helium-neon mixture conductivity

Fig. B-4. Flux versus axial distance

Fig. B-5. Fluence versus axial distance

Fig. B-6. Gamma heat versus axial distance

TABLE B-2
FLUX AND FLUENCE VALUES

Fuel Rod Centerlines	Flux $\times 10^{-18}$ (n/m ² -s)		Fluence $\times 10^{-25}$ (n/m ²) (E > 29 fJ) _{HTGR}	
	Thermal	Fast (HTGR)	Thermal	Fast (HTGR)
1-1	1.16	1.10	3.64	3.45
1-2	1.24	1.54	3.89	4.84
1-3	1.48	2.04	4.65	6.41
1-4	1.78	2.44	5.59	7.66
2-1	1.90	2.57	5.97	8.07
2-2	1.93	2.44	6.06	7.66
3-1	1.69	2.14	5.31	6.72
3-2	1.32	1.85	4.14	5.81
4-1	0.94	1.50	2.95	4.71
4-2	0.78	1.32	2.45	4.14
4-3	0.685	1.14	2.15	3.58
4-4	0.669	0.99	2.10	3.11

APPENDIX C
 ΔT REFERENCE VALUES FROM TAC MODELS AND CURVE FITS
USED IN TEMPERATURE HISTORY CALCULATIONS

The reference ΔT values obtained from TAC runs are given in Table C-1.
The curve fits for the reference values are given in Table C-2.

TABLE C-1
REFERENCE ΔT VALUES OBTAINED FROM TAC RUNS

Crucible	Time Point	ΔT_{AB}	ΔT_{GAP}	ΔT_{FUEL}	Conductivity Fraction ^(a)
4 ^(b)	BOL	128	80	144	0.480
	1/4 L	144	114	178	0.595
	MOL	148	176	151	0.445
	3/4 L	153	190	160	0.635
	EOL	129	200	150	0.605
3 ^(b)	BOL	123	102	182	0.480
	1/4 L	151	182	174	0.595
	MOL	147	202	128	0.445
	3/4 L	159	133	134	0.635
	EOL	103	94	126	0.605
2 ^(b)	BOL	213	107	160	0.480
	1/4 L	227	220	160	0.595
	MOL	180	304	137	0.445
	3/4 L	167	202	153	0.635
	EOL	149	151	153	0.605
1	BOL	137	100	170	0.475
	1/4 L	165	168	158	0.550
	MOL	150	190	107	0.370
	3/4 L	150	142	101	0.390
	EOL	150	86	96	0.455

(a) Conductivity of gas mixture expressed as a fraction of helium conductivity.

(b) Crucibles 2, 3, and 4 had the same sweep gas.

TABLE C-2
CURVE FITS FOR REFERENCE VALUES GIVEN IN TABLE C-1

Conductivity

$$\text{Cell 1: } 4.7081\text{E-1}^{(a)} + 5.7296\text{E-5X}^{(b)} - 1.9461\text{E-8X}^2 + 1.3122\text{E-12X}^3$$

$$\text{Cell 2: } 4.9670\text{E-1} + 1.2658\text{E-5X} - 1.4031\text{E-9X}^2 + 1.2242\text{E-13X}^3$$

ΔT

$$\Delta T_{AB1} = 1.3319\text{E-2} + 1.8529\text{E-2X} - 3.7211\text{E-6X}^2 + 2.0053\text{E-10X}^3$$

$$\Delta T_{GAP1} = 8.4666\text{E-1} + 4.9627\text{E-2X} - 6.9449\text{E-6X}^2 + 2.1617\text{E-10X}^3$$

$$\Delta T_{FUEL1} = 1.7415\text{E-2} - 5.5347\text{E-3X} - 1.7502\text{E-6X}^2 + 1.4962\text{E-10X}^3$$

$$\Delta T_{AB2} = 2.1253\text{E-2} + 1.1325\text{E-2X} - 4.1154\text{E-6X}^2 + 2.3552\text{E-10X}^3$$

$$\Delta T_{GAP2} = 7.3377\text{E-1} + 9.5443\text{E-2X} - 1.3378\text{E-5X}^2 + 4.7610\text{E-10X}^3$$

$$\Delta T_{FUEL2} = 1.6338\text{E-2} - 4.5634\text{E-3X} + 1.8465\text{E-7X}^2 + 1.5448\text{E-11X}^3$$

$$\Delta T_{AB3} = 1.2375\text{E-2} + 5.1472\text{E-3X} + 1.1574\text{E-6X}^2 + 1.6823\text{E-10X}^3$$

$$\Delta T_{GAP3} = 8.0887\text{E-1} + 6.6978\text{E-2X} - 1.1148\text{E-5X}^2 + 4.6629\text{E-10X}^3$$

$$\Delta T_{FUEL3} = 1.8704\text{E-2} - 7.3724\text{E-3X} - 6.5528\text{E-7X}^2 + 7.7620\text{E-11X}^3$$

$$\Delta T_{AB4} = 1.2734\text{E-2} + 4.7170\text{E-3X} + 3.7552\text{E-7X}^2 - 7.4309\text{E-11X}^3$$

$$\Delta T_{GAP4} = 7.2441\text{E-1} + 1.7851\text{E-2X} + 4.8101\text{E-7X}^2 - 9.8144\text{E-11X}^3$$

$$\Delta T_{FUEL4} = 1.4169\text{E-2} + 1.8175\text{E-2X} - 3.6163\text{E-6X}^2 + 1.8786\text{E-10X}^3$$

(a) $\text{E-1} = 10^{-1}$, etc.

(b) X is megawatt days.