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Oak Ridge, TennesseeEXTERNAL DISTRIBUTION
AUTHORIZED**ORNL**
CENTRAL FILES NUMBER

60-3-1

DATE: March 21, 1960
SUBJECT: Numerical Three Dimensional Temperature
Analysis of the EGCR Fuel Rod
TO: Distribution
FROM: L. G. Epel

COPY NO. 34

Abstract

The temperature field in an outer rod of the EGCR fuel assembly is presented. The numerical analysis has taken account of the three dimensional spatial dependence of the thermal neutron flux and has considered the four regions involved, that is, fuel pellets, ceramic disc, steel end caps, and cladding. The convective heat transfer coefficient and fluid temperature were considered constant over the 2.185 in. of rod length studied.

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Introduction

The EGCR fuel assembly is composed of seven cylindrical rods, one at the center and six at the vertices of a regular hexagon. Each rod is made up of a number of cored UO_2 pellets stacked on top of one another inside a stainless steel cylinder. At each end of the stack an MgO disc is added, and then it is closed by means of a stainless steel cap which is welded to the cylindrical clad.

Aside from the gross neutron flux variation in the radial and axial directions in the reactor, there is a flux variation within each individual fuel rod due to heterogeneity of the rod, self shielding effects, and asymmetries in the rod cluster itself. Thus, in any rod there is a variation of heat generation rate with axial position, x , with radial location, r , and with angular displacement, θ . The spatial dependence of the generation rate, together with the heterogeneity of the system makes an analytic solution for the temperature field virtually impossible. Since the temperature gradients produced by the above effects near the end of the cylinder may lead to excessive thermal stresses (as well as a "hot spot" on the cladding), the temperature structure was obtained by numerical methods utilizing codes available for the IBM 704 digital computer.¹ The calculation was performed for an outer rod in the cluster which was at the maximum surface temperature location in the reactor.

Discussion

The fuel element was broken up into 763 separate volumes, each with its own effective conductances to its neighboring volumes and its own heat generation rate. The 763 nodal points were distributed as shown in Fig. 1 among 18 planes normal to the axis of the cylinder (or six planes through the axis).

¹T. B. Fowler and E. R. Volk, Generalized Heat Conduction Code for the IBM-704 Computer, ORNL-2734 (Oct. 16, 1959).

FIG. I NODAL POINT DESIGNATION

The convective heat transfer coefficient was taken as constant at 300 Btu/hr-ft²-°F and the thermal conductivities of the three materials were considered constant at the following values:

Stainless steel	10.00 Btu/hr-ft-°F
Uranium dioxide	1.00 Btu/hr-ft-°F
Magnesium dioxide	1.60 Btu/hr-ft-°F

The conductances (reciprocal of total resistance) between nodal points were calculated by the CURE code on the 704 and served as input data for the General Heat Transfer Code used.

The fluid temperature was considered constant at 0°F. Hence, all temperatures may be considered to be above this datum.

Heat was considered to escape from the solid only through the cylindrical outer surface since there is relatively poor heat transfer at the top end of the element (Fig. 1) and certainly no heat transfer at the cored surface during steady-state conditions. At the bottom end of the body the assumption of an insulated boundary was justified by the expectation that the axial temperature gradients will be nil there.

The heat generation rate at any point in the element was found by means of Figs. 2 and 3 which resulted from previously completed physics calculations on the thermal neutron flux. Figure 2 shows the axial variation of neutron flux with unity as the average value. Figure 3 gives the angular and radial dependence of the flux with unity again as the average. The angular dependence is shown for the inner and outer surfaces of the fuel pellet. Intermediate radial locations were assumed to be represented by Fig. 3 in such a way that at any angle the distance between the two curves shown in Fig. 3 would be proportioned in accordance with the position that the point in question had with respect to the inner and outer pellet surfaces. For example, a point halfway between the inner and outer surfaces of the pellet and 30 degrees off from the "zero degree plane" of Fig. 4 would have its θ and r dependence of heat generation rate determined by point M in Fig. 3, which is halfway

FIG. 2 AXIAL VARIATION OF HEAT GENERATION RATE

between points A and B.

It was assumed throughout the analysis that the axial and radial-angular flux dependence functions were independent of each other and so the factors from Figs. 2 and 3 could be multiplied by each other.

Since the temperature distribution in the rod is symmetrical about the "zero degree plane" of Fig. 4, only one half of the cylinder needed to be analyzed; the other half has a temperature structure which is the mirror image of the first.

Figure 4

The average heat generation rate in the volume of fuel in the reactor at full power is $3858 \text{ Btu/hr-in.}^3$

When the "top loading" scheme of refueling is resorted to the heat generation at the point of maximum surface temperature is 2.158 times the average; that is, $8326 \text{ Btu/hr-in.}^3$ For "inverted loading" the power at the region of maximum cladding temperature is 1.43 times the average or $5517 \text{ Btu/hr-in.}^3$ These values are multiplied by the

product of the factors obtained from Figs. 2 and 3 to ascertain the true value of the heat generation rate at any point in the fuel.

Conclusion

The results of the calculations are reproduced in Appendix A with the temperatures given in degrees Fahrenheit above the ambient fluid temperature. The first temperature quoted for any of the 763 points is for the case of "top loading" and the second temperature noted is the one which would result in the case of "inverted loading". Figure 1 illustrates the nomenclature used to determine locations in the body. Axial positions are designated by the letter of a plane normal to the axis of the cylinder, while the position in that plane is found by the position-number which ranges from 1 through 49.

Since the surface temperature of the rod is of interest in the fuel element design for such purposes as "hot spot" analysis, a contour map of the temperature field has been drawn for the cladding in Fig. 5. The figure is done for "top loading", the more severe case. For the same case Fig. 6, showing some isothermal surfaces in a three-dimensional pictorial representation of the temperature structure, has been included.

FIG. 5. CONTOUR PLOT OF CLAD TEMPERATURES

NOTE: ALL VALUES SHOWN ARE ABOVE
COOLANT TEMPERATURE

THREE DIMENSIONAL TEMPERATURE STRUCTURE
IN EGCR FUEL ROD END

FIGURE 4

SLR-103-8

APPENDIX A

<u>Point Number</u>	<u>Temperature</u>		<u>Point Number</u>	<u>Temperature</u>		<u>Point Number</u>	<u>Temperature</u>	
A1	56	37	C1	72	47	C44	72	47
A2	58	38	C2	76	50	C45	77	51
A3	59	39	C3	80	53	C46	102	68
A8	56	37	C4	107	71	C47	117	77
A9	58	38	C5	122	81	C48	126	83
A10	59	39	C6	131	86	C49	134	89
A15	55	37	C7	139	92			
A16	58	38	C8	71	47	D1	80	53
A17	58	39	C9	75	50	D2	85	56
A22	55	36	C10	80	53	D3	89	59
A23	57	38	C11	107	71	D4	111	73
A24	58	38	C12	122	80	D5	125	83
A29	54	36	C13	130	86	D6	134	88
A30	56	37	C14	139	92	D7	142	94
A31	57	38	C15	71	47	D8	80	53
A36	54	35	C16	75	49	D9	84	56
A37	56	37	C17	80	53	D10	89	59
A38	56	37	C18	106	70	D11	110	73
A43	53	35	C19	121	80	D12	125	82
A44	55	37	C20	130	86	D13	133	88
A45	56	37	C21	138	91	D14	142	94
			C22	70	46	D15	80	53
B1	60	40	C23	74	49	D16	84	55
B2	63	41	C24	79	52	D17	89	59
B3	64	42	C25	105	69	D18	110	73
B8	60	40	C26	120	79	D19	124	82
B9	62	41	C27	129	85	D20	133	88
B10	63	42	C28	137	90	D21	141	93
B15	59	39	C29	69	46	D22	79	52
B16	62	41	C30	73	48	D23	83	55
B17	63	42	C31	78	51	D24	87	58
B22	59	39	C32	104	69	D25	109	72
B23	61	40	C33	118	78	D26	123	81
B24	62	41	C34	127	84	D27	132	87
B29	58	38	C35	135	90	D28	140	92
B30	60	40	C36	68	45	D29	77	51
B31	61	41	C37	72	48	D30	82	54
B36	57	38	C38	77	51	D31	86	57
B37	60	39	C39	103	68	D32	107	71
B38	61	40	C40	117	78	D33	121	80
B43	57	38	C41	126	83	D34	130	86
B44	60	39	C42	134	89	D35	138	92
B45	61	40	C43	68	45	D36	77	51

<u>Point Number</u>	<u>Temperature</u>		<u>Point Number</u>	<u>Temperature</u>		<u>Point Number</u>	<u>Temperature</u>	
D37	81	53	E32	115	76	F27	156	103
D38	85	56	E33	129	86	F28	164	109
D39	106	70	E34	139	92	F29	91	60
D40	120	79	E35	147	97	F30	94	62
D41	129	85	E36	83	55	F31	100	66
D42	137	91	E37	88	58	F32	126	83
D43	76	50	E38	92	61	F33	143	95
D44	80	53	E39	113	75	F34	153	102
D45	85	56	E40	128	85	F35	162	107
D46	106	70	E41	137	91	F36	89	59
D47	120	79	E42	146	96	F37	93	61
D48	129	85	E43	83	55	F38	99	65
D49	137	90	E44	87	58	F39	124	82
E1	88	58	E45	92	61	F40	141	94
E2	92	61	E46	113	75	F41	152	100
E3	97	64	E47	128	84	F42	160	106
E4	119	78	E48	137	91	F43	89	59
E5	134	88	E49	145	96	F44	92	61
E6	143	94	F1	95	63	F45	98	65
E7	151	100	F2	99	65	F46	124	82
E8	87	58	F3	105	69	F47	141	93
E9	92	61	F4	131	86	F48	151	100
E10	97	64	F5	148	98	F49	159	105
E11	118	78	F6	158	105	G1	122	81
E12	133	88	F7	166	110	G2	128	84
E13	142	94	F8	94	62	G3	156	103
E14	151	100	F9	98	65	G4	251	166
E15	87	57	F10	104	69	G5	298	198
E16	91	60	F11	130	86	G6	316	209
E17	96	64	F12	148	98	G7	317	210
E18	118	78	F13	158	105	G8	121	80
E19	132	88	F14	166	110	G9	127	84
E20	142	94	F15	94	62	G10	155	103
E21	150	99	F16	98	65	G11	250	166
E22	86	57	F17	103	68	G12	297	197
E23	90	60	F18	129	86	G13	315	209
E24	95	63	F19	147	97	G14	316	209
E25	116	77	F20	157	104	G15	121	80
E26	131	87	F21	165	109	G16	126	83
E27	140	93	F22	92	61	G17	154	102
E28	149	98	F23	96	64	G18	248	164
E29	84	56	F24	102	67	G19	295	196
E30	89	59	F25	128	85	G20	313	208
E31	94	62	F26	145	96	G21	315	209

<u>Point Number</u>	<u>Temperature</u>		<u>Point Number</u>	<u>Temperature</u>		<u>Point Number</u>	<u>Temperature</u>	
G22	118	78	H17	230	152	I12	796	528
G23	123	81	H18	412	273	I13	761	504
G24	151	100	H19	491	325	I14	575	381
G25	244	162	H20	504	334	I15	206	136
G26	292	194	H21	466	309	I16	225	149
G27	311	206	H22	160	106	I17	361	239
G28	313	208	H23	168	111	I18	680	450
G29	115	76	H24	223	148	I19	789	523
G30	120	79	H25	405	269	I20	758	502
G31	147	97	H26	487	323	I21	574	381
G32	238	158	H27	505	335	I22	198	131
G33	285	189	H28	465	308	I23	216	143
G34	303	201	H29	155	103	I24	344	228
G35	307	203	H30	163	108	I25	666	442
G36	112	74	H31	216	143	I26	787	522
G37	117	78	H32	393	260	I27	785	521
G38	144	95	H33	470	312	I28	577	383
G39	233	154	H34	485	322	I29	192	127
G40	279	185	H35	451	299	I30	209	139
G41	297	197	H36	151	100	I31	333	221
G42	300	199	H37	159	105	I32	644	427
G43	111	74	H38	211	140	I33	754	500
G44	116	77	H39	383	254	I34	727	482
G45	143	94	H40	459	304	I35	554	367
G46	231	153	H41	473	313	I36	187	124
G47	276	183	H42	440	292	I37	204	135
G48	294	195	H43	149	99	I38	324	215
G49	298	197	H44	157	104	I39	627	416
			H45	209	138	I40	733	486
H1	167	111	H46	379	251	I41	705	467
H2	176	116	H47	453	300	I42	539	358
H3	233	154	H48	468	310	I43	184	122
H4	419	278	H49	437	289	I44	201	133
H5	496	329				I45	319	211
H6	507	336	I1	209	138	I46	619	410
H7	469	311	I2	228	151	I47	723	479
H8	166	110	I3	363	241	I48	694	460
H9	174	115	I4	694	460	I49	535	355
H10	231	153	I5	801	531			
H11	416	276	I6	762	505	J1	435	288
H12	494	327	I7	578	383	J2	459	304
H13	506	335	I8	207	137	J3	708	469
H14	468	310	I9	226	149	J4	1363	903
H15	165	109	I10	358	238	J5	1641	1088
H16	173	115	I11	687	455	J6	1716	1137

<u>Point Number</u>	<u>Temperature</u>		<u>Point Number</u>	<u>Temperature</u>		<u>Point Number</u>	<u>Temperature</u>	
J8	429	284	K10	831	551	L12	2054	1362
J9	452	300	K11	1600	1061	L13	2153	1428
J10	698	462	K12	1939	1285	L15	550	365
J11	1348	893	K13	2032	1347	L16	579	384
J12	1623	1076	K15	513	340	L17	863	572
J13	1697	1125	K16	540	358	L18	1659	1100
J15	420	278	K17	813	539	L19	2016	1337
J16	443	294	K18	1568	1040	L20	2115	1402
J17	683	453	K19	1903	1262	L22	536	355
J18	1322	876	K20	1996	1323	L23	564	374
J19	1595	1057	K22	500	331	L24	841	557
J20	1668	1106	K23	526	349	L25	1620	1074
J22	409	271	K24	792	525	L26	1971	1307
J23	431	286	K25	1531	1015	L27	2069	1372
J24	665	441	K26	1861	1234	L29	522	346
J25	1291	855	K27	1953	1295	L30	549	364
J26	1561	1035	K29	486	322	L31	818	542
J27	1635	1084	K30	512	339	L32	1580	1047
J29	397	263	K31	770	510	L33	1926	1277
J30	419	277	K32	1492	988	L34	2023	1341
J31	646	428	K33	1816	1204	L36	509	337
J32	1257	833	K34	1907	1265	L37	535	355
J33	1522	1009	K36	473	314	L38	798	529
J34	1594	1057	K37	498	330	L39	1544	1024
J36	386	256	K38	750	497	L40	1886	1251
J37	408	270	K39	1453	963	L41	1983	1315
J38	629	417	K40	1776	1178	L43	502	333
J39	1226	813	K41	1868	1238	L44	528	350
J40	1488	986	K43	467	309	L45	787	521
J41	1560	1035	K44	492	326	L46	1524	1010
J43	381	252	K45	739	490	L47	1866	1237
J44	402	266	K46	1437	952	L48	1963	1302
J45	619	410	K47	1758	1166	M1	584	387
J46	1208	801	K48	1850	1227	M2	614	407
J47	1471	975	L1	570	378	M3	912	605
J48	1546	1025	L2	600	398	M4	1744	1156
K1	532	352	L3	895	593	M5	2115	1402
K2	560	371	L4	1711	1134	M6	2215	1469
K3	843	559	L5	2074	1375	M8	577	382
K4	1618	1072	L6	2173	1441	M9	606	402
K5	1959	1299	L8	563	373	M10	900	597
K6	2052	1361	L9	592	392	M11	1725	1143
K8	525	348	L10	882	585	M12	2094	1388
K9	552	366	L11	1693	1122	M13	2195	1455

<u>Point Number</u>	<u>Temperature</u>		<u>Point Number</u>	<u>Temperature</u>		<u>Point Number</u>	<u>Temperature</u>	
M15	564	374	N17	882	584	P19	2044	1355
M16	593	393	N18	1691	1121	P20	2145	1422
M17	880	584	N19	2056	1363	P22	549	364
M18	1690	1121	N20	2157	1430	P23	577	383
M19	2056	1363	N22	552	366	P24	855	567
M20	2156	1430	N23	580	385	P25	1642	1089
M22	550	364	N24	860	570	P26	2000	1326
M23	578	383	N25	1651	1095	P27	2099	1392
M24	858	569	N26	2011	1333	P29	535	354
M25	1651	1095	N27	2111	1399	P30	562	373
M26	2010	1333	N29	537	356	P31	833	552
M27	2110	1399	N30	565	375	P32	1603	1063
M29	535	355	N31	837	555	P33	1954	1296
M30	563	373	N32	1611	1068	P34	2053	1361
M31	836	554	N33	1965	1303	P36	522	346
M32	1611	1068	N34	2064	1368	P37	549	364
M33	1964	1302	N36	525	348	P38	813	539
M34	2063	1368	N37	552	366	P39	1568	1040
M36	522	346	N38	817	542	P40	1916	1270
M37	549	364	N39	1577	1045	P41	2014	1335
M38	815	540	N40	1926	1277	P43	515	341
M39	1576	1045	N41	2025	1342	P44	542	359
M40	1925	1277	N43	518	343	P45	801	531
M41	2024	1342	N44	544	361	P46	1549	1027
M43	515	341	N45	805	534	P47	1896	1257
M44	542	359	N46	1557	1033	P48	1994	1322
M45	803	532	N47	1906	1264			
M46	1556	1032	N48	2005	1329	Q1	581	385
M47	1905	1263				Q2	611	405
M48	2004	1329	P1	583	386	Q3	906	600
N1	586	388	P2	613	406	Q4	1728	1146
N2	616	408	P3	909	602	Q5	2094	1389
N3	914	606	P4	1735	1150	Q6	2194	1455
N4	1744	1156	P5	2102	1394	Q8	574	380
N5	2114	1401	P6	2202	1460	Q9	603	400
N6	2214	1468	P8	576	382	Q10	893	592
N8	579	384	P9	606	401	Q11	1709	1133
N9	609	403	P10	897	594	Q12	2075	1375
N10	901	598	P11	1715	1137	Q13	2175	1442
N11	1725	1143	P12	2082	1380	Q15	561	372
N12	2094	1388	P13	2183	1447	Q16	590	391
N13	2195	1455	P15	563	373	Q17	874	579
N15	566	375	P16	592	393	Q18	1675	1111
N16	595	395	P17	877	581	Q19	2037	1350
			P18	1681	1115	Q20	2137	1417

<u>Point Number</u>	<u>Temperature</u>		<u>Point Number</u>	<u>Temperature</u>		<u>Point Number</u>	<u>Temperature</u>	
Q22	547	363	R24	850	563	S26	1984	1315
Q23	575	381	R25	1632	1082	S27	2083	1381
Q24	852	565	R26	1987	1318	S29	531	352
Q25	1636	1085	R27	2086	1383	S30	558	370
Q26	1992	1321	R29	532	352	S31	827	548
Q27	2092	1387	R30	559	370	S32	1590	1054
Q29	533	353	R31	828	549	S33	1939	1286
Q30	560	371	R32	1593	1056	S34	2037	1350
Q31	830	550	R33	1942	1288	S36	518	344
Q32	1597	1059	R34	2040	1353	S37	545	361
Q33	1947	1291	R36	519	344	S38	807	535
Q34	2045	1356	R37	546	362	S39	1556	1032
Q36	520	345	R38	808	536	S40	1901	1260
Q37	547	363	R39	1559	1033	S41	1998	1324
Q38	810	537	R40	1904	1262	S43	512	339
Q39	1563	1036	R41	2001	1327	S44	538	356
Q40	1909	1266	R43	512	339	S45	796	527
Q41	2006	1330	R44	538	357	S46	1536	1018
Q43	513	340	R45	796	528	S47	1880	1246
Q44	540	358	R46	1539	1021	S48	1978	1311
Q45	798	529	R47	1884	1249			
Q46	1543	1023	R48	1982	1314			
Q47	1889	1252						
Q48	1987	1317	S1	579	384			
R1	580	384	S2	609	404			
R2	609	404	S3	903	598			
R3	903	599	S4	1720	1140			
R4	1724	1143	S5	2085	1382			
R5	2089	1385	S6	2185	1449			
R6	2189	1451	S8	572	379			
R8	572	379	S9	601	398			
R9	602	399	S10	890	590			
R10	891	591	S11	1702	1128			
R11	1705	1130	S12	2066	1370			
R12	2069	1372	S13	2166	1436			
R13	2170	1438	S15	559	371			
R15	560	371	S16	588	390			
R16	589	390	S17	871	577			
R17	872	578	S18	1668	1106			
R18	1671	1108	S19	2028	1345			
R19	2032	1347	S20	2128	1411			
R20	2132	1413	S22	545	361			
R22	546	362	S23	573	380			
R23	574	380	S24	849	563			
			S25	1630	1080			

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